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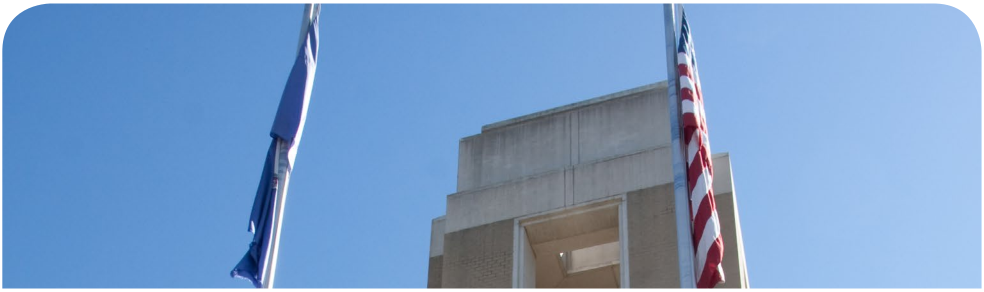

VIRGINIA JOURNAL OF SCIENCE

OFFICIAL PUBLICATION OF THE VIRGINIA ACADEMY OF SCIENCE

THE VIRGINIA JOURNAL OF SCIENCE

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James Madison University, Harrisonburg, Virginia

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Fall 2015

An Introduction for the Symposium

Richard S. Groover[1] and Werner Wieland[2]

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The Commonwealth of Virginia offers much diversity be it in the form of biota, topography, or habitat. Major rivers belong to Atlantic Ocean, Ohio River and Tennessee River drainages. The extreme southwestern part of the state is part of the Appalachian Plateau where elevations range from 2,700 to 3,000 feet. The highest mountain in Virginia, Mount Rogers (5,729 ft.), occurs in the Valley and Ridge Province. Along its eastern boarder lies the Atlantic coast with a series of barrier islands adjacent to the Eastern Shore. This 70-mile long region is part of the Delmarva Peninsula and is separated from the rest of Virginia by the Chesapeake Bay, the largest estuary in the contiguous United States.

The Commonwealth has numerous environmental challenges with which to contend. Pressures on land-use, water quality, air quality, and impact of climate change exist. The Virginia Academy of Science took the lead to offer summaries on numerous related topics, presented at the 93rd Annual Meeting of the Academy which was held at James Madison University. On May 21, 2015, sixteen speakers presented on the State of Virginia's environment. The Academy requested all speakers submit manuscripts of their presentations for publication of symposium proceedings in the Virginia Journal of Science. This issue includes articles covering plants, freshwater mussels, freshwater fishes, amphibians, birds and mammals as well as overviews of forests, seal level rise and air quality. Our objective is that this will provide a baseline for future statewide assessments.

The following individuals served as referees for manuscripts for this publication: Mark Bushnell, CoastalObsTechServices, LLC; W. Mark Ford, Unit Leader, Virginia Cooperative Fish and Wildlife Research Unit, Virginia Tech; Jason Gibson, Virginia Herpetological Society; Jason R. Hill, Virginia Department of Environmental Quality; Rebecca V. LePrell, Div of Environmental Epidemiology, Virginia Department of Health; Stephen McIninch, Center for Environmental Studies, Virginia Commonwealth University; Conley McMullen, James Madison University; Molly Mitchell (Roggero), Center for Coastal Resources Management, Virginia Institute of Marine Science; Karen D. Patterson, Virginia Department of Conservation & Recreation, Division of Natural Heritage; Karen Powers, Radford University; Gene Sattler, Liberty University; Scott M. Smith, Virginia Department of Game and Inland Fisheries; Chris Zervas, Planning Monitoring & Analysis Branch, National Oceanic and Atmospheric Administration. The Academy is grateful for their service by generously providing their expertise in the production of these proceedings. I wish to thank these individuals and the numerous others who have served as referees for articles in the Virginia Journal of Science while I (WW) was Editor. Without such contributions periodicals such as this could not function.

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Status of Plants in Virginia

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OVERVIEW OF BOTANICAL DIVERSITY

Virginia possesses a unique and varied assemblage of plant life. There are 3,164 species, subspecies and varieties of plants in Virginia (Weakley et al. 2012). As classified by the Virginia Departmentof Conservation and Recreation's Division of Natural Heritage (DCR-DNH), they form some 94 ecological groups and 317 community types across five distinct physiographic provinces: Coastal Plain, Piedmont, Blue Ridge, Ridge and Valley, and Appalachian Plateau. The state extends 469 miles from east to west and 201 miles north to south at the widest points, enclosing 42,326 square miles of territory. This diverse range of environmental conditions supports the wide diversity of plant life found within the state. Virginia is on the northern boundary of many southern plant species and on the southern boundary of many northern plant species. This range overlap combined with seashore to mountain variation leads to one of the richer diversities of plant life within the continental United States.

Virginia was the source of some of the earlier plant collections by European botanists (Berkeley and Berkeley 1963).Europeans started observing and documenting Virginia's flora as early as the 1500s (Hugo and Ware 2012). Over the next two centuries, there were various explorations and reports by laypersons and scientifically trained individuals. In the eighteenth century, there were significant contributions to the documentation and descriptions of plants in Virginia. In 1739 J. F. Gronovius published John Clayton's work titled *Flora Virginica* describing some 500 or so plant species (Hugo and Ware 2012). John Mitchell, James Greenway, and prominently, John Bartram wrote extensively about plants of Virginia. Later, such botanists as Andre Michaux, Asa Gray, and John Torrey published work that included plants of Virginia (Hugo and Ware 2012).

Work toward a new Flora of Virginia began in earnest in 1926 when the Virginia Academy of Science established a flora committee through the leadership of A.B. Massey of Virginia Polytechnic Institute (Hugo and Ware 2012). Through Massey's vision and the efforts of many subsequent scientists, a new Flora of Virginia was finally published in 2012 documenting 3,164 plant species, subspecies, and varieties in 189 families in the commonwealth of Virginia (Weakley et al. 2012).

The public charge to inventory and protect this wealth of plant biodiversity is given to the Office of Plant Protection within the Virginia Department of Agriculture and Consumer Services, which under the Virginia Endangered Plant and Insect Species Act has responsibility to list and protect Virginia's endangered and threatened plant species. There were 26 species listed in 2013, whereas there were 17 species listed under the federal Endangered Species Act of 1973 (Townsend 2014). The Virginia Endangered Plant and Insect Species Act also contains provisions for the recovery of endangered and threatened species in Virginia. The VDCR, DNH and the Virginia Department of

Agriculture and Consumer Services(VDACS) all work cooperatively with each other and with the US Fish and Wildlife Service to protect the natural biological diversity of Virginia.

The DNH has the charge to evaluate Natural Heritage Resources such as the habitats of rare, threatened, and endangered plant and animal species; exemplary natural communities, habitats, and ecosystems; and other natural features of the Commonwealth (Fleming and Patterson 2013). The DNH has defined 94 ecological groups and 317 community types within Virginia. Each community has been assigned a global and state conservation status rank based on the relative rarity or endangerment of the community. This is meant to provide a framework for setting conservation priorities while trying to balance economic development within the state. Of the 317 plant communities, 111 are considered to be critically imperiled (Fleming and Patterson 2013). There are 613 species included on the Rare Vascular Plant List in Virginia, and an additional 229 that are considered uncommon and placed on a Watchlist (Townsend 2014). There are also 46 species of nonvascular plants listed as Rare in Virginia (Table 1).

Endemics

Despite the overlap of northern and southern regions of plant growth in Virginia, there are some species found only in Virginia. There are five plant species endemic to Virginia: Virginia round-leaf birch (*Betula uber*), Addison's leatherflower (*Clematis addisonii*), Virginia white-haired leatherflower (*Clematis coactilis*), Millboro leatherflower (*Clematis viticaulis*), and Peter's Mountain-mallow (*Iliamna corei*).

Virginia is a land of transitions. From east to west, our lands transition from coastal plains to piedmont to mountains. Virginia is a transition zone between the northernmost range of southern species and the southernmost range of northern species. Also there is a high human impact factor within the state, disturbing many native habitats. This creates many unique habitats and may help explain why we have endemics with such limited ranges despite the great variety of plant life within the state.

Peter’s Mountain mallow (*Iliamna corei*) is limited to one site on Peter’s Mountain in Giles County. It is found only on shallow sandstone outcrops growing in full sunlight. It is a bushy-branched plant with erect stems and produces 15-20 pink flowers per plant. The fruit is a schizocarp (Weakley et al. 2012). Threats to this species include grazing, plant competition, shading, and fire suppression. This population is now protected by the Nature Conservancy and its partners, and is being carefully managed. The genus *Iliamna* contains only seven species and is restricted to North America.

Three of the endemics are in the genus *Clematis* in the Ranunculaceae. This genus has about 295 species distributed around the world. There are 11 species of Clematis in Virginia, including the three that are endemic to Virginia. Millboro leatherflower (*Clematis viticaulis*) is a small (2-4 dm) upright herbaceous plant with apetalous flowers with 2-4 cm styles and purplish sepals that form a bell-like structure. This species is limited to shale barrens and woodlands. Its range is restricted to Augusta, Bath, and Rockbridge counties(Weakley et al. 2012). Addison's leatherflower (*Clematis addisonii*) is limited to dolomitic outcrops in Botetourt, Montgomery, Roanoke and Rockbridge counties. The herbaceous plant can grow to 10 dm, at first erect, then

TABLE 1. Status and Rankings of Virginia Plants. [1]

Status	No. Species
Rare Vascular Plant Species	613
Uncommon Vascular Plant Species	229
Rare Nonvascular Plant Species	46
State-listed Endangered Plant Species	26
Federal-listed Endangered Plant Species	17
State Critically-Imperiled Vascular Plant Species	360
State Imperiled Vascular Plant Species	166
State Critically-Imperiled Nonvascular Plant Species	31
State Imperiled Nonvascular Plant Species	10
Highly Invasive Plant Species	32
Moderately Invasive Plant Species	32
Low Invasive Plant Species	16

[1] Data from Wilson and Tuberville (2003).

becoming procumbent. It has solitary, terminal apetalous flowers with reddish to bluish purple sepals forming a bell-shaped floral structure(Weakley et al. 2012).Virginia white-haired leatherflower (*Clematis coactilis*) occurs on shale, calcareous sandstone, dolomite, and limestone outcrops and barrens. It is restricted to mountainous counties of the Ridge and Valley region. This is a bushy herbaceous perennial growing to 2-4.5 dm with solitary, terminal apetalous flowers that have purplish sepals that appear white because they are densely plumose with white to pale-yellow hairs. The sepals form a bell-shaped floral structure (Weakley et al. 2012). All three *Clematis* species are perennials, which may aid in their survival and continuation of the populations. These species have elongated styles on numerous pistils and seeds are enclosed within achenes.

The Virginia round-leaf birch (*Betula uber*) was first collected in 1914 and described by Ashe in 1918 (Davis 2006). Subsequently, the tree was not seen again in the wild for some time and was presumed extinct (Mazzeo 1971, Smithsonian 1974).

In 1975, a small population of *B. uber* was discovered in Smythe County, Virginia (Ogle and Mazzeo 1976). Efforts were undertaken to propagate, distribute and protect individuals of this species. Trees were located at the Reynolds Homestead, the National Arboretum, and on other public and private lands (Davis 2006). In addition to traditional methods of propagation, Virginia round-leaf birch has been successfully propagated from dormant buds (Vijayakumaret al.1990) and by in vitro nodal culture (Jamison and Renfroe 1998).

The Virginia round-leaf birch is a small tree (7.6-14 m), with dark aromatic bark, and ovate or short elliptic leaves with rounded or obtuse apex, and a cordate base (Mazzeo 1971, Ogle and Mazzeo 1976). Leaf shape and fruit characteristics in *B. uber* are significantly different than *B. lenta*(Sharik and Ford 1984). Leaf shape difference is maintained in pure populations over decades (Sharik and Ford 1984). *B. uber* has a more compact crown than *B. lenta*. There are chemical distinctions between *B. uber* and *B. lenta*, such as the presence of rhododendrin (Santamour and Vettel 1978). Although wood anatomy is similar between *B. uber* and *B. lenta* (Hayden and Hayden 1984), this should not be surprising since they belong to a common clade (Li et al. 2005). Thomson et al. (2015) suggest that *B. lenta* and *B. uber* possibly have a shared ancestry.

Weakley et al. (2012) relegate Virginia round-leaf birch to varietal status as *Betula lenta* L. var. *uber* Ashe. McAllister and Ashburner (2004) question the species status of *B. uber* based upon variability of leaf traits in a small population of presumptive selfed seedlings. However, other authorities still recognize this as a distinct species of birch including the *Flora of North America* (Furlow 1997). Although several investigations have employed molecular data approaches to resolve the phylogenetic relationships of the birches (Jarvinen et al. 2004, Li et al. 2005, Schenk et al. 2008), only one included *B. uber*, which separated it from *B. lenta* based on sequences of the internal transcribed spacer region of nuclear ribosomal DNA (Li et al. 2005). Mazzeo (1971) recognized *B. uber* as a valid species. Ogle and Mazzeo (1976) noted significant differences among *B. uber*, *B. lenta*, and *B. alleghaniensis* in the field. An examination of trees in the area revealed no apparent hybrids, and as a population, *B. uber* showed a strong uniformity.

Davis (2006) reviewed previous studies of *B. uber* and *B. lenta* and indicated that hybridization studies used to delineate traits were based upon plants that had been growing in close proximity. It is well established and widely recognized that birches readily hybridize (Woodworth 1929, Johnsson 1945, Elkington 1968, Guerriero et al. 1970,Sharik and Barnes 1971, Barnes et al. 1974, Eriksson and Jonsson 1986,Wilsey et al. 1998, Palme et al. 2004). Therefore, it calls to question whether studies of presumptive *B. uber* individuals are truly *B. uber* or whether they may have been introgressed with *B. lenta*. Ogle (2003) recommends that direct DNA testing be performed on the known populations of *B. uber* and *B. lenta* to help resolve the status of this species.

Virginia round-leaf birch is protected by the Endangered Species Act. Following its rediscovery, it was classified as endangered. Recovery efforts toward this species have resulted in a sufficient number of breeding populations such that the status of this species subsequently has been changed from endangered to threatened (USFWS 1994).

HISTORICAL PERSPECTIVE

Around 5000 BC, the general flora of modern eastern U.S. became established. Over the next couple of thousand years, the eastern US experienced a general warming trend. Oak species became prevalent in southwestern Virginia between 3000-2500 BC. In addition, chestnut and hickory trees became an important part of the mixture of trees during this period of warming and dry climate. Oaks, chestnuts, and hickory trees helped support the indigenous people, who began to migrate seasonally into this area around 3000 BC. By 1000 BC, Amerindians began to settle in the eastern US and began a culture of autonomous populations that lasted until European contact (Sarvis 2011).

Around 500 BC to 900 AD, maize was introduced into Virginia by native Americans and populations started to become more settled and less nomadic. During this time, there is evidence of tree girdling and slash-and-burn techniques being introduced. Distinct natural zones developed in Virginia based on geographical variations between the Coastal Plains, Piedmont, Ridge and Valley region, and Appalachian plateau. Indigenous populations developed distinctive cultures reflecting the unique natural resources by which they were surrounded. Improved strains of corn became prevalent and the cultivation of beans began. Southwestern Virginia was a region in which numerous native populations overlapped for hunting purposes, but was not heavily populated. Sioux, Shawnees, Delawares, Catawbas and Tuscaroras all spent time in Virginia hunting, harvesting, and living in transient camps. Native American populations had a fairly minimal impact on the flora of southwestern Virginia (Sarvis 2011).The Cherokee and Shawnee tribes hunted throughout southwestern Virginia. The Cherokee became well-acquainted with the plants not only as a source of food, but also for medicinal uses (Hamel and Chiltosky 1975).

Contact with Europeans during the 1600s led to changes in Amerindian populations. European demand for pelts and hides led to overhunting of deer and other animal populations, and the introduction of European diseases such as smallpox decimated Amerindian populations in the eastern US. By the mid-to-late 1700s, Europeans settlers had made their way into the western areas of Virginia (Sarvis 2011). As Europeans occupied the valley areas of Virginia, they cleared the land, introduced domesticated livestock and began the cultivation of corn, wheat, rye, and oats. Europeans brought potatoes, peach and apple trees, and many other species. They introduced new forage grasses to support their introduced livestock. Kentucky bluegrass, timothy, redtop, white clover and other species were introduced, along with pastoral species such as daisies, yarrow, dandelion, buttercup, garlic mustard, and other species. As native flowering plants became scarcer and forests were cleared, native bee species decreased and Europeans introduced the European honeybee. Tobacco (*Nicotianatabacum*) was introduced as an agricultural commodity and had a major impact on land-clearing and farming in Virginia.

Bottomlands were cleared for growing corn, wheat, rye, and oats. Hillsides were cleared for grazing. Wildlife populations were drastically altered, which had an impact on plant growth and forest regeneration. Forests continued to provide non-timber products such as ginseng, galax, elderberry flowers, polkberries, buck vine, lobelia, moss and cherry bark (Sarvis 2011).

During the 18th and 19th centuries, much of the forest, especially in the bottomlands was cleared. Charcoal production for furnaces and forges led to major tree cutting, as one charcoal iron furnace could consume wood from an acre of land per day. Wythe and Carroll Counties had extensive forest clearing in support of charcoal iron production. Salt production in Saltville consumed about six cubic feet of hardwood per bushel of salt produced by boiling off brine, with peak production of around 4 million bushels per year. In 1880, Virginia salt production consumed about 550,000 cords of wood. Development of railroads and industrial logging led to much more extensive deforestation into the mountainous areas of the state (Sarvis 2011).

Land clearing and overcultivation led to erosion. Growth of cities and industry after the Civil War led to heavy demand for coal, timber and tannin. Development of the railroad industry in the mid-1800s increased timbering and mining in the mountain regions of the state. Stream siltation and flooding increased, causing loss of life and property. Fire also destroyed much of the cutover forest land. The Massanutten range was largely denuded of trees between 1850 and 1880, then experienced many fires that burned over the remaining trees and killed off regeneration (Satterthwaite 1993).

From around 1890 to 1920, industrial timbering and railroad construction led to massive deforestation along the Appalachians. Only the drastic drop in timber prices associated with the Great Depression slowed the deforestation. The U.S. Department of Agriculture established the Division of Forestry in 1881, which became the U.S. Forest Service in 1905 under President Theodore Roosevelt, with Gifford Pinchot becoming the first Chief. The Forest Reserve Act of 1891, along with the Weeks Act of 1911 laid the foundation for the federal government to acquire land and hold it in the public trust to protect watersheds and maintain navigable waters by conserving forest land. The Weeks Act created a National Forest Reservation Commission. During the first several decades of the twentieth century, major land purchases were made from private individuals, corporations, and state governments. Such purchases in Virginia led to the formation of the Jefferson National Forest and the George Washington National Forest (Sarvis 2011).

Three northern Virginia purchase units (Potomac, Massanutten Mountain, and Natural Bridge Purchase Units) were combined in 1917 to form the Shenandoah National Forest. In 1932, the forest was renamed George Washington National Forest to avoid confusion with Shenandoah National Park, also located in Virginia (Satterthwaite 1993).

In the Depression era, the Civilian Conservation Corps (CCC) engaged in replanting forests and began an important program of fire protection. Indigenous Americans used fire in the forest, but not in the way that wild fires decimated the cutover lands following the industrial period of deforestation and land abandonment. Forest protection from fire became an important strategy of the Forest Service, and the CCC provided road and trail construction along with building fire lookout towers, and even engaged in fire suppression (Sarvis 2011).

The national consciousness regarding fire in the forest had been irrevocably altered by events such as the Big Burn that occurred in 1910. Following an extensive drought, fires started in Idaho and spread into Montana and Washington, burning an area the size of the state of Connecticut in 48 hours. Fire swept across the northern Rockies and made its own weather system, racing along until more than three million acres burned and one billion dollars worth of wood was consumed (Egan 2009). Rain and snow of late August finally extinguished the fire. Soot darkened sunsets in Boston, and covered snow in Greenland.

The massive destruction, loss of human life, loss of towns and property, and loss of natural resources of the forest had a profound effect on the perspective of the Forest Service in shaping their view of forest fire suppression. Gifford Pinchot, first Chief Forester of the U.S. Forest Service, regarded loss of forest to fire as a waste of natural resources and understood forest fires to be "wholly within the control of men" (Pinchot 1967). For the newly formed U.S. Forest Service, fire prevention became a top priority that would be maintained for decades.

Workers in the CCC were used to replant forests. White pine was one of the species extensively planted in Virginia. It was during the 1930s that the Chestnut blight was decimating populations in Virginia, and that white pine blister rust started spreading through the Appalachians. Control measures were taken including eradicating the rust's alternate hosts, currant and gooseberry plants, within 900 feet of white pines. As severe as the blister rust epidemic was, it paled in comparison to the devastation caused by the Chestnut blight. In some areas, chestnuts constituted 60-90 % of the standing trees. The forest composition was radically altered by these diseases (Sarvis 2011).

As agriculture and forestry advanced over the decades, they had a major financial impact on the economy of Virginia. In 2006, agriculture-related industries generated over $55 billion and produced 357,100 jobs, while forestry generated over $23 billion and produced 144,400 jobs (Rephan 2008). In 2011, agriculture-related industries generated over $52 billion and produced 310,900 jobs. Forestry generated some $17 billion and produced some 103,800 jobs (Rephan 2013). About 62% of Virginia's forest land is in private hands, held by over 373,600 forest landowners (VDOF 2014a). Corporate forest holdings account for 19% of Virginia's forests, with the forest products industry holding only about 1% (186,700 acres).

Virginia has lost over 500,000 acres of forest land since 1977 (VDOF 2014a). Most of the forests in Virginia are composed of upland hardwood species (61%) and oak-pine mixtures (11%). Pine plantations form 13% of Virginia's forest lands, with 7% of the lands covered in natural pine stands. One of our more valuable pine species, longleaf pine (*Pinus palustris* P. Miller) was decimated by human harvesting following European colonization. Between 1500 and 1850, the longleaf pine population lost over 1 million acres. Today, there are fewer than 200 native longleaf pine trees left in Virginia, but the Department of Forestry has initiated a program to search for seed sources similar to our native populations and start replanting this species back into its native range (VDOF 2014a, VDOF 2014b).

Great Dismal Swamp

One of the unique features of the Coastal Plain is the Great Dismal Swamp located in southeastern Virginia and northeastern North Carolina. The swamp covers about 104,000 ha, and bears the scars of heavy human disturbance (Levy 1991, Whitehead 1972). The Great Dismal Swamp covers some 750 to 1000 square miles of land, about 40% of which lies within Virginia (Davis 1962). Pollen analysis reveals that this land mass has developed through various developmental changes in composition, first supporting a pine-spruce forest, later replaced by a beech-hemlock-birch forest, replaced by an oak-hickory forest, and finally developing into the cypress-gum assemblage some 3,500 years age. The cypress-gum community consisted largely of cypress (*Taxodium distichum*), black gum (*Nyssa sylvatica*), tupelo gum (*Nyssa aquatica*), Atlantic white cedar (*Chamaecyparis thyoides*), red maple (*Acer rubrum*), Carolina ash (*Fraxinuscaroliniana*), loblolly pine (*Pinus taeda*), pond pine (*Pinus serontina*), willow oak (*Quercus phellos*), sweet gum (*Liquidambar styraciflua*), tuliptree (*Liriodendron tulipifera*), holly (*Ilex opaca*) and other species (Whitehead 1972).

Indigenous Americans occupied this area from as early as 12,000 years ago, and were present as the land transitioned into the marsh and swamp. The area was most heavily occupied from about 9,000 to 3,500 years ago, with humans living in and around the area for hunting, fishing, and foraging. Palynological research indicates that maize was present in the swamp about 3.000 years ago, suggesting that native Americans were already cultivating corn in this area (Bradley 2013). European colonization of Virginia and North Carolina would drastically alter the nature of the Great Dismal Swamp. The development of settlements in the Norfolk area in the 1620s and around Suffolk in the 1630s-1640s brought European settlers in close contact with the swamp.

George Washington and a group of other land speculators formed the Dismal Swamp Land Company and in the early 1760s got permission from the Virginia General Assembly to drain and farm 40,000 acres located in the Virginia portion of the swamp. This turned out not to be an easy task. Despite some limited production of rice and corn, Washington and others lost interest in the venture and shortly after the War of 1812, they turned their interests elsewhere (Bradley 2013). The soil beneath the swamp is not suitable for cultivation and is probably what has spared the total clearing of the swamp during historical times (Davis 1962).

The Great Dismal Swamp provided wood for Colonial America. Pine, maple, juniper and cypress provided wood for fencing, buckets, barrels, framing, siding, and shingles. Wood was also used in shipbuilding and charcoal production. Naval stores, pitch, turpentine, and tar were produced from pines from the Great Dismal Swamp (Davis 1962). Despite the lack of agricultural success, the Great Dismal Swamp was heavily logged with most of the cypress being removed for the production of shingles. Canals were cut through the swamp to facilitate transport of logs and in the 1830s to drain lands to enable companies to bring in railroads, establishing more logging camps within the swamp (Bradley 2013). Logging continued at a more advanced rate into the 20th century, with most of the land being privately owned. In the 1900s, the emphasis shifted to logging Atlantic white cedar. Logging of cedar in the Great Dismal Swamp was especially heavy during the first and second World Wars. During World War I, over 20 million board feet (b.f.) of cedar was removed from the swamp per year for several years, and production peaked at 5 million b.f. during World War II (Ward 1989).

In 1973, the Great Dismal Swamp was designated a wildlife refuge, becoming federally protected and managed. Efforts are underway to restore Atlantic white cedar through reforestation. Current research shows that rooted cuttings of Atlantic white cedar grow best at intermediate elevations. On high mounds, Atlantic white cedar may have difficulty with competition from plants such as sweet pepperbush (*Clethra alnifolia*), and may have increased mortality in low sites associated with deep pools (Brown and Atkinson 1999). Studies following cedar regeneration after the forest destruction caused by Hurricane Isabel in 2003 demonstrated that natural disturbances can lead to compositional changes in the forest and depression of cedar regeneration. Without salvage logging, an increase in red maple growth occurred, whereas on salvage logged plots, cedar seedling regeneration constituted the majority of seedlings present (Belcher et al. 2006).

Not all of the Great Dismal Swamp property is contained within the Refuge. Some success has been achieved in protecting more of the land. In 2007, Ecosystem Investment Partners (EIP), a private equity firm, acquired 1,030 acres within the acquisition boundary of the Great Dismal Swamp National Wildlife Refuge in southeastern Virginia. The property had been used as farmland previously. EIP is selling endangered species mitigation credits, and once all the credits are sold, EIP plans to transfer the property to either the Wildlife Refuge or to another private landowner who would be bound to conservations easements (EIP 2010).

PHYSIOGRAPHIC DISTRIBUTION OF PLANTS

Virginia's plant communities are a reflection of the physiographic properties of the state. These communities are described in detail by the Natural Heritage Program (Wilson and Tuberville 2003). The Cumberland Mountains in the southwestern portion of Virginia are characterized by a mixed mesophytic forest with various oak and hickory species, along with beech, sugar maple, eastern hemlock, yellow poplar, birches and other tree species. There are 82 rare species within this province (Table 2). The Ridge and Valley and Allegheny Mountain Provinces contain many oak species (chestnut, scarlet, white, black, and northern red), along with various hickories. At higher elevations, birches and sugar maple are present, and red spruce is found at the highest elevations. Beech and cherry are also mixed in the higher Allegheny Mountains. There are also small communities of red spruce-hemlock swamps and bogs. There are 503 rare species within this area. The Northern Blue Ridge Physiographic Province has a mixed oak and oak-hickory forest cover that includes yellow poplar and supports 130 rare species. The Southern Blue Ridge Physiographic Province has many communities including mixed oaks, oak-hickory, northern hardwood forests, relict stands of red spruce and fraser fir, and rare wetlands such as The Glades near Galax. Within this province, there are 136 rare species.

TABLE. 2. Distribution of rare plant species across Virginia physiographic provinces.[1]

Province	No. Rare plant species
Cumberland Mountains	82
Ridge and Valley/Allegheny Mountains	503
Northern Blue Ridge	130
Southern Blue Ridge	136
Northern Piedmont	108
Southern Piedmont	147
Northern Coastal Plain	125
Southern Coastal Plain	174
Outer Coastal Plain	190

[1] Data from Townsend (2014).

The Northern Piedmont Physiographic Province contains mixed oak forests and mixed hardwood forests with oaks, beech, yellow poplar, hickories, and ash. There are 108 rare species located in this province. The large Southern Piedmont Physiographic Province contains mixed oak and mixed hardwood forests. Additional species that appear in these forests include yellow poplar, sweetgum, Virginia pine, and loblolly pine. There are 147 rare species found within this province (Wilson and Tuberville 2003).

The Northern Coastal Plain Physiographic Province reflects a history of land clearing for agriculture, and repeated forest harvests. The forests here consist of secondary mixed oak and mixed hardwood forests including oak, beech and yellow poplars. Pines, especially planted loblolly, are prevalent. Mountain-laurel establishes dense undergrowths in areas. There are 125 rare species present. The Southern Coastal Plain Physiographic Province historically contained longleaf pine and pond pine, both fire-dependent species. There were also beech, oaks and hickories in ravines, and baldcypress and tupelos in swampy bottomlands. Loblolly is the most common pine today due to replanting practices. There are 174 rare species located within this province. The Outer Coastal Plain Physiographic Province covers the eastern shore and the peninsula off the coast of Virginia. Maritime upland forests are present and include loblolly pine and live oak. Special features of this province include Atlantic white cedar swamps, coastal dunes, pocosins, and other rare communities. Within this province there are 190 rare plant species (Wilson and Tuberville 2003).

PLANTS IN AGRICULTURE

Virginia has a long history of agriculture. Farmland covers about 32% of Virginia, amounting to some 7.9 million acres (VDACS 2015a). Agriculture contributes about $52 billion to the economy each year and provides over 300,000 jobs (Rephann 2013). The allocation of farmland to various crops fluctuates with commodity prices and subsidies. Between 2006 and 2011 vegetable production declined, but soybean, corn and wheat production increased (Rephann 2013). The top fourteen commodities (Table 3) generated cash receipts of about $1.4 billion(VDACS 2013). Soybeans, corn and wheat are the commodities covering the most acreage of farmland (Table 4).

Over 1.4 million acres were dedicated to forage and silage in 2012. Over 3 million acres were used for pasture, with another 434,000 acres of pastured woodland. Over 2 million acres of farmland were wooded (NASS 2014b). In 1997, Virginia had 28,806 acres in orchards. Orchard acreage fell to 26,354 acres in 2002 and to 19,114 in 2012 (NASS 2014a). Over 300 acres of apple orchards went out of production between 2013 and 2014.

Virginia is becoming well-known as a wine producing state. In 2013, Virginia produced 4,942 tons of grapes from Vinifera grapes, 412 tons of grapes from American grapes, and 1,507 tons from hybrid grapes (Virginia Wine Marketing Office 2014). The top producing counties are Loudoun with 1,046 tons, Orange with 1,042 tons, and Albemarle at 1,013 tons. There were 3,089 acres in vineyards in 2013.

Well-managed agricultural systems provide soil retention, food production, carbon sequestration, and aesthetics. Agricultural ecosystems rely on other ecosystems for pollination services. Agricultural mismanagement can have adverse effects on surrounding ecosystems through soil erosion and deposition, stream siltation, pesticide runoff, fertilizer runoff, fecal contamination, and production of volatile organic compounds (Dale and Polasky 2007).

THREATS TO PLANT BIODIVERSITY

Plant biodiversity in Virginia faces a number of threats (Table 5). Non-native or exotic plants can invade, outcompete, and/or inhibit native plant populations. Diseases and insects have had and continue to have major impacts on entire ecosystems. The presence of browsers along with the loss of pollinators and animal dispersers has an impact on plant populations. Finally, forest mismanagement and land development greatly affect plant biodiversity.

Exotic Plants

Non-native plants have been a part of the Virginia landscape since European populations arrived on America's shores. Many non-native plants have escaped cultivation and become naturalized. Non-native species were brought to America as crops, culinary herbs, medicinal plants, and ornamentals. Unfortunately, some introduced species have become competitors with native species, displacing native populations, and altering ecosystems. Invasive species displace native species not just

TABLE 3. Economic value of leading commodities in Virginia during 2011 and 2013.[1]

Commodity	Cash Value (millions)	
	2011	2013
soy beans	302	284
greenhouse/nursery	272	263
grain corn	212	171
hay	123	124
winter wheat	109	120
tobacco	109	113
cotton	69	65
tomatoes	62	37
apples	54	33
peanuts	24	31
potatoes	15	15
cottonseed	12	12
barley	12	9
grapes	11	10
Total	1,386	1,287

[1] Data from VDACS (2013, 2015a).

by offering competition, but also by inhibiting growth of mycorrhizal fungi that are important to the growth of native species (Callaway et al. 2008).

Over 2500 non-native species have become naturalized in the U.S. (Mack 2003). As early as the establishment of the Plymouth Colony in 1620, European species were introduced into the eastern seaboard of America. By 1671, accounts indicated that many of our common exotic weed species had escaped and were well established outside of cultivation. Over the next 350 years, ornamental species became the largest

TABLE 4. Crop acreage and yields of selected crops in Virginia in 2012[1]

Crop	Acres	Yield	Units
soybeans	578,852	22,680,879	bushels
grain corn	338,132	33,984,647	bushels
grain wheat	241,979	14,804,947	bushels
winter grain wheat	240,208	14,701,510	bushels
barley	37,023	2,905,047	bushels
grain rye	4,291	157,851	bushels
grain sorghum	4,043	258,000	bushels
oats	3,456	238,928	bushels
spring grain wheat	1,771	103,437	bushels
Cotton	89,072	191,513	bales
tobacco	22,982	53,179,801	pounds
peanuts	20,208	81,182,563	pounds
potatoes	5,423	1,350,000	cwt

[1] Data from USDA NASS 2012 Census of Agriculture.

category of imported species contributing to the host of exotic species in the United States. Asa Gray, visiting Winchester at the northern end of the Shenandoah Valley in June 1841 noted fields overrun with viper's bugloss (*Echium vulgare*). Japanese honeysuckle (*Lonicera japonica*) was documented in the wild by 1860 (Mack 2003).

Japanese honeysuckle is a climbing vine that will shade out the canopy of trees and kill them from above ground competition or by girdling. It also makes tree crowns more susceptible to snow and ice damage by increasing the weight load on the crowns during snow and ice events. In addition to above ground competition, below ground competition with trees by honeysuckle has a greater effect on tree growth than native vine species such as Virginia creeper (*Parthenocissus quinquefolia*) (Dillenburg et al. 1993). Japanese honeysuckle reduces pine seedling growth by interference and light competition, and litter from Japanese honeysuckle, whether on top of the soil, or incorporated, also reduces growth of pine seedlings, indicating a possible allelopathic

TABLE 5. Major threats to plant biodiversity in Virginia.

Exotic Plants	Pathogens	Insects	Other
Japanese honeysuckle	Chestnut blight	Gypsy moth	White-tailed deer
Amur honeysuckle	Dogwood anthracnose	Hemlock woolly adelgid	Loss of pollinators
Garlic mustard	Dutch elm disease	Emerald ash borer	Loss of fruit dispersers
Japanese stiltgrass	Thousand cankers disease	Kudzu bug	Loss of seed dispersers
Multiflora rose			Forest mismanagement
Japanese barberry			Fire exclusion
Phragmites			Land development
Russian olive			Climate change
Autumn olive			
Tree of heaven			

component (Skulman et al. 2004). Removal of Japanese honeysuckle vines from sweetgum (*Liquidambar styraciflua*) boles and branches results in increased stem diameter (Whigham 1984). However, removal of vines from trees and ground results in an even larger effect, indicating that competition for soil factors and/or allelopathy plays a role in the deleterious effects of vine growth on mature trees.

Japanese honeysuckle is dispersed by birds (Naumann and Young 2007), and is an invasive species from the mountains of Virginia to the coastal forests and the maritime forests of the barrier islands (DCR 2009, Naumann and Young 2007). *Lonicera japonica* has lower herbivory rates in the southeastern United States than the native species *Lonicera sempervirens*, giving Japanese honeysuckle a distinct competitive advantage compared to native species (Schierenbeck et al. 1994).

The exotic, invasive shrub bush honeysuckle or Amur honeysuckle (*Lonicera maackii*) reduces growth and fecundity in three native plants, *Allium burdickii*, *Thalictrum thalictroides*, and *Viola pubescens* (Miller and Gorchov 2004). Extracts of leaves and roots of Amur honeysuckle inhibit germination of seeds of *Impatiens capensis*, *Alliaria petiolata*, and *Arabidopsis thaliana* without any evidence of autotoxicity (Dorning and Cipollini 2006). Both species richness and abundance are reduced under crowns of *L. maackii* (Collier et al. 2002). In addition to deleterious effects on the herbaceous layer, bush honeysuckle increases mortality of native tree seedlings including *Acer saccharum*, *Fraxinus americana*, *Quercus rubra*, and *Prunus serotina* (Gorchov and Trisel 2003). Bush honeysuckle does not have a strong seed dormancy and, following dispersal, can have seedling establishment under various light conditions throughout fragmented forests (Luken and Goessling 1995). *L. maackii* can be controlled by stem injection with herbicide on larger stems and by cut and painting with herbicide on smaller stems (Hartman and McCarthy 2004).

Garlic mustard (*Allaria petiolata*) was brought to America by Europeans as a culinary herb. It has since become a widespread and aggressive invasive species

(Eschtruth and Battles 2009). Garlic mustard inhibits mycorrhizal fungi and lowers the viability and infectivity of arbuscular mycorrhizae spores. Garlic mustard also alters the bacterial communities in American soils, but not in European soils where it is native. Furthermore, garlic mustard, by affecting mycorrhizal fungi, also decreased emergence, growth, and survival of mycorrhizal-dependent plants (Callaway et al. 2008). Canopy disturbance is not an important factor in garlic mustard invasions (Eschtruth and Battles 2009). Such effects can explain why invasive species become so successful in exotic locations. Invasive species can interact with communities in complex fashions, which can lead to more profound interactions than might initially seem likely.

Japanese stiltgrass (*Microstegium vimineum*) is another widespread aggressive invasive species. Japanese stiltgrass is able to invade relatively undisturbed, late-successional forests. Canopy disturbance is not necessary for this annual grass to invade due to an extremely plastic response to shade (Eschtruth and Battles 2009). Japanese stiltgrass is more competitive in high light conditions such as along roadsides, whereas populations growing in low light conditions such as in forest interiors produce less biomass, fewer flowers and set fewer seeds (Huebner 2010). Two-year-old seedlings of northern red oak (*Quercus rubra*), sugar maple (*Acer saccharum*), and yellow poplar (*Liriodendron tulipifera*) are able to escape competition from Japanese stiltgrass, although sugar maple and yellow poplar survival is reduced. This would suggest that planting woody seedlings over top of Japanese stiltgrass may be useful in planning forest regeneration (Beasley and McCarthy 2011).

In the more mesic environment of the Allegheny Plateau and the more xeric environment of the Ridge and Valley Province, Japanese stiltgrass has been shown to grow slowly in forest interiors, and can become established, even without disturbance (Huebner 2010). This demonstrates the necessity of maintaining a healthy tree seedling population to help reduce *Microstegium* establishment inside forest stands. *Microstegium* grows along roadsides in a competitive manner (Huebner 2010).

Multiflora rose (*Rosa multiflora*Thunb.) was introduced into the U.S. by 1886 and was planted as a hedgerow in the 1930s. Multiflora rose has become invasive and is associated with disturbed sites. It can tolerate soils with low fertility, but grows best in fertile soils, invading pastures and forests (Huebner et al 2014). Multiflora rose propagates locally by vegetative propagation and is widely dispersed by bird species (Naumann and Young 2007).

Japanese barberry (*Berberis thunbergii*) is an exotic invasive plant species that is widespread and aggressive. Barberry is more dependent upon canopy disturbance than some other invasive species. Species richness does not appear to strongly affect invasion by exotic plants (Eschtruth and Battles 2009) such as barberry and others.

Phragmites australis is an invasive species that spreads vigorously in wetlands. Created wetlands in eastern Virginia are often heavily infested with *Phragmites*. These created wetlands often have shallow sediment thickness that favors the spread of *Phragmites*. This suggests that disturbance of existing wetlands and the creation of new wetlands as mitigation efforts may favor invasive species over native species (Pyke and Havens 1999).

Natural wetlands are being replaced by constructed wetlands in Virginia as a mitigation effort by industry, developers, and agricultural ventures. An extensive survey of constructed wetlands in Virginia has revealed that 80% of these wetlands are colonized by the invasive species *Phragmites australis*. Aggressive species of *Typha* were also present. *Phragmites* displaces native plant species and could overrun the constructed wetlands before the mid-21st century (Havens et al. 1997).

In a study of all constructed wetlands over an acre in size in the coastal plain of Virginia, 73% were found to be colonized by *Phragmites australis* (Havens et al. 1997). *Phragmites* appears to be limited by extreme nutrient deficiency or high salinity. *Phragmites* spreads by rhizomes to develop a pattern of circular patches. Growth rates indicate that *Phragmites* could dominate constructed wetlands within 40 years. Thus wetlands constructed for mitigation would not be representative of wetlands that had been destroyed (Havens et al. 1997).

A number of exotic tree species have become established outside of cultivation in Virginia. *Paulownia tomentosa* (Thumb.) Steud. is an Asian tree species that has become naturalized in the US, but is not invasive. It produces small populations that arise primarily from large-scale disturbances (Williams 1993), but is not considered particularly invasive. *Pyrus calleryana* is an escaped tree species that has spread from cultivation. This species hybridizes with other *Pyrus* species and has been spreading since the 1950s inside the United States. *Pyrus calleryana* is considered invasive. There are few, if any, natural controls for this species (Vincent 2005).Russian olive (*Elaeagnus angustifolia* L.) is spreading and forming extensive populations that are displacing native species, and is especially a problem in riparian zones and wetlands (Stohlgren 2003). Autumn olive (*Elaeagnus umbellata*Thunb.) tends to form dense monotypic stands. It can grow in shade as an understory tree or can colonize fields and disturbed sites. It produces prolific fruit and is readily dispersed by birds. It grows rapidly, survives in poor soil and resprouts following cutting or burning.

Ailanthus altissima, commonly known as tree-of-heaven, is an invasive woody species widely distributed in the state from the mountains (Kowarik 1995) to the shore (Naumann and Young 2007). This tree has been shown to differentially suppress native herbaceous species while allowing growth of non-native herbaceous species (Small et al. 2010). This may well encourage the spread of other non-native species along with *Alilanthus*. *Ailanthus* produces allelopathic compounds such as ailanthone (Heisey 1996), which exhibits strong phytotoxic properties. Phytotoxins are produced in *Ailanthus* leaves and stems, and accumulate in soil surrounding the trees (Lawrence et al. 1991). The combination of allelopathy and competition with native plants makes *Ailanthus* a problematic species. In addition, *Ailanthus* reproduces sexually and asexually, and rapidly becomes invasive to native plant populations.

Ailanthus establishes large clonal populations by root suckering (Kowarik 1995), and is also wind-dispersed by producing very large numbers of samaras (Naumann and Young 2007). Seeds are dispersed greater distances into open fields than into closed forest canopies (Landenberger et al. 2005). *Ailanthus* samaras are also well adapted for water dispersal and exhibit high percentages of samaras capable of floating for weeks. Germination of seeds can be as high as 87% after three days in water (Kowarik and

Saumel 2008). Stem fragments from first and second year shoots can also produce shoots, set roots and establish new plants after being carried by water for up to 10 days (Kowarik and Saumel 2008). Genetic investigations reveal that *Ailanthus* has a high level of sexual reproduction, and long distance dispersal, especially along road and railway corridors (Aldrich et al. 2010). Dispersal by wind, water, and clonal propagation makes *Ailanthus* a highly invasive species.

Exotic tree species are interfering with efforts to reestablish forests in Virginia. During the first decade of the 21st century, about 1,000 miles of riparian forests were established by the Virginia Department of Forestry and the USDA Natural Resources Conservation Service to protect water quality and enhance wildlife habitat through the CREP program (Bradburn et al. 2010). Tree survival was high in the Coastal Plain (97.6%), high in the Piedmont (90.5%), but lower in the Ridge and Valley region (68.4%). The Piedmont riparian zones contained 29 planted species, but also had 40 naturally regenerated species. Many of the naturally regenerated species were trees with lightweight seeds such as red maple, yellow poplar, boxelder, and green ash.

The Ridge and Valley plantings included 31 species, and 27 additional species regenerated naturally. Unfortunately, 43.5% of the natural regeneration consisted of tree-of-heaven and autumn olive, both invasive exotic species. Natural regeneration exceeded planted trees on each site, and herbivory control increased survival at each site. It is recommended that planting densities be increased in the Ridge and Valley region, along with aggressive control of invasive species (Bradburn et al. 2010).

All fragmented forests in the Shenandoah Valley that were sampled had exotic species present, and in some sites exotics appeared to be inhibiting regeneration of more valuable native species (Siderhurst et al. 2012). Increased forest fragmentation leads to increased edge effects including deeper penetration into the forest by exotic species (Fraver 1994).

Invasive species can profoundly affect plant-pollinator networks. Invasive plants often act as pollination super generalists, potentially drawing pollinators away from plant species with which the pollinator may have mutualistic interactions (Bartomeus et al. 2008). Invasive plants are generally more resistant to herbivory compared to native plants. Native birds, reptiles, and small mammals do not use invasive plants for cover or nesting sites as frequently as native plants. Invasive plants also alter ecosystem processes (Bell et al. 2003) and the effect of invasive species on ecosystem services is vastly underestimated (Funk et al. 2014).

Environmental conditions that promote native species richness also promote exotic species richness. Exotic species that have niche requirements different from native flora can colonize sites with little resistance from native species, and perhaps cause few effects on native species (Gilbert and Lechowicz 2005). Exotic species can become abundant and persistent because of a lack of natural enemies, development of new associations within the ecosystem, artificial and/or disturbed habitats that provide favorable ecosystems, and adaptability and success of alien species. Exotic species are costing billions of dollars per year in crop and forest losses and in attempts to control the pests (Pimentel et al. 2005).

Pathogens

Chestnut Blight

Chestnut blight is caused by the fungus *Cryphonectria parasitica* (formerly *Endothia parasitica*). The blight was most likely introduced into the United States by an infected Japanese chestnut (*Castanea crenata*) that had been imported into New York. In 1904, the chief forester for the New York Zoological Park noticed an American chestnut (*Castanea dentata*) was dying, soon followed by several more. Various states attempted preventive and treatment measures, but all proved unsuccessful (Hepting 1974).Studies of chestnut mortality in the Southern Appalachians indicate that as the blight proceeded through our region during 1928-1938 the death of the chestnuts, comprising some 20% of the forest stands, resulted in a 27% release of understory saplings (Lorimer 1980). This release had a major impact on the ecological succession and change in forest composition in the Appalachian forests. By 1940, mature chestnuts had been killed off throughout their range (Freinkel 2007).

The American chestnut was an extremely important component of the eastern forest. The chestnut tree supported populations of bears, elks, deer, squirrels, raccoons, mice, wild turkeys, passenger pigeons, and the indigenous human populations such as the Cherokee and Iroquois. The tree also provided nectar for honey production. Chestnuts comprised some 25-30% of the trees in the forest. Commercially, chestnut was used for telephone and telegraph poles, mine supports, framing lumber and shingles for housing, furniture of all sorts from cradles to coffins, fiber for pulp and paper production, and tannins for leather production (Freinkel 2007).

In 1902, the U.S. Geological Survey warned President Theodore Roosevelt that industrial loggers were inflicting serious changes on the Appalachian forests. During 1909, four billion board feet of hardwood lumber was cut from Maryland to Georgia from the mountain forests. Over 600 million board feet of chestnut was cut each year, not including poles, posts, and cordage wood. The U.S. Agricultural Census of 1910 recorded that Patrick County and four surrounding counties produced 360,000 pounds of chestnuts, about half of Virginia's crop that year (Freinkel 2007).

Soon after those bountiful harvests of the early 1900s, the blight arrived in Virginia. A survey in 1914 revealed infections in 18 of 95 counties in Virginia. By 1915, the USDA Bureau of Forest Pathology concluded "the chestnut stand of the southern Appalachians was doomed." By 1925, chestnut blight was documented in North Carolina and was spreading westward. Within 25 years, the fungus had covered the southern Appalachians, affecting 33 million acres. By mid-century, the chestnut was largely exterminated (Freinkel 2007) as timber and mast trees.

There are still abundant chestnut sprouts throughout the southern Appalachian region (Paillet 2002). Chestnut is still surviving as sprouts off of established root systems from trees that originated before the blight. However, these trees usually do not reach sufficient size to bear fruit before they are stricken with the blight. The niche and habitat distribution of the American chestnut has also been altered from the original distribution, shifting to drier sites on southern and western slopes (Burke 2012).

Arthur Graves, a Yale botanist, began experiments to hybridize American chestnut with Asian species to find a blight-resistant hybrid. The USDA took over hybridization efforts for about three decades, then largely gave up their efforts. Philip Rutter and Charles Burnham wanted to backcross chestnut hybrids to produce a chestnut that would be 15/16 American chestnut, yet carry the resistance of a Chinese chestnut. In 1983, the American Chestnut Foundation was established to preserve and restore the American chestnut through funding a scientific breeding program and related research. The American Chestnut Foundation maintains a research farm in Meadowview, Virginia, managed by Fred Hebard. Breeding research continues, as well as research in genetic-engineering of resistance genes into chestnut, although the latter is making little progress. In 1985, the American Chestnut Cooperators' Foundation was established and developed a research program based on interbreeding within the species to develop resistant trees (Freinkel 2007). Whatever the future of the American chestnut might be, we are not likely to see this tree as a significant forest tree any time in the next few generations.

Dogwood Anthracnose

Dogwood anthracnose (*Discula destructiva* Red) was noted on the east coast in the early 1980s. This fungal disease causes necrotic lesions on the leaves and leads to twig dieback and eventual tree mortality (Daughtrey and Hibben 1994). The disease has spread all along the east coast from Massachusetts to Alabama. Monitoring of disease incidence in the Great Smoky Mountain national park between 1988 and 1991 revealed an increase of plots with severe epidemics of 638% with tree mortality in 41% of the plots. The native flowering dogwood (*Cornus florida*) on the east coast and the Pacific dogwood (*Cornus nutallii*) on the west coast are highly susceptible to the disease. The non-native Kousa dogwood (*Cornus kousa*) also hosts the disease, but has fewer symptoms (Daughtrey and Hibben 1994).

Dogwood mortality within the Cumberland Plateau has eliminated seedling and sapling size classes completely within cove areas and is likely to be eliminated from upland forest ridges. Lack of fruit production resulted in negligible additions to the population (Hiers and Evans 1997). With the loss of the high fat fruits of dogwood, fall-migrating birds are consuming more fruits and dispersing more seeds of blackgum (*Nyssa sylvatica*) and spicebush (*Lindera benzoin*). Dogwoods are also important calcium reservoirs within the ecosystem and loss of dogwoods can have serious implications for passerine bird egg production dependent upon invertebrates that get their calcium from dogwood leaves and litter. Calcium leaching is also accelerated by acid rain prevalent along the east coast (Hiers and Evans 1997). This loss of dogwoods represents not only a loss of nesting sites and food source, but also has impacts on nutrient cycling in the ecosystem.

Dutch Elm Disease

First discovered in Ohio in 1930, Dutch elm disease was introduced into the United States on imported logs. The fungus is spread by elm bark beetles. Elm trees of all ages and all species are susceptible (Boyce 1961). The first pandemic of elms was caused by *Ophiostoma ulmi*. In the mid-1900s, a new, more virulent species, *O. novo-ulmi* emerged (Santini and Faccoli 2014). The disease was rapidly spread by the small elm bark beetle (*Scolytus multistriatus*). The beetle infects elms when feeding at crotches of young twigs, introducing the fungus into the tree's vascular tissues. Dutch elm disease can also be transmitted from tree to tree through root grafts (Santini and Faccoli 2014). This disease has been devastating to the native elm population. Research on Dutch elm disease has declined dramatically over the last few decades, although modern genomic approaches may open new avenues to understanding and dealing with the elm-fungus-beetle pathosystem (Bernier et al. 2013).

Thousand Cankers Disease

In 2011, thousand cankers disease was discovered on black walnut (*Juglans nigra*) trees growing around the Richmond area, in Fairfax, and Prince William counties (VDOF 2014b). This disease is caused by a fungus, *Geosmithia morbida*, which is spread by the walnut twig beetle (*Pityophthorus juglandis*). Currently, 10 counties and six municipalities have been quarantined to limit the spread of the beetle and the disease (VDOF 2014b). There are no currently available controls for this disease. The disease has been present in the western United States in Colorado, Idaho, Oregon, Utah, and Washington. The first observation of the disease in the eastern US was in Tennessee. Now, it is present in Virginia and Pennsylvania as well. If this disease is not contained, there will be an enormous ecological and economic impact (Randolph et al. 2013).

Insects

Gypsy moth

Oaks comprise a large percentage of forest trees in Virginia with various species distributed from the mountains to the seashore. Anything that can seriously affect oaks can have a devastating effect on Virginia woodlands. As such, gypsy moth (*Lymantra dispar*) has proven to be a serious threat. Gypsy moth was introduced into the US at Medford, Massachusetts, in 1869, in an ill-fated attempt to use the moths for silk production (McManus 2007). Some moths escaped into the wild and established an enduring population in Massachusetts, spreading into Maine, New Hampshire, and Rhode Island over the next 25 years. Gypsy moths reached Virginia in 1984, resulting in our first noticeable defoliations. By 2000, over 71,000 acres had been defoliated in Virginia (Roberts 2001). If unchecked, populations of gypsy moth will spread at a rate of about 13 miles per year (USFS 2007).

Initial infestations generally result in 15-35% tree mortality, but can result in mortality as high as 75% (Roberts 2001). Gypsy moth larvae can defoliate trees, leaving them susceptible to attack by secondary agents that result in tree mortality. Oaks (*Quercus*) are a preferred food source, but gypsy moths will also feed on birches (*Betula*), sweetgum (*Liquidambar*), poplars (*Populus*), willows (Salix), basswood (*Tilia*), hornbeam (*Carpinus*), hophornbeam (*Ostrya*), witch-hazel (*Hamamelis*), hazelnut (*Corylus*), and hawthorne (*Crataegus*) (Davidson et al. 1999). In all, gypsy moths can feed on more than 500 species of plants. As the moths are tannin-adapted, they are able to preferentially feed on oaks that are resistant to feeding by other insect larvae. Oaks with higher levels of carbohydrates and proteins are fed on preferentially, despite high concentrations of tannins (Foss and Rieske 2003).

Gypsy moths preferentially feed on oaks over other tree species. Foliar characteristics such as tannin, carbohydrate, and nitrogen content, leaf toughness, and density have no clear relationship to feeding preference. One study (Foss and Rieske 2003) demonstrated that black, burr, cherry bark, and northern red oaks are most preferred by gypsy moth larvae, while pin, swamp white, white, and willow oak are least preferred. Despite the feeding preference, larvae fed on pin oak grow and develop most rapidly. As a tannin-adapted species, gypsy moth can readily consume oak foliage with high tannin concentrations such as burr oak and pin oak (Foss and Rieske 2003).

Another study (Campbell and Sloan 1977) recorded defoliation of white and black oak tends to be heavy, while scarlet oak defoliation is moderate and red oak defoliation tends to be low. Heavily defoliated oaks require about 10 years to restore pre-attack foliage levels. When defoliation occurs on white pine and red maple, the red maple trees are more likely to die. Defoliation tends to be most severe in the first year of the outbreak, and within species, some trees were more consistently defoliated than others, indicating that individual genetic differences among trees can be important in feeding preferences (Campbell and Sloan 1977).

Control of the spread of gypsy moth was attempted by developing barrier zones in the 1920s and 1930s, but limited funds hampered these efforts. In the 1940s and 1950s, spraying of DDT was employed in selected areas, but was abandoned due to detrimental environmental effects. Carbaryl became the treatment of choice for a number of years until better methods of control were developed. Research efforts in the 1970s led to integrated pest management approaches in an attempt to contain the threat, while allowing differences in regional approaches. In 1972, *Bacillus thuringiensis kurstaki* was introduced for control of gypsy moths. In 1976, diflubenzuron was added to the arsenal, followed by the introduction of Gypchek (gypsy moth nucleopolyhedrosis virus) in 1978, and the use of synthetic pheromone flakes to disrupt mating in the following year 1979 (McManus 2007). Disparlure (cis-7,8-epoxy-2-methyloctadecane) is an important part of the surveillance of gypsy moth spread and the key to the Slow-the-Spread program coordinated through the USDA (Tobin et al. 2012). Gypsy moth females cannot fly and this pheromone is used in baited traps to disrupt mating with males. Dispalure can remain in the environment for a short time after removal of the dispensers, but is primarily emitted from the dispenser for up to two years (Onufrieva et al. 2013).

In Virginia, acres defoliated by gypsy moth increased steadily from 374 acres in 1984 to a peak of 748,000 acres in 1992. Gypsy moth populations show natural fluctuations and defoliation fell to 452,475 acres in 1994, followed by a resurgence in 1995 to 850,000 acres defoliated. Then the population crashed in 1996 and remained at insignificant levels until a population explosion in 2000 resulting in 71,122 acres defoliated. By 2000, a total of 4,428,412 acres had been defoliated in Virginia (Roberts 2001).

Between 1996 and 2000, a couple of factors seems to have been important in suppressing the gypsy moth population. Two pathogens of gypsy moth were found to be present at the sites of the population crash. Nuclear polyhedral virus (LdNPV) and *Entomophaga maimaiga* were found in the local environments (Hajek et al. 1996, Webb et al. 2003). *E. maimaiga* had been introduced into the US years before as a control attempt. The persistence and slow spread of this fungus makes it effective in helping to prevent outbreaks of gypsy moth, whereas the LdPNV seems to be more active when gypsy moth populations reach high densities (Elkinton et al. 1991).

Gypsy moth nuclear polyhedrosis virus (LdNPV) causes epizootics in gypsy moth. The virus particularly affects later instars. Rainfall can distribute LdNPV in tree crowns, washing the virus out of upper branches and distributing the virus to lower branches (D'Amico and Elkinton 1995). Heavy rains can wash the virus from tree bark and solar radiation can inactivate the virus (Podgwaite et al. 1979). Different textures of tree bark can affect the persistence of the virus on the tree bole. LdNPV persists at high concentrations in forest litter and soil (Podgwaite et al. 1979).

LdNPV is spread through the forest through a variety of animals passing the polyhedral inclusion bodies through their alimentary tracts. Animals distributing the virus include the white-footed mouse, short-tailed shrew, southern flying squirrel, opossum, raccoon, house finch, redwing blackbird, and mourning dove (Lautenschlager and Podgwaite 1979).

Entomophaga maimaiga is a pathogenic fungus causing epizootics in gypsy moths. This fungus produces resting spores (azygospores) and airborne conidia that spread the fungus from dead larvae to living larvae. Spores can travel several kilometers during storms with strong winds (Weseloh 2003). Older larvae (fifth or sixth instars) typically produce more resting spores than conidia, and pupae are not infected, but, if infected as larvae, can produce some spores upon their death (Weseloh 2003). Resting spores can germinate during the larval stage of the moth life cycle. Infection of larvae is most likely a function of rainfall and soil moisture when spores are present. Newly hatched larvae are most susceptible to infection from ground spores, whereas most later-stage infections are probably due to secondary infection via conidia (Weseloh and Andreadis 1992).

Beyond LdNPV and *E. maimaiga*, other agents within the forest help control gypsy moth populations. Deer mice, shrews, and birds predate the gypsy moths and help reduce their numbers when populations are scarce. Forest ants are also important in the control of gypsy moth larvae (Weseloh 1994). Finally, temperature is another factor in the survival of gypsy moths. Temperatures can be too high for larval development and pupation and might limit expansion into warmer zones (Tobin et al. 2014). Warmer temperatures associated with the Coastal Plain and Piedmont regions of Virginia have limited the growth of populations of gypsy moth (Tobin et al. 2014). Gypsy moth outbreaks affect bird populations by disrupting or, in some cases, creating nesting sites. These outbreak populations are usually not long-term, but suggest that non-pesticide control measures are best for managing gypsy moth infestations from an ecosystem perspective (Gale et al. 2001).

Hemlock woolly adelgid

Hemlock woolly adelgid (*Adelges tsugae*) is native to Asia. This destructive insect was introduced into the eastern U.S. from southern Japan (Havill et al. 2006) and first detected on eastern hemlock (*Tsuga canadensis*) in Richmond, VA in the 1950s (Souto et al. 1996). Hemlock stands provide an essential habitat for birds, mammals, amphibians, reptiles, some fish, and a number of invertebrates. Decline of hemlock forests will have effects on avian species that are dependent on these habitats for breeding. Several bird species are hemlock obligates. Specialized obligate species will be most affected by loss of hemlocks. One study estimated that hemlock loss would adversely affect 3600 bird pairs in the Delaware Water Gap National Recreation Area, which covers 1130 ha. This would extrapolate to millions of pairs of breeding birds being affected by hemlock loss in the northeastern US alone (Ross et al. 2004). The loss of hemlock stands has a great ecological impact (Degraaf and ChadWick 1987, Quimby 1995, Ross et al. 2004).

Trees infested with woolly adelgid exhibit reduced growth and needle loss. Infestations can kill a mature tree within three to four years (McClure 1991). Aphids in general tend to feed on the phloem tissues in their host plants, but the woolly adelgid feeds on xylem parenchyma in xylem rays, which serve as a transport canal between phloem and pith, and serve as nutrient storage cells. Multiple nymphs insert their stylets at the base of a needle penetrating the petiole and feed off the nutrients of the hemlock (Young et al. 1995).

There are no known natural predators of the woolly adelgid in the eastern U.S., but populations may be limited by weather. Woolly adelgid is a cool-weather species (Day and Salom 2010), and warmer coastal temperatures may limit the spread in the eastern part of the state. Winter temperatures below -20C cause significant reductions in woolly adelgid populations, but these temperatures are not likely to limit Virginia populations due to their rare occurrence.

Mortality in infested hemlock stands is higher in understory trees than overstory trees. Intermediate and sub-dominant trees die out first. Replacements for canopy trees are severely limited due to understory mortality. Thus, as the overstory trees eventually die off, the entire stand of hemlock is lost (Krapfl et al. 2011). The ecological impact of the loss of the hemlock forests may equal the losses resulting from the forest devastation caused by the chestnut blight (Krapfl et al. 2011).

In a study following eastern hemlock stands over nine years (Eschtruth, et al. 2006), 25% of the hemlocks were either dead or in severe decline. Understory light increased significantly and litter cover decreased. There was a shift in angiosperm woody species including increases in tulip tree (*Liriodendron tulipifera* L.), black gum (*Nyssa sylvatica* Marsh.), red maple (*Acer rubrum*), and birches (*Betula* spp.). Most disturbingly, 35% of sample plots contained at least one invasive plant species and 5% contained two or more species. Loss of hemlock stands may dramatically increase the spread of invasive species (Eschtruth, et al. 2006).

The loss of eastern hemlocks may leave *Rhododendron maximum* to define future successional patterns in the Appalachian Mountains due to the high density of this shrubby species in the understory (Krapfl et al. 2011). It was predicted that hemlock stand mortality would result in increased stream flow because hemlocks are such an important tree component in cove and riparian habitats (Ford and Vose 2007). However, a study of water relations in North Carolina found a significant decrease in water flow from a watershed that suffered loss of hemlock following infestation with hemlock woolly adelgid (Brantley et al. 2015). Following hemlock decline, *Rhododendron maximum* became more prevalent, and this combined with species such as *Acer rubrum*, *Betula lenta*, and *Liriodendron tulipifera* with higher transpiration rates than hemlock resulted in water flow reduction.

Hemlock woolly adelgid infestations alter the energy and organic and inorganic nitrogen fluxes in hemlock stands (Stadler et al. 2006). Nitrification rates increase in infested forest stands, and nitrate leaching into waterways can be a problem (Jenkins et al. 1999). Death of hemlock trees also affects carbon cycling from foliage drop, and loss of fine roots further affects nutrient cycling (Nuckolls et al. 2009). Further changes in nutrient and water cycling would be expected to occur with the successional stands that follow the hemlock mortality.

Adelgids are dispersed in the egg and crawler stages by wind, birds, and deer (McClure 1990). This dispersal can be very long range during bird migration periods. Control of infestations in individual trees can be carried out by systemic insecticide applications or applications of dormant oils (Dilling et al. 2009). However, control over forested regions has proven problematical, and may be best addressed by biological control. Biological control has been attempted by releasing *Sasajiscymnus tsugae*, *Scymnus sinuanodulus*, and *Laricobius nigrinus*, but these have not proven effective (Vieira et al. 2011). *Laricobius niginus* released in field tests in Virginia was shown to persist over at least two generations, but adelgid populations were maintained even as the predator population increased in density (Lamb et al. 2006). Another species, *Laricobius osakensis* is highly specific to predating *A. tsugae*. This predatory insect is active in winter, making it synchronous with woolly adelgid activity, while other prey species are dormant. *L. osakensis* appears to have great potential for controlling hemlock woolly adelgid with minimal risks to other populations (Vieira et al. 2011).

Emerald Ash Borer

There are at least 16 species of ash native to the United States. White ash (*Fraxinus americana*) is of economic importance and is used in manufacturing tool handles, baseball bats, flooring, and furniture (MacFarlane and Meyer 2005). Members of the various species of ash cover a wide range of ecological habitats from dry uplands to wet lowlands, and inhabit a variety of soil types (MacFarlane and Meyer 2005). Ash trees have also been widely used in urban areas as a preferred shade tree. Green ash (*Fraxinus pennsylvanica*) is tolerant of salt, high pH, and drought stress, and has been used to replace American elms that were lost to Dutch elm disease. It is expected that emerald ash borer (*Agrilus planipennis*) will lead to widespread loss of ash trees from forest ecosystems and from urban environments (MacFarlane and Meyer 2005).

Emerald ash borer was introduced into the US from Asia, probably in the 1990s, and was first identified near Detroit, Michigan in 2002 following local ash decline and mortality. Infested trees are killed from larva girdling branches and the trunk by feeding in galleries in the phloem and cambium (Herms and McCullough 2014).Between 2002 and 2007, over 20 million ash trees were killed by the borer (Poland 2007) and the infestation was spreading at a rate of 10.6 km/yr (Smitley et al. 2008). It is estimated that the cost of treatment, removal and replacement of ash trees between 2009 and 2019 will reach $10.7 billion (Kovacs et al. 2010).

Following unsuccessful attempts to quarantine the beetle by removal of ashes in the border area, searches began for natural controls by predators, pathogens, and parasitoids. Woodpeckers feed on the larvae (Lindell et al. 2008), and at least one native parasitoid, *Atanycolus cappaerti*, attacks the larvae, but at a fairly low rate (Herms and McCullough 2014). Other native parasitoids include *Balcha indica*, *Eupelmus pini*, and *Dolichomitus vitticrus*, along with a species of *Orthizema* and one species of *Cubocephalus*, but none of these appear to be very effective (Duan et al. 2009). An egg parasitoid, *Oobiusagrili*, native to northern China was introduced into the U.S. for biological control of emerald ash borer. This insect overwinters successfully in the U.S. (Duan et al. 2012) but seems to have had limited success thus far. Two larval parasitioids, *Tetrastichus planipennisi*, and *Spathiusagrili*, may hold more promise, and are still being evaluated (Herms and McCullough 2014).

The fungus *Beauveria bassiana* has also been tested as a biological control measure and may be beneficial in the fight against emerald ash borer (Liu and Bauer 2008). However, in a controlled study comparing the effects of host tree defense, disease, predation, and parasitism, all control measures proved to be relatively ineffective (Duan et al. 2010).

Imidacloprid is a recommended insecticide for treating emerald ash borer, for soil injection, soil drenches, basal trunk sprays, and trunk injections by professional applicators and as a soil drench by homeowners. Application times are mid-spring to late spring or mid-fall (Herms et al. 2014). Trees injected with imidacloprid had larval densities reduced from 82-96 % (McCullough et al. 2010). Injected imidacloprid is translocated mainly through the xylem, and tends to become concentrated in the leaves (Mota-Sanchez et al. 2009). Imidacloprid treatments must be repeated annually (McCullough et al. 2011). Imidacloprid use has serious effects on non-target species as will be discussed elsewhere in this text.

Emamectin benzoate has also proven an effective insecticide with multi-year protection (McCullough et al. 2011, Smitley et al. 2010). Emamectin benzoate provides better protection from ash borer larvae than imidacloprid (Smitley et al. 2010). Emamectin disrupts nerve signal transmission and is used against lepidopterous pests (Zhao et al. 2006). Although this insecticide is very effective against the emerald ash borer, one has to be concerned about the effects on non-target species.

Kudzu bug

One of the emerging threats to agriculture in Virginia is the approach of the Kudzu bug (*Megacopta cribraria*). First noticed in northern Georgia, near Atlanta in 2009, this insect quickly spread from nine counties in Georgia across seven states in only three years. By 2012, the kudzu bug was present in two southern Virginia counties (Ruberson et al. 2013). The kudzu bug is so-named because of its close association with kudzu (*Pueraria montana* var. *lobata*), on which it preferentially feeds. Because kudzu is a severely invasive plant species, the appearance of the kudzu bug might seem like a benefit, and indeed the insect can reduce kudzu biomass production by about a third in its first year of infestation (Zhang et al. 2012), but the bad news is that the kudzu bug will also attack crop plants including soy beans (*Glycine max*), snap beans (*Phaseolus vulgaris*), and cotton (*Gossypium hirsutum*) (Ruberson et al. 2013). Soybeans and cotton were among the top10 agricultural plant commodities for Virginia, generating $284 million and $77 million, respectively, in cash receipts in 2013 (VDACS 2015a). The kudzu bug has been documented to cause up to 50% reduction in soybean yields (Wang et al. 1996).

The climate of the southeastern U.S. is ideal for the growth and reproduction of this insect which has no natural enemies here. It is anticipated that this pest will continue to spread rapidly. Human contact with this insect (especially in the nymph stage) can cause skin rashes. The insects are attracted to light-colored structures, and invade homes and other structures and can congregate in large numbers. Control can be accomplished by wide-spectrum insecticides such as organophosphates and pyrethroids, but organophosphates are particularly dangerous around humans and pets. Biological control may be a better route to pursue. Kudzu bug is the only plataspid species in North America, so finding a parasitoid species that feeds exclusively on kudzu bug would be beneficial without harming native species of insects. *Paratelenomus saccharalis* (Dodd) has been proposed as a biological control agent because it is highly host-specific, its ecology is well understood, and it has a wide geographic distribution. *Paratelenomus saccharalis* only attacks several species in the family Plataspidae, and given the geographic distribution, finding one or more populations that can survive in the US should be likely (Ruberson et al. 2013).

Browsers

White-tailed Deer

Tree regeneration in Virginia has been negatively affected by white-tailed deer (*Odocoileus virginianus*) browse. Deer reduce growth and survival of seedlings and saplings. Deer intensely browse American beech (*Fagus grandifolia*), black cherry (*Prunus serotina*), blackgum (*Nyssa sylvatica*), flowering dogwood (*Cornus florida*), ironwood (*Carpinus caroliniana*), and ash species (*Fraxinus* spp.) (Carter and Fredericksen 2007).

Deer have a pronounced effect on the forest ecosystem. Red oak (*Quercus rubra*) regeneration is very strongly limited by deer. Eastern hemlock (*Tsuga canadensis*) and northern white-cedar (*Thuja occidentalis*) are important winter food sources for deer. The largest species component of forests is the herbaceous species of plants, often by a factor of 10:1 herbaceous to tree species. Changes in plant species diversity by deer affects insect diversity through alterations in the food web. Heavy browsing pressure by deer often favors graminoids and ferns. This reduces pollen and nectar availability and can decrease invertebrate diversity (Rooney and Waller 2003). High deer densities produce a threat to biological diversity.

Browse-tolerant tree species tend to have higher lignin contents, and with heavy herbivory, decomposition and mineralization rates can be altered, affecting soil fertility in the forest (Rooney and Waller 2003).Browsing by deer, even at densities as low as four deer/km^2, negatively influences woody vegetation height and species richness. After 20 years of excluding deer on forest plots, seedling heights were 2.25 times higher and stem count was 4.1 times greater than outside the exclosure (McGarvey et al. 2013).Deer browsing can lead to impoverishment of the herbaceous layer. In a study spanning 26 years, deer in the southern Appalachians caused the disappearance of 46 herbaceous species, while species richness increased by 106% and cover increased by 183% in reference plots without chronic herbivory. Chronically browsed areas tended to become more homogeneous in species composition as they decreased in species diversity (Thiemann et al. 2009).

Loss of Pollinators and Fruit/Seed Dispersers

Insects are important plant pollinators and are an important source of food for many bird species. In turn, many bird species are important in fruit and seed dispersal, as well as acting as pollinators themselves. The increasing use of neonicotinoid insecticides to treat farm and forest pests is posing a grave threat to the plant community by reducing or removing components of the ecosystem that provide vital ecosystem services.

Neonicotinoids are systemic insecticides that are relatively long-lived, water-soluble, and can accumulate in soils and move into surface and ground waters and thus have the potential to affect many organisms. They can affect non-target invertebrates and can cause prey-base collapses, which can subsequently affect avian populations. Farmland bird populations show negative or lower growth rates in response to higher concentrations of neonicotinoids. Neonicotinoids can cause cascading trophic effects in the ecosystem (Hallmann et al. 2014).

Imidacloprid in leaves can adversely affect non-target leaf-shredding invertebrates. Toxic effects of leaf material inhibit feeding. Neonicotinoids adversely affect leaf litter breakdown, organic-matter processing, nutrient cycling, and detritus-based food webs. Riparian forest corridors are especially vulnerable where leaf litter inputs are important drivers of the aquatic ecosystems. Alternatives to neonicotinoids should be considered for the control of invasive forest insects (Kreutzweiser et al. 2009). Imidacloprid binds the acetylcholine receptor of insects, resulting in movement coordination problems, trembling, and tumbling (Suchail et al. 2000).

Honeybees that are important crop pollinators and our source of commercial honey are especially sensitive to the effects of neonicotinoid pesticides such as imidacloprid and related compounds. Imidacloprid is a potent insecticide to honeybees and should not be applied during flowering times. Neonicotinoids can enter honeybee hives through contaminated nectar, pollen and water. As imidacloprid is metabolized, some of its metabolites show toxicity levels close to the parent compound. Acute exposure to imidacloprid or its metabolites produce symptoms of neurotoxicity. Low dose chronic exposure of honeybees to imidacloprid and its metabolites are all toxic (Suchail et al. 2001).

Honeybees exposed to sub-lethal concentrations of imidacloprid show significant increases in *Nosema* infections. Gut parasites *Nosemaapis* and *Nosemaceranae* were significantly higher in the guts of honeybees that were exposed to even low, sub-lethal concentrations of imidacloprid (Pettis et al. 2012).

Sublethal exposure of honey bees to neonicotinoids (imidacloprid and clothianidin) leads to colony collapse. The effect is worsened by severity of winter weather. Members of colonies exposed to neonicotinoids fail to resume brood rearing, even into warm weather. Bees also abandon hives during winter, atypical of non-treated populations (Lu et al. 2014).

Bee diversity benefits pollination services by increasing fruit and seed set, increasing pollination stability, and enhancing efficiency of pollinators within the community (Rogers et al. 2014). A mixture of pollinator generalists and specialists best supports plant communities. Overuse and indiscriminate use of pesticides, and especially the neonicotinoid insecticides pose an imminent threat to the diversity of our plant communities.

Forest Mismanagement

Non-industrial private forestland (NIPF) is often harvested by "high-grading" in Virginia. The lack of a market for low-grade logs and pulpwood leads to selective harvesting of the best stems. High-grading leaves trees with defective stems and non-merchantable species of trees to regenerate the forest. Very little silviculture is practiced on NIPF in Virginia. About 77% of Virginia's forest land is in private hands, held by over 300,000 forest landowners. As of 2003, only 3% of family forest owners in the southern U.S. had a written management plan (Butler and Leatherberry 2004).

Consider the effects of population mismanagement on eastern redcedar (*Juniperus virginiana*) in Virginia. Eastern redcedar, has been subjected to over 300 years of negative genetic selection. High-grading, or removal of the superior members (most commercial) of the species, leaves behind the genetically inferior members of the species to repopulate and produce a new generation that is less merchantable than the prior generation. This practice has resulted in the successive lowering of the quality of eastern redcedar to the point that there is virtually no market for Virginia eastern redcedar, which now lacks the quality heartwood that is essential to its use in chests, paneling, and other uses.

We need to guard against repeating this scenario with other commercial species such as oaks, tuliptree, and other commercial species. It may be that their longer generation time has slowed the genetic degradation suffered by eastern redcedar.

Fire Exclusion

It may seem strange to think that fire exclusion may be a threat to native biodiversity, but fire has been a large part of Virginia's history. Indigenous populations and European settlers used fire to clear land and to control brush growth. Consequently, fire-adapted species became established in Virginia. Also, by excluding small, regular fires, fuel accumulation can lead to more intense wildfires that are more destructive to native vegetation. Forest Service, Park Service, and Nature heritage personnel are currently using controlled burns to reduce forest litter and to maintain fire-dependent species.

Threats to Agriculture

Herbicide resistance

Herbicide resistance is now increasing at a rate comparable to the rise of insecticide resistance and fungicide resistance in the past (Holt 1992). Weeds had developed resistance to fifteen different classes of herbicides by 1989 (Holt 1992). Chickweed (*Stellaria media*) that is resistant to chlorsulfuron has shown cross-resistance to imidazolinone herbicides as well (Hall and Devine 1990). As one example, Asiatic dayflower (*Commelina communis*) has become a serious weed problem in soybean fields and is showing resistance to glyphosate (Ulloa and Owen 2009). Asiatic dayflower, or slender dayflower has become a problem weed along the east coast. *Commelina communis* is an animal-dispersed invasive plant species (Naumann and Young 2007). Seeds persist in the soil bank and can germinate at very high rates after four years.The rapid adoption of glyphosate-resistant crops such as corn, soybean, canola and cotton has increased the selection pressure for herbicide resistant weed species.

Land Development

Agriculture and forestry are facing considerable pressure from population increase and land development. The population of Virginia increased by about 14.4% (890,000 people) between 1990 and 2000. This increase is faster than the national average. Within the state, the largest growth rates are seen in Northern Virginia, Hampton Roads, and around Richmond. Loudoun County grew the fastest of any county during this period. Northern Virginia added 435,320 people between 1990 and 2000, pushing growth into Spotsylvania, Stafford, Caroline, and King George counties. Richmond, during this time, added 130,872 persons increasing population pressure in Chesterfield, Henrico, Hanover, and Powhatan counties. In Hampton Roads, population increased by 120,377 adding to James City County and York County (Pollard 2007).

Virginia's farmlands, natural areas, and open spaces are being lost to development, which is occurring even faster than population growth. In 15 years between 1982 and 1997, 784,500 acres were developed, and development is increasing at an increasing rate. Furthermore, 31% of the 343,500 acres developed between 1992 and 1997 was prime farmland. Between 2007 and 2010, over 79,500 acres of land in Virginia were lost to development (UDA 2013). If trends continue, several counties stand to lose all their farmland. A similar impact is occurring on forestry, with 650,000 acres of forest land lost to development between 1992 and 2001 (Pollard 2007). During the 15 years between 1997 and 2012, the number of farms decreased by 3,336.

Virginia is also continuing to pave more and more land. As miles of roads increase, so does the amount of travel by car and transport by truck, with a concomitant increase in carbon emissions. Virginia is making large contributions to carbon dioxide emissions, showing a 34% increase between 1990 and 2004, the ninth highest of any state during that time. Transportation is the leading source of carbon dioxide emissions (Pollard 2007). Rather than looking at mass transit solutions and moving freight from roads to rail, Virginia continues to pursue a policy of building more roads, consuming more land, leading to more damage to forests, farmland, and wildlife communities. Road expansion has not relieved congestion or time lost in traffic delays, but has spurred more development, population increase, and more congestion (Pollard 2007). The economic model of endless growth is as much of a myth as the idea of endless natural resources. We must shift from a model of endless economic growth to one of economic and environmental sustainability (Meadows et al. 1992, Ekins 1993, Hofkes 1996, Giddings et al. 2002). No longer can expansion be considered the solution to societal problems, and no longer can environmental degradation be considered an externality without economic cost. The future of human society depends upon finding a balance between economic welfare and environmental sustainability.

Climate Change and Agroforestry

The increase in atmospheric carbon dioxide and other greenhouse gases is causing a rise in average global temperature (Mann et al. 1998, Karl and Trenberth 2003). We can expect warmer summers, milder winters, and more weather extremes to occur in Virginia in the future. Future temperature increases may reduce wildflower reproduction and crop yields because of effects on pollen viability. Changes in plant phenology may lead to loss of pollinators and birds and pollen for reproduction and fruit/seed dispersal.

The effects of climate change are likely to be numerous and problematic for farming in the southeastern United States (Asseng et al. 2013). Increased summer heat stress is likely to reduce crop productivity. Flowering and seed set are particularly vulnerable to heat stress, especially if combined with drought. Increased diurnal temperatures have resulted in reduced yields of rice and corn in several agricultural regions around the world. Increased temperatures will also result in increased water demand by plants due to increased transpiration. If water needs are not met, yields will decrease. Increased seasonal temperatures will result in an advanced phenology. Warmer temperatures in winter months may reduce fruit set on crops with a chilling requirement such as blueberry and peach (Asseng et al. 2013). In addition, higher temperatures inhibit photosynthesis and carbon uptake in plants (Zinn et al. 2010).

Pollen is particularly sensitive to temperature changes. Various cultivars of corn (Herrerro and Johnson 1980), wheat (Dawson and Wardlaw 1989), and grain sorghum (Prasad et al. 2006) all showed loss of pollen viability at elevated temperatures. Even at elevated carbon dioxide levels, seed set and yield was reduced in sorghum at elevated temperatures (Prasad et al. 2006). In addition to these grain species, cotton is sensitive to elevated temperatures and shows reduced pollen germination (Song et al. 2014), reduced pollen tube growth (Snider et al. 2011a, Snider et al. 2011b), and reduced boll retention and development (Reddy et al. 1992). Peanuts have reduced pollen production, pollen viability, and reduced fruit set at higher temperatures (Prasad et al. 1999). Finally, vegetable crops such as tomatoes (Abdul-Baki and Stommel 1995), and beans (Halterlein et al. 1980) also show reduced pollen germination and elongation at higher temperatures. For fruit and grain production, anything that interferes with plant reproduction decreases yield.

Weed management is likely to become more problematical because of the benefits of warmer temperatures and increased carbon dioxide availability for these weed species. While more atmospheric carbon dioxide may increase rates of photosynthesis up to a point, it does not necessarily correlate to an increase in crop yield. Increases in biomass with increased carbon dioxide availability depends upon water availability and soil nutrient content. Other factors that may limit increases in crop yield include increased predation by pests and competition from weeds (Asseng et al. 2013).

Virginia is highly susceptible to damage from hurricanes, storms, and tidal surges, which are likely to intensify with forecast climate change. Increases in storm intensity is likely to increase damage to most agricultural systems, with wind damage causing long lasting damage to perennial crops. Coastal areas may be affected by rising sea levels leading to salt water intrusion into ground water and increased salinity in coastal rivers affecting irrigation efforts from surface waters (Asseng et al. 2013).

Climate change is posing a threat to the future of eastern forests. Warmer annual temperatures lead to relaxation of range constraints for insects such as the hemlock woolly adelgid, and increases survival and fecundity of the insect. We are likely to see increases in mortality of oaks from forest tent caterpillar (*Malacosoma disstria*) (Asseng et al. 2013).

High elevation forests of the Appalachians are particularly susceptible to changes from a warming climate. A 3C increase in July temperatures would raise climate-elevation bands by about 480m. Mid-elevation cove forests support a diversity of fire-intolerant tree species, ephemeral spring wildflowers, and populations of amphibians that would be substantially changed in an adverse manner by warming and precipitation variability, both of which have been documented since the early 1980s. Increases in intensity of hurricanes as predicted with climate change could cause catastrophic changes to Virginia woodlands. Even a Category 2 storm such as Hurricane Isabel in 2003 damaged many canopy trees in a maturing hardwood forest in the Coastal Plain (McNulty et al. 2013).

CONSERVATION OF NATURAL RESOURCES

There are numerous agencies and organizations that help protect and preserve Virginia's plant life. These include federal and state level public agencies and private or non-governmental agencies working at the state, national, or international levels.

State

Within the Virginia Department of Conservation and Recreation, the Virginia Natural Heritage Program is charged with preserving the diversity of biological resources. The Natural Heritage Program was founded in 1986 and helps establish conservation priorities, and develop management plans for natural communities and rare species (Wilson and Tuberville 2003).

Virginia Land Conservation Foundation

The Virginia Land Conservation Foundation (VLCF) was established in 1999 by the General Assembly and Governor of Virginia. The Foundation has members representing each congressional district. Members are appointed by the governor, the senate and the House of Delegates. In addition, the Secretary of Agriculture and Forestry is also a member. The VLCF is chaired by the Secretary of Natural Resources. The General Assembly funds the VLCF to conserve open spaces and parks, natural areas, historic areas, and forest and farmland. Monies are made available through grants awarded by the Foundation and often involve matching funds from other sources. In addition to purchasing land, funds may be used to establish permanent conservation easements. Grant applications are considered from local governments, state agencies, and qualified nonprofit groups. As of 2012, VLCF grants have helped to protect over 45,500 acres in 130 separate projects (Virginia Land Conservation Foundation 2015).

Virginia Outdoors Foundation

The Virginia Outdoors Foundation (VOF) was established by the Virginia General Assembly in 1966 to promote the preservation of open-space lands. The Foundation uses private gifts (money, securities, land, or other properties) to preserve the natural, scenic, historic, scientific, open-space, and recreational lands of Virginia. The VOF administers the Open Space Lands Preservation Trust Fund. The VOF holds conservation easements, restricting certain types of development on lands in perpetuity. Through the VOF, over 750,000 acres in Virginia has been protected (Virginia Outdoors Foundation 2014).

Virginia Department of Forestry

The Virginia Department of Forestry (VDOF) manages 24 state forests occupying 68,626 acres of forest land. The VDOF is charged with protecting forest resources from fire, managing the Commonwealth's forest resources, protecting our water resources, conserving the forest land, and managing the forests and state tree nurseries. Nurseries provide seedlings for timber stand establishment, provide pulpwood crops, provide trees for Christmas tree plantations, enhance wildlife habitat, stabilize stream banks, and improve watersheds (VDOF 2014a).

Office of Farmland Preservation

The Virginia Department of Agriculture and Consumer Services administers the Office of Farmland Preservation, which helps localities to obtain agricultural conservation easements, helps develop farmland preservation policies at state and local levels, and helps to educate citizens about the importance of farmland preservation. Importantly, they also operate a program that helps connect potential farmers with retiring farmers so that farmland can be kept in the hands of farmers through the Farm Link Program (VDACS 2015b).

Virginia Department of Conservation and Recreation

The Virginia Department of Conservation and Recreation (VDCR) manages and protects the state parks. It also identifies, inventories and protects rare plants, animals, and communities. There are currently 36 state parks, five undeveloped parks, and 61 natural areas and preserves covering over 126,000 acres under the VDCR jurisdiction (VDCR 2015).

State Natural Area Preserve System

Natural area preserves are established through a legal deed that protects the area in perpetuity by limiting activities on the land to those appropriate and compatible with protection goals for that site. Preserves may be either public or private lands. Currently there are 36 dedicated preserves covering 27,899 acres, and protecting 151 rare plant species (Wilson and Tuberville 2003).

Open Space Recreation and Conservation Fund

The Open Space Recreation and Conservation Fund receives funds monies voluntary contributions designated from state income tax refunds. The funds are used to acquire land for recreation, to preserve natural areas, and to improve state parks. The Fund also provides grant opportunities on a matching basis to localities for recreation projects. The Fund is administered through the Department of Conservation and Recreation (Open Space Recreation and Conservation Fund 2015).

Federal

The Federal Government owns more than 2.3 million acres in Virginia, including national forests, national parks, wildlife refuges, and military bases. The U.S. Forest

Service has 1,785,663 acres of public forest in Virginia. The U.S. Department of Interior National Parks Service has 299,642 acres of parkland in Virginia. The U.S. Department of Interior Fish and Wildlife Service has 128,310 acres in Virginia in wildlife refuges. The U.S. Fish and Wildlife Service has enforcement authority for the federal Endangered Species Act. At the state level, authority for enforcement is located in the Virginia Department of Agriculture for threatened and endangered plant species.

Private and Non-governmental organizations

Nature Conservancy

The Nature Conservancy, founded in 1951, is a private, nonprofit organization that protects biodiversity through acquisition of unique and sensitive habitats for direct management or through transfer to public agencies who take over the protection and management function, usually in cooperation with the Conservancy and/or other environmental groups. The Nature Conservancy has chapters in every state within the United States and is also active internationally. The Nature Conservancy holds 86,000 acres in protection from development. In Virginia the Nature Conservancy has helped to protect over 340,000 acres of land, and maintains 16 preserves open to the public and an additional four preserves that are protected and not open to the public (Nature Conservancy 2015a, 2015b).

Virginia Native Plant Society

The Virginia Native Plant Society is a nonprofit organization dedicated to the protection and preservation of the native plants of Virginia and their habitats. Their goals are to slow the conversion of natural landscape to built and planted landscape areas and to reduce damage to natural ecosystems. The Society provides information about conserving and growing native plants, among other activities. They address plant conservation issues at the state level as well as those in particular communities and regions. The Society organizes local chapters that take the lead in identifying and addressing local concerns (Virginia Native Plant Society 2009).

The Land Trust of Virginia

The Land Trust of Virginia is a nonprofit organization that partners with private landowners to establish conservation easements. Land protected through this program remains in private ownership, and can be sold or passed to heirs (Land Trust of Virginia 2015).

The American Farmland Trust

The American Farmland Trust is a national organization founded in 1980 and is dedicated to protecting farmland and ranchland and to promoting sound farming practices. It operates a national level farmer-to-farmer land exchange program and promote sound agricultural policy development (American Farmland Trust 2015).

NATURE AND HUMAN HEALTH

So, what is the value of conserving our green spaces, our forests, fields, and natural communities? Why should we support conservation efforts at the local, state, and national levels? As a species that evolved outdoors, humans have a visceral connection with nature for nurture and well-being. Numerous scientific studies have demonstrated the connection between nature and human health (Bowler, et al. 2010). The relationship between nature and human health and well-being is clearly established and increasingly supported by scientific research. Spending time in natural settings has been shown to reduce childhood obesity and improve mental health (McCurdy et al. 2010). Outdoor activity reduces the incidence of myopia in children (Rose et al. 2008). Numerous studies demonstrate the beneficial effects of outdoor experiences on improving concentration and reducing hyperactivity in children (Faber Taylor et al. 2001, Kuo and Faber Taylor 2004, Faber Taylor and Kuo 2009, van den Berg and van den Berg 2010, Sahoo and Senapati 2014).

A longitudinal public health study conducted in areas where emerald ash borer killed millions of ash trees examined human mortality caused by cardiovascular and lower-respiratory-tract illness (Donovan et al. 2013). As the ash borer infestation increased, and tree mortality increased, there were an additional 6,113 human deaths related to respiratory illness and an additional 15,080 human deaths related to cardiovascular disease over what would have been expected without the tree loss. Exposure to natural landscapes also can lower heart rate and blood pressure, and enhance immune system defenses such as natural killer cells that help protect against cancer (Laumann et al. 2003, Hartig et al. 2003, Li et al. 2008). Compared to urban settings, people in natural settings are happier and have lowered anger and less aggression (Hartig et al. 1991). Measures of psychological well-being in humans had positive associations with species richness in greenspaces, with species richness of plants giving the strongest benefits (Fuller et al. 2007). The greater the plant biodiversity in one's environment, the greater are the positive benefits.

Virginia has a great diversity of plant life including many rare species distributed across the state. This richness of plant biodiversity supports the animal biodiversity found in Virginia.

Biodiversity is the single best promoter of ecological stability. From plants, we obtain food, medicines, fibers, various wood products, chemical feedstocks, and many other items that are essential to our civilization. By protecting and sustaining our plant communities, we provide not only economic security, but undergird human health and well-being. The value of maintaining natural spaces for humans to enjoy is inestimable. We must face the challenges of invasive plants, insects, diseases, land development, and climate change if we are to maintain the world as we know it for our children and future generations. Only by protecting and sustaining Virginia's natural resources can we sustain ourselves.

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Viewing the Status of Virginia's Environment Through the Lens of Freshwater Fishes

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ABSTRACT

We summarize a range of topics related to the status of Virginia's freshwater fishes, their reflection of environmental quality, and their contribution to human wellbeing. Since 1994 the list of extant Virginia fishes has lengthened from 210 species to 227 species, mostly due to taxonomic reorganizations. Virginia's list of Species of Greatest Conservation Need currently contains 96 fish species, predominated by darters (32 species) and minnows (28 species). Increasing trends in species rarity and threats to fishes suggest that Virginia's aquatic environment is becoming less hospitable for fishes. Prevailing anthropogenic threats to fishes include agriculture, urban development, mineral extraction, forestry, and power generation; emerging threats include introduction of nonnative species and climate change. Agency assessments of Virginia's streams, rivers, and lakes indicate that over 40% of them are impaired and that dozens of these waterbodies have fishes that, if consumed by people, contain harmful levels of mercury and polychlorinated biphenyls. Multiple state agencies are responsible for managing Virginia's freshwaters and fishes to achieve objectives related to recreation, conservation, and environmental health. We close with a discussion of the challenges and opportunities associated with conserving Virginia's diverse fish fauna and identify several research, management, and outreach actions that may enhance conservation effectiveness.

INTRODUCTION

Freshwater fishes represent a substantial component of Virginia's rich natural heritage and are tightly interwoven into our economic, environmental, and cultural fabrics. With over 200 native species, Virginia's fish fauna far exceeds the average diversity among other states in the United States. One reason for this remarkable diversity is that the state is uniquely situated at the distributional crossroads of many southern, northern, eastern and western fish species. The importance of fishes to

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Virginians goes back centuries to connect with Native Americans and European colonists (McPhee 2002) but still holds true today, albeit in different ways. Whereas most early Virginians were connected to fishes primarily as a major source of food, most Virginians today are not. Instead, our main uses of freshwater fishes are related to recreation (e.g., sportfishing) and environmental monitoring. Of course, fishes are also an important source of natural beauty and knowledge for those who take the time to study them. In this paper, we focus on the insights that fishes offer regarding the condition of our precious water resources.

Fishes are excellent environmental monitors because they reflect conditions in the water bodies where they live; those conditions are strongly affected by how people use water and land nearby. Water bodies integrate environmental conditions in their watersheds and, in turn, fishes integrate the conditions of the water in which they live (Karr and Chu 1999). Ultimately, fishes' abilities to persist in a water body reflect the environmental conditions to which they are exposed. For example, human activities are shifting the spatial and temporal dynamics of the water cycle, accelerating the rates at which sediment and nutrients enter freshwaters, preventing some animals from migrating upstream and downstream, and altering river flooding patterns (Helfman 2007). Common practices that alter freshwater availability through time include building impoundments (especially those that regulate the release of water) and altering land cover. The many ways in which people use land and water affect water quality by altering a wide range of its physical, chemical, and biotic properties. Intensive uses of land and water, such as uses by large industries or many people, commonly diminish water quality. The regional and local status of freshwater fishes can teach us a lot about our performance as environmental stewards.

Below, we discuss a range of topics connecting Virginia's fishes to environmental quality and human wellbeing. We begin with a brief summary of ecological factors limiting fish distributions, then describe key recent changes to the state's fish fauna and its conservation status. We also devote considerable text to the prevailing anthropogenic threats to fishes and how fishes are used to measure stream health. We close with a summary of Virginia's regulatory framework germane to fish conservation and some thoughts on needs for fish conservation going forward.

FACTORS LIMITING FISH DISTRIBUTIONS

Well over 200 species of freshwater fish live among Virginia's water bodies, including streams, swamps, rivers, ponds, lakes and estuaries (Jenkins and Burkhead 1994; Figure 1). However, the particular species living in a water body vary greatly among locations, depending on a suite of factors that includes zoogeography, prevailing physicochemical conditions, dispersal abilities of fishes, interspecific interactions, and anthropogenic impacts. Many physicochemical factors collectively determine if a given water body is suitable for a given fish species, and each species has distinctive sensitivities to these factors. Further, these limiting factors vary naturally through space and time but can also be dramatically influenced by human uses of air, land, and water. Herein, we follow Jenkins and Burkhead (1994) and Jelks et al. (2008) in defining 'freshwater' fishes. This definition encompasses all fishes that commonly spend much of their life in fresh waters, including diadromous species.

Fishes are especially sensitive to water chemistry and temperature and most species have narrow ranges of chemistry and temperature under which they can thrive.

Chemical parameters such as pH, dissolved oxygen, nutrients, salinity, and a vast array of toxicants (e.g., metals, pesticides, chlorine) commonly limit fish distributions (Matthews 1998, Helfman 2007). Different tolerances to salinity distinguish most freshwater fishes from marine fishes but a few freshwater species, such as American Eel (*Anguilla rostrata*) and Striped Bass (*Morone saxatilis*), can adapt to very different ranges of salinity during certain life stages. Similarly, seasonally high or low water temperatures preclude coldwater or warmwater fishes, respectively, from occurring in certain water bodies.

In addition to being sensitive to properties of the water itself, fishes are also sensitive to the physical structure of water bodies, such as their size, slope, depth, movement, and bottom composition. Thus, species are differentially adapted to live and thrive in streams versus rivers, rivers versus lakes, rocky streams versus sandy streams, and other structural types of water bodies. Collectively, parameters of temperature, water chemistry, and physical structure are used to describe fish habitats; the availability of suitable habitat is a fundamental factor regulating species' distributions.

The types of habitat available to fishes can vary widely, so in turn the fish assemblages present at a locality also vary considerably among regions of Virginia. Each of the five physiographic provinces represented in Virginia (i.e., Appalachian Plateau, Ridge and Valley, Blue Ridge, Piedmont, and Coastal Plain) exhibit distinctive geology, topography, and land use, all of which promote distinctive arrays of habitat types and distinctive fish assemblages. Similarly, each of the ten major river drainages (i.e., Potomac, Rappahannock, York, James, Chowan, Roanoke, Peedee, New, upper Tennessee, and Big Sandy; see Jenkins and Burkhead 1994) is bounded by barriers to fish dispersal (e.g., ridge tops and ocean), which promote evolution of sibling species and differentiation among assemblages. Accounting for the various combinations of elevation (a surrogate for temperature), stream size, physiography, and river drainage, Virginia supports approximately 90 distinctive types of freshwater fish assemblage (Angermeier and Winston 1999).

Understanding natural patterns of habitat availability and fish distribution across Virginia is crucial to using fishes as a lens to interpret environmental quality. Readers interested in learning more about natural and anthropogenic factors that limit freshwater fish distributions, including patterns specific to Virginia, are encouraged to see Jenkins and Burkhead (1994), Matthews (1998), and Helfman (2007) for additional details.

CHANGES IN VIRGINIA'S FISH LIST SINCE 1994

Over 20 years ago, Robert Jenkins and Noel Burkhead authored the seminal volume on the systematics, morphology, biology, habitat, and distribution of Virginia's freshwater fishes (Jenkins and Burkhead 1994). In that volume they provided a thorough summary account for each of the 210 species known to occur in Virginia waters, including chronologies of taxonomic reorganizations, introductions, and extirpations.

Many changes in Virginia's freshwater fish fauna have occurred since Jenkins and Burkhead's book was published, largely due to introductions, discoveries, and taxonomic reorganization. In short, the list of extant Virginia fishes has lengthened from 210 species and 230 taxa (i.e., species, subspecies, and undescribed forms) to 227 species and 235 taxa (Tables 1 and 2). Two species have been introduced: Northern Snakehead (*Channa argus)* and Blackside Dace (*Chrosomus cumberlandensis*). One

TABLE 1. List of freshwater fish families and species known from Virginia. The order is taxonomic. Scientific names are followed by common names. Numbers in parentheses indicate species counts. "*" indicates a species is extirpated or extinct. "**" indicates a species name is not officially recognized by the American Fisheries Society (Page et al. 2013).

Petromyzontidae – Lamprey (5)
Ichthyomyzon bdellium – Ohio Lamprey
Ichthyomyzon greeleyi – Mountain Brook Lamprey
Petromyzon marinus – Sea Lamprey
Lampetra aepyptera – Least Brook Lamprey
Lethenteron appendix – American Brook Lamprey

Acipenseridae – Sturgeon (2)
Acipenser brevirostrum – Shortnose Sturgeon
Acipenser oxyrinchus – Atlantic Sturgeon

Polyodontidae – Paddlefish (1)
Polyodon spathula – Paddlefish

Lepisosteidae – Gar (1)
Lepisosteus osseus – Longnose Gar

Amiidae – Bowfin (1)
Amia calva – Bowfin

Anguillidae – Eel (1)
Anguilla rostrata – American Eel

Clupeidae – Herring (6)
Dorosoma cepedianum – Gizzard Shad
Dorosoma petenense – Threadfin Shad
Alosa aestivalis – Blueback Herring
Alosa pseudoharengus – Alewife
Alosa mediocris – Hickory Shad
Alosa sapidissima – American Shad

Esocidae – Pike (4)
Esox lucius – Northern Pike
Esox masquinongy – Muskellunge
Esox niger – Chain Pickerel
Esox americanus americanus – Redfin Pickerel

Umbridae – Mudminnow (1)
Umbra pygmaea – Eastern Mudminnow

Cyprinidae – Minnow (73; *1 extirpated)
Cyprinus carpio – Common Carp
Carassius auratus – Goldfish
Ctenopharyngodon idella – Grass Carp
Notemigonus crysoleucas – Golden Shiner
Chrosomus tennesseensis – Tennessee Dace
Chrosomus oreas – Mountain Redbelly Dace
Chrosomus cumberlandensis – Blackside Dace
Chrosomus sp. cf. *saylori* – Clinch Dace**
Clinostomus funduloides – Rosyside Dace
Rhinichthys cataractae – Longnose Dace
Rhinichthys atratulus – Blacknose Dace
Rhinichthys obtusus – Western Blacknose Dace**
Campostoma anomalum – Central Stoneroller
Campostoma oligolepis – Largescale Stoneroller
Margariscus margarita – Allegheny Pearl Dace
Semotilus corporalis – Fallfish
Semotilus atromaculatus – Creek Chub
Exoglossum laurae – Tonguetied Minnow
Exoglossum maxillingua – Cutlip Minnow
Nocomis platyrhynchus – Bigmouth Chub
Nocomis micropogon – River Chub
Nocomis raneyi – Bull Chub
Nocomis leptocephalus – Bluehead Chub
Erimystax cahni – Slender Chub
Erimystax dissimilis – Streamline Chub
Erimystax insignis – Blotched Chub
Phenacobius mirabilis – Suckermouth Minnow
Phenacobius teretulus – Kanawha Minnow
Phenacobius crassilabrum – Fatlips Minnow
Phenacobius uranops – Stargazing Minnow
Hybopsis amblops – Bigeye Chub
Hybopsis hypsinotus – Highback Chub
Erimonax monachus – Spotfin Chub
Cyprinella labrosa – Thicklip Chub*
Cyprinella galactura – Whitetail Shiner
Cyprinella whipplei – Steelcolor Shiner
Cyprinella analostana – Satinfin Shiner
Cyprinella spiloptera – Spotfin Shiner
Luxilus coccogenis – Warpaint Shiner
Luxilus cerasinus – Crescent Shiner
Luxilus albeolus – White Shiner
Luxilus cornutus – Common Shiner
Luxilus chrysocephalus – Striped Shiner
Lythrurus lirus – Mountain Shiner
Lythrurus ardens – Rosefin Shiner
Lythrurus fasciolaris – Scarlet Shiner
Notropis rubellus – Rosyface Shiner
Notropis micropteryx – Highland Shiner
Notropis leuciodus – Tennessee Shiner
Notropis rubricroceus – Saffron Shiner
Notropis chiliticus – Redlip Shiner
Notropis atherinoides – Emerald Shiner
Notropis amoenus – Comely Shiner
Notropis photogenis – Silver Shiner
Notropis semperasper – Roughhead Shiner

TABLE 1. Continued.

Notropis volucellus – Mimic Shiner
Notropis spectrunculus – Mirror Shiner
Notropis stramineus – Sand Shiner
Notropis procne – Swallowtail Shiner
Notropis alborus – Whitemouth Shiner
Notropis bifrenatus – Bridle Shiner
Notropis chalybaeus – Ironcolor Shiner
Notropis altipinnis – Highfin Shiner
Notropis buccatus – Silverjaw Minnow
Notropis scepticus – Sandbar Shiner
Notropis sp. – Sawfin Shiner**
Hybognathus regius – Eastern Silvery Minnow
Pimephales promelas – Fathead Minnow
Pimephales vigilax – Bullhead Minnow
Pimephales notatus – Bluntnose Minnow

Catostomidae – Sucker (19; *1 extinct)
Carpiodes cyprinus – Quillback Carpsucker
Erimyzon sucetta – Lake Chubsucker
Erimyzon oblongus – Creek Chubsucker
Hypentelium nigricans – Northern Hog Sucker
Hypentelium roanokense – Roanoke Hog Sucker
Thoburnia rhothoeca – Torrent Sucker
Thoburnia hamiltoni – Rustyside Sucker
Moxostoma sp. – Brassy Jumprock
Moxostoma cervinum – Blacktip Jumprock
Moxostoma ariommum – Bigeye Jumprock
Moxostoma duquesnei – Black Redhorse
Moxostoma macrolepidotum – Shorthead Redhorse
Moxostoma breviceps – Smallmouth Redhorse
Moxostoma erythrurum – Golden Redhorse
Moxostoma carinatum – River Redhorse
Moxostoma anisurum – Silver Redhorse
Moxostoma collapsum – Notchlip Redhorse
Moxostoma pappillosum – V-lip Redhorse
Moxostoma lacerum – Harelip Sucker*
Catostomus commersoni – White Sucker

Ictaluridae – Catfish (15)
Ictalurus furcatus – Blue Catfish
Ictalurus punctatus – Channel Catfish
Ameiurus catus – White Catfish
Ameiurus platycephalus – Flat Bullhead
Ameirus brunneus – Snail Bullhead
Ameiurus natalis – Yellow Bullhead
Ameiurus nebulosus – Brown Bullhead
Ameiurus melas – Black Bullhead
Noturus flavus – Stonecat
Noturus gilberti – Orangefin Madtom
Noturus insignis – Margined Madtom
Noturus gyrinus – Tadpole Madtom
Noturus flavipinnis – Yellowfin Madtom
Noturus eleutherus – Mountain Madtom
Pylodictis olivaris – Flathead Catfish

Salmonidae – Trout (3)
Salvelinus fontinalis – Brook Trout
Salmo trutta – Brown Trout
Onchorynchus mykiss – Rainbow Trout

Percopsidae – Trout-Perch (*1 extripated)
Percopsis omiscomaycus – Trout-perch*

Aphredoderidae – Pirate Perch (1)
Aphredoderus sayanus – Pirate Perch

Amblyopsidae – Cavefish (1)
Chologaster cornuta – Swampfish

Atherinidae – Silverside (1)
Labidesthes sicculus – Brook Silverside

Fundulidae – Killifish (5)
Fundulus heteroclitus - Mummichog
Fundulus diaphanus – Banded Killifish
Fundulus rathbuni – Speckled Killifish
Fundulus catenatus – Northern Studfish
Fundulus lineolatus – Lined Topminnow

Poeciliidae – Livebearer (1)
Gambusia holbrooki – Eastern Mosquitofish

Gasterosteidae – Stickleback (1)
Gasterosteus aculeatus – Threespine Stickleback

Cottidae – Sculpin (10)
Cottus bairdi – Mottled Sculpin
Cottus caeruleomentum –Blue Ridge Sculpin
Cottus baileyi – Black Sculpin
Cottus cognatus – Slimy Sculpin
Cottus sp. – Holston Sculpin**
Cottus sp. – Clinch Sculpin**
Cottus sp. – Bluestone Sculpin**
Cottus carolinae – Banded Sculpin
Cottus kanawhae – Kanawha Sculpin
Cottus girardi – Potomac Sculpin

Moronidae – Temperate Bass (3)
Morone americana – White Perch
Morone saxatilis – Striped Bass
Morone chrysops – White Bass

Centrarchidae – Sunfish (20)
Ambloplites rupestris – Rock Bass
Ambloplites cavifrons – Roanoke Bass
Acantharchus pomotis – Mud Sunfish
Centrarchus macropterus – Flier
Pomoxis annularis – White Crappie

TABLE 1. Continued.

Pomoxis nigromaculatus – Black Crappie
Enneacanthus obesus - Banded Sunfish
Enneacanthus gloriosus – Bluespotted Sunfish
Enneacanthus chaetodon – Blackbanded Sunfish
Micropterus dolomieu – Smallmouth Bass
Micropterus punctulatus – Spotted Bass
Micropterus salmoides – Largemouth Bass
Lepomis gulosus – Warmouth
Lepomis cyanellus – Green Sunfish
Lepomis auritus – Redbreast Sunfish
Lepomis megalotis – Longear Sunfish
Lepomis marginatus – Dollar Sunfish
Lepomis macrochirus – Bluegill
Lepomis gibbosus – Pumpkinseed
Lepomis microlophus – Redear Sunfish

Percidae – Perch (50; *1 extirpated)
Sander vitreus vitreus – Walleye
Sander canadensis – Sauger
Perca flavescens – Yellow Perch
Percina sciera – Dusky Darter
Percina oxyrhynchus – Sharpnose Darter
Percina burtoni – Blotchside Logperch
Percina rex – Roanoke Logperch
Percina caprodes – Logperch
Percina bimaculata – Chesapeake Logperch*
Percina williamsi – Sickle Darter
Percina maculata – Blackside Darter
Percina notogramma – Stripeback Darter
Percina gymnocephala – Appalachia Darter
Percina peltata – Shield Darter
Percina nevisense – Chainback Darter
Percina crassa – Piedmont Darter
Percina roanoka – Roanoke Darter
Percina evides – Gilt Darter
Percina aurantiaca – Tangerine Darter
Percina copelandi – Channel Darter
Ammocrypta clara – Western Sand Darter
Etheostoma cinereum – Ashy Darter
Etheostoma swannanoa – Swannanoa Darter
Etheostoma variatum – Variegate Darter
Etheostoma kanawhae – Kanawha Darter
Etheostoma osburni – Candy Darter
Etheostoma blennioides – Greenside Darter
Etheostoma zonale – Banded Darter
Etheostoma simoterum – Snubnose Darter
Etheostoma tennesseense – Tennessee Darter
Etheostoma stigmaeum – Speckled Darter
Etheostoma jessiae – Blueside Darter
Etheostoma longimanum – Longfin Darter
Etheostoma podostemone – Riverweed Darter
Etheostoma nigrum – Johnny Darter
Etheostoma olmstedi – Tessellated Darter
Etheostoma vitreum – Glassy Darter
Etheostoma camurum – Bluebreast Darter
Etheostoma chlorobranchium – Greenfin Darter
Etheostoma rufilineatum – Redline Darter
Etheostoma denoncourti – Golden Darter
Etheostoma acuticeps – Sharphead Darter
Etheostoma vulneratum – Wounded Darter
Etheostoma caeruleum – Rainbow Darter
Etheostoma flabellare – Fantail Darter
Etheostoma humerale – Chesapeake Fantail Darter
Etheostoma brevispinum – Carolina Fantail Darter
Etheostoma percnurum – Duskytail Darter
Etheostoma serrifer – Sawcheek Darter
Etheostoma fusiforme – Swamp Darter
Etheostoma collis – Carolina Darter

Sciaenidae – Drum (1)
Aplodinotus grunniens – Freshwater Drum

Channidae – Snakehead (1)
Channa argus – Northern Snakehead

species, Clinch Dace (*Chrosomus sp.* cf. *saylori*), was newly discovered, while 15 species emerged from taxonomic reorganizations (Table 2; Robert Jenkins, personal communication).

A few miscellaneous changes in the fish list are also noteworthy. First, Jenkins and Burkhead (1994) included "Smallfin Redhorse" (*Scartomyzon robustus)* in their book, but Robust Redhorse (*Moxostoma robustum*) was subsequently rediscovered and described, which invalidated the name "Smallfin Redhorse". As a result, "Smallfin Redhorse" is now called Brassy Jumprock (*Moxostoma sp.),* an undescribed species occurring in the PeeDee drainage. Second, we added Mummichog (*Fundulus heteroclitus)* to our list because it has a high tolerance to varying salinities and often

Table 2. List of freshwater fish species new to Virginia since the publication of Jenkins and Burkhead (1994), along with reasons for their addition.

Scientific name	Common name	Reason
Channa argus	Northern Snakehead	Introduced
Moxostoma breviceps	Smallmouth Redhorse	Elevated subspecies of *M. macrolepidotum*
Moxostoma collapsum	Notchlip Redhorse	Split from *M. anisurum*
Cottus caeruleomentum	Blue Ridge Sculpin	Split from *C. bairdi*
Cottus kanawhae	Kanawha Sculpin	Elevated subspecies of *C. carolinae*
Campostoma oligolepis	Largescale Stoneroller	Elevated subspecies of *C. anomalum*
Chrosomus sp. cf. *saylori*	Clinch Dace	New discovery
Chrosomus cumberlandensis	Blackside Dace	Introduced
Lythrurus fasciolaris	Scarlet Shiner	Elevated subspecies of *L. ardens*
Notropis micropteryx	Highland Shiner	Elevated subspecies of *N. rubellus*
Notropis specticus	Sandbar Shiner	New discovery
Rhinicthys obtusus	Western Blacknose Dace	Elevated subspecies of *R. atratulus**
Lepomis marginatus	Dollar Sunfish	New discovery
Etheostoma brevispinum	Carolina Fantail Darter	Elevated subspecies of *E. flabellare*
Etheostoma denoncourti	Golden Darter	Split from *E. tippecanoe*
Etheostoma humerale	Chesapeake Fantail Darter	Elevated subspecies of *E. flabellare*
Etheostoma jessiae	Blueside Darter	Elevated subspecies of *E. stigmaeum*
Etheostoma tennesseense	Tennessee Darter	Elevated from *E. simoterum*
Percina bimaculata	Chesapeake Logperch	Elevated subspecies of *P. caprodes*
Percina nevisense	Chainback Dater	Elevated from *P. peltata*

* - not yet accepted by American Fisheries Society

occurs in tidal freshwaters. Jenkins and Burkhead (1994) briefly discussed this species but omitted it from their list. Third, Dollar Sunfish (*Lepomis marginatus*) has been collected in Virginia since the late 1980s; it is presumably native, though rare and restricted in its range. Because this species was first discovered in Virginia as Jenkins and Burkhead (1994) was going to press, its account was omitted.

Our fish list also includes four species that are completely extinct (Harelip Sucker [*Moxostoma lacerum*]) or judged to be extirpated from Virginia: (Trout-perch [*Percopsis omiscomaycus*], Chesapeake Logperch [*Percina bimaculata*], and Thicklip Chub [*Cyprinella labrosa*]). The latter three species still occur in other parts of their historic ranges.

SPECIES DISTRIBUTIONS AMONG FAMILIES AND RIVER DRAINAGES

The distribution of Virginia's fish species among its 26 families mirrors that of the rest of the eastern United States. The most diverse families by far are Cyprinidae (minnows; 73 species) and Percidae (perches; 50 species), with Catostomidae (suckers), Ictaluridae (catfishes), Cottidae (sculpins), and Centrarchidae (sunfishes) also contributing 10-20 species each (Table 1).

The distribution of fish species among Virginia's ten major river drainages varies greatly, depending on drainage area, diversity of habitat types, and connection to the speciose Mississippi River basin. Drainages with larger area, more habitat types, and fluvial links to the Mississippi River tend to support more species than drainages with opposing features. The upper Tennessee drainage supports the most fish species (120), while the Peedee drainage supports the least (27; Table 3). Ranks of drainages, with respect to fish species numbers, are similar for total species versus native species. Native species predominate the faunas of most drainages. Exceptions include the New and Potomac drainages, where 51% and 32%, respectively, of the extant fish species are introduced (Table 3).

CONSERVATION STATUS OF VIRGINIA FISHES

The U.S. Fish and Wildlife Service (USFWS) and the Virginia Department of Game and Inland Fisheries (VDGIF) recognize 22 fish species as being significantly imperiled and have conferred protective status to those species (Table 4). A species is designated as "endangered" if it is currently in danger of extinction throughout all or a significant portion of its range. A "threatened" species is likely to become endangered within the foreseeable future (see http://www.fws.gov/endangered/laws-policies/index.html). All ten species with federal protective status also have state status. These designations aim to protect individual fish, their populations, and their habitat from harm. To assist with protecting habitats, the VDGIF maintains a database of Threatened and Endangered Species Waters, which includes locations where imperiled species have been documented.

Imperilment and eventual extinction do not occur randomly across fish species. Rather, species with certain traits are more likely to become imperiled than others. Among Virginia's fishes, traits that predispose species to imperilment include a) diadromy (i.e., use of freshwater and marine habitats during sequential phases of life history), b) small range of suitable physiographies or stream sizes, and c) food and habitat specialization (Angermeier 1995). Every species listed in Table 4 exhibits one or more of these traits. Most of Virginia's imperiled fishes are darters (nine species) or minnows (seven species; Table 4).

In addition to monitoring and protecting imperiled species, VDGIF also has developed a comprehensive wildlife conservation strategy – or Wildlife Action Plan (WAP) – for all Virginia wildlife, including fishes (VDGIF 2005). The plan is based on input from partners, stakeholders, and citizens, and aims to anticipate and prevent imperilment. The WAP summarizes information on a) locations, abundances, and habitat requirements of species; b) threats to species and habitats; c); potential management actions to conserve species; and d) research, survey, and monitoring needs. Expert biologists for each major taxon developed a list of Species of Greatest Conservation Need (SGCN), then assigned those species to one of four tiers reflecting degrees of conservation need: critical (Tier 1), very high (Tier 2), high (Tier 3), and moderate (Tier 4). These tiers enable managers to prioritize threats to species and associated conservation actions based on conservation need. The WAP was initially developed in 2005, then revised in 2015 to reflect updated knowledge of status and threat (http://www.bewildvirginia.org/wildlife-action-plan/draft/).

The SGCN list currently contains 96 fish species, predominated by darters (32 species) and minnows (28 species), the most diverse taxa in Virginia freshwaters.

TABLE 3. Numbers of total fish species, native species, and percentage of introduced species for each of the ten major river drainages in Virginia.

Drainage	Total species	Native species	% Introduced
Potomac	100	68	32.0
Rappahannock	80	66	17.5
York	76	57	25.0
James	107	80	25.2
Chowan	93	82	11.8
Roanoke	116	98	15.5
Peedee	24	18	25.0
New	89	44	50.6
Upper Tennessee	120	97	19.2
Big Sandy	51	39	23.5

Between 2005 and 2015, 45 species changed status, including those added or removed from the list and those changing tiers; the status of 62 species remained the same (Table 5). The number of Tier I species increased 55% in the 2015 assessment while the number of Tier II species decreased 40%. During the 2015 re-assessment, the most common justification for removing a species from the SGCN list or shifting it to a lower-need tier was the committee of experts' judgment (based on available data) that its abundance or number of locality occurrences had increased (11 species). Other justifications included a) the species was peripheral to Virginia waters (six species) and b) revisions in taxonomy or native range (two species). Conversely, the most common justification for adding a species to the SGCN list or shifting it to a higher-need tier was a judgment that the species' abundance or number of locality occurrences had decreased (14 species). Other justifications included a) threats to the species were increasing (six species) and b) revisions in taxonomy (five species). Even as we learn more regarding life history and distribution for several species (Argentina et al. 2013, Starnes et al. 2014, White and Orth 2014), the overall increasing trends in species' rarity and threats suggest that Virginia's aquatic environment is becoming less hospitable for fishes.

ANTHROPOGENIC THREATS TO VIRGINIA FISHES

A wide range of human activities can directly or indirectly harm freshwater fishes by impairing their reproduction, survival, or growth. The most pervasive and impact-

TABLE 4. Legal protective status for 21 fish species in Virginia. FE=Federal Endangered; FT=Federal Threatened; FP=Federal Proposed; SC=Federal Species of Concern (not a legal status); SE=State Endangered; ST=State Threatened. "WAP tier" refers to designations of conservation need in Virginia's Wildlife Action Plan: I=critical; II=very high; III=high; and IV=moderate. Tiers do not confer legal status (see VDGIF 2005). Blank entries indicate no status.

Common Name	Scientific name	Federal status	State status	WAP tier
Atlantic Sturgeon	*Acipenser oxyrinchus*	FE	SE	I
Blackbanded Sunfish	*Enneacanthus chaetodon*		SE	I
Carolina Darter	*Etheostoma collis*		ST	II
Duskytail Darter	*Etheostoma percnurum*	FE	SE	I
Emerald Shiner	*Notropis atherinoides*		ST	IV
Golden Darter	*Etheostoma denoncourti*	SC	ST	II
Greenfin Darter	*Etheostoma chlorobranchium*		ST	I
Orangefin Madtom	*Noturus gilberti*	SC	ST	II
Paddlefish	*Polyodon spathula*		ST	IV
Roanoke Logperch	*Percina rex*	FE	SE	II
Sharphead Darter	*Etheostoma acuticeps*		SE	I
Shortnose Sturgeon	*Acipenser brevirostrum*	FE	SE	I
Sickle Darter	*Percina williamsi*		ST	I
Slender Chub	*Erimystax cahni*	FT	ST	I
Spotfin Chub	*Erimonax monachus*	FT	ST	I
Steelcolor Shiner	*Cyprinella whipplei*		ST	III
Tennessee Dace	*Chrosomus tennesseensis*		SE	I
Variegate Darter	*Etheostoma variatum*		SE	I
Western Sand Darter	*Ammocrypta clara*		ST	IV
Whitemouth Shiner	*Notropis alborus*		ST	II
Yellowfin Madtom	*Noturus flavipinnis*	FT	ST	I

TABLE 5. Status summary of Virginia fish species in the Wildlife Action Plan (WAP; VDGIF 2005). The WAP assigns each Species of Greatest Conservation Need to one of four tiers: I=critical; II=very high; III=high; and IV=moderate. Assignations were determined by expert fish biologists. The WAP was initially developed in 2005, then revised in 2015. Entries are numbers of species.

Status	2005	2015
Tier I	11	17
Tier II	15	9
Tier III	18	18
Tier IV	53	50
Total	97	94
Added	--	10
Need increased	--	16
Removed	--	13
Need decreased	--	6
Unchanged	--	62

prone of such activities, such as intensive uses of land and water, are performed for economic benefits (Czech 2000, Czech et al. 2000). As human populations and their resource consumption continue to increase, so will the magnitude of anthropogenic impacts, which could ultimately threaten the existence of many fish species (Burkhead 2012). Natural and anthropogenic factors interact to limit the success of individual fish, which translates into effects on population persistence and assemblage composition. The hundreds of potential anthropogenic impacts on fishes can be categorized as those that affect water quality, habitat structure, flow regime, energy and food dynamics, and biotic interactions (Karr et al. 1986). Any intensive use of water or land is likely to shift one or more of these categories away from natural conditions, thereby altering a fish species' ability to thrive. To the extent that human activities make an aquatic environment less suitable for the fishes naturally occurring there, that activity can be considered a threat to fishes.

The most common economic activities that threaten fishes in Virginia include agriculture, urban development, mineral extraction (especially coal mining [Stauffer and Ferreri 2002, Hill and Chambers 2014]), forestry, and power generation (Tables 3.19 and 3.23 in VDGIF [2005]). Notably, these activities occur primarily on land upslope of water bodies, as opposed to in the water bodies themselves (an exception is hydropower generation). The most harmful by-products of these activities, which typically flow downslope into streams, include a) excessive fine sediment (i.e., clay and silt), b) excessive nutrients (i.e., nitrogen and phosphorus), and c) industrial toxins (e.g., synthetic organics, herbicides, and insecticides) (Tables 3.19 and 3.21 in VDGIF [2005]). Some economic activities also involve direct structural changes to water bodies, such as channelizing streams, hardening shorelines, and building dams or culverts; other activities directly manipulate flow regimes, such as reducing overall discharge or increasing temporal variation in discharge. Such changes often lead to decreases in habitat suitability and/or increases in habitat fragmentation for fishes (Helfman 2007). The threats described above have been common in Virginia for decades and instrumental in causing fish imperilment. For example, impacts of agriculture, urban development, coal mining, forestry, dams, and industrial pollution were all cited in 1995 as contributing to the decline of one or more of the following State-Endangered species: Sharphead Darter (Smogor et al. 1995a) and Tennessee Dace (Smogor et al. 1995b). Furthermore, impacts stemming from urban development and industrial pollution seem likely to expand in the foreseeable future, as urbanization continues its rapid growth around northern Virginia, Richmond, Norfolk, Virginia Beach, and Lynchburg and along interstate highways 95 and 64 (VDGIF 2005).

Anthropogenic threats to, and impacts on, aquatic biota may interact in complex ways. First, a single source (e.g., urban development) can cause multiple impacts mediated via adverse effects on water quality, habitat structure, flow regime, energy and food dynamics, and/or biotic interactions (Wheeler et al. 2005). For example, some effects of urbanization may be direct and obvious, such as fish kills from point-source industrial effluents, whereas other effects may be indirect and obscured, such as reduced population abundance resulting from impaired reproduction, growth, and survival due to stressful flow and temperature regimes and excessive fine sediment. Second, multiple sources of biotic impact can interact to exacerbate their respective impacts on fishes. For example, effects of urbanization and climate change are likely to interact synergistically, so that impacts on Virginia fish populations are greater than if only one of the two sources were contributing (Nelson et al. 2009). Finally, anthropogenic impacts typically accrue and manifest over a range of spatiotemporal frames. Unfortunately, the protocols conventionally used by state and federal agencies to assess environmental impacts largely ignore large-scale, long-term impacts of activities such as road building and urban development, which often impose serious impacts on aquatic ecosystems (Angermeier et al. 2004).

Another pervasive threat to native freshwater biota that has garnered much attention by researchers and managers over the past few decades is the introduction of nonnative species, including parasites, predators, and competitors. Historically, fishes were most commonly introduced via government-sanctioned stocking (e.g., for sport-fishing or biocontrol) but fish introductions due to aquarium release, bait release, and escape from aquaculture are now more prevalent in the mid-Atlantic region of the U.S. (Lapointe et al. 2016). Recent examples germane to Virginia fishes include a) *Anguillicola crassus*, a parasitic nematode that originated in Asia but now infects swim-bladders of American Eel in much of its range (Barse and Secor 1999); b) Northern Snakehead (*Channa argus*), a large piscivorous fish that originated in Asia but now occurs in the Potomac and Rappahannock river drainages (Odenkirk and Owens 2005); and c) Variegate Darter (*Etheostoma variatum*), which is State-Endangered in Virginia but was illegally introduced into streams of the New River drainage in West Virginia, where it seems to be supplanting Candy Darter (*Etheostoma osburni*) (Switzer et al. 2007). Candy Darter is endemic to the New River drainage and a Tier 1 species on Virginia's SGCN list. If Variegate Darter spreads or is introduced to streams supporting Candy Darter in Virginia, Candy Darter may become increasingly imperiled.

Introductions of nonnative fishes are common across the United States (Nico and Fuller 1999, Rahel 2000), including Virginia, but their general severity as a risk to native biota, as well as how to manage them, are still debated (Leprieur et al. 2009, Gozlan et al. 2010). In some cases, ecological and/or economic impacts are clearly significant (Vitule et al. 2009) but standard methods for quantifying impact are lacking (Lapointe et al. 2012a). Managing introduced fishes is complicated by great variation in the propensity for particular species to become invasive and in the susceptibility of particular ecosystems to invasion. Across river basins of the Mid-Atlantic region of the United States, which includes Virginia, the number of nonnative fish species is positively correlated with colonization (i.e., propagule) pressure and range in elevation (Lapointe et al. 2012b). Montane basins in the Mid-Atlantic region have more nonnative species, in part due to their greater habitat heterogeneity induced by the widespread lentic habitats formed by impoundments.

As is the case for other anthropogenic threats to fishes, most introductions of nonnatives stem from widespread economic activities (Ericson 2005, Hulme 2009). The two main pathways by which nonnative fish species have been introduced into Virginia waters are both linked to recreational fishing: a) authorized stocking of gamefishes by state fisheries managers to enhance fishing opportunities and b) unauthorized release by anglers of game and bait fishes (Jenkins and Burkhead 1994). The former pathway has become less common in recent decades while the latter pathway has become more common (Lapointe et al. 2016). Some introduced species (e.g., Redbreast Sunfish, *Lepomis auritus,* now in the upper Tennessee drainage) originate from other waters in Virginia, while others originate from other states (e.g., Blue Catfish, *Ictalurus furcatus*) or other continents (e.g., Brown Trout, *Salmo trutta*). In any case, recreational fishing is a widespread, popular activity. According to a USFWS survey, 8% of Virginia residents fished in 2011 for a total of 9367 person-days (including saltwater fishing), spending $2.6 billion (USFWS 2012). Social demand for fishing opportunities is especially high in and around Virginia's growing urban centers (Villamagna et al. 2014). Thus, as these areas continue to grow, so will the threat of additional nonnative introductions for native fishes.

State and federal agencies are developing regulations to reduce the threats posed by introductions of nonnative species. In 2003, the Virginia General Assembly passed §29.1-570, the Nonindigenous Aquatic Nuisance Species (NANS) Act to control snakehead fishes (Channidae) and exotic mussel species (VDGIF 2011). This law empowers VDGIF to control, eradicate, or prevent the introduction or spread of NANS. These are defined in Virginia code (§29.1-571) as nonindigenous freshwater species "whose presence in state waters poses or is likely to pose a significant threat of harm to (i) the diversity or abundance of any species indigenous to state waters; (ii) the ecology stability of state waters; or (iii) the commercial, industrial, agricultural, municipal, recreational, aquacultural, or other beneficial uses of state waters." The General Assembly also approved creation of the Virginia Invasive Species Council, which includes representatives from eight state agencies and is responsible for coordinating state activities regarding invasive species. The VDGIF regularly assesses emerging threats associated with species likely to be introduced, then considers potential regulatory actions. For example, they recently prohibited the importation and sale of Oriental Weatherfish (*Misgurnus anguillicaudatus*), which is known to be invasive in neighboring states (http://nas.er.usgs.gov/queries/FactSheet.aspx?speciesID=498). However, because commercial pathways of fish introduction often cross state boundaries, effective regulation of nonnative introductions must be based on interstate cooperation (Environmental Law Institute 2007).

Climate change is an over-arching, impending threat to some freshwater ecosystems but its potential impacts have not been examined explicitly for most Virginia fishes. Recent analysis indicates that stream temperatures in Virginia are increasing, on average, about 0.028 °C per year (Rice and Jastram 2015). However, water temperature can vary considerably across a watershed, as it is mediated by a complex suite of processes and factors such as riparian vegetation and subsurface flow (Johnson 2004) and groundwater inputs (Dugdale et al. 2015, Snyder et al. 2015). Thus, the severity and extent of impacts on Virginia fishes due to climate change remain largely unassessed.

Three main forms of climate-change impact seem likely. First, warming water temperatures, which directly influence fish growth, development, reproduction, and survival (Hester and Doyle 2011), are likely to reduce the extent and connectivity of suitable habitat for coldwater and coolwater fishes over the long term. Published analyses of these impacts on Virginia fishes have focused on salmonids (Clark et al. 2001, Flebbe et al. 2006, Hester and Doyle 2011,). However, any species unable to move along stream/river corridors to find suitable habitat during climatic shifts may be threatened with local or regional extirpation (Poff et al. 2001). Second, projected increases in frequencies of severe weather patterns, such as floods and droughts, would favor species especially tolerant of such events. Third, to the extent that climate change promotes conditions stressful to fishes, the new stresses may interact synergistically with preceding stresses (e.g., from urbanization [Nelson et al. 2009]) to drive some populations to extinction. Overall, projected changes in land use and climate are likely to be especially harmful to fish species that have small geographic ranges, ecological specialization, a requirement for flowing water, or migratory behavior (Poff et al. 2001). These traits are common among Virginia fishes, especially darters.

USE OF FISHES TO ASSESS WATERBODY HEALTH

Fishes are widely used across the United States to assess anthropogenic impacts on streams, rivers, and lakes. Extensive knowledge of fish species' ecological traits provides insight into how human-induced environmental changes lead to shifts in population abundance and assemblage composition (Frimpong and Angermeier 2010). This knowledge has been used to develop assessment protocols that enable water resource managers to distinguish between the variation in environmental conditions that occur naturally from place to place and the variation caused by human impacts (Karr et al. 1986, Smogor and Angermeier 1999). Such fish assemblage-based protocols, along with protocols to assess water and sediment (physicochemical) quality, are used by many state agencies, including the Virginia Department of Environmental Quality (VDEQ), to monitor stream health. However, although VDEQ began collecting fish assemblage data for its statewide assessment of streams in 2008, the indexes it plans to use to summarize the data are still in draft form (Jason Hill, VDEQ, personal communication). Thus, assessment results are not publically available.

VDEQ also monitors stream health via probabilistic sampling of benthic macroinvertebrates in selected water bodies. Macroinvertebrate responses to stream conditions are germane to fishes because a) the vast majority of Virginia fishes primarily eat macroinvertebrates at some point during their life cycle (Jenkins and Burkhead 1994) and b) the two groups respond similarly to some anthropogenic impacts (Karr and Chu 1999). VDEQ's Probabilistic Monitoring Program is designed to answer questions about statewide and regional water quality. This program sampled over 250 sites from 2007 to 2012 for the 2014 assessment report. Based on that report, most water quality parameters met applicable water quality criteria, but 43.5% of the stream miles sampled exhibited sub-par biological conditions (http://www.deq.virginia.gov/Portals/0/DEQ/Water/WaterQualityMonitoring/ProbabilisticMonitoring/ProbMon2014.pdf). The top three causes of biological impairment seem to be streambed sedimentation (39.7%), habitat disturbance (19.7%) and total phosphorus (17.1%), all of which can adversely affect fishes. These percentages have changed only slightly since 2008, when 45.1% of the stream miles sampled exhibited biological impairment and the same top three causes accounted for impairment in 44.6%, 17.1%, and 15.9%, respectively, of stream miles (http://www.deq.virginia.gov/Portals/0/DEQ/Water/WaterQualityMonitoring/ProbabilisticMonitoring/ir08_Pt2_Ch2.4_Freshwater_ProbMon.pdf).

Another measure of a stream's health is how safe it is for people to eat the fish that live there. VDEQ and Virginia Department of Health (VDH) monitor levels of selected toxins (e.g., mercury and polychlorinated biphenyls [PCBs]) in tissues of selected fish species. These toxins pose health risks to people who eat them, especially pregnant and nursing women and young children (http://www.vdh.virginia.gov/Epidemiology/dee/PublicHealthToxicology/Advisories/). VDH maintains lists of fish-consumption advisories for Virginia, which indicate that fish taken from a particular body of water may contain harmful levels of toxins in certain fish species. At any given time, dozens of advisories may be in force. For example, on 26 April 2015, each major river drainage was represented by three (New) to nine (Potomac) water bodies with consumption advisories. Across Virginia waters, PCBs were the most common toxin in fish tissue.

Statewide temporal trends in contaminant levels in fish tissues are difficult to assess because the locations and numbers of sites, species, and individual fish sampled vary greatly among years. In 2013 (the most recent data available at http://www.deq.virginia.gov/Programs/Water/WaterQualityInformationTMDLs/WaterQualityMonitoring/FishTissueMonitoring/FishTissueResults.aspx), VDEQ found total PCB concentrations in fish tissues to exceed the VDH level of concern (50 ppb) in one to eight species in six waterbodies; Roanoke River had eight contaminated species. In contrast, the 2008 data indicated that total PCB concentrations exceeded the VDH level of concern in one to seven species in 42 waterbodies; Chopawamsic Creek had seven contaminated species. Differences between years cannot be interpreted as trends because sampling effort for PCBs in fish tissue was much greater in 2008 than in 2013, reflecting budget cuts to VDEQ's fish-tissue monitoring program (Jason Hill, VDEQ, personal communication). Further, the PCB sampling was distributed across different areas in 2008 versus 2013. The 2008 fish samples were collected mainly in the York River drainage and small coastal drainages plus selected sites in the James and Potomac river drainages, but the 2013 samples were collected mainly in the Rappahannock, Dan, and Roanoke river drainages.

VIRGINIA'S REGULATORY FRAMEWORK GERMANE TO FISH CONSERVATION

VDGIF is responsible for the management of inland fisheries, wildlife, and recreational boating for the Commonwealth of Virginia. Department policy for "conserving, protecting, replenishing, propagating and increasing the supply of game birds, game animals, fish and other wildlife of the Commonwealth" is set by its Governor-appointed Board under Code of Virginia §29.1-103. VDGIF is authorized to create regulations governing the taking, possession, and sale of "wild animals and birds and freshwater fish, and of endangered species of any form of wildlife." Thus, VDGIF regulates all issues related to the harvest, capture, importation, imperilment, and recovery of fish species. Regulations and resolutions are proposed by VDGIF staff to the Board based on perceived management needs and accompanied by sound biological justification. After a public comment period, the Board may adopt, modify, or reject proposed regulations while conferring with the VDGIF Director.

VDGIF manages all game and nongame fishes in Virginia's freshwaters. Gamefish populations are managed for the recreational enjoyment of its citizens through maintenance of wild populations and stocking of hatchery-produced fishes; most stocked fishes are trouts. Harvest regulations are used to prescribe fees for fishing licenses and permits, creel limits, capture methods, and fishing seasons. Nongame fish species are managed to provide harvestable bait for anglers and fish for personal possession (e.g., in an aquarium), while maintaining viable wild populations. Many introduced species have caused or have the potential to cause negative impacts to the Commonwealth's environment and economy. For those nonnative species determined to be too predatory or otherwise undesirable, VDGIF regulates them through the issuance of special permits to import, possess, or sell. Special permits are now required for 25 fish taxa (Table 6). In 1972, the Virginia General Assembly passed the Virginia Endangered Species Act, which allowed VDGIF to adopt the federal list of threatened and endangered species. Conservation and recovery efforts aimed at federally protected species are coordinated with the USFWS through Section 6 of the U.S. Endangered Species Act. A list of state-endangered species was first developed by VDGIF in 1987 (Terwilliger 1991) and is periodically updated (Table 4). VDGIF initiates and pursues conservation and recovery of these species as well.

CONSERVATION NEEDS FOR VIRGINIA FISHES

As threats to fishes become increasingly extensive and intensive, the need for effective conservation strategies and tactics will become more pressing. In our view, three main types of actions need greater support to enhance conservation effectiveness: research, management, and outreach. The main actors in these efforts will continue to be VDGIF and USFWS but other state and federal agencies will often be crucial partners. Research generates new knowledge to inform management and outreach. Most species on the SGCN lists remain poorly studied and lack sufficient funding for conservation. Key research needs for these species include studies to a) clarify exactly where species are (and are not), b) describe basic life history and habitat associations,

TABLE 6. List of nonnative fish taxa for which a special permit is needed to import, possess, or sell in Virginia. "spp." refers to all species of a genus or family.

Scientific name	Common name
Catastomidae	
Ictiobus bubalus	Smallmouth Buffalo
I. cyprinellus	Bigmouth Buffalo
I. niger	Black Buffalo
Channidae	
Channa spp.	(all snakeheads)
Parachanna spp.	
Characidae	
Pygopristis spp	(all piranhas)
Pygocentrus spp.	
Rooseveltiella spp.	
Serrasalmo spp.	
Serrasalmus spp.	
Taddyella spp.	
Cichlidae	
Tilapia spp.	Tilapia
Clariidae spp.	Air-breathing catfishes
Cobitidae	
Misgurnus anguillicaudatus	Oriental Weatherfish
Cyprinidae	
Aristichythys nobilis	Bighead Carp
Ctenophargyngoden idella	Grass Carp
Cyprinella lutrensis	Red Shiner
Hypophthalmichthys molitrix	Silver Carp
Mylopharyngodom piceus	Black Carp
Scardinius erythrophthalmus	Rudd
Tinca tinca	Tench
Gobiidae	
Neogobius melanostomus	Round Goby
Proterorhinus marmoratus	Tubenose Goby
Percidae	
Gymnocephalus cernuus	Ruffe
Synbranchidae	
Monopterus albus	Swamp Eel

c) document species' responses to selected anthropogenic impacts, d) develop reliable methods to track changes in distribution and abundance, and e) quantify the connection and value of healthy waters and fish communities to people. Previous experience in Virginia indicates that wise investment in targeted research can yield important findings that make species management more cost-effective (Rosenberger and Angermeier 2003, Roberts et al. 2008, Roberts et al. 2013).

The list of affordable and politically viable management actions that can be implemented to advance fish conservation is not long. The main field-based actions include those aimed at habitat restoration, such as a) re-vegetating riparian zones to stabilize stream banks and b) breaching (or removing) dams and replacing perched road culverts to facilitate fish passage. For a few species (e.g., Yellowfin Madtom [*Noturus flavipinnis*], Roanoke Logperch [*Percina rex*], and Blackbanded Sunfish [*Enneacanthus chaetodon*]), reintroductions may also be feasible if suitable, unoccupied habitat is available within their historic range. Because most Virginia water bodies drain private land, all these field-based actions require substantial partner collaboration to be successful. A management tool used to make this possible is the nonessential experimental population (NEP) designation provided by the U.S. Endangered Species Act. The NEP designation allows an endangered species to be reintroduced into its unoccupied, historic range while not subjecting federal agencies to activities that may jeopardize the species under Section 7 of the Act. Furthermore, accidental or incidental take is allowed by legal activities (i.e., agriculture, recreation, forestry) under a NEP designation. Governmental and non-profit organizations are currently moving forward to reintroduce Yellowfin Madtom into the North Fork Holston River, via a NEP designation (Conservation Fisheries, Inc. 2015). Finally, key regulatory actions to support conservation include restricting bait-harvest for narrowly distributed species (e.g., Tennessee Dace, *Chrosomus tennesseensis*) and reducing risks of further species introductions. Because these actions are politically difficult to implement and because such regulations impinge on some recreational and/or commercial activities, they too need substantial public support to be successful.

An important tactic for garnering political support for fish conservation is public outreach. Fish biologists have a central role and responsibility in engaging a range of publics regarding conservation (Angermeier 2007). Outreach messages that warrant delivering repeatedly include a) how healthy fishes are analogous to clean water and contribute to human wellbeing and b) what people can do individually to enhance water quality and fish conservation. One innovative outreach method currently being used in Virginia is the training of citizens to become naturalists through the Virginia Master Naturalist Program (VMNP). Many VMNP courses adopt a holistic approach with emphasis on aquatic species. After graduation, each naturalist must volunteer in nature-related roles to continue her/his certification. Since 2006, over 1,300 volunteers have contributed over 417,900 hours toward conservation efforts. In this manner, the public gains a long-term appreciation for aquatic ecosystems and becomes more likely to advocate for their protection. Another valuable outreach program used by some states is Trout in the Classroom, a collaboration between Trout Unlimited and state wildlife agencies. This program uses hands-on experiences to teach students about the water quality and habitat conditions required for fish growth and survival. Lastly, the display of native fish species at public aquariums is an excellent way to educate large numbers of citizens in a fun, comfortable setting. For many Virginians, seeing these species in a controlled environment may be the first and only opportunity to learn about native fishes and the importance of clean water to both people and fishes.

Although the number of freshwater species formally protected in the southeastern United States, including Virginia, probably underrepresents those in actual need of protection (Jelks et al. 2008), establishing legal protection is highly contentious, requires substantial resources, and can be counter-productive. In 2010, the Center for Biological Diversity (CBD) petitioned the USFWS to list 404 aquatic, riparian, and wetland species as federally threatened or endangered (http://www.biologicaldiversity.org/programs/biodiversity/1000_species/the_southeast_freshwater_extinction_crisis/index.html). To date, only one of those species, Alabama shad (*Alosa alabamae*), has been reviewed for protective listing; it was ultimately rejected. While such listings are necessary to protect some fishes, listings do not necessarily aid species recovery. For some people, "endangered" species have negative connotations such as government intrusion, impeding of progress, and trampling of private property rights (personal observations, Olive and Raymond 2010). These stigmas may impede rather than advance species recovery. Thus, for a species that can be propagated in captivity and for which suitable, but unoccupied, habitat is available, conservation may be more effective if it is not formally listed as imperiled. For example, Candy Darter, endemic to the New River drainage, is on the CBD's 2010 list. Because the species occurs primarily on U.S. Forest Service lands in Virginia, VDGIF has been able to develop a collaborative partnership to protect the species without assigning it a formal protective status. For waters occupied by Candy Darter, this partnership has facilitated a) elimination of stocking brown trout (a potential predator), b) purchase of significant, nearby private parcels, and c) research on the species' life history and habitat associations. Future research will continue to inform reintroduction efforts for this species. In the case of Candy Darter, it is unclear if formal protective status would make its conservation more effective.

People are more likely to value and become emotionally attached to animals they frequently see, such as birds (Messaris 1994, Czech and Krausman 1999). Because fishes live underwater where they are difficult for people to see, fishes often do not receive the attention they deserve unless being targeted for sport, food, or bait. Unknown by most, there is a remarkable diversity of freshwater fishes in Virginia that present a seemingly endless variety of colors, shapes, and behaviors. To bring more citizen attention and connection to fishes, we suggest more effort is needed to encourage the public to observe them in the wild (Monroe et al. 2009). Fish observation platforms, snorkeling field trips, and fish-related educational signage near waterbodies are but a few ideas that might promote the conservation of this unique and under-appreciated taxon.

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Virginia's Land Mammals: Past and Present, with Some Thoughts About Their Possible Future

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ABSTRACT

Mammals encountered today in Virginia's forests and fields include native and nonnative species, feral populations, and free-ranging pets. We examine factors that have influenced Virginia's terrestrial mammal fauna since the arrival of European colonists in the 1600s and some of the factors that are shaping the fauna today. We look in depth at changes since Handley and Patton's (1947) first complete monograph on Virginia mammals and augment Linzey's (1998) book, *The Mammals of Virginia*. We include current nomenclature, baseline information, and references to comprehensive literature. We discuss some of the current and developing anthropogenic factors that have impacted, or that likely will impact, our native land mammals as well as factors that bode well for many species, especially in areas of conservation of habitat.

BACKGROUND

Approximately 115 species of mammals live in or frequent Virginia; of these, about 28 are marine mammals (e.g., porpoises, whales, seals, and manatees) that are known from its shores, bays, and tidal rivers (Handley and Patton 1947; Linzey 1998). Including extirpated species, 77 species of native land mammals (those species that occurred here or reached here without purposeful or accidental introduction by humans) have been recorded since Europeans arrived in Virginia (Table 1). The diversity of Virginia's land mammals reflects a complex history of evolution, adaptation, and migration that has occurred over millions of years on a varied land surface and under changing climatic conditions (Woodward and Hoffman 1991). With elevations ranging from sea level to more than 1,500 m, the east-west orientation of the long axis of the state intersects five physiographic regions (Fig. 1), which results in a wide variety of habitats. As detailed by Handley (1992), most (42 of 74 extant species) Virginia land mammals have boreal (northern) affinities and the rest have austral (southern) affinities (Table 1). As a general rule, boreal species either occur statewide or in the west. By contrast, austral species tend to occur only in the east or south if their distributions are not statewide. As a result of its latitudinal position, Virginia is near the northern edge of the distributions of about a dozen austral species and the southern edge of

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TABLE 1. Land mammals native to Virginia, including species present at the time of European contact and those that have naturally colonized Virginia since that time. Common or vernacular name (as suggested by Wilson and Reeder 2005) is indicated for each species, along with current classification, current distribution, distributional affinity (distrib. affinity, after Handley 1992), habitat in Virginia, and the citation for a comprehensive monograph or review of the biology of that species. Virginia's Eastern Shore is comprised of Accomack and Northampton counties, at the southern end of the Delmarva Peninsula. For bats (Chiroptera), habitat describes roost sites, which may change seasonally. The following denote special circumstances that are detailed in text: E= extirpated; ER= extirpated (or nearly so), restoration attempted; EE = extirpated (or nearly so), range expansion from nearby states; A = augmented to increase populations and/or restore regionally.

Scientific name	Common name	Family	Order	Distribution	Distrib. affinity	Habitat	Citation
Didelphis virginiana	Virginia opossum	Didelphidae	Didelphimorphia	statewide	austral	generalist	McManus 1974
Sorex cinereus	cinereus shrew	Soricidae	Soricomorpha	mountains and Eastern Shore	boreal	generalist	Whitaker 2004
Sorex dispar	long-tailed shrew	Soricidae	Soricomorpha	mountains	boreal	forest, rocks and boulders	Kirkland 1981
Sorex fumeus	smoky shrew	Soricidae	Soricomorpha	mountains	boreal	forest	Owen 1984
Sorex hoyi	American pygmy shrew	Soricidae	Soricomorpha	statewide except Eastern Shore	boreal	generalist	Long 1974
Sorex longirostris	southeastern shrew	Soricidae	Soricomorpha	statewide except Eastern Shore	austral	oldfield, early succession	French 1980
Sorex palustris	American water shrew	Soricidae	Soricomorpha	mountains	boreal	mountain headwater streams	Beneski and Stinson 1987

TABLE 1. Continued.

Scientific name	Common name	Family	Order	Distribution	Distrib. affinity	Habitat	Citation
Blarina brevicauda	northern short-tailed shrew	Soricidae	Soricomorpha	statewide except south-central and parts of east	austral	generalist	George et al. 1986
Blarina carolinensis	southern short-tailed shrew	Soricidae	Soricomorpha	south-central and parts of east except Eastern Shore	austral	generalist	McCay 2001
Cryptotis parva	North American least shrew	Soricidae	Soricomorpha	statewide	austral	oldfield, early succession	Whitaker 1974
Parascalops breweri	hairy-tailed mole	Talpidae	Soricomorpha	mountains	boreal	generalist	Hallett 1978
Scalopus aquaticus	eastern mole	Talpidae	Soricomorpha	statewide	boreal	generalist	Yates and Schmidly 1978
Condylura cristata	star-nosed mole	Talpidae	Soricomorpha	statewide	boreal	near water	Petersen and Yates 1980
Myotis austroriparius	southeastern myotis	Vespertilionidae	Chiroptera	east except Eastern Shore	austral	buildings	Jones and Manning 1989

TABLE 1. Continued.

Scientific name	Common name	Family	Order	Distribution	Distrib. affinity	Habitat	Citation
Myotis grisescens	gray myotis	Vespertilionidae	Chiroptera	mountains, southwest	austral	caves	Decher and Choate 1995
Myotis leibii	eastern small-footed myotis	Vespertilionidae	Chiroptera	mountains	boreal	caves and rocky outcrops	Best and Jennings 1997
Myotis lucifugus	little brown myotis	Vespertilionidae	Chiroptera	statewide	boreal	caves and buildings, hollow trees, under tree bark	Fenton and Barclay 1980
Myotis septentrionalis	northern myotis	Vespertilionidae	Chiroptera	statewide	boreal	caves and buildings, hollow trees, under tree bark	Caceres and Barclay 2000
Myotis sodalis	Indiana myotis	Vespertilionidae	Chiroptera	mountains	austral	caves, hollow trees, under tree bark	Thomson 1982
Lasiurus borealis	eastern red bat	Vespertilionidae	Chiroptera	statewide	austral	tree foliage	Shump and Shump 1982a

TABLE 1. Continued.

Scientific name	Common name	Family	Order	Distribution	Distrib. affinity	Habitat	Citation
Lasiurus cinereus	hoary bat	Vespertilionidae	Chiroptera	statewide	austral	tree foliage	Shump and Shump 1982b
Lasiurus intermedius	northern yellow bat	Vespertilionidae	Chiroptera	southeast (one record)	austral	tree foliage	Webster et al. 1980
Lasiurus seminolus	Seminole bat	Vespertilionidae	Chiroptera	southeast (one record)	austral	tree foliage	Wilkins 1987
Lasionycteris noctivagans	silver-haired bat	Vespertilionidae	Chiroptera	statewide	boreal	tree foliage, under tree bark	Kunz 1982
Perimyotis subflavus	tri-colored bat	Vespertilionidae	Chiroptera	statewide	austral	caves, tree foliage, and buildings	Fujita and Kunz 1984
Eptesicus fuscus	big brown bat	Vespertilionidae	Chiroptera	statewide	boreal	caves, hollow trees, and buildings	Kurta and Baker 1990
Nycticeius humeralis	evening bat	Vespertilionidae	Chiroptera	primarily east of Blue Ridge	austral	hollow trees and buildings	Watkins 1972

TABLE 1. Continued

Scientific name	Common name	Family	Order	Distribution	Distrib. affinity	Habitat	Citation
Corynorhinus rafinesquii	Rafinesque's big-eared bat	Vespertilionidae	Chiroptera	southeast except Eastern Shore	austral	hollow trees and buildings	Jones 1977
Corynorhinus townsendii	Townsend's big-eared bat	Vespertilionidae	Chiroptera	mountains	boreal	caves and rocky outcrops	Kunz and Martin 1982
Tadarida brasiliensis	Brazilian free-tailed bat	Molossidae	Chiroptera	statewide except Eastern Shore	austral	buildings	Wilkins 1989
Sylvilagus floridanus	eastern cottontail	Leporidae	Lagomorpha	statewide	austral	oldfield, forest edge	Chapman et al. 1980
Sylvilagus obscurus	Appalachian cottontail	Leporidae	Lagomorpha	mountains	boreal	forest	Chapman 2007a
Sylvilagus palustris	marsh rabbit	Leporidae	Lagomorpha	southeast except Eastern Shore	austral	marsh,wet areas	Chapman and Willner 1981
Lepus americanus ***ER***	snowshoe hare	Leporidae	Lagomorpha	mountains	boreal	forest, dense understory	Chapman 2007b
Tamias striatus	eastern chipmunk	Sciuridae	Rodentia	statewide	boreal	generalist, wooded	Snyder 1982
Marmota monax	woodchuck	Sciuridae	Rodentia	statewide	boreal	generalist	Kwiecinski 1998

TABLE 1. Continued.

Scientific name	Common name	Family	Order	Distribution	Distrib. affinity	Habitat	Citation
Sciurus carolinensis	eastern gray squirrel	Sciuridae	Rodentia	statewide	boreal	forest	Koprowski 1994a
Sciurus niger ***A***	eastern fox squirrel	Sciuridae	Rodentia	west and southeast and Eastern Shore	austral	forest	Koprowski 1994b
Tamiasciurus hudsonicus	red squirrel	Sciuridae	Rodentia	mountains and upper Piedmont	boreal	mixed forest	Steele 1998
Glaucomys sabrinus	northern flying squirrel	Sciuridae	Rodentia	mountains	boreal	forest, northern hardwood, spruce/fir	Wells-Gosling and Heaney 1984
Glaucomys volans	southern flying squirrel	Sciuridae	Rodentia	statewide	austral	forest	Dolan and Carter 1977
Castor canadensis ***ER***	American beaver	Castoridae	Rodentia	statewide	boreal	forest, near water	Jenkins and Busher 1979
Oryzomys palustris	marsh oryzomys	Cricetidae	Rodentia	lower Piedmont and east	austral	near water	Wolfe 1982

TABLE 1. Continued.

Scientific name	Common name	Family	Order	Distribution	Distrib. affinity	Habitat	Citation
Reithrodontomys humulis	eastern harvest mouse	Cricetidae	Rodentia	statewide except Eastern Shore	austral	oldfield	Stalling 1997
Peromyscus gossypinus	cotton deermouse	Cricetidae	Rodentia	east except Eastern Shore	austral	lowland forests, swamps	Wolfe and Linzey 1977
Peromyscus leucopus	white-footed deermouse	Cricetidae	Rodentia	statewide	boreal	generalist	Lackey et al. 1985
Peromyscus maniculatus	North American deermouse	Cricetidae	Rodentia	mountains and upper Piedmont	boreal	forest and oldfield	Laerm and Castleberry 2007
Ochrotomys nuttalli	golden mouse	Cricetidae	Rodentia	southern half of state except Eastern Shore	austral	disturbed areas in forests, forest edges	Linzey and Packard 1977
Sigmodon hispidus	hispid cotton rat	Cricetidae	Rodentia	extreme southwest; Blue Ridge to east except Eastern Shore	austral	oldfield	Cameron and Spencer 1981

TABLE 1. Continued.

Scientific name	Common name	Family	Order	Distribution	Distrib. affinity	Habitat	Citation
Neotoma magister	Allegheny woodrat	Cricetidae	Rodentia	mountains	austral	caves, outcrops with boulders	Castleberry et al. 2006
Myodes gapperi	southern red-backed vole	Cricetidae	Rodentia	mountains	boreal	mesic forest, coarse woody debris, rocks	Merritt 1981
Microtus chrotorrhinus	rock vole	Cricetidae	Rodentia	mountains	boreal	mesic forest, rocks, logs, roots	Kirkland and Jannett 1982
Microtus pennsylvanicus	meadow vole	Cricetidae	Rodentia	statewide	boreal	oldfield, grasslands	Reich 1981
Microtus pinetorum	woodland vole	Cricetidae	Rodentia	statewide	austral	brushy, orchards	Smolen 1981
Ondatra zibethicus	common muskrat	Cricetidae	Rodentia	statewide	boreal	near water	Willner et al. 1980
Synaptomys cooperi	southern bog lemming	Cricetidae	Rodentia	mountains and southeast except Eastern Shore	boreal	bogs, wet meadows	Linzey 1983

TABLE 1. Continued.

Scientific name	Common name	Family	Order	Distribution	Distrib. affinity	Habitat	Citation
Zapus hudsonius	meadow jumping mouse	Dipodidae	Rodentia	statewide	boreal	oldfield	Whitaker 1972
Napaeozapus insignis	woodland jumping mouse	Dipodidae	Rodentia	mountains	boreal	forest	Whitaker and Wrigley 1972
Erethizon dorsatum ***EE***	North American porcupine	Erethizontidae	Rodentia	mountains	boreal	generalist	Woods 1973
Canis latrans	coyote	Canidae	Carnivora	statewide	boreal	generalist	Bekoff 1977
Canis lupus ***E***	wolf	Canidae	Carnivora	not present	boreal	not present	Mech 1974
Vulpes vulpes	red fox	Canidae	Carnivora	statewide	boreal	oldfield, open woodlands	Larivière and Pasitschniak-Arts 1996
Urocyon cinereoargenteus	gray fox	Canidae	Carnivora	statewide	austral	forest, brushy woodlands	Fritzell and Haroldson 1982
Ursus americanus	American black bear	Ursidae	Carnivora	statewide except Eastern Shore	boreal	forests primarily	Larivière 2001

TABLE 1. Continued.

Scientific name	Common name	Family	Order	Distribution	Distrib. affinity	Habitat	Citation
Procyon lotor	raccoon	Procyonidae	Carnivora	statewide	austral	generalist	Lotze and Anderson 1979
Pekania pennanti ***EE***	fisher	Mustelidae	Carnivora	mountains	boreal	forest	Powell 1981
Mustela frenata	long-tailed weasel	Mustelidae	Carnivora	statewide	austral	generalist	Sheffield and Thomas 1997
Mustela nivalis	least weasel	Mustelidae	Carnivora	statewide except Eastern Shore	boreal	generalist	Sheffield and King 1994
Neovison vison	American mink	Mustelidae	Carnivora	statewide	boreal	near water	Larivière 1999
Lontra canadensis ***A***	North American river otter	Mustelidae	Carnivora	statewide	boreal	near water	Larivière and Walton 1998
Spilogale putorius	eastern spotted skunk	Mephitidae	Carnivora	west	austral	forest	Kinlaw 1995
Mephitis mephitis	striped skunk	Mephitidae	Carnivora	statewide	boreal	generalist	Wade-Smith and Verts 1982

TABLE 1. Continued.

Scientific name	Common name	Family	Order	Distribution	Distrib. affinity	Habitat	Citation
Lynx rufus	bobcat	Felidae	Carnivora	statewide	boreal	generalist, much cover	Larivière and Walton 1997
Puma concolor ***E***	cougar	Felidae	Carnivora	not present	boreal	not present	Currier 1983
Odocoileus virginianus ***A***	white-tailed deer	Cervidae	Artiodactyla	statewide	austral	generalist	Smith 1991
Cervus canadensis ***ER***	wapiti	Cervidae	Artiodactyla	extreme southwest	boreal	clearings in high-elevation forests	Maehr et al. 2007
Bison bison ***E***	American bison	Bovidae	Artiodactyla	not present	boreal	not present	Meagher 1986

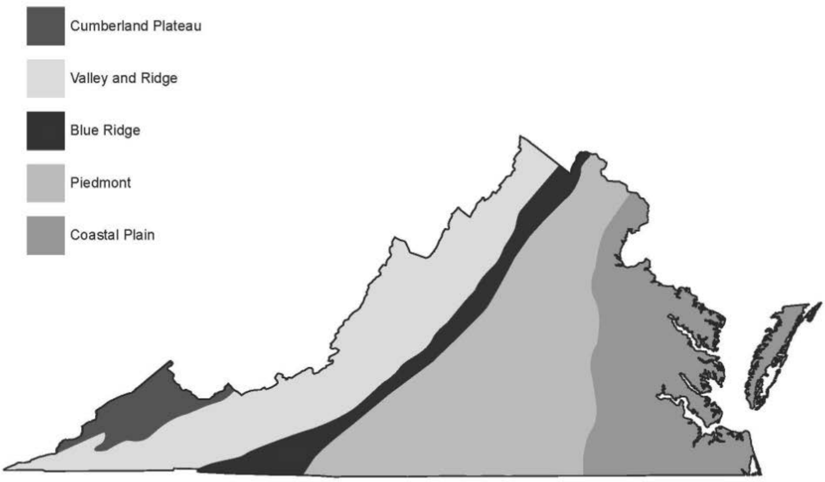

FIGURE 1. The physiographic provinces of Virginia.

distribution for about as many boreal species (Hall 1981). Ranges and statuses of several boreal species were the subject of a recent study by Campbell et al. (2010), motivated in part by Dobson et al.'s (1997) identification of the central and southern Appalachian mountains as a "hot spot of threatened biodiversity." The central and southern Appalachians have many specialized habitats, including caves, cliffs, talus, bogs, and boreomontane forests, that support populations of 7 of the 11 extant species listed in Virginia as threatened or endangered (Tables 1 and 2).

In this review, we summarize current information about the distribution and species composition of Virginia's native land mammals, with emphasis on studies that documented changes in the land mammal fauna since Handley and Patton's 1947 monograph. We also discuss long-term and ongoing threats to native species in the state. In doing so, we cite key literature that directs present and future students of Virginia mammals to pertinent resources.

HISTORICAL OVERVIEW

The history of the study of land mammals in Virginia was summarized recently by Linzey (1998) and Rose (2013). Although many mammals, especially game species, were documented and described by the earliest European explorers, and later by colonists, in the late 1500s and early 1600s, Rose (2013) credits C. H. Merriam with conducting the first systematic studies of Virginia's mammals in the late 1800s. Both Linzey (1998) and Rose (2013) characterize Handley and Patton's (1947) book *Wild Mammals of Virginia* as being the seminal work for chronicling the mammal fauna of the state. Therefore, we use that book as a basis for comparison throughout this review.

Rose (2013) acknowledged contributions in recent decades by a number of researchers that increased our understanding of mammals in particular regions of

TABLE 2. Special legal status (as of 13 April 2016) of native land mammals extant in Virginia (USFWS 2016, VDGIF 2016). The common, or vernacular, names are those used by the Virginia Department of Game and Inland Fisheries.

Scientific name	Common name	State legal status	Federal legal status
Sorex palustris	American water shrew	endangered	
Myotis grisescens	gray bat	endangered	endangered
Myotis lucifugus	little brown bat	endangered	
Myotis septentrionalis	northern long-eared bat	threatened	threatened
Myotis sodalis	Indiana bat	endangered	endangered
Perimyotis subflavus	tri-colored bat	endangered	
Corynorhinus rafinesquii macrotis	Rafinesque's eastern big-eared bat	endangered	
Corynorhinus townsendii virginianus	Virginia big-eared bat	endangered	endangered
Lepus americanus	snowshoe hare	endangered	
Glaucomys sabrinus coloratus	Carolina northern flying squirrel	endangered	endangered
Microtus chrotorrhinus	rock vole	endangered	

Virginia. To Rose's (2013) list we add W. M. Ford and J. L. Orrock, especially for their work in western Virginia, R. E. Eckerlin for work on mammals and their parasites, and J. C. Mitchell for his collaborative studies.

Handley and Patton (1947) described mammals known to occur in the state, those that were already extirpated by the early 1900s, and species from nearby states not yet recorded in Virginia. Subsequent publications of Handley (1979a, 1991) summarized information about Virginia's threatened and endangered mammal species. In addition to detailing changes in species composition since the Pleistocene, Handley (1992) commented on destruction of habitat, climate change, and other ongoing threats to mammals. Linzey's (1998) book, which included a comprehensive bibliography, summarized information for all mammals in Virginia.

NATIVE TAXA OVER TIME

Taxonomic changes since 1947 – In the nearly 70 years since Handley and Patton (1947), revisions in systematics and taxonomy reflect changes in our understanding of the evolutionary relationships of many mammals that inhabit Virginia (Table 3). We use the nomenclature for scientific names and vernacular, or common, names recognized by authors of taxonomic accounts in Wilson and Reeder (2005), with a few

TABLE 3. Current scientific name, scientific name (synonym) for the same taxon used by Handley and Patton (1947), if the names differ between publications, and citation(s) that documents our reason(s) for using a different name.

Current scientific name	Scientific name in Handley and Patton (1947)	Citation
Sorex hoyi	*Microsorex hoyi*	George 1988
Blarina brevicauda	*Blarina telmalestes*	George et al. 1986
Blarina carolinensis	*Blarina brevicauda carolinensis*	Genoways and Choate 1972; Tate et al. 1980
Myotis leibii	*Myotis subulatus leibii*	Glass and Baker 1968; Herd 1987
Myotis septentrionalis	*Myotis keenii septentrionalis*	van Zyll de Jong 1979
Perimyotis subflavus	*Pipistrellus subflavus*	Menu 1984; Hoofer and Van Den Bussche 2003; Hoofer et al. 2006
Corynorhinus rafinesquii	*Corynorhinus macrotis*	Jones 1977; Tumlison and Douglas 1992; Hoofer and Van Den Bussche 2001
Sylvilagus obscurus	*Sylvilagus transitionalis*	Chapman et al. 1992
Ochrotomys nuttalli	*Peromyscus nuttalli*	Blair 1942; Carleton 1980
Myodes gapperi	*Clethrionomys gapperi*	Kretzoi 1964; Carleton et al. 2014
Microtus pinetorum	*Pitymys pinetorum*	Conroy and Cook 2000; Conroy et al. 2001
Ondatra zibethicus	*Ondatra zibethica*	misspelling/gender issue
Vulpes vulpes	*Vulpes fulva*	Larivière and Pasitschniak-Arts 1996
Pekania pennanti	*Martes pennanti*	Li et al. 2014; Samuels and Cavin 2013; Koepfli et al. 2008
Mustela nivalis	*Mustela rixosa*	Sheffield and King 1994; Abramov and Baryshnikov 1999
Neovison vison	*Mustela vison*	Abramov 1999; Kurose et al. 2000
Lontra canadensis	*Lutra canadensis*	van Zyll de Jong 1972; Bininda-Edmonds et al. 1999
Puma concolor	*Felis concolor*	Pocock 1917; Kratochvil 1982

exceptions. We follow the recommendations of Hoofer and Van Den Bussche (2003) and Hoofer et al. (2006) for the tri-colored bat (*Perimyotis subflavus*), and those of Koepfli et al. (2008), Samuels and Cavin (2013), and Li et al. (2014) for the fisher (*Pekania pennanti*). For the wapiti (*Cervus canadensis*), we have followed the recommendations of Ludt et al. (2004), Pitra et al. (2004), and Skog et al. (2009) in recognizing it as a species that is distinct from the elk (*Cervus elaphus*). Handley and Patton (1947) also used the name *Cervus canadensis* for the wapiti, although *Cervus elaphus* was the name applied to this taxon by many subsequent workers (e.g., Hall 1981, Maehr et al. 2007).

Changes in the number of taxa documented since 1947 – The documentation of native taxa of land mammals in Virginia has changed since 1947 due to the collection of specimens and to changes in mammalian systematics (Table 4). One species, the Dismal Swamp short-tailed shrew (*Blarina telmalestes*), was judged to be conspecific with the northern short-tailed shrew (*Blarina brevicauda*), and we have removed it from the list. We have added the southern short-tailed shrew (*Blarina carolinensis*), which was formerly named *Blarina brevicauda carolinensis* (Tables 3 and 4), also because of systematic and taxonomic revisions.

Another taxon, the Maryland shrew (*Sorex cinereus fontinalis*), has been collected in Virginia (Moncrief and Dueser 1998). The systematic status of this shrew is in need of study. Based on morphology, Kirkland (1977) and others (e.g., Van Zyll de Jong 1991) assigned specimens they examined to *Sorex cinereus fontinalis.* On the basis of allozymic evidence, George (1988) recognized *Sorex fontinalis* as a distinct species. A subsequent study that examined mitochondrial DNA (mtDNA) diversification within the *Sorex cinereus* group (Demboski and Cook 2003) seemed to support George's (1988) findings, and another study of relationships within the genus *Sorex* (Hope et al. 2012) reported high mtDNA divergence of eastern populations of *Sorex cinereus* that is also consistent with George's (1988) conclusion. However, Hope et al. (2012) also reported variation at nuclear loci that places all specimens they examined from eastern localities within *Sorex cinereus* (*sensu stricto*). Neither Demboski and Cook (2003) nor Hope et al. (2012) examined specimens from Pennsylvania, Maryland, Delaware, or Virginia, where *Sorex cinereus fontinalis* has been documented. Additionally, as noted by Stewart et al. (1993), George's (1988) analysis included only a few specimens (n = 7) of *Sorex cinereus fontinalis* and may have been subject to sampling error. In the absence of additional, convincing evidence to the contrary, we take a conservative approach and treat this taxon as a subspecies of the cinereus shrew (*Sorex cinereus*). Further, we suggest that additional collections and analyses of specimens of *Sorex* from northern Virginia may reveal the Maryland shrew to have a broader distribution than is now considered to be the case.

Another taxon that requires additional study in Virginia is the wolf (or gray wolf, *Canis lupus*). We note that Linzey (1998) included 2 species of wolves, *Canis lupus* and *Canis rufus* (the red wolf), in his accounts of Virginia mammals. Since the publication of Linzey's book in 1998, numerous morphologic and genetic studies (reviewed by Chambers et al. 2012) have been conducted on *Canis* in North America in order to determine how many different species should be recognized in this genus and to determine the historic distributions of species of *Canis* on this continent. All studies of taxa in eastern North America have been hampered by a scarcity of museum

TABLE 4. Changes in documentation of native taxa of land mammals in Virginia since 1947 (Handley and Patton 1947), with citations that provide details about these changes.

Scientific name	Change	Reason for change	Citation
Sorex dispar	added to list	specimens collected	Handley 1956; Holloway 1957; Pagels 1987
Sorex palustris	added to list	specimens collected	Pagels and Tate 1976; Pagels et al. 1991; Pagels et al. 1998
Blarina telmalestes	removed from list	taxonomic revision	George et al. 1986; Handley 1979b; Webster et al. 2011
Blarina carolinensis	added to list	taxonomic revision	Handley 1971; Genoways and Choate 1972; Ellis et al. 1978; Tate et al. 1980
Myotis austroriparius	added to list	specimens collected	Hobson 1998
Myotis grisescens	added to list	specimens collected	Holsinger 1964; Decher and Choate 1995
Myotis leibii	added to list	specimens collected	Johnson 1950
Lasiurus intermedius	added to list	specimen collected	Rageot 1955; Webster et al. 1980
Lasiurus seminolus	added to list	specimen collected	Padgett 1987; Padgett and Rose 1991
Corynorhinus townsendii	added to list	specimens reported	Handley et al. 1979
Tadarida brasiliensis	added to list	specimens reported	Cranford and Fortune 1994; Reynolds and Fernald 2015
Glaucomys sabrinus	added to list	specimens collected	Handley 1979a; Reynolds et al. 1999
Peromyscus maniculatus bairdii	added to list	specimens collected	Peacock and Peacock 1962; Pitts and Kirkland 1987
Microtus chrotorrhinus	added to list	specimens collected	Pagels 1990; Orrock et al. 1999
Canis latrans	added to list	specimens collected	Hill et al. 1987; Bozarth et al. 2011

specimens, which has resulted in substantial chronological and geographic gaps in the data. None of these studies, including Nowak's (2002) widely cited work on the historical distribution of the red wolf, examined material from Virginia. Nevertheless, Nowak (2002) and Chambers et al. (2012) included the entire state of Virginia in the historical distribution of the red wolf and considered it to have been the only species present in Virginia at the time of European contact.

Wolves were extirpated from Virginia and most of North America east of the Mississippi River by the early 1900s (Handley and Patton 1947, Linzey 1998, Nowak 2002). Linzey (1998) reported that no wolf specimens from Virginia (of either *Canis lupus* or *Canis rufus*) are known to exist in collections. Our searches of collections records and our literature review for this project revealed specimens identified as *Canis* sp. in prehistoric deposits from Virginia (Eshelman and Grady 1986, FAUNMAP Working Group 1994). Until this material, or other evidence from Virginia, can be analyzed, we take a conservative approach and recognize a single species, *Canis lupus*, which, as defined by Wilson and Reeder (2005), includes specimens referable to *rufus*.

Species known to occur in nearby states in 1947 – Thirteen taxa have been recorded as new to Virginia since 1947 (Table 4), although many of them were known from adjacent states, and Handley and Patton (1947) speculated that seven of these species did, in fact, occur here. For example, the eastern small-footed myotis (*Myotis leibii*) and the gray myotis (*Myotis grisescens*) were known from West Virginia and Tennessee, respectively, in 1947, and Handley and Patton (1947) encouraged work to document these species in Virginia.

In several cases, the first individuals collected in Virginia were only captured by intensive survey efforts and/or by using methods that were not common in the past. Snap traps, live traps, and mist nets are often used for mammal studies. However, such trapping can be labor- and time-intensive, may not be legally permitted, or may be ineffective for detection of some species. Pitfall traps have been especially useful in studies of shrews (Handley and Kalko 1993, Padgett and Rose 1994), including the American water shrew (*Sorex palustris;* Pagels and Tate 1976, Pagels 1987). Also, largely with the use of pitfall traps, Rose (2006) found that a thought-to-be-extinct subspecies of the southern bog lemming (*Synaptomys cooperi*) was widespread in southeastern Virginia. Nest boxes attached to trees are often the most effective method for capturing arboreal squirrels (Pagels et al. 1990). Technological advances have revolutionized our ability to detect and identify species of mammals. For example, polymerase-chain-reaction analysis of DNA may only require the “capture” of hairs (Moncrief et al. 2008) or scat (Bozarth et al. 2011) to document the presence of a species. Remotely triggered digital game cameras, such as those used in the observations of the fisher and porcupine (*Erethizon dorsatum*), as discussed below, are often now used in surveys in combination with other trap types (i.e., Chupp et al. 2013). Such cameras can document species that would go undetected using traditional traps and permit broadscale survey efforts that would otherwise be cost-prohibitive (Erb et al. 2012). Similarly, increasingly sophisticated ultrasonic detectors are now used for bat surveys (Britzke et al. 2011).

Among the 13 new taxa collected since 1947 (Table 4) are the American water shrew, northern flying squirrel (*Glaucomys sabrinus*), and rock vole (*Microtus chrotorrhinus*). These species are largely confined to high elevation sites (i.e., mountain-top “islands” or nearly so) in the western part of the state (Table 1), and all are considered boreal Ice Age relicts (Handley 1992). Habitat specialization, limited geographical distributions, and apparent small population sizes of these species in Virginia reflect characteristics of threatened and endangered species (Yu and Dobson 2000).

The American water shrew lives in high-elevation moist, cool, largely undisturbed shaded habitats, which have likely prevailed throughout historic time (Pagels et al. 1991). Known from five sites in Bath and Highland counties along nearly pristine headwater streams (Pagels and Tate 1976, Pagels et al. 1998), the American water shrew is endangered in Virginia (Table 2).

The Virginia northern flying squirrel (*Glaucomys sabrinus fuscus*), known only from Highland County, was recently delisted from federal endangered status (USFWS

2008, 2013b), and it was subsequently removed from the state endangered species list (B. Gwynn, pers. comm.). We disagree with the DGIF's actions to delist this taxon in Virginia. The Virginia northern flying squirrel occurs at only a few sites in Highland County, and its habitat (high elevation northern hardwood and northern conifer) is very rare in Virginia, as detailed below. For these reasons, we contend that this taxon is in danger of extirpation in Virginia, and therefore, warrants protection under the Virginia Endangered Species Act. A second subspecies, the Carolina northern flying squirrel (*Glaucomys sabrinus coloratus*) is federal and state endangered (Table 2). Populations of the northern flying squirrel in southwestern Virginia (Grayson and Smyth counties) are considered intergrades of the Virginia and Carolina forms (Fies and Pagels 1991, Sparks 2005) and are listed as federal endangered. According to Payne et al. (1989), habitat of the northern flying squirrel in the southern Appalachians is high elevation, mesic forest characterized by northern hardwood and northern conifer species [i.e., red spruce (*Picea rubens*) or Fraser fir (*Abies fraseri*)]. These forests in Virginia are now largely restricted to Whitetop and Mount Rogers in Grayson and Smyth counties, and to a few sites in Highland County (Pagels et al. 1990, Reynolds et al. 1999). Recent studies by Ford and collaborators provide habitat models and new information on the Virginia (Menzel et al. 2006, Ford et al. 2010) and Carolina northern flying squirrels (Ford et al. 2015), respectively. They found that except for increasingly higher elevations to the south (i.e., southwest Virginia and North Carolina), habitat of the northern flying squirrel in the mid- to southern Appalachians is high elevation, cool, moist forest characterized by montane conifers [such as red spruce, Fraser fir, or eastern hemlock (*Tsuga canadensis*)], and a northern hardwoods component [such as yellow birch (*Betula alleghaniensis*), sugar maple (*Acer saccharum*) and black cherry (*Prunus serotina*)]. Desirable areas for the northern flying squirrel have few, if any, hard-mast-producing trees, such as American beech (*Fagus grandifolia*) or oak species (*Quercus* spp.), which are more favorable habitat components for southern flying squirrels (*Glaucomys volans*).

The rock vole is known from sites in Highland and Bath counties (Pagels 1990, Orrock et al. 1999) in mixed mesophytic habitats characterized by yellow birch, with abundant large, often moss-covered rocks (Orrock and Pagels 2003). Rock voles were also captured among rocks along a roadway in Highland County where the rocks appeared to have been placed for road stabilization (W. Bulmer, R. Eckerlin, and A. Gardner, pers. comm.). That site also had abundant yellow birch. Mixed mesophytic forests (Orrock et al. 2000, McShea et al. 2003), or montane mesic forests in general (Ford et al. 2006b), are important to many small mammals, and localized areas of moss-covered rocks and associated microhabitat in these forests seem to be critical to the rock vole in Virginia. One of us (JFP) and collaborators conducted surveys for the rock vole and the American water shrew in the late 1980s and 1990s at many sites in what appeared to be prime habitat in southwestern Virginia, notably the Whitetop, Mount Rogers and Clinch Mountain areas. Despite these surveys, neither the rock vole nor American water shrew has been found there to date, indicative of their localized distribution.

The long-tailed shrew (*Sorex dispar*), first reported from the Mountain Lake area of Giles County (Handley 1956, Holloway 1957), was later found in several other counties in western Virginia (Pagels 1987). Often associated with talus or boulder areas, the long-tailed shrew has a more continuous distribution than the American water shrew, northern flying squirrel, and rock vole (Table 1).

Handley and Patton (1947) stated that neither the coyote (*Canis latrans*) nor the red fox (*Vulpes vulpes*) occurred in Virginia in pre-colonial days, although Rose (1986) later reported red fox from Woodland Period archeological sites, which dated to approximately 2,000 years before European settlement. Both of these species now occur statewide (Linzey 1998). These species characteristically inhabit open woods, grasslands, and overgrown fields. However, coyotes often occupy a broader array of habitats (including inner cities; Gehrt et al. 2009) than do red foxes.

There has been debate over the source of eastern populations of both of these species. For many years, it was believed that red foxes in the eastern United States were of European origin, introduced to the American colonies for sport hunting (Churcher 1959, Linzey 1998, Kamler and Ballard 2002). Kasprowicz et al. (2016) recently presented genetic findings that European red foxes were, in fact, introduced to the mid-Atlantic region of North America. However, Kasprowicz et al. (2016) and Statham et al. (2012) also presented genetic evidence that red foxes were indigenous to the eastern United States at the time of European contact. As we noted above, red foxes were present at Woodland Period archeological sites in Virginia (Rose 1986).

Frey (2013) suggested that early naturalists in eastern North America probably believed red foxes were exotic because the colonists observed rapid range expansions and increases in abundance of this species in areas of the Southeast where, because of lack of suitable habitat, the red fox had been uncommon at the time of European settlement. Frey (2013) also provided historical information on population fluctuations of the red fox and the gray fox (*Urocyon cinereoargenteus*). Colonial-era clearing for agriculture and extensive deforestation increased abundance of red fox prey (e.g., rabbits and voles), whereas subsequent reforestation in some areas favored the gray fox, a woodland species, and its prey (e.g., insects, birds, and small mammals). The red fox possibly also benefitted from mesopredator release after wolves were reduced in numbers, and then extirpated in the Southeast (Frey 2013). However, the absence of wolves also likely played a role in the coyote's eastward range expansion. Red fox populations in the eastern United States may be suppressed again, but this time by coyotes (Frey 2013; Newsome and Ripple 2015).

Handley and Patton (1947) noted that coyotes had been collected in several western counties. They went on to comment that they "hesitate to recognize [the coyote] as an authentic Virginia species because many coyote pups are brought by tourists from the west and are released or escape when they reach maturity" (Handley and Patton 1947, page 140). Linzey (1998) reported a 1965 record of the coyote from Rockingham County, a record unknown at the time of the first symposium on Virginia's Rare and Endangered Species (Linzey 1979), when the coyote was said to be on the verge of entering Virginia (Pagels 1979). Mastro (2011) reported that prior to 1983, only eight coyotes had been recorded from Virginia. Mastro's (2011) review of literature on coyotes includes a time-line of range expansion into the mid-Atlantic states, observations on life history and ecology, and information about hybridization with other canids. Bozarth et al. (2011) provided mtDNA evidence that coyotes expanded their range into Virginia from northern and southern fronts, and they and Mastro (2011) observed that the mid-Atlantic states are the terminus of coyote range expansion in the continental US. Translocation by humans cannot be ruled out for spotty coyote introductions (Hill et al.1987, Linzey 1998); however, like others, we suggest habitat alteration and the extirpation of wolves were dominant factors in the colonization of Virginia by coyotes. We consider the coyote to be part of Virginia's native fauna and its presence in the state to be the result of natural range expansion. The coyote is an opportunistic feeder and known to predate white-tailed deer (*Odocoileus virginianus*); Montague (2014) found deer to be the most frequent food item of coyotes during all months of the year in western Virginia. Perhaps the abundance of white-tailed deer since the 1970s has played a complementary role in the rapid range expansion of the coyote in the state, including (as in other regions, see Gehrt et al. 2009), suburban and urban areas.

Range expansions of species not included in Handley and Patton (1947) – Six taxa not mentioned by Handley and Patton (1947) have naturally expanded their ranges into Virginia since 1947 (Table 4). Bats added to the list include the Brazilian free-tailed bat (*Tadarida brasiliensis*), which may be a very recent arrival. It was first reported by Cranford and Fortune in 1994 based on two specimens captured in Giles County, far north of its published geographic limits in North Carolina at the time, where it was considered a recent arrival (Wilkins 1989). Reynolds and Fernald (2015) reported on a specimen from southeastern Virginia in the 1990s and a pup collected in Charlottesville in 2014. More recently, R. Reynolds (pers. comm.) learned of an additional record from southeast Virginia and another from the Richmond area. This species has a surprisingly broad distribution in the state, given its recent range expansion.

Two species of bats are known from single records in the southeast: the Seminole bat (*Lasiurus seminolus*) from the Great Dismal Swamp (Padgett 1987) and the northern yellow bat (*Lasiurus intermedius*) from what is now the City of Norfolk (Rageot 1955). The southeastern myotis (*Myotis austroriparius*) was first recorded in the Great Dismal Swamp in 1998 (Hobson 1998), but it is now known to also occur at inland sites in the upper Coastal Plain (Reynolds and Fernald 2015). Virginia is at the northern edge of the range of each of these species. Another bat, Townsend's big-eared bat (*Corynorhinus townsendii*), occurs only in westernmost, mountainous portions of the state (Table 1). The subspecies of Townsend's big-eared bat that occurs here, *Corynorhinus townsendii virginianus*, is on the state and federal endangered lists (Table 2).

A subspecies of the North American deermouse (*Peromyscus maniculatus*), the prairie deermouse (*Peromyscus maniculatus bairdii*), was first collected in northern Virginia in 1960 (Table 4; Peacock and Peacock 1962). Another subspecies (*Peromyscus maniculatus nubiterrae*), which was included in Handley and Patton (1947), is a long-tailed mouse that is abundant in mountainous areas of Virginia at relatively high elevations and typically occupies mesic forests (McShea et al. 2003). In contrast, the prairie deermouse is a short-tailed mouse that is abundant in the Midwestern US. It is found in early successional and agricultural habitats and has been recorded in the Shenandoah Valley as far south as Harrisonburg (Hensley 1976). Francl and Meikle (2009) included the North American deermouse and white-footed mouse (*Peromyscus leucopus*) among other species captured with the hispid cotton rat (*Sigmodon hispidus*) at an early successional, relatively low-elevation site, 510 m, in Montgomery County in southwestern Virginia. Specimens were assigned to species based on tail length; the long-tailed specimens were identified as deermice and those with shorter tails as white-footed mice (K. Powers, pers. comm.). They did not assign the deermice to subspecies. The forest subspecies of deermouse (*Peromyscus maniculatus nubiterrae*), is usually found above 800 m (Handley and Patton 1947). Except for a Rockbridge County record (Pitts and Kirkland 1987), we know of no other efforts to document the presence of the prairie deer mouse in Virginia. However, we suspect *Peromyscus maniculatus bairdii* has a broader and more southerly distribution in the Shenandoah Valley than is indicated by published records.

Augmentation, regional translocations, undetected occurrence, and natural range expansions within Virginia since 1947 – Handley and Patton (1947) indicated that several species were absent from one or more regions of Virginia. In some cases, the Virginia Department of Game and Inland Fisheries (VDGIF) translocated animals from other regions of Virginia and from other parts of North America, in an attempt to restore populations of those species. In other cases, we believe natural range expansion has occurred, and we provide details and explanations for these expansions. The white-tailed deer was restricted to far southeastern Virginia and a few counties in the mountains by the early 1900s (Handley and Patton 1947). Between 1930 and 1950, more than 2000 animals from Florida, Michigan, North Carolina, Pennsylvania, and Wisconsin were released in Virginia (Linzey 1998). The augmentation efforts were successful. By the 1990s their numbers had rebounded to the point that the VDGIF sold some "limitless" tags to reduce populations and curtail damage to crops and ornamental plantings (Thompson and Francl-Powers 2013).

In 1947, Handley and Patton reported that the northern river otter (*Lontra canadensis*) was rare in the mountains. In the late 1980s, to supplement natural re-expansion of its range, VDGIF translocated animals from the Coastal Plain of Virginia and from Louisiana to areas west of the Blue Ridge (Handley 1991), and the northern river otter again occurs statewide (Linzey 1998).

Handley and Patton (1947) indicated that the eastern fox squirrel (*Sciurus niger*) was rare and localized in most regions of the state in 1947. More recently, Fies (1993) provided evidence that populations of eastern fox squirrels west of the Blue Ridge may be naturally expanding eastward. Although this species occurs in the Coastal Plain, its distribution is highly fragmented and population densities are low (Linzey 1998). In an effort to restore this species to Virginia's Eastern Shore (where it was listed as federal endangered until December 2015, USFWS 2015a), the US Fish and Wildlife Service translocated animals from Maryland to Accomack County between 1968 and 1971, and then from Accomack to Northampton County in 1982 and 1983 (Handley 1991).

Handley and Patton (1947) reported very restricted distributions for several taxa that are now known to be more widespread. Their records indicated that a subspecies of the southeastern shrew (*Sorex longirostris*), the Dismal Swamp southeastern shrew (*Sorex longirostris fisheri*), was restricted to the historic Dismal Swamp of extreme southeastern Virginia and extreme northeastern North Carolina. This taxon subsequently was found to occur throughout the Coastal Plain of North Carolina and well west of the Dismal Swamp in Virginia (Webster et al. 2009). Handley and Patton (1947) also reported the star-nosed mole (*Condylura cristata*) was unknown from most of the Piedmont and that the hoary bat (*Lasiurus cinereus*) had only been recorded at three localities. These three species now have statewide distributions (Linzey 1998), and it is likely they occurred statewide in 1947, but had gone undetected. Handley and Patton (1947) also reported that the American pygmy shrew (*Sorex hoyi*) was rare and known from only two localities. Because of extensive studies using pitfall traps (Pagels 1987), this species is now known to occur statewide (Linzey 1998), and it is sometimes locally abundant (Bellows et al. 2001).

The hispid cotton rat, a species that inhabits oldfields, was first collected in southern Virginia in 1941 (Patton 1941), then in Chesterfield County (Pagels and Adleman 1971), and later at many sites in southcentral Virginia (Pagels 1979). It has been reported from many locations across the southern half of the state: the Great Dismal Swamp (Rose 1999), Buckingham County (Pagels et al. 1992), a Blue Ridge site in Nelson County (Francl and Meikle 2009), sites in Botetourt and Montgomery counties (Francl and Meikle 2009), and Lee County in southwestern Virginia (Pagels 1979). It is likely that more northerly expansion will ensue in the Great Appalachian Valley (which includes the Shenandoah Valley) and in portions of the Piedmont and Coastal Plain.

The least weasel (*Mustela nivalis*) was only known from Montgomery and Rockingham counties in 1947, but Handley and Patton (1947) suggested that it probably occurred in all montane counties. More recently, the species was recorded from scattered mountain localities and two sites in the upper Piedmont (Handley 1991), and it was subsequently captured in the Coastal Plain (Bellows et al. 1999). Sheffield and King (1994) noted reports of many range extensions by the least weasel. Unlike several of the aforementioned species that have demonstrated range expansions, the least weasel is not a habitat specialist, but it is a predator specialist of small mammals, especially voles and other mice (Sheffield and King 1994).

The bobcat (*Lynx rufus*) was absent from the lower Piedmont and Coastal Plain, except it occurred in the Dismal Swamp and was "common in the mountains" (Handley and Patton 1947). Similarly, at the time of Handley and Patton's (1947) publication, the distribution of the black bear (*Ursus americanus*) was restricted to montane counties and the Dismal Swamp. Although still most abundant in those areas, both species now have statewide distributions (Linzey 1998); these reestablishments are likely the result of management and enforcement of game regulations by VDGIF.

Extirpations without reintroductions – At least three species of native land mammals present in Virginia at the time of the establishment of Jamestown were extirpated between 1607 and 1947 (Table 1) and remain absent today: wolf, cougar (also known as puma or mountain lion, *Puma concolor*) and American bison (*Bison bison*). Wolves and the cougar were eliminated from most of eastern North America by the early 1900s because of their reputation as predators of livestock. Handley and Patton (1947) stated that the last wolf was killed in the winter of 1909-1910 in Tazewell County, and the last known cougar was killed in Washington County in 1882. Linzey (1998) summarized what he considered to be reliable reports of cougars in Virginia between 1979 and 1998, but none of these were accompanied by verified physical evidence (specimens, hair, scat, or photographs). Our searches of museum databases (see Acknowledgments) returned one record of a *Puma concolor* specimen at the US National Museum (USNM, catalog number 270142) collected in 1940 at an archeological deposit (Keyser Farm site) in Page County, and another specimen at the Museum of Comparative Zoology (catalog number BOM-7120) of unknown date from Lee County. The US Fish and Wildlife Service (McCollough 2011) recently reviewed evidence of cougars in the eastern United States and recommended delisting the eastern cougar (*Puma concolor couguar*) because it is extinct. Most biologists consider the cougar to be extirpated in Virginia (Kocka and McShea 2011).

Handley and Patton (1947) reported that American bison were common in the early 1600s. William Byrd II in his 1728 survey of the "dividing line" between Virginia and North Carolina reported that a member of his party shot a two-year-old male American bison on 11 November (Rose 2013). Byrd wrote an extensive description of the massive shoulders of the animal, as well its legs, horns, hair, and herding behavior (Rose 2013). American bison were also reported in other early historical accounts of Virginia (Rose 1986). Skeletal remains of the American bison have been reported from archaeological deposits from one site in extreme southwestern Pennsylvania (Gilmore 1946). However, none have ever been reported from Virginia (E. Moore, pers. comm.). Although herds of the American bison were certainly present east of the Mississippi by the 18th Century, the lack of archaeological evidence in Virginia suggests they occurred in this region irregularly (if at all) prior to European colonization (E. Moore, pers. comm.). Handley and Patton (1947) cite Coues (1871) in reporting that the last remaining American bison in this region was killed in western Virginia (possibly what is now eastern West Virginia or eastern Kentucky) in the late 1790s.

Reintroductions and range expansions following extirpations and near extirpations – Several native species were extirpated, or nearly so, following arrival of Europeans; efforts have been made to restore most of these species to their former ranges through translocation of individuals (Table 1). Handley and Patton (1947) indicated that the snowshoe hare (*Lepus americanus*) probably occurred at high elevations throughout the mountains of Virginia, but by 1947 it was restricted to Highland County. Between 1961 and 1978, hundreds of animals from New Brunswick, Canada were released at several sites in Virginia; however, these attempts to establish populations of snowshoe hares failed (Fies 1991). In 1989, 26 animals captured in West Virginia were released in Highland County (Fies 1992), but by 1991 hares were absent in some previously occupied areas (Fies 1991). Fies (1991) noted that lack of understory threatened the remaining populations of snowshoe hares in Virginia, and Handley (1991) predicted that snowshoe hares could not survive in Virginia without appropriate habitat management. Our searches of museum databases (see Acknowledgments) returned electronic records of three specimens (skulls only) of *Lepus americanus* (USNM catalog numbers 448849-448851) collected in 1986 from Highland County. Also, a road-killed specimen (VMNH 134967, formerly VCU 4968) was collected in 1986 in extreme eastern Pocahontas County, West Virginia, near the Virginia border. The portion of the George Washington-Jefferson National Forest in northwestern Highland County where the hare was last seen currently is managed as the US Forest Service's Laurel Fork Special Management Area. This designation generally prohibits habitat alteration that otherwise could benefit the snowshoe hare. Although extant populations are present nearby in West Virginia within a few km of the state line, the conservation status of the snowshoe hare in Virginia is questionable, and this species may be extirpated.

The American beaver (*Castor canadensis*) is among the species that were extirpated and later successfully reintroduced (Table 1). Handley and Patton (1947) reported that American beavers were absent from Virginia by 1910, due to overtrapping. Linzey (1998) provides details of the restocking program implemented by VDGIF in the 1930s and 1940s. The American beaver is now considered to be a pest or nuisance species in some locations in the state (Linzey 1998).

The presence (or not) of the North American porcupine in Virginia at the time of European contact and recent evidence that it now occurs here present an enigma. Handley and Patton (1947) considered the porcupine to be "vanished" (extirpated) from Virginia's fauna, based on an anecdotal account from the 1730s. In the late 1800s, credible reports of live porcupines in West Virginia and Maryland were published in the Proceedings of the National Museum of Natural History; Goode (1878) described a live specimen from West Virginia, and Lugger (1881) provided details of specimens, including a live and a recently killed animal, from three localities in Maryland. Harman and Thoerig (1968) and Feldhamer et al. (1981) reported on porcupines killed by hunters in western Maryland, and Paradiso (1969) stated that the porcupine had been extirpated from Maryland, even though he mentioned "records and reports of the porcupine in the western part of Maryland right up to the present time." More recently, Linzey (1998) cited literature of occasional reports of animals in western Maryland, West Virginia, and Virginia through the late 1980s.

Our searches of museum databases returned one record (USNM catalog number 570136) of a porcupine found by D.E. Carr in 2006; it was dead on a road on North Mountain in Frederick County. M. Fies also reported (pers. comm.) a roadkill porcupine in 2010 near Swoope in Augusta County and two animals that were killed between September 2010 and July 2011 near I-81 in Frederick County. Joseph and Janet Trout used game cameras on Stone Mountain (in western Frederick County) to obtain numerous photographs of porcupines during 2008-2011. Among the photographs (which were examined by M. Fies, J. Pagels, and S. Roble, in litt.) were adults with young that apparently represent the first breeding records of the porcupine for Virginia. M. Fies (pers. comm.) also reported photos of porcupines from game cameras in western Shenandoah County (adjacent to Frederick County) in 2010 and 2013. More recently, a porcupine that had been hit by an automobile in western Frederick County in September 2014 was rehabilitated and released (Fies, pers comm.). Almost all recent evidence of the porcupine in the state was from areas near the border with West Virginia and Maryland. This is consistent with a statement in October 2015 by B. Sargent (pers. comm.) that the porcupine is "becoming more commonly reported in northeastern West Virginia." While we concede that it is possible that some animals have been accidentally transported to Virginia and nearby states on logging trucks heading south through Pennsylvania (Handley 1991), we concur with M. Fies (pers. comm.) that most of the porcupines recently observed in Virginia likely are the result of dispersal from expanding populations in West Virginia and Maryland. Regardless of origin and political boundaries, there is a breeding population of porcupines in western Maryland, northeastern West Virginia, and portions of northwest Virginia; the porcupine is once again part of our mammal fauna.

The fisher probably was present in western Virginia before being extirpated in the late 1800s (Handley and Patton 1947), although no specimen from Virginia was reported in a museum collection until very recently (Moncrief and Fies 2015). In 1969, the West Virginia Division of Natural Resources released 23 animals from New Hampshire at two sites in eastern West Virginia; at the time, no fisher population was known within 460 km of West Virginia (Pack and Cromer 1981). Periodic observations of fishers in Virginia, which Handley (1979a, 1991) considered to be reliable, were reported between 1969 and 1990, including one by JFP in 1989. However, none of these reports were accompanied by verified physical evidence of fishers (specimens, hair, scat, or photographs). In 2008, personnel from VDGIF examined and photographed two taxidermy mounts of fishers that were killed by hunters in Frederick Co., Virginia during 2006 and 2007 (Moncrief and Fies 2015). Trail cameras provided photographic evidence that documented fishers in five western counties between 2009 and 2015 (Moncrief and Fies 2015). In addition, four animals were collected in two of those counties between 2011 and 2015, and these specimens were deposited in the Mammal Collection of the Virginia Museum of Natural History (Moncrief and Fies 2015). According to Moncrief and Fies (2015), fishers that are now present in Virginia almost certainly dispersed from expanding populations in eastern West Virginia and western Maryland. Based on fisher sightings nearly 25 years ago, as well as the more recent specimens and photographic evidence, it is likely there will be documentation of reproduction in Virginia fishers in the near future.

The wapiti was hunted to extinction in Virginia by 1855 (Handley and Patton 1947). In 1917, animals from Yellowstone National Park were released into several western counties, and the population was estimated at about 300 individuals by 1922 (Handley 1979a). However, after a nematode parasite [*Pneumostrongylus* (syn. *Parelaphostrongylus*) *tenuis*] lethal to the wapiti was introduced by translocated white-tailed deer, the wapiti again disappeared (Handley 1979a). Another attempt to restore the wapiti in Virginia has been made within the past decade. A total of 71 animals from Kentucky was released from 2012 to 2014 in Buchanan County (part of the three-county restoration area that also includes Dickenson and Wise counties). Each year, the animals (16 in 2012, 10 in 2013, and 45 in 2014) were held for quarantine and disease testing before they were released. Including individuals that have entered Virginia from Kentucky on their own, the estimated population size was 150 to 200 animals following the 2016 calving season (D. Kalb, pers. comm.).

ONGOING AND NEW LONG-TERM THREATS TO VIRGINIA'S NATIVE LAND MAMMALS

Clearing for agriculture and other purposes, roadways, invasive plants, nonnative mammals, disease, climate change, and wind turbines are among the threats to native land mammals in Virginia. Before humans arrived, natural forces such as floods, wind, ice storms, and landscape-level wildfires (c.f. Francl and Small 2013), initiated or retarded succession. Both Native Americans and Europeans often used burning and clear cutting to prepare the land for crops and to manage habitat for early successional wildlife. Changes in land-use patterns since the arrival of Europeans have undoubtedly affected the distributions and abundances of our mammals, and some of these changes threaten continued existence of some species. Forests have been alternately cleared for agriculture and replanted. Networks of roadways have been established to move goods and people. Some introduced plants and animals have become invasive, compete with native organisms, or spread diseases to other mammals, including humans. Reliance on fossil fuels and the resultant climate change are altering distributions of species. These and other factors will continue to impact Virginia's land mammals. In the following sections, we provide details of the current status of these threats and efforts to mitigate them.

Virginia's landscape today – In western Virginia, as a result of reforestation after extensive early timbering and the abandonment of small farms, plus many years of control of natural fires, there is less early successional habitat than in the past. Forest abundance may be returning to pre-Colonial times, although tree species composition has been altered (e.g., American chestnut, *Castanea dentata,* is almost absent, Stephenson et al. 1992). Old-growth forests and forest types critical to uncommon plants and animals must be preserved, and connectivity must be encouraged in our mountainous areas. However, well-planned wildlife "openings," regardless of how they are produced, and continued USFS burning at previous fire intervals will benefit forest species and nongame and game species of mammals and birds.

In eastern Virginia, land use changes, increased urbanization, and changes in agricultural practices have decreased abundance of early successional habitats that benefit many species of wildlife. In most agricultural areas, early successional habitat is nearly non-existent because fields are cultivated, mowed or bush-hogged to the forest edge, the fields and pastures are of great acreage, and the fence rows, which provided cover and food in the past, are now nearly non-existent. Fies et al. (1992) described effects of changing land-use patterns on habitat for northern bobwhite (*Colinus virginianus)*, including the impact of "clean farming" methods. The same effects and impacts apply to numerous old field and generalist mammals.

Nearly all human activities lead to fragmentation of habitat far beyond the levels caused by natural factors such as fires and floods. Studies in landscape ecology have demonstrated that habitat fragmentation and the resultant size, shape, and isolation of patches and the inter-patch matrices have far-reaching effects on populations of organisms (Watling et al. 2011). Regardless of scale, habitat fragmentation will have lasting impacts on earth's ecosystems (Haddad et. al 2015). Whether viewed positively or negatively, managed forests, agroforestry, deforestation, reforestation, agricultural development, urbanization, suburbanization and exurbanization (low density rural development) all impact many of the state's 10.2 million ha. In 1630, about 9.9 million ha was forested. About 800,000 ha of reforestation followed extensive timbering in the early 1900s, so that a total of about 6.4 million ha, including plantation forests or otherwise highly managed sites, are forested today (VDOF 2015a,b). More than 3.3 million ha, or about 33% of Virginia's area, is agricultural land (VDACS 2015). In a nutshell, Virginia's landscape has become increasingly fragmented in modern times.

Roadways – Roadways are a major part of our environment and can affect both the biotic and the abiotic components of landscapes by changing the dynamics of populations of plants and animals, introducing exotic elements, and changing levels of available resources, such as water, light and nutrients (Coffin 2007). Virginia maintains more than 14,000 km of interstate and primary roads and 77,000 km of secondary roads (VDOT 2015). Among the most obvious, negative impacts are dead animals on or along roadways. Romin and Bissonette (1996) estimated the number of deer (all species) killed on US roadways to be at least 500,000 in 1991. In the mid-1980s, Pagels and French (1987) estimated that about 24 small mammals, primarily shrews, were entrapped in discarded bottles per km of Virginia's secondary roads. Forman (2000), who earlier coined the phrase "road ecology" (Forman and Alexander 1998), estimated one-fifth of the land area in the United States is affected by the cumulative effects of public road systems. Beckmann et al. (2010) encouraged road engineers and planners to consider impacts on animal movement in their design of new roadways. Methods are available for reducing wildlife mortality on roads. One solution includes fencing that directs wildlife to existing culverts or specially constructed underpasses. Sparks and Gates (2012) found that at least 57 wildlife species used culverts in western Maryland. In a novel approach, Kelly et al. (2013) installed gliding posts (modified wooden utility poles) that allowed successful gliding by the northern flying squirrel across a scenic byway in the mountains of North Carolina. In brief, many management tools are available to reduce the carnage of wildlife on our highways.

Invasive plants – Habitats in Virginia and elsewhere are becoming increasingly altered by invasive plants, which disrupt ecosystem processes and alter plant community composition and structure (Vilà et al. 2011). Some plants (e.g., *Elaeagnus umbellata*, autumn olive) were introduced in an attempt to benefit wildlife, yet they are now known for their negative impact on native habitats. Japanese stilt grass (*Microstegium vimineum)* is spreading rapidly in much of Virginia, including sites in the Coastal Plain, Piedmont, Blue Ridge, and Ridge and Valley provinces (JFP, pers. obs.). This invasive species can dominate ground-level habitats and shade out important native plants, and its high allelopathic potential (Pisula and Meiners 2010) is perhaps the reason for the large monocultures seen in many areas. A non-native form of common reed (*Phragmites australis*), which forms 2-m tall thickets where few native biota can coexist, dominates edges of salt and freshwater marshes and other damp places in the Coastal Plain and undoubtedly impacts many organisms, including mammals. Further, cold season fescue grasses (*Festuca arundinacea* varieties), of European origin, are often planted along roadsides, stream embankments, pastures, and cultural areas (including battlefield parks). The thick, matted growth form of fescue grass nearly prevents the germination of warm-season grasses and forbs, and severely limits movement of ground-nesting and ground-feeding wildlife (IDFW 2006). Allelopathic compounds produced by fescue grass also inhibit germination and establishment of native herbaceous species, and fescue grass often has a high occurrence of an endophytic fungus (*Acermonium coenophialium*) that produces alkaloids toxic to many organisms, including certain insects, wildlife, and many domestic animals (Conover 1998, IDFW 2006). These are but a few examples of the invasive plants and the damage caused by them in Virginia (VDCR 2015a). Some of the fescue fields are being reconverted to animal- and plant- friendly warm-season grasses and herbs. In general, some of the best efforts for countering loss of old-field habitats are found in groups working for recovery of game species (e.g., northern bobwhite quail), which benefits numerous other bird species and mammals, including the eastern cottontail (*Sylvilagus floridanus*).

Wildlife diseases and parasites – In recent decades, several diseases that affect free-living wildlife have been labeled emerging infectious diseases (EIDs), which can be placed into three broad categories: 1) diseases that "spill-over" to domestic animals and wildlife living nearby; 2) diseases resulting from human translocation of hosts and/or parasites; and 3) diseases with no obvious direct involvement of domestic animals or humans (Daszak et al. 2000). Emerging infectious diseases are frequently associated with changes in the ecology of the host, the pathogen, or both. These ecological changes are, in turn, often caused by anthropogenic habitat modification (e.g., deforestation, habitat fragmentation, agricultural development; Colwell et al. 2011, Gottdenker et al. 2014).

Wildlife diseases sometimes threaten the health of humans or domestic animals (Sleeman 2006, Joseph et al. 2013). Sleeman (2006) provided a comprehensive review of potential risks and instructions to prevent or reduce exposure to several notable wildlife diseases, including hantavirus pulmonary syndrome, tularemia, and tick-borne diseases such as Lyme disease and Rocky Mountain spotted fever.

Rabies, which can infect any mammal and is nearly always fatal, provides an example of a disease that was rapidly, and unintentionally, spread to Virginia by translocation (Smith et al. 1984). In the late 1970s, an outbreak of raccoon rabies occurred on the border of Virginia and West Virginia. It was later attributed to the interstate translocation of infected raccoons (*Procyon lotor*) that were captured in the southeastern United States and relocated to the mid-Atlantic region as part of an effort by hunting clubs to restock dwindling raccoon populations in this region (Guerra et al. 2003).

Another disease associated with raccoons is caused by the ascariid roundworm parasite *Baylisascaris procyonis*. This parasite has been documented in Virginia (Davidson 2006), and it has been described as an emerging zoonosis (Sorvillo et al. 2002) because of the increasing abundance and proximity of raccoons, its primary host, to humans. The ingestion of *Baylisascaris procyonis* eggs from soil or materials contaminated by raccoon feces, although very rare, may be fatal in humans. The parasite is also known to impact many wild mammals and some birds (Sorvillo et al. 2002), and it has been implicated in the extirpation of the Allegheny woodrat (*Neotoma magister*) in New York and New Jersey (LoGiudice 2003, Page 2013). In a study of Allegheny woodrats in the mid-Atlantic Highlands of Maryland, Virginia, and West Virginia, Ford et al. (2006a) indicated that, although the status of *Baylisascaris procyonis* throughout this region is uncertain, the parasite has been documented from raccoon feces in northern West Virginia and much of Maryland. These authors (Ford et al. 2006a) also cautioned that raccoons have been observed in rock outcrops with Allegheny woodrats in this region, so that a potential transfer mechanism is in place if *Baylisascaris procyonis* becomes a common enzootic in the mid-Atlantic Highlands, as may already be occurring north of the Potomac River.

Another parasite, *Toxoplasma gondii*, is a protozoan that can infect all birds and mammals. It relies on felids to complete its life cycle, and it is an emerging threat from free-roaming domestic cats (*Felis catus*). A recent study (Ballash et al. 2015) concluded that feral cats are likely the primary cause of white-tailed deer infections of *Toxoplasma gondii i*n northeastern Ohio. Feces of a single cat can deposit hundreds of millions of oocysts that may remain infectious for up to 18 months (Tenter et al. 2000). The implication for humans for the disease, which has been linked to schizophrenia, miscarriages, blindness, memory loss, and death (Torrey and Yolken 2013, Gajewski et al. 2014), is that humans can acquire toxoplasmosis from cysts in venison of undercooked white-tailed deer, a situation that may be exacerbated by the close association of humans, cats and deer in urban and suburban areas.

Although many studies of diseases in wildlife are motivated by concerns related to the health of humans and livestock, a number of diseases mainly or only affect wild mammals. Hemorrhagic disease, which is the most important infectious disease of white-tailed deer in the southeastern United States and in Virginia (VDGIF 2015c), seems to be in this category. Chronic wasting disease (CWD) is another disease that seems to naturally occur only in wild mammals, including white-tailed deer and wapiti

(Davidson 2006, VDGIF 2015a). In this case, the disease agent appears to be abnormally shaped proteins called prions that affect the central nervous system and lymphatic tissues (Davidson 2006). The first Virginia case of CWD was confirmed in Frederick County in 2009 (VDGIF 2015a).

In some instances, EIDs may lead to extirpation and/or extinction (Daszak et al. 2000, Joseph et al. 2013). For example, white-nose syndrome, which is caused by the fungal pathogen *Pseudogymnoascus destructans*, has been documented in numerous cave-dwelling bats, including species that occur in Virginia (Zukal et al. 2014, Powers et al. 2015). This pathogen is responsible for killing millions of bats in North America; it may alter the structure of bat communities and change ecosystem function (Jachowski et al. 2014), and it may extirpate one or more species of bats (listed in Table 2) that inhabit Virginia (Thogmartin et al., 2013). Additional parasites and diseases that cause mortality in native land mammals of Virginia are described in Davidson (2006).

Introduced and feral mammals — Ten species of mammals have been introduced intentionally or accidentally since the arrival of Europeans in Virginia, and many of these negatively impact our native environment. The house mouse (*Mus musculus*), the brown rat (*Rattus norvegicus*), and the roof rat (*Rattus rattus*) accompanied Europeans and remain commensals of humans (Table 5). Efforts to control these rodents and their damage to stored grains and foods result in great economic costs. However, their impact on native mammals, though largely unmeasured, probably is slight. More recent, and intentional, introductions were those of the sika (*Cervus nippon*) to Assateague Island (Accomack County) and the black-tailed jackrabbit (*Lepus californicus*) to Cobb Island (Northampton County). Introduced for hunting around 1960 (Linzey 1998), both species survive on their respective islands. The coypu (or nutria, *Myocastor coypus*) is a semiaquatic rodent native to South America. It was held in captivity for its fur in the 1930s, but animals escaped or were released when the fur market collapsed, and populations have become established on the Coastal Plain (Klopfer and St. Germain 2012). The coypu consumes large amounts of aquatic vegetation, can damage earthen dams, and likely competes with, and displaces, the (native) muskrat (*Ondatra zibethicus*, USFWS 2013a). Klopfer and St. Germain (2012) provide details about the distribution of the coypu in Virginia and adjacent states, and recent collaborative efforts to eradicate this invasive species.

Free-ranging and feral domestic mammals in Virginia (Table 5) include the horse (*Equus caballus*), the wild boar (pig or hog, *Sus scrofa*), the domestic cat, and the domestic dog (C*anis lupus familiaris*). Feral horses are restricted to Assateague Island (Accomack County) and Mount Rogers (Grayson and Smyth counties). The herd of horses on Assateague Island (the "Chincoteague ponies") is maintained at 150 head, and it is managed by local and federal guidelines. A goal of the 2013 Interim Chincoteague Pony Management Plan is to ensure the horses remain healthy and do not detract from the island's diverse natural resources (USFWS 2013c). Similarly, there are about 120 horses on the grassy balds near Mount Rogers (two herds on the Mount Rogers National Recreational Area with about 90 animals and one herd on Grayson Highlands State Park of about 30 animals) that are maintained by the Wilburn Ridge Pony Association (H. Thompson, pers. comm.). Such grassy, high elevation balds as those at Mount Rogers are being lost to encroachment by weedy vegetation and surrounding forests in the US and elsewhere. Weigl and Knowles (2014) hypothesized these areas owe their origin and persistence to past climatic extremes and activities of

TABLE 5. Land mammals introduced to Virginia, either accidentally or intentionally. Common or vernacular name (as suggested by Wilson and Reeder 2005) is indicated for each taxon, along with current classification and the citation for a comprehensive monograph or review of the biology of that taxon. Asterisks denote taxa with feral and/or free-ranging individuals.

Scientific name	Common name	Family	Order	Citation
Lepus californicus	black-tailed jackrabbit	Leporidae	Lagomorpha	Best 1996
Mus musculus	house mouse	Muridae	Rodentia	Laerm and Webster 2007a
Rattus norvegicus	brown rat	Muridae	Rodentia	Laerm and Webster 2007b
Rattus rattus	roof rat	Muridae	Rodentia	Laerm and Webster 2007c
Myocastor coypus	coypu	Myocastoridae	Rodentia	Woods et al. 1992
*Canis lupus familiaris**	domestic dog	Canidae	Carnivora	Serpell 1995
*Felis catus**	domestic cat	Felidae	Carnivora	Turner and Bateson 2013
*Equus caballus**	horse	Equidae	Perissodactyla	Mills and McDonnell 2005
*Sus scrofa**	wild boar	Suidae	Artiodactyla	Chapman and Trani 2007
Cervus nippon	sika	Cervidae	Artiodactyla	Feldhamer 1980

large mammalian herbivores, many of which are now extinct or extirpated. The horses largely fulfill that maintenance role today.

Feral wild boars consume wildlife and plants, destroy food caches of small mammals, compete with native wildlife for hard mast, and often severely damage plant communities and habitats (Campbell and Long 2009). Although populations of feral wild boars are localized in Virginia, they seem to be increasing and are being monitored by the VDGIF (2015b).

The literature is voluminous on the negative impact of domestic cats on native wildlife. Loss et al. (2013) estimated that free-ranging pets and feral cats kill 1.4-3.7 billion birds and 6.9 to 20.7 billion mammals annually in the US. Loss et al. (2013) also found that the majority of mortality is caused by truly feral cats and un-owned, stray cats (i.e., those without habitation but perhaps being fed). However, even house pets that spend only part of the day or night outside kill large numbers of small, native animals. A study that used "kittycams" to monitor hunting by such house pets in a suburban area of the southeastern USA found that almost half of them hunted wildlife, with an average of 2.4 kills per week (Loyd et al. 2013). These authors also showed that domestic cats brought home fewer than one in four kills, a finding that greatly increases earlier mortality estimates (e.g., Mitchell and Beck 1992). Loss et al. (2013) suggested that free-ranging pets and feral cats likely are the greatest source of anthropogenic mortality for US birds and mammals. Further, abundance of native predators typically reflects prey numbers and habitat quality of prey, and crashes of prey populations are followed by crashes of predator populations. In contrast, predation by free-ranging pet or feral cats (including those in trap, neuter, release programs) occurs regardless of prey numbers. Even those cats fed by humans continue to hunt, to the detriment of native wildlife (see Hawkins et al. 2004, among others).

The domestic dog has a long history in North America, perhaps as long as that of Native Americans. Companion, hunter, protector, herder, guide, and law enforcement describe some of the roles of modern dogs. Dogs also can adversely affect wildlife, but differ from cats in a number of ways, including mechanisms of disturbance, numbers of prey individuals consumed, and prey size. Free-ranging dogs, even when accompanied by their owners, often disturb and harass wildlife species (see Hughes and Macdonald 2013). Leashed dogs jumping after squirrels or depositing scent (that of a predator) while on a casual walk provide familiar examples of such harassment, potential or real.

Climate change – In the past 50 years, human-induced modification of climate has caused temperatures to rise, precipitation regimes to change, and icecaps to melt (Duffy and Tebaldi 2012, Abatzoglou and Barbero 2014, McCain and King 2014). Handley (1992) noted that regional disasters such as the gypsy moth (*Lymantria dispar*), acid rain, and the chestnut blight fungus (*Cryphonectria parasitica*) can have long-lasting or permanent impacts on the environment, but that all of these pale in comparison to the destructive potential of climate change. Handley (1992) and many others (e.g., Lawler et al. 2009) predicted a shift in the distributional ranges of some flora and a concomitant shift in the range of some mammals in response to climate change. Such shifts will change the composition, but not necessarily change the species richness, of mammal communities in Virginia (Handley 1992).

Recent models (McCain and King 2014) have identified factors (body size and activity time) that may mediate response of individual mammal species to climate change. We suggest that in the short-term, several species isolated in high elevation habitats in Virginia (e.g., American water shrew, northern flying squirrel, and rock vole) face the greatest threat of local extirpation due to climate change. Despite certain, often political, arguments that climate change is part of a natural cycle, we note extinction is also natural, but that both extinction and climate change are exacerbated by human activities. There is no evidence that Virginia is being spared the effects of climate change. In fact, the state has recently taken an active role to address climate change by developing a strategy to safeguard species of greatest concern (VDGIF et al. 2009). In addition, Kane et al. (2013) recently conducted a suite of climate modeling and species vulnerability assessments. Although their models did not explicitly include any mammals, we deem the animals used in that study to be appropriate surrogates for Virginia's mammals.

Wind energy and wind turbines — Large numbers of bats and other wildlife are killed by wind turbines each year (Kunz et al. 2007, Arnett et al. 2008). For years, arguments in support of wind energy development noted that wind is free, that fossil fuel costs are high, oil production is subject to political disruption in other countries, and the US is exhausting its coal deposits. More often now we hear from promoters of wind energy that wind is (still) free and that turbines produce zero greenhouse gas emissions and hence do not promote climate change. These arguments of the American Wind Energy Association and the American Wind Wildlife Institute can be compelling. However, wind turbines are substantial potential threats to Virginia bats, especially the hoary bat, the eastern red bat (*Lasiurus borealis*), and the silver-haired bat (*Lasionycteris noctivagans*; R. Reynolds, pers. comm.).

WILDLIFE MANAGEMENT AND HABITAT PROTECTION

Thompson and Francl-Powers (2013) recently summarized the history of wildlife management in Virginia. Between 1607 and the early 1900s, many species of mammals were hunted or trapped for sustenance, for sport, or for their pelts and other body parts. By 1916, the VDGIF was established to conserve, protect, and manage wildlife and non-marine fishes of the state. This mission continues today, and this state agency is charged with managing all land mammals, whether game or non-game species.

Over time, the mandate of the VDGIF has expanded to include management and conservation of land and habitat as well as the wildlife species themselves (Thompson and Francl-Powers 2013). In 2015, VDGIF maintained 41 management areas totaling more than 82,000 ha (VDGIF 2015d). Two other state agencies, Virginia Department of Conservation and Recreation (VDCR) and Virginia Department of Forestry (VDOF), also conserve natural resources and manage land for wildlife. In 2015, VDOF managed 22 state forests that total more than 27,000 ha (VDOF 2015c), and VDCR maintained more than 48,000 ha, including 36 state parks and 62 natural areas and preserves (VDCR 2015b).

In 2015, federal lands under management for wildlife and habitat conservation in Virginia included the George Washington and Jefferson National forests, which comprised more than 647,000 ha in Virginia (USDA 2015), 14 USFWS National Wildlife Refuges, which protected more than 52,000 ha of habitat (USFWS 2015b), and 21 national parks and other sites totaling more than 80,000 ha that are administered by the National Park Service (NPS 2015). In addition, the federal Department of Defense (DOD) properties in Virginia comprised 104,814 ha (Gorte et al. 2012), and most undeveloped area on DOD sites is managed as habitat for local wildlife. In 2015, the Virginia Outdoor Foundation (VOF) administered conservation easements on more than 300,000 ha of private land, including some of the highest-quality forests, cleanest waterways, and richest wildlife habitat in the state (VOF 2015). In sum, about 16.7 percent (about 1.7 million ha) of the estimated total land area of Virginia is protected in 2015 (VDCR 2015c).

SUMMARY

Although species richness, abundance and distribution of Virginia's land mammals reflect natural processes, the consequences of long-term human activities are also evident. As we described above, the recent range expansion of the hispid cotton rat provides an example of how humans have influenced the roles of habitat availability and habitat contiguity, in part through climate change. Further, with continued warming, we predict subsequent expansion of the ranges of additional species and contraction of the ranges of others. This will change species composition, but not necessarily species richness, as certain boreal species are lost from Virginia's fauna and replaced by austral species.

We suggest early successional habitats are more abundant now in much of the Piedmont and Coastal Plain than at the time of European settlement. In those same regions, future land use patterns may cause those early successional associations to persist, except in areas where cover is removed (e.g., modern clearing of vacant land and "clean farming"). In western Virginia, especially on large expanses of public lands, reforestation has reduced the amount of early successional habitat, and creation of additional openings would benefit certain wildlife.

Invasive plants will increasingly alter our native communities, degrading and eliminating habitats suitable for native mammals and other organisms. Feral and free-ranging cats and dogs will continue to harass and kill native wildlife. Lessening the impact of these non-native predators will require measures that evoke emotional reactions and cause contentious situations; it is unlikely this problem will be solved anytime in the near future. The public must be educated regarding the potential negative consequences (e.g., habitat destruction, competition with native species, new diseases) of introductions of exotic species, translocated game species, and the free rein given to domestic species.

The quest for alternative, renewable energy sources is urgent and includes capturing solar and wind energy. We caution that wind energy is not a panacea to the ills of fossil fuels. Animals may be killed by turbines, and habitat destruction on ridgetops, somewhat akin to surface mining, must be considered in the siting of wind facilities. We urge decision makers to seek information from qualified biologists and from refereed journals and to otherwise be aware of conflicts of interests when considering sources of information regarding the effects of wind turbines on wildlife.

Demands placed on our environment by an ever-increasing human population and the ongoing perturbations of natural systems portend that protection, management, and conservation of our natural resources will continue to be major challenges. Most of the lands under management for wildlife and habitat conservation in Virginia, especially east of the mountains, are not contiguous. Moreover, much of the habitat in the matrices surrounding managed areas is unsuitable for many species. Challenges will be greatest for maintenance of viable populations of species considered to be habitat specialists, whether in mesic forests, overgrown fields, swamps, marshes, or clear, 1st-2nd order headwater streams. Despite these and other ongoing challenges, many of Virginia's land mammals have demonstrated resilience in their ability to persist during the more than 400 years since European contact. With the combined efforts of state and federal agencies and non-governmental organizations, most species should continue to be a part of our natural heritage well into the future.

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Breeding Birds of Virginia

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ABSTRACT

Virginia supports a diverse community of breeding birds that has been the focus of investigation for more than 400 years. The avifauna reflects the latitudinal position of the state and the fact that the border extends from the Atlantic Ocean to the Appalachian Mountains. A total of 224 species have been recorded breeding in Virginia, 214 of which are extant. Twenty species have colonized the state since 1900 including 14 since 1950. Of all extant species, 102 (48%) are considered common at least somewhere in the state and 64 (30%) are rare to very rare. Diversity varies by physiographic region with 179 (83%), 168 (78%) and 141 (66%) in the Coastal Plain, Mountains and Piedmont, respectively. Two significant landscape features make significant contributions to the state-wide diversity including tidal waters along the coast and isolated spruce-fir forests of the Appalachians that represent Pleistocene-era relicts. In all, nearly 25% of the state-wide avifauna is either wholly or nearly confined to tidal water and 10% is confined to "sky island" refugia.

Since 1978, 25 species of birds throughout Virginia have been identified as requiring immediate conservation action. A retrospective assessment shows that 5 of these species including osprey (*Pandion haliaetus*), bald eagle (*Haliaeetus leucocephalus*), peregrine falcon (*Falco peregrinus*), brown pelican (*Pelecanus occidentalis*) and piping plover (*Charadrius melodus*) have recovered to or beyond historic numbers. Three species including Bewick's wren (*Thryomanes bewickii*), Bachman's sparrow (*Peucaea aestivalis*) and upland sandpiper (*Bartramia longicauda*) have been lost from the state and the black rail (*Laterallus jamaicensis*), loggerhead shrike (*Lanius ludovicianus*) and Henslow's sparrow (*Ammodramus henslowii*) are in imminent danger of extirpation. Several species including the peregrine falcon, piping plover, Wilson's plover (*Charadrius wilsonia*) and red-cockaded woodpecker (*Picoides borealis*) are the focus of intensive monitoring and management programs. The underlying causes of imperilment remain unclear for several species of concern, limiting our ability to development effective conservation strategies.

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INTRODUCTION

The ornithological record in Virginia stretches back more than four centuries. From the time of settlement at Jamestown in 1607, residents of Virginia and visitors to the state reported on the birds they encountered or were told about by Native Americans. William Strachey who lived in the settlement from 1610 to 1612 remarked at length on the birds he observed (Strachey 1849). Contemporaries including Captain John Smith, Raphe Hamor, and Edward Topsell describe many species including the waterfowl on the Chesapeake Bay, cardinals, mockingbirds and ruby-throated hummingbirds (Smith 1612, Hamor 1615, Christy 1933). Later in the century significant accounts by George Percy and John Clayton, Vicar of Crofton, would describe immense flocks of passenger pigeons and Carolina parakeets (Clayton 1685). These were followed by contributions by Thomas Glover and William Byrd (Glover 1676, Byrd 1841). Early accounts were primarily anecdotal descriptions or lists of birds within localities.

As time passed, early local accounts began to coalesce and were compiled into growing lists that began to provide a more complete assessment of the avifauna within the state. One of these early treatises, Mark Catesby's work (Catesby 1771), though centered to the south, had its beginning on Westover Plantation and generally includes the species described to that time. Thomas Jefferson would later give a list of 125 bird species for the "Virginias" (Jefferson 1787). These early treatments lead up to two significant works that gave a more complete assessment of the breeding birds including William Cabell Rives' "A catalogue of the birds of the Virginias" and Harold Bailey's "The Birds of Virginia" (Rives 1890, Bailey 1913).

Throughout the early 1900s a community of bird enthusiasts including academics and citizen volunteers would form, eventually leading to the establishment of the Virginia Society of Ornithology in 1929 (Johnston 2003). One of the stated missions of the organization was "to gather and assemble data on the birds of Virginia." Through annual forays designed to document breeding birds in specific locations that moved throughout the state an increasingly complete accounting of the breeding bird community would emerge over time. The long period of "ornithological exploration" in Virginia would eventually come to a close with Murray's production of "A check-list of the birds of Virginia" (1952). This benchmark work was a comprehensive compilation of birds observed in the state that provided a blueprint followed by subsequent updates (Larner 1979, Kain 1987, Rottenborn and Brinkley 2007). Incredibly, virtually all of the breeding species that have been added to the avifauna since Murray's initial checklist have been the result of range expansions into the state rather than new discoveries of long-existing species.

The early writings about Virginia birds were more than lists of occurrences. Descriptions of forces effecting populations such as market hunting and habitat loss demonstrate a conservation ethic that extends back in time. This ethic would build throughout the twentieth century and eventually become consolidated with the passage of Virginia's Endangered Species Act (§29.1-563 - §29.1-570) in 1972 and the federal Endangered Species Act (16 U.S.C. 1531-1543; 87 Stat. 884) in 1973. These two laws laid the foundation for the establishment of an organized effort to protect the nongame bird species of Virginia. In order to facilitate this mission, an avian taxonomic committee was formed and charged with identifying bird populations that were most in need of conservation efforts and funding. The committee would report on its assessment to a symposium held in Blacksburg during the spring of 1978 focused on endangered and threatened plants and animals of Virginia (Linzey 1979). This event would be followed by subsequent assessments in 1989 (Terwilliger 1991) and 2005 (VDGIF 2005).

Both the avifauna of Virginia and the conditions experienced by threatened populations are ever changing. The objectives of this paper are 1) to present an updated list of the bird species known to breed in Virginia and 2) to provide an update and retrospective on the status of species that have been identified as requiring the highest level of conservation attention (i.e. recommended for threatened or endangered status or placed in Tier I) during the 1978, 1989 and 2005 benchmark treatments.

METHODS

This treatment includes all bird species (extant or extinct) with recognized breeding records within the state of Virginia as of June 2014. Presentation follows the scientific and English nomenclature, and the order, of the seventh edition of the American Ornithologists' Union check-list of North American Birds (American Ornithologists' Union 1998) through the 55th supplement (Chesser et al. 2014). In order to provide information on broad distribution within the state, status is provided by physiographic region. To simplify for this presentation, regions include the 1) Coastal Plain, 2) Piedmont and 3) Mountains and Valleys. The Coastal Plain is bounded by the Atlantic Ocean to the east and the fall line to the west. The fall line is an erosional scarp where the metamorphic rocks of the Piedmont meet the sedimentary rocks of the Coastal Plain. Between these two boundaries the land slopes gently toward the fall line where it generally reaches an elevation of less than 80 m. The Piedmont is bounded to the east by the fall line and to the west by the escarpment of the Blue Ridge. In the northern parts of the state the Piedmont is only 75 km wide but broadens to the south reaching nearly 300 km wide at the state line. The land slopes up to the west reaching 300 m in elevation at the escarpment. The Mountains and Valleys Region is bounded by the east slope of the Blue Ridge and the state line. For ease of presentation this region has been forged from three provinces including the Blue Ridge Province, the Ridge and Valley Province and the Appalachian Plateaus Province. The region supports many areas above 1,000 m including Mount Rogers (1,746 m) and Whitetop (1,682 m), the two highest peaks in the state.

Within each physiographic region, the status of breeding populations was assessed in broad categories including common, uncommon, and rare. For species with known population estimates these categories follow the values: common – greater than 10,000 pairs, uncommon – greater than 1,000 but less than 10,000 pairs, rare – greater than 100 but less than 1,000 pairs and very rare – less than 100 pairs. For species with no population estimates these categories follow the following conditions: common – species with a relatively common habitat that is found easily, uncommon – species that requires a limited habitat and may be difficult to find, rare – species that is restricted to a limited habitat or is so scarce that it cannot be expected with any certainty, very rare – species that is restricted to only a few localities or has a small number of documented occurrences in the state. Although these categories are broad and have not been subjected to rigorous evaluation, they provide a description of relative abundance.

Sources of data

The treatment of breeding status and distribution presented here relied heavily on the work of the Virginia Society of Ornithology. Over the past 70 years, the society has produced four annotated checklists of Virginia birdlife published in the years 1952 (Murray 1952), 1979 (Larner 1979), 1987 (Kain 1987) and 2007 (Rottenborn and Brinkley 2007). These works represent an initial distillation of the historic records of the society and periodic updates reflecting advances in our understanding of the state's avifauna and its ongoing changes. In 1989, the society formed the Virginia Avian Records Committee to formalize the process for reviewing new records and for maintaining records of significance. The work presented here represents a continuation and update of the synthesis of those records presented in Rottenborn and Brinkley (2007).

Species of Conservation Concern

Many schemes exist for delineating and classifying species that are of high conservation concern. The benchmark symposia held in 1978 and 1989 used identical classification categories to rank relative endangerment and very similar methods for arriving at such classification for species (Linzey 1979, Terwilliger 1991). Both symposia brought together experts within taxonomic disciplines from throughout the state to assess the status of species of concern. Species were submitted for consideration to each taxonomic committee, assessed based on available information and placed into status categories. Four status categories were used including 1) endangered, 2) threatened, 3) special concern, and 4) status undetermined (Table 1). Although recommendations were considered in the listing process under Virginia law, it should be noted that recommendations from these symposia represent a statement about biological rather than legal status.

Methodology for the Wildlife Action Plan (VDGIF 2005) differed from the symposia in two respects including 1) how the list of species to be considered by taxonomic experts was derived and 2) the categories used for classifying relative endangerment. Managers used a matrix approach to delineate species for further consideration. The matrix included state, regional, national, and international conservation concern lists that included ranking schemes. An aggregation procedure was used to identify species that exhibited broad patterns of conservation concern. The resulting species list was assessed by a taxonomic committee and species were placed in one of four tiers that represented different levels of endangerment (Table 1).

For the purpose of this paper, I conducted a retrospective assessment of status for those bird species that were identified in either the 1978 or 1989 symposia or the Wildlife Action Plan as being in the highest categories of endangerment. This included those species recommended for endangered or threatened status in either symposia or species placed in Tier I in the Wildlife Action Plan. I describe each species overall breeding range, breeding history and distribution in Virginia, primary threats to breeding populations, rationale for endangerment recommendations, current status in Virginia and any management activities where applicable.

RESULTS

General Avifaunal Analysis

The breeding avifauna of Virginia is diverse reflecting both the geographic position of the state and the wide range of available habitats. A total of 224 species have been recorded breeding and 214 of these are extant (Appendix 1). Of the 10 species that have been lost to the state, 3 are globally extinct including the passenger pigeon, Carolina parakeet and Bachman's warbler. Of the remaining, the purple gallinule, roseate tern,

TABLE 1. Categories used to classify relative imperilment for bird species in Virginia during benchmark assessments.

Classification	Definition
Symposia (1978,1989)	
Endangered	A species which is in danger of extinction throughout all or a significant portion of its range in Virginia.
Threatened	Any species which is likely to become an endangered species in the foreseeable future through all or a significant portion of its range in Virginia.
Special Concern	A species which should be monitored because one or more of the following conditions apply to its status in Virginia: 1) it is geographically restricted or occurs at low density throughout its broad range, 2) its habitat is being threatened, 3) it is a specialist, and/or 4) other factors have been identified as imminent threats.
Undetermined	A species which has been suggested for placement in any of the above categories but for which there are insufficient data to accurately determine its status.
Action Plan (2005)	
Tier I	Critical conservation need. Faces an extremely high risk of extinction or extirpation. Populations of these species are at critically low levels, face immediate threat(s), or occur within an extremely limited range. Intense and immediate management action is needed.
Tier II	Very high conservation need. Has a high risk of extinction or extirpation. Populations of these species are at very low levels, face real threat(s), or occur within a very limited distribution. Immediate management is needed for stabilization and recovery.
Tier III	High conservation need. Extinction or extirpation is possible. Populations of these species are in decline, have declined to low levels, or are restricted in range. Management action is needed to stabilize or increase populations.
Tier IV	Moderate conservation need. The species may be rare in parts of its range, particularly on the periphery. Populations of these species have demonstrated a declining trend or a declining trend is suspected which if continued, is likely to qualify this species for a higher tier in the foreseeable future. Long-term planning is necessary to stabilize or increase populations.

upland sandpiper, Bewick's wren and Bachman's sparrow have undergone range contractions away from the state and the ring-necked pheasant and Japanese green pheasant were introduced species that were unable to sustain viable populations.

In many ways, Virginia is positioned within a latitude of faunal interchange with 30 (14% of extant species) species reaching their northern and southern breeding range limits within the state and an additional 15 (7%) reaching limits within adjacent states. Included in the list of species reaching their northern limits are red-cockaded woodpecker, Wilson's plover, white ibis and loggerhead shrike while those reaching their southern limits include common merganser, bobolink, northern harrier and northern waterthrush.

Twenty species have colonized the state since 1900 including 14 (70%) since 1950. Species documented to breed for the first time prior to 1950 include black vulture, European starling and herring gull while those after 1950 include white ibis, brown pelican and Mississippi kite. The most recent species known to colonize Virginia was the anhinga that was documented to breed for the first time in 2010. Six of the colonization events resulted from introductions. All of the remaining new species reached the state through natural range expansions. Interestingly, 8 of these expansions have moved from south to north, 5 have moved from north to south and only 1 has moved west to east.

Of all the extant species documented to breed in the state, 102 (48%) of these are considered common at least somewhere in the state (Appendix 1). Sixty-four species (30%) are rare to very rare throughout the state. Although more than half (125, 58%) of all extant breeding species occur across the entire state, diversity varies by physiographic region. The Coastal Plain supports 179 (83%) species compared to 168 (78%) and 141 (66%) in the Mountains and Piedmont, respectively. Sixty-eight (32%) species are exclusive to a single physiographic region including 40 (19%) in the Coastal Plain and 28 (13%) in the Mountains and Valleys. Twenty-two and 20 of these exclusive species are rare to very rare for the Coastal Plain and Mountains respectively. Currently, no breeding species occur exclusively in the Piedmont.

Two important physical features in Virginia contribute to the high diversity in the Mountains and Coastal Plain physiographic regions and to Virginia in general. These include the high elevations of the southern Appalachians in the Mountain region and tidal waters of the Coastal Plain. Twenty-two of the 28 species that are exclusive to the mountains are confined to high elevations that support habitats that are primarily restricted to northern latitudes. Included in this community are 10 high-elevation endemic subspecies (e.g. Appalachian winter wren – *T. h. pullus*, Appalachian sapsucker - *S. v. Appalachiensis*). Similarly, 36 of 40 species that are exclusive to the Coastal Plain are associated with tidal waters including beach-nesting birds (e.g., American oystercatcher, piping plover), seabirds (e.g., brown pelican, laughing gull), long-legged waders (e.g., snowy egret, little blue heron) and marsh birds (e.g., seaside sparrow, clapper rail).

Species of Conservation Concern

Twenty-five bird species have been recommended for threatened or endangered status or placed on Tier I in Virginia since 1978 (Appendix 1). This includes 14, 17 and 15 in 1978, 1989 and 2005 respectively. Interestingly, this includes 13 species that were only included on the list during one of these benchmark treatments and 3 species that were only included on two. This list includes species that have recovered during the interim (e.g., osprey, bald eagle), species that in retrospect were either not felt to warrant the highest designation (e.g., brown pelican, yellow-crowned night heron), species for which information remains insufficient to assess endangerment (e.g., sharp-shinned hawk, sedge wren) or species that have been faced with emerging threats in recent times (e.g., black rail, golden-winged warbler).

Nine of the species including peregrine falcon, Wilson's plover, piping plover, upland sandpiper, gull-billed tern, red-cockaded woodpecker, loggerhead shrike, Bewick's wren, and Henslow's sparrow appear on all three lists indicating a consensus on their continued imperilment. Two of these species including upland sandpiper and Bewick's wrens have been extirpated from the state and two others including loggerhead shrike and Henslow's sparrow are on the verge of extirpation. The Bachman's sparrow, appearing on the last two lists, has also been extirpated from the state. Most of the remaining species including peregrine falcon, Wilson's plover, piping plover and red-cockaded woodpecker are the focus of intensive conservation efforts. Focused management programs have not been established for gull-billed terns, loggerhead shrikes and Henslow's sparrows.

Retrospective Assessments

Brown Pelican – Threatened (1989)

Brown pelicans breed from the Chesapeake Bay of Maryland south to Venezuela and along the Pacific Coast from California to central Chile (Shields 2002). The species is highly sensitive to organochlorine pesticides (Blus 1982) and was listed as federally threatened in 1970 due to pesticide-induced reproductive failure and associated population declines in the United States and Mexico. Brown pelicans were removed from the Endangered Species List along the Atlantic Coast of North America in 1985 due to population recovery. The small population size and the potential for human disturbance within nesting colonies were listed as reasons for proposed listing as threatened in Virginia (Byrd 1991a). The decision by the taxonomic committee to propose a status of threatened is perplexing given that the regional population had been removed from the federal list four years earlier and the species had only recently colonized the state as part of a northward range expansion.

The Brown Pelican was first found breeding in Virginia on Fisherman Island in 1987 (Williams 1989). During this same year, birds were also found nesting on Metomkin Island. In 1992, an additional colony was formed in the upper Chesapeake Bay on Shanks Island north of Tangier (Watts and Byrd 1998). In the intervening years, the colony on Fisherman Island has been lost and nesting has been documented on Sandy, Ship Shoal and Wreck Islands along the Delmarva seaside. Since its discovery, the Shanks Island colony has grown exponentially, apparently fueled by continued immigration. In 1993, there were only 53 pairs documented in this colony (Watts and Byrd 1998). The colony supported 913 and 1,857 breeding pairs in 1999 and 2013 respectively (Watts 2000a, Watts and Paxton 2014). The Virginia population is now approaching 2,500 breeding pairs (Watts and Paxton 2014). Brown pelicans were not placed within any of the conservation tiers (I through IV) in 2005 (VDGIF 2005) no focused management program has been established since the 1978 recommendation.

Yellow-crowned Night Heron – Threatened (1989)

The yellow-crowned night heron breeds throughout the new world tropics and extends into the temperate zone of North America (Watts 1995). The species breeds within coastal lowlands from Baha to Peru along the Pacific Coast and from

Connecticut south through Central America and east to Brazil. Also breeds within many island groups throughout tropical to subtropical latitudes including the Greater and Lesser Antilles and the Galapagos. In North America, the yellow-crowned night heron is centered in the Deep South and associated with the extensive swamp forests. The species experienced a dramatic northward range expansion along the Atlantic Coast between 1925 and 1960 with 11 new state breeding records over this time. Many of these areas had been previously occupied during the mid-1800s but the species underwent a rapid range contraction by the late 1800s.

The yellow-crowned night heron breeds throughout Virginia but breeding is concentrated along the coast and breeding inland is isolated and periodic (Rottenborn and Brinkley 2007). The species likely bred in Virginia during the 1800s but was apparently absent by the early 1900s. The first modern breeding records were in 1944 in King William County (F. M. Jones, unpublished report) and in 1947 in Norfolk (Darden 1947). The population within the lower tidewater areas of Norfolk, Hampton, Virginia Beach and Portsmouth appear to have increased from the 1960s to at least the early 1990s (Watts, unpublished data). A series of surveys of the Coastal Plain recorded 388 pairs in 35 colonies, 241 pairs in 40 colonies and 299 pairs in 61 colonies during the breeding seasons of 1993, 2003 and 2013 respectively (Watts and Byrd 1998, Watts and Byrd 2006, Watts and Paxton 2014) a decline of nearly 23%.

The yellow-crowned night heron was recommended for threatened status in Virginia in 1989 (Watts 1991). The reasons cited for the recommendation were ongoing conflicts between residential landowners and breeding colonies and the impact of urban development on foraging habitat and prey populations. Interestingly, the decline recorded between 1993 and 2013 has been due to the loss of birds within colonies on islands of the upper Chesapeake Bay and seaside of the Delmarva Peninsula. Despite considerable movement, the urban population has remained stable. Yellow-crowned night herons were placed in Tier II in 2005 (VDGIF 2005) reflecting a reduction in concern for the population. No active management is currently focused on this species.

Osprey – Threatened (1978)

The osprey is nearly cosmopolitan in distribution breeding throughout the northern latitudes of North America, Europe and Asia and extending south into Australasia and the Caribbean (Prevost 1983). In North America osprey breed throughout the boreal zone, along both coasts and along major water bodies (Henny 1983, Poole 1989). The Chesapeake Bay is believed to support the largest breeding population in the world (Henny 1983). As with many similar populations, ospreys in the Chesapeake Bay experienced dramatic declines in the post-World War II era due to reproductive suppression (Truitt 1969, Wiemeyer 1971, Kennedy 1977) induced by environmental contaminants (Via 1975, Wiemeyer et al. 1975). The population appears to have reached a low point by the early 1970s when Henny et al. (1974) estimated its size to be 1,450 breeding pairs. By the mid-1970s the Virginia portion of the population was estimated to have declined by approximately 80% (Stinson and Byrd 1976). The osprey was recommended for threatened status in Virginia due to the recognized population decline, ongoing reproductive suppression and concerns over management of nesting substrates (Byrd 1979).

Since the 1970s osprey reproductive rates have improved (Watts and Paxton 2007) leading to a dramatic population recovery (Watts et al. 2004). In little more than twenty years, the population has more than doubled in size. Populations within the tidal fresh and brackish portions of the Chesapeake Bay have experienced the most rapid growth rates since the 1970s. Average doubling times between the 1970s and the 2000s for several tidal fresh and oligohaline reaches of Virginia appear to be less than 4 yrs. The population has advanced down the salinity gradient and has extended into the non-tidal portions of the Piedmont and mountains for the first time in more than a century. Osprey were not placed within any of the conservation tiers (I through IV) in 2005 (VDGIF 2005) reflecting their dramatic recovery and secure status.

Bald Eagle – Endangered (1978, 1989)

The bald eagle breeds throughout much of North America along both the Atlantic and Pacific Coasts and near significant water bodies throughout the continent (Buehler 2000). The United States Fish and Wildlife Service (FWS) originally listed the bald eagle as federally endangered on 11 March 1967 under The Endangered Species Protection Act of 1966 (16 U.S.C. 668aa-668cc) and subsequently under The Endangered Species Act of 1973 (16 U.S.C. 1531 et seq). The primary reason cited for the original listing was broad-scale population declines linked to dichloro-dephenyl-trichloroethane (DDT) and associated reproductive failure. Since the ban on DDT and formal listing under The Endangered Species Act, bald eagle populations have increased dramatically across much of the lower 48 states. During a periodic population review, the FWS determined that specific reclassification goals had been reached as outlined in regional recovery plans. The bald eagle was formally reclassified from endangered to threatened on 12 July 1995 (60 FR 36000) and subsequently removed from the list on 28 June, 2007 (72 FR 37346). The species continues to be protected under the Bald and Golden Eagle Protection Act (16 U.S.C. §668-668d).

The Virginia bald eagle population is part of the broader breeding population within the Chesapeake Bay region (Watts 2005). The population has been systematically monitored from the air since 1962 (Watts 2010) and reached a low of 26 pairs in the early 1970s (Abbott 1975). The species was proposed for endangered status within Virginia during both 1978 and 1989 (Byrd 1979b, 1991b) due to the reduced population status, contaminant-induced reproductive suppression and ongoing habitat loss. Since this time, the population has undergone a dramatic recovery with an average doubling time of approximately 8 years (Watts and Byrd 2002, Watts et al. 2007, 2008) reaching 726 pairs by 2011 (Watts and Byrd 2011). The population is now estimated to exceed 1,000 pairs (Watts and Byrd, unpublished data). Although habitat loss due to urban expansion continues to be a concern for the population (Watts 2006), the bald eagle was removed from the list of threatened and endangered species of Virginia on 1 January, 2013. The bald eagle was placed on Tier II in 2005 (VDGIF 2005) reflecting the recovered status of the population but ongoing concerns about disturbance and habitat loss.

Northern Harrier – Endangered (1989)

The northern harrier (also known as hen harrier) breeds throughout the Palearctic including North America, Europe and Asia (Brown and Amadon 1989). Breeding is widespread in North America including Alaska and Canada, extending down into the mid-continent grasslands to Oklahoma and Texas and along portions of the Pacific Coast to California (Smith et al. 2011). Along the Atlantic coast, harriers reach their southern limit of normal breeding in coastal Virginia, becoming a rare and erratic breeder further south (Dinsmore and Williams 1997).

The status of the Northern Harrier breeding population in Virginia has never been well known. Bailey (1913) describes breeding as uncommon to rare and primarily along the barrier islands. This status had apparently not changed by 1952 (Murray 1952). Watts and Rottenborn (2002) compiled observations made from 1991 – 1996 and estimated a population of 25 breeding pairs on the outer Coastal Plain. Pairs were restricted to large patches of salt marsh along the lower Western Shore of the Chesapeake Bay and bayside of Accomack County and on the barrier islands of the Eastern Shore. Very few pairs have been reported within inland locations. Watts and Rottenborn (2002) observed pairs over agricultural fields in both Henrico and Sussex Counties and Brown (1937) observed a pair near Blacksburg. Reclamation of mountain top removal coal mining throughout the southern Appalachians has expanded the range of this species (Brauning 1992) and this may result in colonization of the western mountains of Virginia. In 1989, the Northern Harrier was recommended for the status of endangered in the state of Virginia due to its small breeding population and threats to habitat (Bazuin 1991a). However, the small population size in the state appears to reflect the limited amount of habitat available for the population and the fact that Virginia represents the edge of the breeding range. There is no indication that either the distribution or status of the species has changed substantively over the past 100 years. The northern harrier was placed in Tier III in 2005 (VDGIF 2005). No management program has been established for this species.

Sharp-shinned Hawk – Threatened (1978)

The sharp-shinned hawk breeds widely throughout the Americas but is confined to boreal-type coniferous forests and is rarely observed outside of unbroken forest canopies during the breeding season (Bildstein and Meyer 2000). Within eastern North America breeding extends down the southern Appalachians in boreal forests of the higher elevations. In Virginia, the status and distribution of the breeding population has been poorly understood due both to the secretive nature of the species during the breeding season and confusion by observers in separating the species from the more widely distributed Cooper's hawk (Kain 1987). Breeding is almost entirely confined to the higher elevations in the mountains.

The sharp-shinned hawk was recommended for threatened status throughout Virginia in 1978 citing a lack of suitable habitat and ongoing threats to reproduction from persistent chemicals (Williams 1979). A nearly complete lack of information on population status was noted. Since this recommendation there has been no significant change in available information on status. The species appears to have maintained the same distribution with a similar low rate of breeding reports (Rottenborn and Brinkley 2007) compared to the 1970s. Despite being recommended for threatened status in 1978, sharp-shinned hawks were not placed within any of the conservation tiers (I through IV) in 2005 (VDGIF 2005) reflecting the ongoing confusion about status.

American Kestrel – Threatened (1978)

The American kestrel breeds throughout the Americas including North America, Central America, South America and the Caribbean wherever nest cavities are available near open habitats with short, ground vegetation (Smallwood and Bird 2002). The population in North America has remained relatively stable. However, the continental trend masks the fact that increases in the central United States are offsetting declines in the North East and Pacific Coast. Dramatic declines experienced in the North East are believed to reflect losses of open foraging habitat caused by secondary succession on lands cleared in the late 1800s and residential development of farmlands. The population in Virginia has experienced the largest declines throughout the Coastal Plain with farmlands of the Piedmont and the Great Valley remaining strongholds. Breeding within the Coastal Plain is mostly confined to industrial and urban areas with adequate foraging habitat.

The American Kestrel was recommended for threatened status throughout Virginia in 1978 citing dramatic declines in the previous 25 years possibly due to the broad use of agricultural chemicals (Scott 1979). Since this time, the species has continued to decline throughout the state with the exception of geographic locations that continue to maintain a high proportion of area in open habitats. In recent years, populations within these locations have been assisted by nest box programs. Despite being recommended for threatened status in 1978 and continued declines since this time, not placed within any of the conservation tiers (I through IV) in 2005 (VDGIF 2005).

Peregrine Falcon – Endangered (1978, 1989), Tier I (2005)

The peregrine falcon has a global distribution and is only absent as a breeder from the Amazon Basin, Sahara Desert, most of the steppes of central and eastern Asia, and Antarctica (White et al. 2002). Historically, peregrines nested throughout North America where sufficient nesting substrate was found (Hickey 1969) and in recent decades the addition of human-made structures to the landscape has allowed them to colonize new areas (Cade et al. 1996). Throughout the 1950s and 1960s peregrine falcon populations throughout parts of Europe and North America collapsed (Hickey 1969) due to reproductive suppression related to broad-scale use of persistent pesticides (Cade et al. 1971, Peakall et al. 1975, Ratcliffe 1980). The species was believed to have been extirpated east of the Mississippi River by the early 1960s (Berger et al. 1969). The peregrine falcon was listed as endangered under the Endangered Species Conservation Act of 1969 (P.L. 91-135, 83, Stat. 275) and, subsequently, under the Endangered Species Act of 1973 (16 U.S.C. 1531 et seq). The historic status and distribution of peregrine falcons in Virginia is not completely known because no systematic survey of the species was completed prior to the loss of the population. From published records and accounts, there have been 24 historical peregrine eyries documented in the Appalachians of Virginia (Gabler 1983) and 2 nesting sites were documented on old osprey nests along the Delmarva Peninsula (Jones 1946).

The peregrine falcon was recommended for endangered status throughout Virginia in 1978 (Byrd 1979c) and 1989 (Byrd 1979c) and was placed in Tier I in 2005 (VDGIF 2005) due to the complete loss of the population and continuing concerns about disturbance. As part of a national restoration effort, the Virginia Department of Game and Inland Fisheries, Cornell University, and the College of William and Mary initiated an aggressive program to restore peregrines to Virginia in 1978. Between 1978 and 1993, approximately 250 captive-reared falcons were released in Virginia including phases on the coast (1978-1985) and mountains (1985-1993) (Watts et al. 2011a). Since 2000, nearly 300 wild-reared falcons have been translocated from the coast to the mountains of Virginia. From a single breeding pair in 1981, the Virginia population has increased to 27 known pairs in 2015 (Watts and Mojica 2015). Although the population has now reached the population size estimated from historic accounts, only 4 breeding territories have been identified in recent years and their use appears to be erratic. All remaining pairs nest on artificial structures on the Coastal Plain (Watts et al., In press). On 25 August 1999, *F. p. anatum* was officially removed from the federal list of threatened and endangered species (Mesta 1999). Peregrine falcons continue to be listed as threatened in the state of Virginia.

Black Rail – Tier I (2005)

The black rail breeds in tidal and freshwater marshes throughout the Americas with two subspecies including the eastern black rail (*L. j. jamaicensis*) and California black rail (*L. j. coturniculus*) breeding in North America and three subspecies occurring elsewhere (Eddleman et al. 1994). Historically, the eastern form bred along the Atlantic Coast north to Massachusetts, around the Gulf Coast, inland to Colorado, south to Panama and the West Indies. The California form nests in large estuaries in California south into Baja with some inland occurrences. The range of both forms has been contracting in recent decades (Eddleman et al. 1994). In addition to a retreat from the northern and western edges of the range, the eastern black rail has virtually collapsed within the core of the breeding range (Wilson et al. unpublished data).

Historically, the black rail bred widely throughout Virginia within wet meadows inland and in tidal marshes along the coast (Wilson and Watts 2012). Most inland records are from the 1930s through the 1950s following the period of broad land clearing (e.g., Murray 1931, Handley 1939, 1941, Stevenson 1946). The species is now rare inland with periodic observations of single individuals (Rottenborn and Brinkley 2007). Breeding records along the coast included both the seaside (Bailey 1927, Clapp 1997) and bayside (Wilson et al. 2009) marshes of the Delmarva Peninsula. The species is now apparently absent from the seaside marshes and much reduced along the bayside. A systematic survey conducted in 2009 recorded no birds within 110 locations in the seaside marshes and only 10 birds within 128 locations along the bayside (Wilson et al. 2009). A subsequent survey detected only 2 birds within the same network of sites along the bayside (Wilson et al. 2015a).

The black rail population in Virginia has collapsed over the past two decades and was listed on Tier I in 2005 (VDGIF 2005). Since that time a survey program has been initiated to assess status, distribution and trends (Wilson et al. 2009, 2015). Management options are not clear at this time. Currently, the black rail is in eminent danger of extirpation in Virginia.

Wilson's Plover – Threatened (1978), Endangered (1989), Tier I (2005)

The Wilson's plover is restricted to coastal areas breeding along the Pacific Coast from California to Peru, along the Atlantic Coast from Virginia to the Florida Keys, around the Gulf Coast from Florida to Belize, and on many islands throughout the Caribbean (Corbat and Bergstrom 2000). The breeding range of the Atlantic Coast population (*C. w. wilsonia*) has been contracting south with the last known breeding record in New Jersey in 1955 (Sibley 1997) and in Maryland in 1985 (Hoffman 1996). Because they require beaches for nesting, Wilson's plovers continue to suffer from human disturbance and development throughout much of their range.

The Virginia barrier islands represent the northern range limit for breeding Wilson's plovers. Once considered common along the islands (Rives 1890, Chapman 1903, Murray 1937a) the species has experienced significant declines. Surveys of the islands from 1975 to 1988 recorded a range of 18 to 64 individuals (Williams et al. 1990). Systematic surveys for pairs between 1989 and 1995 recorded a mean of 40 pairs that used 11 of the 15 islands surveyed (Watts et al. 1996). The population declined since this time, averaging just below 30 pairs from 1997 to 2015 (VDGIF unpublished data). Wilson's plovers were recommended for threatened status in 1978 (Via 1979a), endangered status in 1989 (Bergstrom 1991) and were placed on Tier I in 2005 (VDGIF 2005). The primary threats listed to the population for listing were mammalian and avian predation, human disturbance to nesting birds, and habitat loss. Since this time the population has been intensively monitored, a predator control program has been executed on strategic islands and nesting areas have been posted to reduce human disturbance.

Piping Plover – Threatened (1978), Endangered (1989), Tier I (2005)

The piping plover is endemic to North America breeding in three distinct geographic areas including the Atlantic Coast from the Maritime Provinces of Canada to North Carolina, the northern Great Lakes region along the shores of Lake Superior, Lake Michigan and Lake Huron, and the northern Great Plains from the southern prairies of Canada south to Kansas, Colorado and Iowa (Haig and Elliot-Smith 2004). The species has suffered significant declines throughout most of its range due to human disturbance of nesting birds, predation, development of coastal areas, and control of inland water levels (Haig 1986). The piping plover is listed as endangered in Canada and the United States Great Lakes and threatened elsewhere (Haig 1985, U.S. Fish and Wildlife Service 1985). In recent years, the species has contracted from the northern reaches of its breeding range.

In Virginia, the piping plover is restricted to beach habitats on the outer coast. Birds have been documented to nest along the western shore of the Chesapeake Bay, including Gwynn's Island (White 1981), Grandview Nature Preserve in Hampton (Akers 1975) and Craney Island Dredge Material Management in Portsmouth. Since the late 1990s the population has been confined to the barrier islands in Accomack and Northampton counties. Between 1986 and 1995 the population along the island chain was relatively stable averaging nearly 105 pairs per year (Watts et al. 1996). The population remained stable through 2003 when an intensive mammalian predator management program began to bear fruit and the population increased to 152 pairs in 2004 (Boettcher et al. 2007).

The piping plover was recommended for threatened status in 1978 (Via 1979b), endangered status in 1989 (Cross 1991), and was listed as a Tier I species in 2005 (VDGIF 2005). Reasons cited for the recommendations were human disturbance of nesting birds, habitat loss and predation pressure. Since these recommendations were made an intensive monitoring and management program has been executed within all breeding locations. Management has included control of mammalian and avian predators on targeted islands, use of nest exclosures on selected islands, and posting of all breeding areas to reduce human traffic (USFWS 2006, Boettcher et al. 2007). The population has responded dramatically, increasing to a high of 259 pairs in 2012 (VDGIF unpublished data). Piping plovers should be considered to be recovered in Virginia.

Upland Sandpiper – Threatened (1978), Endangered (1989), Tier I (2005)

The core of the upland sandpiper's breeding range includes the prairies of the north-central United States extending north into Manitoba, Saskatchewan and Alberta (Houston and Bowen 2001). Isolated breeding areas also occur in western Canada and Alaska. Beginning in the 1800s the species underwent a large range expansion into the northeastern United States coincident with broad land clearing. A peak in abundance was reached from the late 1800s to the mid-1900s before precipitous declines began in the 1950s as open habitats were lost to secondary succession and urban expansion (Foss

1994, Smith 1996). By the mid-1990s the upland sandpiper was listed as either threatened or endangered within 10 northeastern states (French and Pence 1996).

The historic stronghold for upland sandpiper in Virginia was the Great Valley with most consistent breeding in Pulaski, Montgomery, Rockbridge, Albemarle and Botetourt counties. By the mid-1980s only a few sites were known. The Virginia Breeding Bird Atlas (1989-1992) detected only one potential nesting site in Loudon County (Ridd 1990). The site supported breeding pairs from the mid-1930s through the early 1990s (Bazuin 1990). The upland sandpiper was recommended for threatened status in 1978 (Scott 1979a), endangered status in 1989 (Bazuin 1991b) and was placed on Tier I in 2005 (VDGIF 2005). Since this time, no effort to manage habitat for this species has been initiated. The upland sandpiper is now believed to have been extirpated from the state with the last known breeding site on Remington Sod Farm in Faquier County in 2001 (Iliff 2002).

Least Tern - Threatened (1978, 1989)

The least tern breeds on open sandy beaches and islands along both coasts of North America, in Central America from Mexico to Belize and Honduras, widely throughout the Caribbean Basin and inland along rivers and lakes where such habitat occurs (Thompson et al. 1997). Least terns have experienced a roller coaster of population changes over the past 150 years with steep declines related to the millenary trade followed by recovery prompted by the passage of the Migratory Bird Treaty Act, followed by inland declines related to the installation of water-control devices and coastal declines caused by development and recreational use of beaches. Although protections have been established over much of their breeding range, most populations have not recovered to former levels.

Historically, the least tern bred throughout the Coastal Plain of Virginia along the outer coast and Chesapeake Bay shorelines extending up tributaries to the fall line (Rives 1891, Murray 1952). The birds were shot out for the millinery trade by the early 1900s (Howell 1911, Bailey 1913). They returned to nest along the barrier islands (Williams et al. 1990), in lower tidewater (Grey 1950a, Murray 1952), within the upper bay islands (Akers 1979) and lower western shore (Scott 1953) of the Chesapeake Bay reaching a peak possibly during the early 1980s only to decline again (Beck et al. 1990). The population has continued to decline from 1,178 pairs in 1993 to 925 pairs in 2013 (Watts and Byrd 1998, Watts and Paxton 2014). Currently, 60% of the population nests on the barrier islands of the Eastern Shore and remaining birds are within urban areas of lower tidewater including two roof-top colonies.

The least tern was recommended for threatened status in 1978 (Akers 1979a) and 1989 (Beck 1991a). The primary reason cited for the recommendation included the loss of breeding sites due to residential development and human disturbance. Since this recommendation, the population has been monitored periodically and breeding sites have been posted to reduce human disturbance.

Gull-billed Tern - Threatened (1978, 1989), Tier I (2005)

The gull-billed tern has a nearly global distribution breeding throughout the Americas, parts of Europe, Asia, the Middle East, northwest Africa and Australia (Blakers et al. 1984, Cramp 1985, Parnell et al. 1995). Despite this wide distribution, the species is very localized throughout its range and has a relatively small population size. Two subspecies breed in North America including *S. n. aranea* that breeds from Long Island, NY to Florida and along the Gulf Coast to northeastern Mexico and *S. n.*

vanrossemi that breeds locally from California to at least northwestern Mexico. The mid-Atlantic population has experienced a severe decline and is listed as endangered in Maryland and threatened in Virginia and North Carolina (Molina and Erwin 2006).

The Gull-billed Tern has experienced extreme population swings in coastal Virginia over the past 150 years. Considered to be abundant on the Virginia barrier islands in the mid-1800s, the population was much reduced by the late 1800s (Rives 1891) and virtually shot out by the early 1900s (Bailey 1913). Throughout the early 1900s, numbers remained very low (Austin 1932). The population appears to have reached a peak by the mid-1970s. Surveys along the barrier islands declined by 88% from 1975 (high of 2,228) to 1988 (Williams et al. 1990). This decline has continued to the present time. Surveys of the Coastal Plain recorded only 294 pairs in 9 colonies in 2013 compared to 606 pairs in 30 colonies in 1993 (Watts and Byrd 1998, Watts and Paxton 2014) a decline of nearly 52%. The species is now nearly restricted to shell piles within the barrier island/lagoon system and to a single colony on the Hampton Roads Bridge Tunnel.

The gull-billed tern was recommended for threatened status in Virginia in 1978 (Akers 1979b) and 1989 (Williams 1991) as was placed in Tier I in 2005 (VDGIF 2005). The primary reasons cited for the recommendations were loss of habitat to erosion and development, human disturbance of nesting birds, threats posed by predators, and potential exposure to agricultural pesticides. Since these recommendations, most of the population has moved from the barrier islands to shell piles within the lagoon system. The underlying causes of both these shifts and the ongoing declines are unclear.

Appalachian Yellow-bellied Sapsucker – Tier I (2005)

The yellow-bellied sapsucker breeds within hardwoods and conifers across the boreal region of North America from Alaska to Newfoundland (Walters et al. 2002). Within the northeast, sapsuckers extend south to Pennsylvania and then are patchily distributed within the higher elevations along the spine of the southern Appalachians south to Georgia. A distinct subspecies (*S. v. Appalachiensis*) of the yellow-bellied sapsucker referred to as the "Appalachian yellow-bellied sapsucker" occupies the extreme southern Appalachians from southwest Virginia through Georgia (Granier 1954). The location of the transition from this form to the northern subspecies (*S. v. atrothorax*) is not clear but the latter is believed to occupy most of the Blue Ridge and northern Appalachians.

The status of the Appalachian sapsucker in Virginia has never been well known. The form appears to be restricted to southwestern Virginia including Mount Rogers within Smyth and Grayson counties (Murray 1937b, Scott 1974, Scott 1982), the vicinity of Mountain Lake in Giles County (Hostetter 1937, Burns 1960) and Tazewell County (Scott 1973). The form was placed in Tier I in 2005 (VDGIF 2005) suggesting that it is a conservation priority and among the species of greatest conservation need in the state. Why this form was selected for this status over several other southern Appalachian endemics (e.g. Appalachian winter wren (*T. h. pullus*), Appalachian Swainson's thrush (*C. u. appalachiensis*) is not clear. No targeted management program has been established for this species.

Red-cockaded Woodpecker – Endangered (1978, 1989), Tier I (2005)

The red-cockaded woodpecker is endemic to the southeastern pine ecosystem breeding from Texas and Oklahoma east to Florida and north to Virginia (Jackson

1994). Highly specialized, the species requires old growth, fire maintained pine savannas. Throughout the twentieth century advances in transportation, wood processing, and silvicultural practices shifted the emphasis from long-rotation lumber production to maximum-yield fiber production and resulted in catastrophic declines in habitat availability for this species. Breeding distribution contracted from the edges of the range and became localized within the core of the historic range where remnant old growth remained. The red-cockaded woodpecker was listed as endangered in 1970 and received protection with the passage of The Endangered Species Act in 1973 (16 U.S.C. 1531 et seq).

The historic status and distribution of the red-cockaded woodpecker in Virginia is poorly known because no systematic survey of the species was completed prior to dramatic habitat losses. Early accounts of red-cockaded woodpeckers were made from all physiographic provinces of Virginia. Jurisdictions with records include the counties of Giles (Bailey 1913), Albemarle (Rives 1890), Brunswick (Murray 1952), Dinwiddie (Murray 1952), Chesterfield (Murray 1952), Southampton (Steirly 1949), Sussex (Steirly 1950), Prince George (Steirly 1957), Greensville (Steirly 1957), Isle of Wight (Steirly 1957) and the current independent cities of Norfolk (Bailey 1913), Suffolk (Steirly 1957), Virginia Beach (Sykes 1960), and Chesapeake (van Eerden and Bradshaw, unpublished observation). The first systematic survey of the species was initiated in 1977 and resulted in the documentation of 43 clusters within 5 counties (Miller 1978). By 1980, only 9 of these clusters were still forested (Bradshaw 1990). During the 20-year period between 1980 and 2000, the decline of the Virginia population is well documented (Watts and Bradshaw 2005). By 1990, only 5 of the original 23 clusters detected in 1977 were still active. During the breeding season of 2002, Virginia supported only 2 breeding pairs and 2 clusters with solitary males.

The red-cockaded woodpecker was recommended for endangered status in 1978 (Byrd 1979d) and 1989 (Beck 1991b) and was listed on Tier I in 2005 (VDGIF 2005). The stated rationale for recommendations was the extremely low and declining population in Virginia, continued loss and degradation of required old growth forests and the fact that all remaining breeding sites existed on private lands making appropriate management unfeasible. Following these recommendations, the Virginia Department of Game and Inland Fisheries and partners have mounted extensive monitoring and management efforts for the past 30 years. Acquisition of the Piney Grove Preserve in 1998 by The Nature Conservancy was a critical turning point in the species' recovery (Watts and Bradshaw 2005). Intensive habitat and population management on this last remaining site in Virginia has resulted in a population increase from 2 breeding groups in 2002 to 13 breeding groups in 2014 (Wilson et al. 2015b). A three-phase conservation plan is in place for the Virginia population that includes the establishment of additional breeding locations (Watts and Harding 2007). Translocation of birds into the Great Dismal Swamp is planned for the fall of 2015.

Loggerhead Shrike - Threatened (1978), Endangered (1989), Tier I (2005)

The loggerhead shrike breeds throughout the southern latitudes of North America, extends north through the mid-continent open lands and south through Mexico (Yosef 1996). During the early to mid-1800s the species underwent a large range expansion throughout the forested region of eastern North America as lands were cleared for farming with first breeding records across New England and eastern Canada recorded from the 1850s to the early 1900s. As small farms were abandoned throughout the region and were returned to forest and as horsepower gave way to tractors and more intensive farming practices, loggerhead shrikes quickly retreated south and last breeding records were recorded throughout the region from the 1970s through the 1990s.

During the heyday years, the loggerhead shrike bred throughout all physiographic regions of Virginia and has been documented in 54 of 95 counties and 12 of 41 independent cities (Luukkonen and Fraser 1987). By 1989, breeding was confirmed in only 26 counties (Trollinger and Reay 2001). Over the past 30 years, the population in Virginia has declined by more than 50% (Sauer et al. 2005) and has likely been extirpated over most of the Coastal Plain (Watts and Scholle 1999). The 2 remaining strongholds appear to be the Shenandoah Valley and the southern Piedmont with most recent records concentrated in Culpeper, Rappahannock, and Madison counties. The loggerhead shrike was recommended for threatened status in 1978 (Via 1979c) for endangered status in 1989 (Fraser 1991) and was listed as a Tier I species in 2005 (VDGIF 2005). The underlying causes for declines are poorly understood. Factors contributing to status recommendations include the loss of appropriate breeding habitat and winter mortality possibly linked to contaminants (Blumton et al. 1990). The loggerhead shrike was formally listed as threatened in Virginia in 2002 (4VAC15-20-130). Since this time, no management actions have been taken and the population has continued to decline.

Sedge Wren – Endangered (1989)

The sedge wren breeds throughout densely vegetated wetlands, wet grasslands, hayfields, and retired croplands where these habitats occur throughout the Americas (Herkert et al. 2001). The core of the North American range includes the north-central United States and Canada extending south to Missouri and Illinois. Localized breeding occurs from New England to Virginia. The sedge wren expanded its range beyond its core breeding area both east and north in response to extensive land clearing during the 1800s (Gibbs and Melvin 1992). The population within the eastern breeding range has been declining in recent decades (Gibbs and Melvin 1992, Peterjohn and Sauer 1999) due to reforestation and conversion of meadows to agriculture or development.

The sedge wren reaches its southern range limit in Virginia and is a sporadic breeder throughout all physiographic areas of the state (Rottenborn and Brinkley 2007) reflecting its nomadic life history (Herkert et al. 2001). Historically, the most consistent breeding locations have been within large wetland patches in the Coastal Plain including lower tidewater (Howell and Burleigh 1934, Grey 1950b), the lower Western Shore of the Chesapeake Bay (Watts 1992) and the bayside of Accomack County (Ake and Scott 1975, Kinzie and Scott 1983). Breeding within inland physiographic regions has been in wet fields with scattered shrubs and has been more erratic (e.g., Stevens 1952, Scott 1953, Mays 2005). Inland breeding locations may be more vulnerable to impacts such as filling and ditching that influence the "wet-dry" dynamics required by sedge wrens. The sedge wren was recommended for endangered status in 1989 (Day 1991) due to its small population size in the state and threats to inland habitats from urban expansion and the intensification of agricultural practices. Sedge wrens were placed in Tier III in 2005 (VDGIF 2005) and no management efforts have been initiated on their behalf.

Bewick's Wren - Threatened (1978), Endangered (1989), Tier I (2005)

The Bewick's wren currently breeds throughout the south-central United States into Mexico and along the Pacific Coast from British Columbia to Baha (Kennedy and White 1997). The species expanded its range east of the Mississippi River from the early 1800s through the early 1900s coincident with land clearing for small farms and pasturelands. At the peak of its distribution in the early 1900s, Bewick's wren nested from New York south to central Georgia. Decline of the eastern range began in the 1920s and continued through the 1970s as secondary succession overtook abandoned farms and as the house wren expanded its range (Kennedy and White 1997). By the 1980s, the species was absent throughout virtually the entire range east of the Mississippi River.

Historically the Bewick's wren bred throughout Virginia with the highest numbers reported from the mountains. As within other eastern states, the species appears to reach its greatest distribution and numbers in Virginia during the first half of the twentieth century only to decline sharply after 1950. By the 1970s the species was considered rare in the state. The most recent nesting record was collected from Dickenson County in 1989 (Ridd 1990). Other recent nesting records were collected from Highland County in 1982 (Teuber 1985) and Montgomery County in 1974 (Conner 1975) and 1976 (Adkisson 1991). Unpublished breeding season observations were being reported throughout the 1980s and into the 1990s. Most of these were of single birds. The last known breeding season observations are from Highland County in 1998 (S. Thornhill, unpublished data – David Shoch, personal comm.) and 1991 (D. Schwab and T. Gwynn, personal comm.), and in Dickenson County in 1990 (Sauer et al. 2007). There were no birds detected in a systematic survey of 863 patches in 2006 (Wilson et al. 2007). Bewick's wrens appear to have been extirpated from Virginia during the 1990s.

The Bewick's wren was recommended for threatened status in 1978 (Adkisson 1979), endangered status in 1989 (Adkisson 1991) and was placed in Tier I in 2005 (VDGIF 2005). Due to their clear association with small farms, townships and settlements during the height of the population expansion (Bent 1948), a suggested management approach was to utilize nest boxes within known population strongholds (Adkisson 1991). However, no active management program was initiated prior to extirpation.

Golden-winged Warbler – Tier I (2005)

The core of the breeding range for the golden-winged warbler is now centered around the Great Lakes, extending from Manitoba to Ontario in the north and including open habitats from Minnesota to New York (Confer et al. 2011). Breeding extends down the higher elevations of the southern Appalachians to Georgia. The species has undergone a dramatic range expansion over the past 150 years as forest lands were cleared for farmland and subsequently abandoned. The breeding population appears to have been released from traditional high-elevation meadows into cleared lands resulting in both a range expansion and a movement into lower altitudes. The population is now contracting back from many areas colonized more than 100 years ago. Breeding areas within the southern Appalachians have declined dramatically over recent decades while the population continues to expand in north-central states and adjacent southern Canada (Confer et al. 2003, Buehler et al. 2007). Recent declines throughout the historic core of the breeding range have been attributed to both habitat loss as secondary succession has reclaimed much of the previously cleared land and competition with blue-winged warblers. Golden-winged and blue-winged warblers interbreed, produce fertile hybrid offspring and have been genetically isolated for a relatively short period of time (Vallender et al. 2007). Over the past 50 years blue-winged warblers have expanded their range into areas formerly occupied by golden-winged warblers.

Historically, golden-winged warblers likely bred where shrub habitats occurred throughout the higher elevations of Virginia. In recent decades, Highland and Bath counties have supported the greatest concentration of pairs (Larner and Scott 1983, Spahr 2003, Wilson et al. 2007) with smaller concentrations in Craig and Tazewell counties (Scott 1973, 1981a). Like elsewhere in the southern portion of the breeding range, the Virginia population has declined dramatically over the past several decades. Golden-winged warblers were placed in Tier I in 2005 (VDGIF 2005). Since that time, a systematic survey of 863 early successional patches in 2006 (Wilson et al. 2007) found the species breeding in much lower numbers compared to historic counts in core areas and no pairs in many counties where they were once documented to breed. In recent years, work within core breeding areas has been focused on developing potential management strategies (Bullock, Pers. Comm.).

Swainson's Warbler – Threatened (1989)

The Swainson's warbler breeds in the southeast from Texas and Oklahoma east to the Atlantic Coast and north to Maryland and Delaware but excluding peninsular Florida (Meanley 1971, Brown and Dickson 1994). Historically believed to be a specialist of southern swamp forests, a disjunct population was discovered in the southern Appalachians during the 1930s that expanded the general perception of the species. Swainson's warblers are vulnerable to changes in silvicultural practices that have altered the structure and availability of bottomland hardwood forests. The species was believed to have declined throughout the early twentieth century (Meanley 1971) but more recently may be increasing in the southern Coastal Plain but declining in the Appalachians (Hunter et al. 1993).

The Swainson's warbler breeds in two distinctly different systems in Virginia including the humid swamp forests of the southern Coastal Plain and steep ravines of the southwestern mountains (Peake 1991). A common characteristic of breeding sites within both regions is dense understory vegetation including primarily switch cane (*Arundinaria spp.*) on the coast and mountain laurel (*Kalmia latifolia*) in the mountains. Distribution in the Coastal Plain is mostly restricted to the Great Dismal Swamp (Meanley 1976, 1977) but likely includes several of the other remote swamps south of the James River. Distribution in the mountains is focused on the Holston and Big Sandy drainages and includes records from Ablemarle (Merkel 1961, Murray 1962), Amherst (Larner and Scott 1982), Caroll (Dalmas 1999), Dickenson (Peake 1986), Grayson (Dalmas 1999), Roanoke (Middleton 1981), Smyth (Decker 1999), Tazewell (Peake 1987), and Wise counties (Stevens 1976). The population within the Great Dismal Swamp appears to have declined over the past two decades (Schwab, pers. comm). Very little information is available on the population in southwestern Virginia. The population within the southern Appalachians appears to have increased since the 1960s (Sauer et al. 2001). The Swainson's warbler was recommended for threatened status in 1989 (Peake 1991) due to habitat loss in both regions of occurrence related to residential development, lumbering, and mining. The species was listed on Tier II in

2005 (VDGIF 2005). Since this time, no active management program has been initiated that focuses on habitat for Swainson's warblers.

Wayne's Black-throated Green Warbler – Tier I (2005)

The black-throated green warbler breeds in conifers throughout the northern boreal forest from Newfoundland to British Columbia where it is often the most numerous breeding bird (Morse and Poole 2005). Black-throated green warblers extend down the higher elevations of the southern Appalachians to Georgia and Alabama. The Wayne's warbler (*S. v. waynei* Bangs) is a unique, disjunt subspecies of the black-throated green warbler (Bangs 1918) that is restricted to a narrow band within the outer Coastal Plain from Virginia to South Carolina (Sprunt 1953). This population is 500 km east of the Appalachian population and 1,200 m lower in elevation. The factors that lead to the isolation of the Wayne's form from the nominate race are not known. It is possible that this subspecies was originally associated with the extensive stands of Atlantic White Cedar (*Chamaecyparis thyoides*) that were once an important component of the regions plant community (Watts et al. 2011b). Wayne's appears to reach its highest density from southeastern Virginia through northeastern North Carolina, the historic location of the most extensive tracts of white cedar (Ashe 1894). More than 100,000 acres of this habitat were harvested in the area in the late 1800s and early 1900s for the shingle industry. This event virtually eliminated this unique plant community from the region. The vegetation that has reclaimed many of the historic sites after harvest is dominated by hardwoods rather than white cedar (Frost 1987).

The Wayne's warbler appears to have declined dramatically in Virginia in recent decades (Wilson and Watts 2012). The only known regular occurrence of the form in Virginia is from the Great Dismal Swamp (Meanley 1977). High counts from the accessible portions of the swamp have varied from 12 to 23 birds (Murray 1931, Meanley 1977). A recent foray detected only 5 birds in 2000 (LeClerc 2001). A systematic survey within the breeding range of North Carolina and Virginia detected birds within 114 of 266 (52.6%) survey plots but failed to detect any within 83 plots in the swamp (Watts et al. 2011). Wayne's warbler was placed in Tier I in 2005 (VDGIF 2005). No focused management program has been established for this species.

Bachman's Sparrow – Endangered (1989), Tier I (2005)

The Bachman's sparrow is endemic to the southeastern United States where, historically, it inhabited open pinelands and savannah-like habitats (Dunning and Watts 1990, Dunning 1993). At the beginning of the 20th century, this species underwent a large northerly range expansion coincident with a broad wave of deforestation. First breeding records were reported from Illinois, Ohio, West Virginia and Pennsylvania (Eifrig 1915, Brooks 1938). Since the 1930s this trend has apparently been reversed throughout the northern fringe of the species' new range as secondary succession has reclaimed much of the landscape. This range contraction coupled with declines within the original range (Dunning and Watts 1990) has led to ongoing concerns about status.

The Bachman's sparrow was first documented as a breeding species in Virginia in 1897 (Murray 1933). Throughout the early 1900s the species was observed during the summer months in 16 different Virginia counties, primarily west of the fall line (Watts 2000b). The number of sightings declined throughout the mid-1900s ending abruptly in the late 1960s. Between 1968 and 1986, no observations of Bachman's sparrows were reported for Virginia (Watts 2000b). In 1986 the species was rediscovered in Brunswick County (Dalmas, unpublished report). This finding was followed by reports from Sussex County (Hilton 1990) and Greensville County (Dalmas 1992). Breeding populations were also located within artillery firing ranges on Fort Picket and Fort A. P. Hill (Fleming and Alstine 1994a, 1994b). In 1996 a systematic survey of a one degree block including all modern locations outside of military installations was conducted that included portions of Brunswick, Dinwiddie, Greensville, Sussex and Southampton Counties (Watts et al. 1998). Birds were detected within only 4 (1.4%) of 280 clearcuts surveyed. Fort Picket appears to be the last site supporting the species in Virginia (Haas and Titus 1998, Murray et al. 2004).

The Bachman's sparrow was proposed for endangered status throughout Virginia in 1989 due to the ongoing population decline related to habitat loss and degradation (Ridd 1991). Recommendations were made to locate remaining breeding sites for protection and management. Although efforts have been made to survey recently occupied sites (Haas and Titus 1998, Watts et al. 1998) there has been no effort to manage either critical habitat or the population. Despite the fact that Bachman's have been retained as a Tier I species within the Virginia (VDGIF 2005) the species is believed to have been extirpated from the state in the early 2000s (Wilson and Watts 2012).

Henslow's Sparrow - Threatened (1978), Endangered (1989), Tier I (2005)

Prior to 1850, the Henslow's sparrow had two centers of occurrence including the central prairies and the coastal salt marshes from Massachussets to Virginia (Herkert et al. 2002). These two isolated populations represent weakly differentiated subspecies including *A. h. henslowii* (Audubon) that inhabited prairies and *A. h. susurrans* (Brewster) that inhabited coastal marshes. As the extensive forests between these two areas were cleared providing suitable habitat, Henslow's sparrows expanded their range. By 1915, the breeding range extended from Nebraska east to the coast with the exception of the higher elevations of the Appalachians (Hyde 1939). The range expansion brought the two subspecies into contact. Although it is presumed that the expansion moved from west to east and mostly involved the prairie subspecies, this issue remains unresolved.

During the peak in abundance, the Henslow's sparrow was considered a common breeder throughout the Coastal Plain and Piedmont of Virginia and rare in the mountains (Murray 1955). During the 1930s inland breeding records within the Coastal Plain were common (Haynes 1935, Nelson and Greenfield 1936, Mcllwaine 1940) but declined rapidly between the 1970s and 1990s. The last breeding report from Fairfax was during the atlas period (Ridd 1990). Six individuals were found in Sussex County in 1991 (Dalmas 1992) and at two locations in 1998 (Watts et al. 1998). Four birds were found in Prince William County as recently as 2005 (Day 2005). All of these records were within wet clearcuts. In the Piedmont, observations have declined dramatically with the only regular occurrences reported from Loudon County. Dulles Airport supported a high of at least 30 birds and has been the most consistently used site (Scott 1980). The Henslow's sparrow has never been regularly detected within the mountains. The single location where the species regularly occurs is the Radford Arsenal in Pulaski County (Titus et al. 1998). Of particular significance is that the coastal subspecies (*A. h. susurrans*), the historic form associated with Virginia appears to have been extirpated. Once regularly observed in Saxis Marsh (Ake and Scott 1975, Kinzie et al. 1983, Armistead 1991) there have been none recorded since 1995

(Schwab, pers. com.). The last known record suspected to be this form was in the Wallops Island salt marsh in 2006 (Smith, pers. com.).

The Henslow's sparrow was recommended for threatened status in 1978 (Scott 1979b) for endangered status in 1989 (Brindza 1991) and was placed in Tier I in 2005 (VDGIF 2005). The primary rationale cited was low population size relative to historic levels and threats to inland habitats. No active management program has been initiated to reverse population declines.

Red Crossbill – Tier I (2005)

The red crossbill breeds throughout the northern hemisphere from North America through Asia where appropriate conifers occur (Cramp and Perrins 1994, Adkisson 1996). In North America, breeds throughout Taiga forests from Alaska to Newfoundland and south along the Pacific Coast and the Rockies to the limits of conifers. Also breeds through central Mexico south to Honduras and Nicaragua. A small, disjunct population occurs in the southern Appalachians. The species represents a complex taxonomy with several distinct forms occurring in North America (Groth 1993). Eastern populations almost certainly declined during the period of widespread logging (Dickerman 1987).

In Virginia, breeding red crossbills are confined to the high elevations with records from 11 counties (Kain 1987). Focal areas appear to be Mount Rogers and vicinity (Scott 1974) and Shenandoah Mountain (Scott 1981b). Our understanding of their distribution and ecology has been hampered by their restriction to remote locations, their early breeding season, and their wide-ranging movements. Most records involve fleeting glimpses of small flocks (Murray 1966, Stevens 1968). Red crossbills were listed as a species of special concern in 1989 (Shelton 1991) and were placed on Tier I in 2005 VDGIF (2005). The primary threat listed is the ongoing loss and degradation of high-elevation forests. Given the lack of information on status, distribution and trends the selection of this species for Tier I designation over the list of other species that depend on the same habitat and have similar population concerns is unclear. No monitoring or management efforts have been initiated for this species.

DISCUSSION

The breeding avifauna of Virginia is diverse reflecting the geographic position of the state and the wide range of available habitats. In many ways, the avifauna is transitional containing a mix of species centered in the southeast or the northeast with some additional species spilling over from more inland physiographic regions. More than 14% of the species reach their southern or northern range limit within Virginia. These include southern species such as the Wilson's plover, Red-cockaded woodpecker, white ibis and loggerhead shrike and northern species such as the bobolink, northern harrier and northern waterthrush. Species that have recently expanded their range into Virginia such as the Mississippi kite and anhinga have added to this growing diversity. This pattern of south-to-north colonization is expected to continue into the foreseeable future as the ongoing shift in climate drives southern habitats into Virginia and provide conditions suitable for species historically centered in the Deep South.

One of the most significant factors contributing to bird diversity in Virginia is that the state extends from the Atlantic Ocean to the Appalachian Mountains and so includes a wide range of habitats. Two features that contribute a great deal to the state-wide diversity are tidal waters and high-elevation forests. Water and water-associated habitats are essential to the character of the regional avifauna. Throughout the Coastal Plain, hundreds of permanently flooded tidal rivers and streams come in close contact with virtually the entire upland surface area. Subsidence of coastal sediments has "drowned" the mouths of major rivers and lead to the formation of shallow bays. For species such as the bald eagle, osprey, brown pelican and great blue heron that depend on fish or other aquatic prey, these waters define their distribution. Slowly draining soils have led to the development of extensive wetlands of numerous types. Hundreds of thousands of hectares of wetlands exist within coastal Virginia with dominant types including forested wetlands and salt marshes. Species such as seaside sparrows, least bitterns and clapper rails are confined to these habitats. Finally, sandy beaches used by American oystercatchers, least terns and piping plovers are created and maintained by the forces of tidal waters. In all, more than 50 species (representing nearly 25% of the state-wide avifauna) are either wholly or nearly confined to this landscape feature.

Near Virginia's western border, cooler temperatures and elevated humidities within higher elevations allow mountain summits to serve as refugia for species that once had much broader distributions in the region. These ecological communities are relicts of the colder Pleistocene eras when spruce-fir forests covered much of eastern North America (Delcourt and Delcourt 1981). Climate warming around the beginning of the Holocene resulted in shifts in these communities upslope and northward, leaving isolated “sky islands” within the southern Appalachians. In Virginia, high-elevation forest communities include a gradient of assemblages moving south to north that are typified by the red spruce-Fraser fir forest of Mount Rogers, the red spruce forests of Beartown Mountain (Russell County) and Allegheny Mountain (Highland County) and the mixed spruce and broadleaf forests of Mountain Lake (Giles County). The plant communities and the animal populations that depend on them are extensions of the boreal communities to the north. Because these communities represent isolated relicts, they have received attention from observers and researchers for more than 100 years (e.g., Rives 1884, 1889, Murray 1938). Currently, these refugia support 22 bird species (representing more than 10% of the state-wide diversity) that occur nowhere else in the state including 10 endemic subspecies.

With relatively few exceptions that represent habitat specialists (e.g., peregrine falcon, red-cockaded woodpecker, Swainson's warbler), most bird species in Virginia occur within upland habitats that are widely distributed throughout the state. These habitats include deciduous forests, pine forests, shrublands and grasslands. Because these habitats relate to commercial enterprises (i.e. agriculture, forestry) and are subject to residential and urban development, they have experienced dramatic swings in distribution and availability through time with obvious consequences to bird populations.

No single historical event has shaped the avian community throughout eastern North America more than the wave of land clearing that followed European colonization and the subsequent wave of secondary succession that followed. Between 1750 and 1940 forests were cleared beginning along the Atlantic Coast and moving westward as settlers dispersed from colonial centers (Williams 1989, Pimm and Askins 1995). Forests were cleared for wood products to fuel colonial development and for agricultural expansion leaving only small forest patches in the form of farm woodlots (Harper 1918). This trend would later reverse as small family farms were out competed by more productive farming operations in the Midwest, leading to a wave of abandonment and forest regeneration (Black 1950, Irland 1982, Trani et al. 2001). Across many landscapes of the east, forest cover declined from more than 90% to below 50% only to recover back to more than 90% in the span of a century (Litvaitis 1993).

The whip-saw in the availability of open habitats has had a profound influence on the bird community within Virginia. Many species including Bachman's sparrow, loggerhead shrike, upland sandpiper, Bewick's wren and horned lark expanded their range into the state while many other early successional species experienced population increases in response to the habitat boom. Large-scale forest regeneration would reclaim these lands and result in population declines since the 1950s. Bachman's sparrow, upland sandpiper and Bewick's wren would all contract back toward their former ranges and become extirpated in the state. Although the initial land clearing predated the establishment of agencies and organizations such as the United Stated Department of Interior, the Virginia Game Commission, and the Virginia Society of Ornithology that are concerned with species conservation, species declines resulting from forest regeneration did not and these species would draw the attention of the broader conservation community. Nearly one third of all species that have been proposed for the highest level of conservation concern in Virginia are part of this habitat change.

The list of species suggested as requiring the greatest conservation attention in Virginia has evolved over the past 40 years. This evolution reflects the recovery of species that were previously imperiled, increases in information about populations that have improved our assessment of populations and risks and the emergence of new threats either real or perceived. In general, causes of imperilment fall into two classes including demographic (animals are not reproducing enough to offset mortality) and habitat loss. All of the species recommended for high conservation status where threats were demographic in nature have recovered back to historic levels. Osprey, bald eagle and peregrine falcon populations that were decimated due to contaminant-induced reproductive suppression coupled with elevated adult mortality have recovered over recent decades. The combined effects of banning DDT and establishing management programs have resulted in improved reproductive rates, releasing populations to recover. In a similar way, consistent execution of a predator control program along the barrier islands has greatly improved productivity of piping plovers and allowed the population to recover.

No species that was recommended for the highest level of concern in Virginia due primarily to habitat constraints has recovered. Although strides have been made in halting and reversing the decline of red-cockaded woodpeckers in recent years, the population remains a fraction of historic levels. Early successional species that expanded their ranges into Virginia during the height of forest clearing have mostly contracted back to their historic breeding ranges. Although we may hold some of these species in the state within agricultural strongholds like the Great Valley, the populations will never return to levels reached during the late 19th and early 20th centuries. As species have moved across the landscape in response to waves of habitat change, we must adjust our expectations for species recovery to the realities of habitat trends.

The underlying cause of imperilment is unclear for several species (e.g., gull-billed tern, black rail, Wayne's warbler, red crossbill) that have been recommended for high concern, some of which are in imminent danger of extirpation from the state. Without some understanding of the principal drivers of declines it is not possible to design conservation strategies to reverse them. Recovery of these species depends on basic research focused on the roots of population declines and such research should be a priority moving forward.

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APPENDIX. List of bird species documented to breed in Virginia. Superscript dates associated with common names indicate dates of estimated colonization (c) or extirpation (e). See methods for description of physiographic areas and definitions of status terms. Recommendations from the avian taxonomic committee for the 1978 and 1989 symposia include E – endangered, T – threatened, SP – special concern – and SU – status undetermined. See Table 1 for definitions of these terms and for Tier designations for the 2005 committee meeting.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
Canada Goose [1940(c)]	*Branta canadensis*	Common	Common	Common			
Mute Swan [1957(c)]	*Cygnus olor*	Uncommon	Very Rare				
Wood Duck	*Aix sponsa*	Common	Common	Common			
Gadwall [1955(c)]	*Anas strepera*	Very Rare					
American Black Duck	*Anas rubripes*	Uncommon	Rare	Very Rare			Tier II
Mallard	*Anas platyrhynchos*	Common	Common	Common			
Blue-winged Teal	*Anas discors*	Very Rare	Occasional	Occasional			
Northern Pintail	*Anas acuta*	Occasional					
Green-winged Teal	*Anas crecca*	Occasional					
Hooded Merganse1r [977(c)]	*Lophodytes cucullatus*	Rare	Rare	Rare			
Common Merganser	*Mergus merganser*	Occasional	Occasional	Occasional			
Northern Bobwhite	*Colinus virginianus*	Uncommon	Uncommon	Uncommon			Tier IV

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
Ring-necked Pheasant 2003(e)	*Phasianus colchicus*	Former	Former	Former			
Japanese Green Pheasant 1995(e)	*Phasianus versicolor*	Former					
Ruffed Grouse	*Bonasa umbellus*	Former	Uncommon	Uncommon			
Wild Turkey	*Meleagris gallopavo*	Common	Common	Common			
Pied-billed Grebe	*Podilymbus podiceps*	Very Rare	Very Rare	Very Rare			
Double-crested Cormorant 1978(c)	*Phalacrocorax auritus*	Uncommon					
Anhinga 2010(c)	*Anhinga anhinga*	Very Rare					
Brown Pelican 1987(c)	*Pelecanus occidentalis*	Uncommon				T	
American Bittern	*Botaurus lentiginosus*	Very Rare			SU		Tier II
Least Bittern	*Ixobrychus exilis*	Uncommon	Rare	Rare	SU	SU	Tier III
Great Blue Heron	*Ardea herodias*	Common	Uncommon	Rare	SC		
Great Egret	*Ardea alba*	Uncommon			SC	SC	
Snowy Egret	*Egretta thula*	Rare					

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
Little Blue Heron	*Egretta caerulea*	Rare			SC	SC	Tier II
Tricolored Heron	*Egretta tricolor*					SC	Tier III
Cattle Egret	*Bubulcus ibis*						
Green Heron	*Butorides virescens*	Uncommon	Uncommon	Uncommon			Tier IV
Black-crowned Night-Heron	*Nycticorax nycticorax*	Rare	Occasional	Occasional	SC		Tier III
Yellow-crowned Night-Heron 1946(c)	*Nycticorax violacea*	Rare	Very Rare	Very Rare	SU	T	Tier II
White Ibis 1977(c)	*Eudocimus albus*	Rare					
Glossy Ibis	*Plegadis falcinellus*	Rare			SC	SC	Tier III
Black Vulture 1920(c)	*Coragyps atratus*	Common	Common	Common			
Turkey Vulture	*Cathartes aura*	Common	Common	Common			
Osprey	*Pandion haliaetus*	Common	Uncommon		T		
Mississippi Kite 1995(c)	*Ictinia mississippiensis*	Very Rare					
Bald Eagle Northern	*Haliaeetus leucocephalus*	Uncommon	Rare	Rare	E	E	Tier II
Harrier	*Circus cyaneus*	Very Rare				E	Tier III

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
Sharp-shinned Hawk	*Accipiter striatus*	Rare	Rare	Uncommon	T	SU	
Cooper's Hawk	*Accipiter cooperii*	Common	Common	Common	SU	SU	
Red-shouldered	*Buteo lineatus*	Common	Uncommon	Uncommon	SC		
Hawk Broad-winged	*Buteo platypterus*	Very Rare	Very Rare	Uncommon			
Hawk Red-tailed	*Buteo jamaicensis*	Common	Common	Common			
Hawk Black Rail	*Laterallus jamaicensis*	Very Rare				SU	Tier I
Clapper Rail	*Rallus crepitans*	Common					Tier IV
King Rail	*Rallus elegans*	Uncommon	Very Rare	Very Rare		SU	Tier II
Virginia Rail	*Rallus limicola*	Uncommon	Very Rare	Very Rare		SU	Tier IV
Sora	*Porzana carolina*	Very Rare	Very Rare	Very Rare			
Purple Gallinule	*Porphyrio martinicus*	Former					
Common Moorhen	*Gallinula chloropus*	Occasional	Occasional		SU	SU	
American Coot	*Fulica americana*	Occasional	Occasional				
Black-necked Stilt	*Himantopus mexicanus*	Very Rare					
American Avocet 1971(c)	*Recurvirostra americana*	Occasional					

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
American Oystercatcher	*Haematopus palliatus*	Uncommon					Tier II
Wilson's Plover	*Charadrius wilsonia*	Very Rare			T	E	Tier I
Piping Plover	*Charadrius melodus*	Rare			T	E	Tier I
Killdeer	*Charadrius vociferus*	Common	Common	Common			
Spotted Sandpiper	*Actitis macularius*	Rare	Rare	Rare		SU	
Willet	*Tringa semipalmata*	Common					
Upland Sandpiper	*Bartramia longicauda*	Former	Former	Former	T	E	Tier I
American Woodcock	*Scolopax minor*	Uncommon	Uncommon	Uncommon			
Laughing Gull Herring	*Leucophaeus atricilla*	Common					
Gull 1942(c)	*Larus argentatus*	Common					
Great Black-backed Gull 1970(c)	*Larus marinus*	Common					
Least Tern	*Sternula antillarum*	Rare			T	T	Tier II
Gull-billed Tern	*Gelochelidon nilotica*	Rare			T	T	Tier I
Caspian Tern	*Hydroprogne caspia*	Very Rare			SC	SC	

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
Roseate Tern 1927(e)	*Sterna dougallii*	Former					
Common Tern	*Sterna hirundo*	Uncommon					Tier III
Forster's Tern	*Sterna forsteri*	Uncommon			SC		Tier IV
Royal Tern	*Thalasseus maximus*	Uncommon			SC		Tier II
Sandwich Tern	*Thalasseus sandvicensis*	Very Rare			SU	SC	
Black Skimmer	*Rynchops niger*	Uncommon					Tier II
Rock Pigeon	*Columba livia*	Common	Common	Common			
Eurasian Collared-Dove 2001(c)	*Streptopelia decaocto*	Very Rare					
Passenger Pigeon	*Ectopistes migratorius*			Former			
Mourning Dove	*Zenaida macroura*	Common	Common	Common			
Yellow-billed Cuckoo	*Coccyzus americanus*	Common	Common	Common			Tier IV
Black-billed Cuckoo	*Coccyzus erythropthalmus*	Rare	Rare	Uncommon	SU		
Barn Owl	*Tyto alba*	Very Rare	Rare	Rare	SU	SC	Tier III

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
Eastern Screech-Owl	*Megascops asio*	Uncommon	Uncommon	Uncommon			
Great Horned Owl	*Bubo virginianus*	Common	Common	Common			
Barred Owl	*Strix varia*	Common	Common	Common			
Long-eared Owl	*Asio otus*		Rare	Rare		SU	
Short-eared Owl	*Asio flammeus*	Occasional	Occasional			SU	
Northern Saw-whet Owl	*Aegolius acadicus*			Very Rare		SU	Tier II
Common Nighthawk	*Chordeiles minor*	Very Rare	Rare	Rare			
Chuck-will's-widow	*Antrostomus carolinensis*	Common	Uncommon	Rare			Tier IV
Whip-poor-will	*Antrostomus vociferus*	Uncommon	Uncommon	Common			Tier IV
Chimney Swift	*Chaetura pelagica*	Common	Common	Common			Tier IV
Ruby-throated Hummingbird	*Archilochus colubris*	Common	Common	Common			
Belted Kingfisher	*Megaceryle alcyon*	Common	Common	Common			
Red-headed Woodpecker	*Melanerpes erythrocephalus*	Uncommon	Uncommon	Uncommon			
Red-bellied Woodpecker	*Melanerpes carolinus*	Common	Common	Common			

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
Yellow-bellied Sapsucker	*Sphyrapicus varius*			Rare	SU		Tier I
Downy Woodpecker	*Picoides pubescens*	Common	Common	Common			
Hairy Woodpecker	*Picoides villosus*	Uncommon	Uncommon	Uncommon			
Red-cockaded Woodpecker	*Picoides borealis*	Very Rare	Former		E	E	Tier I
Northern Flicker	*Colaptes auratus*	Common	Common	Common			
Pileated Woodpecker	*Dryocopus pileatus*	Common	Common	Common			
American Kestrel	*Falco sparverius*	Rare	Uncommon	Uncommon	T		
Peregrine Falcon	*Falco peregrinus*	Very Rare		Very Rare	E	E	Tier I
Monk Parakeet 1973(c)	*Myiopsitta monachus*	Very Rare					
Carolina Parakeet	*Conuropsis carolinensis*	Former					
Olive-sided Flycatcher	*Contopus cooperi*			Possible			
Eastern Wood-Pewee	*Contopus virens*	Common	Common	Common			Tier IV
Yellow-bellied Flycatcher	*Empidonax flaviventris*			Very Rare			
Acadian Flycatcher	*Empidonax virescens*	Common	Common	Common		SU	

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
Alder Flycatcher	*Empidonax alnorum*			Rare	SU	SU	
Willow Flycatcher	*Empidonax traillii*	Very Rare	Uncommon	Uncommon			Tier IV
Least Flycatcher	*Empidonax minimus*			Rare			
Eastern Phoebe	*Sayornis phoebe*	Uncommon	Uncommon	Uncommon			
Great Crested Flycatcher	*Myiarchus crinitus*	Common	Common	Common			
Eastern Kingbird	*Tyrannus tyrannus*	Common	Common	Common			Tier IV
Scissor-tailed Flycatcher	*Tyrannus forficatus*		Occasional	Occasional			
Loggerhead Shrike	*Lanius ludovicianus*	Foremer	Very Rare	Very Rare	T	E	Tier I
White-eyed Vireo	*Vireo griseus*	Common	Common	Common			
Yellow-throated Vireo	*Vireo flavifrons*	Uncommon	Uncommon	Uncommon			Tier IV
Blue-headed Vireo	*Vireo solitarius*		Rare	Common			
Warbling Vireo	*Vireo gilvus*	Rare	Uncommon	Uncommon	SC		
Red-eyed Vireo	*Vireo olivaceus*	Common	Common	Common			
Blue Jay	*Cyanocitta cristata*	Common	Common	Common			

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
American Crow	*Corvus brachyrhynchos*	Common	Common	Common			
Fish Crow	*Corvus ossifragus*	Common	Uncommon	Uncommon			
Common Raven	*Corvus corax*		Uncommon	Common			
Horned Lark 1940(c)	*Eremophila alpestris*	Uncommon	Uncommon	Uncommon			
Purple Martin	*Progne subis*	Common	Uncommon	Uncommon			
Tree Swallow	*Tachycineta bicolor*	Uncommon	Uncommon	Rare			
Northern Rough-winged Swallow	*Stelgidopteryx serripennis*	Uncommon	Common	Common			Tier IV
Bank Swallow	*Riparia riparia*	Uncommon	Uncommon	Uncommon		SC	
Cliff Swallow	*Petrochelidon pyrrhonota*	Rare	Uncommon	Uncommon	SC	SC	
Barn Swallow	*Hirundo rustica*	Common	Common	Common			
Carolina Chickadee	*Poecile carolinensis*	Common	Common	Common			
Black-capped Chickadee	*Poecile atricapillus*			Common			
Tufted Titmouse	*Baeolophus bicolor*	Common	Common	Common			
Red-breasted Nuthatch	*Sitta canadensis*			Rare			

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
White-breasted Nuthatch	*Sitta carolinensis*	Common	Common	Common		SU	
Brown-headed Nuthatch	*Sitta pusilla*	Common	Uncommon	Rare			Tier IV
Brown Creeper	*Certhia americana*	Former		Rare			Tier IV
House Wren	*Troglodytes aedon*	Common	Common	Common			
Winter Wren	*Troglodytes hiemalis*			Rare		SU	Tier II
Sedge Wren	*Cistothorus platensis*	Rare	Occasional	Occasional		E	Tier III
Marsh Wren	*Cistothorus palustris*	Common	Rare	Occasional			Tier IV
Carolina Wren	*Thryothorus ludovicianus*	Common	Common	Common			
Bewick's Wren 1989(e)	*Thryomanes bewickii*	Former	Former	Former	T	E	Tier I
Blue-gray Gnatcatcher	*Polioptila caerulea*	Common	Common	Common			
Golden-crowned Kinglet	*Regulus satrapa*			Rare		SU	
Eastern Bluebird	*Sialia sialis*	Common	Common	Common			
Veery	*Catharus fuscescens*			Uncommon			
Swainson's Thrush	*Catharus ustulatus*			Vary Rare		SU	

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
Hermit Thrush	*Catharus guttatus*			Rare		SU	
Wood Thrush	*Hylocichla mustelina*	Common	Common	Common			Tier IV
American Robin	*Turdus migratorius*	Common	Common	Common			
Gray Catbird	*Dumetella carolinensis*	Common	Common	Common			Tier IV
Brown Thrasher	*Toxostoma rufum*	Common	Common	Common			Tier IV
Northern Mockingbird	*Mimus polyglottos*	Common	Common	Common			
Bachman's Warbler 1958(e)	*Vermivora bachmanii*	Former					
Golden-winged Warbler	*Vermivora chrysoptera*			Rare		SU	Tier I
Blue-winged Warbler	*Vermivora cyanoptera*		Rare	Uncommon			Tier IV
Black-and-white Warbler	*Mniotilta varia*	Uncommon	Uncommon	Common			Tier IV
Prothonotary Warbler	*Protonotaria citrea*	Common	Uncommon	Rare			Tier IV
Swainson's Warbler	*Limnothlypis swainsonii*	Rare		Very Rare		T	Tier II
Nashville Warbler	*Oreothlypis ruficapilla*			Rare			
Mourning Warbler	*Geothlypis philadelphia*			Rare		SC	

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
Kentucky Warbler	*Geothlypis formosa*	Common	Common	Common			Tier Iv
Common Yellowthroat	*Geothlypis trichas*	Common	Common	Common			
Hooded Warbler	*Setophaga citrina*	Common	Common	Common			
American Redstart	*Setophaga ruticilla*	Uncommon	Uncommon	Uncommon			
Cerulean Warbler	*Setophaga cerulea*	Former	Rare	Uncommon			Tier II
Northern Parula	*Setophaga americana*	Common	Common	Common			Tier IV
Magnolia Warbler	*Setophaga magnolia*			Uncommon		SU	
Blackburnian Warbler	*Setophaga fusca*			Rare			
Yellow Warbler	*Setophaga petechia*	Uncommon	Common	Common			Tier IV
Chestnut-sided Warbler	*Setophaga pensylvanica*			Common			
Black-throated Blue Warbler	*Setophaga caerulescens*			Common			
Pine Warbler	*Setophaga pinus*	Common	Common	Common			
Yellow-rumped Warbler	*Setophaga coronata*			Rare			
Yellow-throated Warbler	*Setophaga dominica*	Common	Common	Uncommon			

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
Prairie Warbler	*Setophaga discolor*	Common	Common	Common			Tier IV
Black-throated Green Warbler	*Setophaga virens*	Rare	Rare	Uncommon	SC		Tier I
Canada Warbler	*Cardellina canadensis*			Uncommon			Tier IV
Yellow-breasted Chat	*Icteria virens*	Common	Common	Common			Tier IV
Eastern Towhee	*Pipilo erythrophthalmus*	Common	Common	Common			Tier IV
Bachman's Sparrow [2000(e)]	*Peucaea aestivalis*	Former	Former	Former		E	Tier I
Chipping Sparrow	*Spizella passerina*	Common	Common	Common			
Field Sparrow	*Spizella pusilla*	Common	Common	Common			Tier IV
Vesper Sparrow	*Pooecetes gramineus*		Very Rare	Uncommon			
Lark Sparrow	*Chondestes grammacus*		Occasional	Occasional			
Savannah Sparrow [1973(c)]	*Passerculus sandwichensis*		Very Rare	Very Rare			
Grasshopper Sparrow	*Ammodramus savannarum*	Common	Common	Common	SC		Tier IV
Henslow's Sparrow	*Ammodramus henslowii*	Former	Rare	Rare	T	E	Tier I
Saltmarsh Sparrow	*Ammodramus caudacutus*	Rare				SC	Tier II

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
Seaside Sparrow	*Ammodramus maritimus*	Common					Tier IV
Song Sparrow	*Melospiza melodia*	Common	Common	Common			
Swamp Sparrow	*Melospiza georgiana*	Very Rare		Rare		SU	
Dark-eyed Junco	*Junco hyemalis*			Common			
Summer Tanager	*Piranga rubra*	Common	Common	Uncommon			
Scarlet Tanager	*Piranga olivacea*	Uncommon	Common	Common			Tier IV
Northern Cardinal	*Cardinalis cardinalis*	Common	Common	Common			
Rose-breasted Grosbeak	*Pheucticus ludovicianus*			Uncommon			Tier IV
Blue Grosbeak	*Passerina caerulea*	Common	Common	Uncommon			
Indigo Bunting	*Passerina cyanea*	Common	Common	Common			
Dickcissel	*Spiza americana*	Rare	Rare	Rare	SU	SU	
Bobolink	*Dolichonyx oryzivorus*	Very Rar	Rare	Rare			
Red-winged Blackbird	*Agelaius phoeniceus*	Common	Common	Common			
Eastern Meadowlark	*Sturnella magna*	Common	Common	Common			Tier IV

APPENDIX continued.

Common Name	Species Name	Coastal Plain	Piedmont	Mountains	1978	1989	2005
Common Grackle	*Quiscalus quiscula*	Common	Common	Common			
Boat-tailed Grackle	*Quiscalus major*	Common					
Brown-headed Cowbird	*Molothrus ater*	Common	Common	Common			
Orchard Oriole	*Icterus spurius*	Common	Common	Common			
Baltimore Oriole	*Icterus galbula*	Rare	Common	Common			
House Finch 1976(c)	*Haemorhous mexicanus*	Common	Common	Common			
Purple Finch	*Haemorhous purpureus*			Rare		SC	
Red Crossbill	*Loxia curvirostra*			Rare		SC	Tier I
Pine Siskin	*Spinus pinus*			Rare			
American Goldfinch	*Spinus tristis*	Common	Common	Common			
House Sparrow	*Passer domesticus*	Common	Common	Common			

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Virginia's Amphibians: Status, Threats and Conservation

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ABSTRACT

Virginia's diverse environments support 84 amphibian species (anurans and caudates), making it the third highest state in terms of species richness. However, the Commonwealth matches the global trend in declining amphibian populations with over one-third of its amphibian species in conservation need. The Species of Greatest Conservation Need included in the most recent Virginia Wildlife Action Plan cut across amphibian families and ecoregions. It is challenging to ascertain the exact cause of most of the population declines. In one degree or another, all of the global threats to amphibians exist within Virginia's borders. While an active research program on amphibians exists in the Commonwealth, there are an abundance of data deficient topics where research can help detect and inform the cause of these declines, as well as evaluate management efforts. On a positive note, there are a large number of existing conservation efforts being undertaken across Virginia that directly or indirectly benefit local amphibians.

"These foal and loathsome animals are abhorrent because of their cold body, pale color, cartilaginous skeleton, filthy skin, fierce aspect, calculating eye, offensive smell, harsh voice, squalid habitation, and terrible venom; and so their Creator has not exerted his powers to make many of them." Carolus Linnaeus 1758

INTRODUCTION

Some people would likely still describe amphibians as Linnaeus once did, but today we know they are a diverse class of vertebrates, many in number and integral components of ecosystems (Hocking and Babbitt 2014). They are ecologically recognized for their energy efficiency and nutrient cycling. Amphibians serve as prey to many different organisms and as predators consuming vast numbers of insects, including those species that are vectors for diseases or cause agricultural damage.

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People have, and continue, to use amphibians for a variety of purposes, including as food, pets and cultural icons. Additionally, the applications of amphibians for human health are wide ranging, including serving as important research subjects and for the treatment of all kinds of ailments (Burggren and Warburton 2007, O'Rourke 2007, Hocking and Babbitt 2014).

Amphibians are the earliest terrestrial Tetrapods, first appearing during the late Devonian Period about 360 million years ago. Their physiological, biological, behavioral and ecological adaptations have enabled them to inhabit every continent except Antarctica. Over 7,400 species of amphibians have been described globally across three orders: Anura (frogs and toads), Caudata (salamanders and newts) and Gymnophiona (caecilians) (refer to www.amhibiaweb.org for the most up to date species list). Amphibians are ectothermic organisms mostly known for their permeable skin, complex life cycles, limited mobility, and strong site fidelity. They have anamniotic (jelly-like) eggs with dozens of reproductive modes, ranging from internal to external fertilization, and small clutches of guarded eggs on land to thousands of eggs deposited in standing water. The same characteristics which make amphibians unique are the very attributes which also make them susceptible to changes in the environment. For these reasons, amphibians are considered good indicator species of ecosystem health (Blaustein et al. 1994, Welsh and Droege 2001, Davic and Welsh 2004, Hopkins 2007). However, if the responses of these organisms are truly indicative of what is happening in the environment, there is great cause for continued concern. Over the past few decades, amphibian populations across the globe have experienced declines, local extirpations and species extinctions (Blaustein and Wake 1990, Gibbons et al. 2000, Stuart et al. 2004, Lannoo 2005, Bishop et al. 2012). Amphibians are now considered one of the most threatened groups of organisms globally, with approximately 40% of species threatened (Stuart et al. 2004, Bishop et al. 2012). This paper explores the status of amphibian populations across Virginia, their potential threats, and actions taken to conserve them.

VIRGINIA'S AMPHIBIANS

Noted for their loud calls, the first printed record of frogs in Virginia is from Robert Beverley's *The History and Present State of Virginia* in 1705 (Mitchell 2013). However, it was not until the early 1900s when Emmet Reid Dunn conducted his seminal work on Virginia's amphibians that the true diversity was realized (Mitchell 2013). Even today, studies using genetic techniques are describing new species (Tilley et al. 2008, Fienberg et al. 2014).

There are currently 84 documented species of anurans (referred to as frogs throughout the remainder of paper) and caudates (referred to as salamanders throughout the remainder of paper) in the Commonwealth of Virginia (Appendix). The Big Levels Salamander (*Plethodon sherando*), Shenandoah Salamander (*P. shenandoah)* and Peaks of Otter Salamander (*P. hubrichti*) are endemic to the Commonwealth; meaning they are found only in Virginia and nowhere else in the world. The other 81 species are found in at least one other adjacent state. The most recent addition to Virginia's species list came in 2015, with the Atlantic Coast Leopard Frog (*Rana kauffeldi*) (Feinberg et al. 2014).

Virginia has the third highest amphibian diversity of the states (Stein 2002). Supported by a diverse array of habitats, these amphibians span the Commonwealth, from coastal wetlands to mountain top ridgelines. Some species of amphibians are habitat generalists, such as the ubiquitous American Bullfrog (*Lithobates catesbeianus*) which occupies every county in Virginia and a variety of freshwater aquatic habitats. Other species are habitat specialists, such as the rock outcrop residing Green salamander (*Aneides aeneus*).

Virginia has six main ecoregions as described by The Nature Conservancy, including the Cumberland and Southern Ridge and Valley, Southern Blue Ridge, Central Appalachian Forest, Piedmont, Mid-Atlantic Coastal Plain, and the Chesapeake Bay Lowlands. Each region differs in topography, geology, climate and vegetation. Both frogs and salamanders occupy each ecoregion, but they display different patterns of species richness (Figure 1). In general, frogs predominate in the eastern ecoregions, while more salamanders reside in the western ecoregions.

STATUS OF VIRGINIA'S AMPHIBIANS

Species assessments are conducted by multiple organizations and for a variety of purposes. This paper uses established rating systems in discussing the status of Virginia's amphibians (Appendix), including the IUCN Red List, NatureServe Conservation Status (global=GRank and state=SRank), U.S. Fish and Wildlife Service endangered species listing (ESA), State of Virginia endangered species listing (State) and the Virginia Wildlife Action Plan (2005 and 2015 WAP). The authors consider a species of concern to be one that has been ranked as imperiled by at least one of the known ranking systems.

All 28 species of frogs found in Virginia also occur in at least one other state. According to the range-wide assessments (i.e. IUCN, NatureServe GRank and ESA), none of these species are imperiled. On the local level, eight of the 28 species (29% of total frogs) are of conservation concern in Virginia. Five species are listed by both NatureServe SRank and Virginia's WAP, while an additional three species are listed only on the WAP. The Barking Treefrog (*Hyla gratiosa*), listed as State Threatened, is the only State listed species. The Atlantic Coast Leopard Frog is not considered in any ranking system because it is newly described (Fienberg et al. 2014) and therefore no previous data for comparison are available for assessment purposes.

A different story holds true for the salamanders. According to the NatureServe GRank, ten species are of conservation concern across their entire range. The IUCN ranking is in agreement with the NatureServe GRank on eight of these species. According to the NatureServe SRank and Virginia's WAP an additional 19 species are of conservation concern within Virginia. Four of these species, however, are only listed by NatureServe and one additional species only by the WAP. Including all listings, the total salamander species of conservation concern in Virginia is 29 (52% of total). Three of these species are listed as State Threatened or Endangered, including the Mabee's Salamander (*Ambystoma mabeei) (ST),* Eastern Tiger Salamander *(A.*

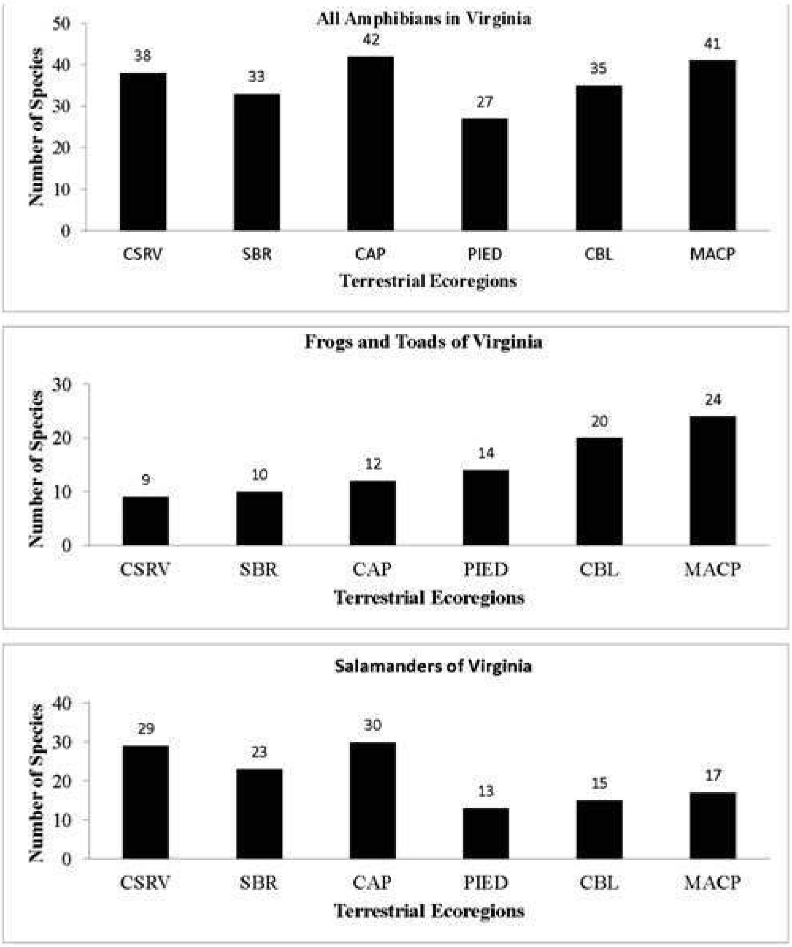

FIGURE 1. Number of Virginia amphibians based on the six terrestrial ecoregions designated by The Nature Conservancy. A species may be represented in more than one ecoregion. Ecoregions include CSRV = Cumberland and Southern Ridge and Valley, SBR = Southern Blue Ridge, CAP = Central Appalachian Forest, PIED = Piedmont, CBL = Chesapeake Bay Lowlands and MACP = Mid-Atlantic Coastal Plain.

tigrinum) (SE) and Shenandoah Salamander (SE)). The Shenandoah Salamander is the only amphibian in Virginia listed by the U.S. Fish and Wildlife Service as Federally Endangered.

Of note are the discrepancies in the different assessments. There may be a number of contributing factors for the differences, but two considerations are worth mentioning in relation to rankings in Virginia. The NatureServe listings were last reviewed on average 11 years ago and in some cases may be outdated. In addition, useful information about species on a state or more local level are not always published in the peer-reviewed literature used in conducting the larger assessments. Considering government biologists and local researchers are consulted in drafting state WAPs, heavier weight on these rankings may be warranted.

Directed by the U.S. Fish and Wildlife Service, the first Virginia WAP was developed in 2005 with 38% of Virginia's amphibians listed as Species of Greatest Conservation Need (SCGN). During the recent 2015 review of the WAP, none of the species on the 2005 list were removed or downgraded in ranking. Although no additional species were added to the list either, the Eastern Hellbender (*Cryptobranchus alleganiensis alleganiensis*), Peaks of Otter Salamander, Cow Knob Salamander (*P. punctatus*) and Weller's Salamander (*P. welleri*) were moved up in ranking to Tier 1 species. The Big Levels Salamander was omitted from consideration in the 2005 WAP because it had just been identified and its status in the revised 2015 WAP is being reviewed. The 2015 WAP is meant to be more detailed than that from 2005. It includes an additional conservation opportunity ranking for listed species, emphasizes habitats, and provides for local action plans with effectiveness measures.

The SGCN listed in the 2015 WAP cut across orders, families and ecoregions. Four of the five families of frogs and five of the six families of salamanders contain species listed in the WAP. When taking into account ecoregions, those frogs found within the Mid-Atlantic Coastal Plain and Chesapeake Bay Lowlands ecoregions appear to be more imperiled than those species farther inland (Table 1). The imperiled salamanders, however, are distributed more broadly across the different ecoregions. For most of these species, the exact cause of decline is unknown. What is known is that amphibians face many threats across the Commonwealth.

ENVIRONMENTAL THREATS AND IMPACTS TO VIRGINIA'S AMPHIBIANS

Virginia's amphibians follow the global trend with nearly 40% of all species listed as SCGN. An abundance of threats are present across the Commonwealth and it is challenging to ascertain the direct cause(s) of decline for each of the amphibian species. Amphibians may be affected directly or indirectly from the threats, which could be acute or chronic. Impacts may manifest in lethal or sublethal manners and affect each species, and even life stage, differently. Furthermore, amphibians are affected not only by individual threats, but likely also by multiple threats acting synergistically. The information presented here is not meant to be an exhaustive review or indicative of all known or possible environmental threats to amphibians. The intent is to highlight the leading threats to amphibians globally and put them in the context of Virginia.

TABLE 1. Distribution of amphibian species by number and percentage (in parentheses) listed as Species of Greatest Conservation Need on the 2015 Virginia Wildlife Action Plan. Some species are listed in more than one ecoregion. Ecoregions include CSRV = Cumberland and Southern Ridge and Valley, SBR = Southern Blue Ridge, CAP = Central Appalachian Forest, PIED = Piedmont, CBL = Chesapeake Bay Lowlands and MACP = Mid-Atlantic Coastal Plain.

	CSRV	SBR	CAP	PIED	CBL	MACP
Anurans	1 (11)	0 (0)	1 (8)	1 (7)	4 (20)	6 (25)
Caudates	11 (38)	7 (30)	9 (30)	2 (15)	4 (27)	7 (41)

Habitat Loss

Changes in habitats are credited with being the largest threat to amphibians globally (Bishop et al. 2012). Maintaining large patches of undisturbed forests, wetlands and other habitats is challenging anywhere where there is a large demand on natural resources and human population. Farming, the leading economic industry in Virginia, covers approximately 32% of Virginia's land (VDACS 2016). The leading factor in loss of forest land, however, is urbanization and development (VDOF 2016). According to the U.S. Census Bureau, Virginia's population is over 8 million, an increase of 5 million since 1950. Since 1977, Virginia has lost over a half million acres of forest land (VDOF 2014) and over 40% of the Commonwealth's wetlands have been lost since colonial times (Booth 2012). Despite loss of habitat, co-author J. D. Kleopfer believes many species listed in the WAP have abundant habitat to maintain viable populations. He believes their limited distribution and dispersal ability within the Commonwealth makes them vulnerable, particularly to stochastic events and climate change.

Roads

Roads as a form of infrastructure are a threat to amphibians globally (Andrews et al. 2008). Amphibians are often seen crossing Virginia's roads during the breeding season, rains, or when roads are adjacent to wetlands or other prime habitat. The vast network of roads across the landscape coupled with the inability of amphibians to quickly escape automobile traffic results in direct impacts (i.e. injury or mortality), as well as indirect affects (i.e. barriers to gene flow, introduction of pollution) (Andrews et al. 2008, Beebee 2013, Cosentino et al. 2014). Despite the prevalence of amphibians on roads in Virginia, there is only one known study which looked at road mortality over five visits in three years of juvenile red-spotted newts (red efts; *Notophthalmus viridescens*) on a portion of Country Road 629 (Mitchell 2000). The highest observed mortality was 182 dead individuals over a 0.25 km distance, but other visits only found 10 or less dead salamanders (Mitchell 2000). Actions have been taken to reduce mass mortality of explosive breeders when they migrate to breeding sites. For instance, Riverside Drive has been closed to facilitate the migration of Spotted Salamanders (*A.*

maculatum) to and from Richmond's James River State Park during spring rains. In addition, the Loudoun Wildlife Conservancy and other organizations have a brigade of citizens who help amphibians cross roads safely during breeding events.

Less evident and harder to mitigate are the indirect impacts of roads (Andrews et al. 2008). Even unpaved roads can create forest-edge effects and negatively impact salamander abundance adjacent to them (Marsh and Beckman 2004, Marsh 2007). Wide paved roads are considered a possible barrier to gene flow of Red-backed Salamanders (*P. cinereus*) (Marsh et al. 2008), although this species also shows genetic differentiation over areas 200 meters or more in contiguous habitat (Cabe et al. 2007). Additionally, pollution originating from roads is a threat to amphibians. Stormwater runoff from roads and paved surfaces is a source of pollution into amphibian habitats. American Bullfrog and Green Frog (*L. clamitans*) tadpoles in highway drainages in Virginia had higher concentrations of heavy metals than their counterparts (Birdsall et al. 1986). Litter (solid waste) along roadsides may also pose a challenge to amphibians. A study conducted to quantify impacts of littered bottles on small mammals along Virginia roads documented trapped amphibians (Benedict and Billester 2004). Nylon landscaping netting often used on roadsides to control erosion has also been observed to entangle and kill frogs (J. D. Kleopfer, pers. obs. 2016).

Pollution

Pollution, whether from a specific episodic event, or chronic input over an extended period of time, can negatively influence amphibians in lethal and sub-lethal ways. There is a breadth of information globally on pollution impacting amphibians, ranging from pesticides as endocrine disruptors to nutrients increasing the prevalence of deformities in amphibians (Karraker 2009, Mann et al. 2009, Bishop et al. 2012, Egea Serrano et al. 2012, Baker et al. 2013). However, there is a great need for researching the potential impacts of pollution on amphibians from agriculture, road deicing and other sources in Virginia. Locally, acidity and mercury are the two pollutants investigated most frequently.

Acid pollution in Virginia originates from both non-point sources, such as acid rain, and point sources, including acid mine drainage. The characteristics of a particular habitat, the species and species' life stages all play roles in the response of amphibians to acidic inputs (for laboratory levels of acidity impacting amphibians refer to Freda et al. 1991, Green and Peloquin 2008). The acid neutralizing capacity (ANC) of a habitat is an important predictor of how a particular system will respond to inputs of acid. In Virginia, habitats with little or no ANC, such as ephemeral ponds in York County, are becoming more acidic over time (Fairman et al. 2013). Many amphibians rely on these types of habitats for breeding. The breeding of Spotted Salamanders decreased over an eight year period in ephemeral ponds with higher acidity and concentrations of aluminum, copper, silicon, and zinc than in other ponds (Blem and Blem 1991). Fairman et al. (2013) also documented a decrease in pond occupancy by Mabee's Salamanders in highly acidic ponds, but it was difficult to make a direct causal relationship to acidity.

In other cases where the measured pH of aquatic habitats is decreasing, the impact on amphibian populations is not evident. In Shenandoah National Park, where stream acidity has been increasing, amphibian species richness and abundance have remained stable (Mitchell 1999, Grant et al. 2005). The acidity of these streams, however, has not dropped below pH 4.9 (Grant et al. 2005) and laboratory studies indicate Virginia stream salamanders show susceptibility starting around pH 4.2 (Green and Peloquin 2008). In models predicting occupancy of plethodontid salamanders, pH is a covariate with low level support in candidate models (Grant et al. 2014). The acidity levels in the streams included in the models were quite low (avg. pH 5.5) but a stronger negative association may become evident at higher acidity levels (Grant et al. 2014).

Mercury is another pollutant which enters the environment from both point and non-point sources. Widespread emissions result in wet and dry deposition of mercury across the landscape. The mercury then becomes available for uptake by amphibians through their skin or by ingesting contaminated prey. Hamed (2014) found Black-bellied Salamanders (*Desmognathus quadramaculatus*) on Whitetop Mountain to contain extremely high levels of mercury. Furthermore, salamanders from higher elevations and north facing slopes, where deposition was greater, had higher levels of mercury than other salamanders. Interestingly, mercury levels in salamanders from museum samples taken in the 1950s from the same location were found to have even higher levels of mercury, indicating that regulations have been successful in reducing levels of mercury pollution (Hamed 2014).

Old manufacturing factories in Virginia, such as those on the South River and North Fork of the Holston River, are sources of point source mercury inputs. Amphibians from downstream sites have higher mercury levels than reference sites above the pollution source (Bergeron et al. 2010, Bergeron et al. 2011, Burke et al. 2010). Contaminated Two-lined Salamanders (*Eurycea* spp.) from the study area demonstrated altered locomotor performance and prey capture (Burke et al. 2010). American Toads (*Anaxyrus americanus*) transferred mercury to eggs, although this did not appear to impact population numbers (Bergeron et al. 2011).

Introduced, Naturalized and Invasive Species

Often considered a type of biological pollution, invasive species have been linked to declines in native amphibian populations around the globe. There are no known naturalized or invasive amphibian species in Virginia (VDGIF 2014), although there are records of some non-native amphibian species being introduced into the Commonwealth without establishing naturalized populations. The U.S. Geological Service Aquatic Nuisance Database (2015) documents introductions of Cuban Tree Frogs (*Osteopilus septentrionalis*) and African Clawed Frogs (*Xenopus laevis*). The Cuban Treefrogs were not expected to be able to survive the mid-Atlantic winter and the African Clawed Frogs are believed to have been eradicated during two collection events (USGS 2012). At least one known native Virginia amphibian was introduced outside its range. Between 1935-1945 the Northern Gray-Cheeked Salamander (*P. montanus*, formerly *P. jordani*) was introduced to Mountain Lake Biological Station for research purposes. A breeding population was established, but the addition of this species to the community has no apparent impact on the local salamander species, particularly its congener the Slimy Salamander (*P. glutinosus)* (Cunningham and Rissler 2013).

Unfortunately, naturalized and invasive species of other taxa are present in Virginia. No study has linked any one of these species to declines in local amphibians, but the threat is possible. For instance, the invasive Snakehead Fish (*Channidae* spp.) are known to consume amphibians (Courtenay and Williams 2004), as are the introduced Brown Trout (*Salmo trutta*) (Gratwicke 2008). Feral and pet cats, believed to be killing millions of birds a year, are also known to kill and eat amphibians (Mitchell and Beck 1992). Beyond predation, invasive species can also alter amphibian habitat, such as the Hemlock Woolly Adelgid (*Adelges tsugae*), an insect which kills hemlock trees (*Tsuga* spp.) causing an increase in soil erosion and stream sedimentation (VISWG 2012). Feral Hogs (*Sus scrofa*) are a growing issue in Virginia (VDGIF 2016). Their impacts on local amphibian populations are unknown, but among eating amphibians as prey, they have also been known to destroy wetlands used as amphibian breeding sites (Jolley et al. 2010).

Emerging Infectious Diseases

A number of pathogens and parasites, including trematodes, fungi, bacteria, and viruses have been associated with declines and deformities of amphibian species globally (Daszak et al. 2003). While malformations of amphibians have been documented in Virginia, the numbers are not high enough to warrant concern (J.D. Kleopfer, pers. Obs. 2015). The discussion here only focuses on a few higher profile diseases.

Ranavirus is a genera of DNA-based iridoviruses found in amphibians, reptiles and fish. Each taxon experiences different symptoms, but often the disease becomes apparent only when a mass die-off occurs. Die-offs occur suddenly and, at least in most amphibians, are usually associated with the metamorphosing stages. There are unpublished data and anecdotal evidence of mass amphibian die-offs occurring in Virginia, but no published records. One author (J. Sevin, unpublished) knows of multi-year die offs of Wood Frog (*L. sylvaticus*) metamorphosing tadpoles in two artificial ponds in Warren County.

Infection by *Ranavirus*, however, does not always result in disease and mortality. The presence of *Ranavirus* has been detected in the wild in a number of salamander species in Virginia without any known mortality (Davidson and Chambers 2011, Hamed et al. 2013, Blackburn et al. 2015). Nelson (2010) documented the presence of *Ranavirus* in anuran tadpoles associated with some Virginia fish-hatcheries. It is possible some amphibians testing positive for *Ranavirus* may be asymptomatic and serve as reservoirs for the pathogens (Goodman and Ararso 2012). Likewise, *Ranavirus* is not ubiquitous in amphibian communities. Muletz et al. (2014) did not find *Ranavirus* across an array of amphibian species. Surprisingly, Goodman and Ararso (2012) did not find *Ranavirus* in frogs in Prince Edward County, even when it was detected in syntopic aquatic turtles.

Much about *Ranavirus* is still unknown, including the best method to use in its detection. Virginia is one of several states taking part in a Regional Conservation Need project to document the extent of *Ranavirus*. Preliminary results of this study indicate that 11 of 25 breeding ponds surveyed in Virginia would have tested positive for *Ranavirus* using older analytical techniques (S. Smith, MDNR, pers. comm.).

However, use of a new stricter protocol would only classify one of these sites as positive.

Another notorious amphibian disease is the fungus *Batrachochytrium dendrobatidis* (*Bd*), which causes chytridiomycosis infections. *Bd* has been linked to amphibian mass mortalities globally (Bishop et al. 2012). In Virginia, there have been multiple studies to investigate the prevalence of *Bd* both in frogs and salamanders. Despite being detected in various counties in the Commonwealth and across a diversity of amphibian species, the prevalence of *Bd* has been relatively low (Rothermel et el. 2008, Hossack et al. 2010, Davidson and Chambers 2011, Gratwicke et al. 201, Eskew et al. 2014, Goodman and Ararso 2012, Hughey et al. 2014, Muletz et al 2014, Bales et al. 2015). A recent study of Green Salamanders found the highest prevalence of *Bd* in the Commonwealth at 15% of the sample (6 of 41 individuals) (Blackburn et al. 2015). There are no published records of high levels of zoospore infections or observations of dead or dying amphibians attributed to chytridiomycosis in Virginia. Furthermore, Muletz et al. (2014) found no evidence of *Bd* in museum specimens of salamanders from Virginia in the 1970s-1980s, when Highton (2005) noted many population declines in the area. Unlike many other areas around the world, it appears *Bd* has not resulted in population declines of amphibian species in Virginia. The Commonwealth also initiated early measures to reduce the spread of amphibian related diseases by prohibiting the sale or possession of African Clawed Frogs and the African Dwarf Frogs (*Hymenochirus* spp.*)*, believed to be carriers and transmitters of the disease, unless a permit is issued.

It is worth noting that a novel fungal species, *B. salamandrivorans* (*Bsal*), was first linked to die offs of Fire Salamanders (*Salamandra salamandra*) in Europe (Martel et al. 2014). In laboratory experiments, salamander species found to occur in Virginia, such as the Red-spotted Newt, were deemed to be highly susceptible to *Bsal* (Martel et al. 2014). Early studies have not detected the presence of *Bsal* in wild salamander species from the central Appalachians (Muletz et al. 2014, Bales et al. 2015). However, the potential transmission of *Bsal* or similar novel pathogens to the United States through the amphibian pet trade is a great concern. Recently, the U.S. Fish and Wildlife Service took measures to reduce potential *Bsal* transmission by publishing an interim report to prevent the trade of 201 species of salamanders (USFWS 2016).

The bacterium *Salmonella* is an infectious disease associated with herpetofauna and is briefly mentioned here because it is a zoonotic disease (transfers between wildlife and humans). *Salmonella* poisoning can result in human illness or death. Regulations already existed in Virginia limiting the sale of small turtles, but in 2009, 11 cases of *Salmonella* were reported in Virginia from aquatic pet frogs (VDH 2011). Individuals in contact with amphibians should wash their hands with soap and water following contact.

Climate Change

Climate change is a global threat that will have local repercussions with higher sea levels, increasing temperatures and storm events, as well as seasonal changes in precipitation. The 2015 WAP seeks consideration of climate change as a threat to species and the inclusion of related management efforts in action plans. Virginia's

Climate Modeling and Species Vulnerability Assessment used three amphibians as candidate species in their models: the Oak Toad (*A. quercicus*), Cope's Gray Treefrog (*Hyla chrysoscelis*) and Wood Frog (*L. sylvaticus*) (Kane et al. 2013). The particular models, which used 40 variables, indicate that expected conditions in Virginia with climate change may actually be favorable to these three species (Kane et al. 2013). The report cautioned that having more favorable conditions for amphibians does not mean their distribution will increase, since they have limited dispersal ability and a number of anthropogenic barriers exist. It should also be mentioned that no salamanders were included in this particular study.

Recent climate models conducted by Milanovich et al. (2010) indicate all Appalachian salamanders will experience range contractions in the future. This is supported by the models of Sutton et al. (2015) which estimated climate niches for salamanders would decrease by 2050. Some species, including the State threatened Mabee's Salamander, are predicted to lose most of their climate niches. Furthermore, Hamed (2014) also used down scaled climate models to predict that three of 12 salamanders on Whitetop Mountain will likely become extirpated by 2070, while the other nine will have to move up in elevation to survive the changing conditions. In addition, stream temperature has been shown to be an important variable in salamander models (Grant et al. 2014).

Current evidence linking existing changes in amphibian populations to climate change are few and far between. Some papers have documented how unseasonable changes in precipitation and temperature in Virginia, such as warm fronts occurring during January, affected the breeding phenology of amphibians and survival of individuals (Briggs 1994, Bulmer and Cherok 1998, Gibson et al. 2008). Surveys conducted on Whitetop Mountain show at least some salamander species have either expanded or contracted their ranges compared to 1950s values of the mean elevations (Hamed 2014). However, these changes were not able to be correlated with changes in temperature as no temperature readings were available for Whitetop Mountain and the closest measurements showed no temperature changes over that time period. Another recent study documented the body size of plethodontid salamanders has decreased over the last 55 years and attributed the decrease to an increased metabolism due to climate change (Caruso et al. 2014). However, Connette et al. (2015) cautioned that other factors could have produced the change in body size.

CONSERVATION INITIATIVES

Numerous conservation actions are underway across Virginia to conserve amphibians, as well as to directly address many of the threats. The information below is meant to illustrate the breadth of efforts and highlight some of the initiatives being undertaken.

Habitat Preservation, Acquisition and Restoration

Acquiring, preserving and restoring amphibian habitats are priority conservation actions. Land is preserved in Virginia by State agencies as wildlife management areas, parks, forests and more. No land acquisitions or preservation, however, have been directly attributed to amphibians, but they are secondary benefactors of these actions.

According to Virginia Department of Conservation and Recreation's Conservation Lands Database, over 16,000 square kilometers (~16% of the Commonwealth's land) is preserved by private owners, organizations and government agencies. State laws also protect certain types of habitat that are privately owned, such as the commitment for "no net loss" to the amount and function of wetlands. Permits for impacts on surface waters, including wetlands, must be obtained by the Virginia Department of Environmental Quality. Financial and technical resources are also made available through the State and Federal government to help private land owners place their property under conservation easements and implement actions, such as creating stream buffers.

Amphibians in Virginia benefit from small and large scale practices, such as installation of backyard ponds and restoration of large wetland areas. Multiple agencies in the Commonwealth undertake initiatives that help improve amphibian habitat. The Virginia Aquatic Resources Trust Fund is an example of one such program. The Trust Fund, a collaboration of the Army Corps of Engineers, the Virginia Department of Environmental Quality and The Nature Conservancy, is a mitigation project for streams and wetlands where the government has permitted certain impacts to take place. Over $42 million has been invested in 121 mitigation projects. Another example comes from the Virginia Department of Mines, Minerals and Energy Orphaned Land Program where land undergoes reclamation. For instance, acid mine drainage from a lead-zinc mine and an adjacent gold mine resulted in such poor water quality of Knights Branch that no flora or fauna could survive. A reclamation process begun in 2001 and ending in 2005 resulted in decreased acidity and metals. As the habitat was restored Southern Leopard Frogs (*L. sphenocephalus*) and Pickerel Frogs (*L. palustris*) were observed (Sobeck et al. 2008). While State and Federal agencies have supported many initiatives across Virginia, various non-profit organizations and many individuals have also protected and restored habitat.

The saying "if you build it, they will come" easily applies to amphibians as they are known to use created and restored habitats (Brown et al. 2012). Non-profit organizations play a significant role in facilitating habitat conservation through providing funding and expertise, as well as recruiting a large volunteer work force. For instance, the Chesapeake Bay Foundation has a number of initiatives, including planting riparian buffers along streams and rivers. Other organizations initiate efforts that remove invasive species from habitats. Individuals are taking action on their own properties to enhance amphibian habitat, such as blocking cattle from streams to minimize erosion, building ephemeral ponds, leaving rocks and woody debris on lawns, and much more.

Outreach and Education

Amphibians may not be considered charismatic megafauna, but they certainly do have a following in Virginia. Many of Virginia's zoological facilities have exhibits on herpetofauna that draw large crowds. While many exhibits include non-native species, groups such as the National Zoo are highlighting more of the areas unique amphibian diversity. The National Zoo's Reptile Discovery Center includes a salamander lab for the public to learn about ongoing research on local amphibians and a newly opened *Jewels of the Appalachia* exhibit that includes 10 native species of salamanders.

Herpetologists affiliated with government agencies, academic institutions and non-profit organizations often conduct lectures for the public on topics related to amphibian conservation. County, State and National Parks also offer a wide variety of interpretive signage, classes, camps and public events related to amphibians. Fairfax County Park Authority, for example, offers programs for scouts where they can earn their Reptile and Amphibian Merit Badge. In addition to informal opportunities, the Virginia Aquarium and Marine Science Center and the Virginia Living Museum are among the groups providing lessons correlated to Virginia's standards of learning for teachers to easily integrate amphibian education into their curricula.

A number of organizations and agencies provide resources for youth and adults on amphibians. Online videos and other social media offer a plethora of information on amphibians at anyone's fingertips. The topics range from identifying species to creating a backyard habitat. VDGIF's designation of 2015 as the *Year of the Frog*, which was promoted through public events and social media outlets, was extremely popular. The Virginia Herpetological Society's (VHS) website, which is a great resource for disseminating information on local amphibians, receives on average 46,000 visitors per month. Professionals also have the opportunity to share and gain knowledge through VHS and the regional Partners in Amphibian and Reptile Conservation (PARC) groups.

Citizen Science

Individuals interested in using their education to take a more active role in amphibian conservation can engage in various citizen science initiatives being offered in Virginia. Since 1999 VDGIF's Frog and Toad Calling Survey has been part of the North American Amphibian Monitoring Program (NAAMP) which uses volunteers from across the Commonwealth to survey various wetland habitats for frogs and toads. There are 53 designated routes ensuring a wide variety of habitats are covered. The NAAMP data are then used by the U.S. Geological Survey and other researchers to study trends. A similar initiative offered through the Association of Zoos and Aquariums is the nationally run FrogWatch USA program. Volunteers from local chapters document frog and toad calls. There are currently eight chapters across the Commonwealth.

Not limiting citizen science to just frogs, VHS organizes various surveys each year where amateur and professional herpetologists help inventory the diversity of amphibians in various locations across Virginia. Citizens can also be engaged in collecting important data on habitat, such as vernal pools. Virginia Commonwealth University, Virginia Master Naturalists and a number of state agencies are collaborating to locate, characterize and monitor vernal pools on public lands (S. Watson, VDGIF, pers. comm.) A number of other habitat-related initiatives are available as well, such as the VA Department of Environmental Quality's Citizen Water Quality Monitoring Program.

Research

Having the proper information to make conservation decisions is critical. Unfortunately it is challenging to have up-to-date and scientifically robust information on every species across Virginia. Over the last ten years, VDGIF has issued research permits for almost every species of amphibian (S. Dressler, VDGIF, pers. comm.). Research is also conducted through State agencies, such as DCR's Natural Heritage Program. Despite this, there still remains a large research gap. Approximately 45% of Virginia's frogs and less than 20% of salamander species have had at least one population monitored for four or more years (Walls 2014). The type of research needing to be conducted to gain a holistic understanding of a species requires time, funding and people with considerable expertise.

State funding for amphibian research is almost exclusively limited to State Wildlife Grants and the Virginia Nongame Fund. The State Wildlife Grants Program provides funds for developing and implementing programs that move species towards recovery and eventual delisting or preclude the need for federal listing under the Endangered Species Act. Its primary focus is on those species identified as Species of Greatest Conservation Need listed in the WAP. The Virginia Nongame Fund's revenue source is through the Virginia Tax Check-Off Program. The Federal government also supports research in the Commonwealth through its various agencies, including the National Park Service, National Science Foundation, U.S. Fish and Wildlife Service, and the U.S. Geological Survey. Non-governmental organizations, such as VHS, provide small research grants. Additionally, research is supported through funding mechanisms within academic institutions, zoos and aquaria and foundations. Fortunately, many conservation programs not specifically focused on amphibians also indirectly benefit them.

Virginia Laws, Regulations and Enforcement

Establishing and enforcing policies are important conservation mechanisms. Regulations regarding Virginia's amphibians are clearly stated on the VDGIF website (http://www.dgif.virginia.gov/wildlife/laws/). In summary, it is unlawful to take, possess, import, cause to be imported, export, cause to be exported, buy, sell, offer for sale or liberate within the Commonwealth any wild animal unless otherwise specifically permitted by law or regulation. No threatened or endangered amphibian species or the Eastern Hellbender may be possessed. Otherwise, individuals may possess up to five amphibians listed on the VDGIF Native and Naturalized Fauna of Virginia list, with the exception of the American Bullfrog which has a 15 per day bag-limit. Only under specific conditions are native amphibians allowed to be released, but naturalized species may never be released. No salamanders can be taken from Grayson Highlands State Park or on parts of the Jefferson National Forest.

No amphibian species native or naturalized to Virginia may be bought or sold, except the American Bullfrog, Green Frog, Southern Leopard Frog and Green Treefrog, which can only be bought for educational or researcher purposes and must be purchased from a permitted captive breeder in Virginia or from a properly permitted business out-of-state. Non-native (exotic) amphibian species may be possessed, bought or sold, as long as it is in compliance with all other Local, State, Federal and International laws and regulations. However, special permits are needed for the following species: Giant or Marine Toad (*Rhinella marina)*, African Clawed Frog and Barred Tiger Salamander (Gray Tiger Salamander and Blotched Tiger Salamander - *A.*

mavortium). Special permits are required for exhibiting or conducting research on amphibians.

VDGIF has been active in enforcing laws related to amphibians. However, there is no database containing documentation on the number of fines, confiscations and other related information. Biologists and law enforcement staff from VDGIF occasionally visit pet stores, trade shows, markets and other locations where amphibians may be sold illegally. Reports of violations from the public are also received and responded to by VDGIF.

Conservation Strategies and Collaborations

There are currently no captive breeding or rearing programs for any amphibian species in Virginia. The priority has always been, and will continue to be, to conserve all of Virginia's amphibian species in the wild. Success in these endeavors requires the collaboration among various organizations and agencies to inform, develop and implement conservation strategies. Several of the WAP listed species have management-related plans in place. For instance, Conservation Agreements were developed for the Cow Knob Salamander in 1994 and the Peaks of Otter Salamander in 1997. These agreements are signed by multiple agencies with the purpose and intent to prevent the need for federal listing of these species under the Endangered Species Act. In 1994, a Recovery Plan was developed for the endangered Shenandoah Salamander. Unlike other recovery plans which seek to increase population sizes, the Shenandoah Salamander plan highlights needs for research and ongoing monitoring. No Conservation Agreements exist for any frog species in Virginia.

Considering the range of most of Virginia's amphibians include other states and that threats to species also cut across boundaries, VDGIF actively collaborates with larger conservation initiatives. VDGIF is active in both the southeast and northeast chapters of PARC. PARC produces national and regional materials, such as the Habitat Management Guidelines, hosts meetings and facilitates working groups on issues which cut across State boundaries. VDGIF is also a member of both the Appalachian and North Atlantic Landscape Conservation Cooperative (LCC). The North Atlantic LCC is currently engaged in mapping all vernal ponds and identifying priority amphibian conservation areas. The U.S. Geological Survey's Amphibian Research and Monitoring Initiative (ARMI) is active in Shenandoah National Park and Prince William Forest Park.

RECOMMENDATIONS

There is much already being done in Virginia to address the declines in amphibian species, but there is still much more that needs to be achieved. Researchers can prioritize their efforts to gain a better understanding of local distributions of species and how these are changing over time, investigate potential causes of declines and study whether or not conservation actions are helping amphibians. Funding organizations can assist by recognizing the importance of these organisms and increase funding opportunities available for research, monitoring and conservation. Individuals, organizations and businesses can continue to highlight how critical this taxon is to ecosystems and people. To maintain healthy populations of amphibians in Virginia, prevention and mitigation of threats must continue.

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APPENDIX. Status of Virginia's Amphibians

GR refers to NatureServe Global Ranking and SR refers to NatureServe State Ranking. NatureServe rankings include 1=critically imperiled, 2=imperiled, 3=vulnerable, 4=apparently secure, 5=secure and NR=no ranking; The 05 refers to 2005 Virginia Wildlife Action Plan and 15 refers to 2015 Virginia Wildlife Action Plan. Only Species of Greatest Conservation Need are issued a Tier level; 1=critical conservation need, 2=very high conservation need, 3=high conservation need and 4=moderate conservation need. In 2015 an additional Opportunity Ranking (OP) was added to the Wildlife Action Plan. These include A = managers have identified "on the ground" species or habitat management strategies expected to benefit the species, B = managers have only identified research needs for the species or managers have only identified "on the ground" conservation actions that cannot be implemented due to lack of personnel, funding, or other circumstance., C = managers have failed to identify "on the ground" actions or research needs that could benefit this species or its habitat or all identified conservation opportunities for a species have been exhausted. State (ST) refers to the listing of a species as threatened (T) or endangered (E). ESA refers to the Endangered Species Act and the federal listing of a species as threatened (T) or endangered (E). IUCN refers to the IUCN Redlist of species, with rankings of CR=critically endangered, EN= endangered, VU=vulnerable, NT= near threatened, LC=least concern and NE = not evaluated.

Species	Common name	GR	SR	05	15	OP	ST	ESA	IUCN
Anaxyrus americanus	American Toad	5	5						LC
Anaxyrus fowleri	Fowler's Toad	5	5						LC
Anaxyrus quercicus	Oak Toad	5	2	2	2	C			LC
Anaxyrus terrestris	Southern Toad	5	4						LC
Acris crepitans	Eastern Cricket Frog	5	4						LC

APPENDIX continued.

Species	Common name	GR	SR	05	15	OP	ST	ESA	IUCN
Acris gryllus	Southern Cricket Frog	5	4						LC
Hyla crysoscelis	Cope's Gray Treefrog	5	5						LC
Hyla cinerea	Green Treefrog	5	4						LC
Hyla femoralis	Pine Woods Treefrog	5	4						LC
Hyla gratiosa	Barking Treefrog	5	1	2	2	C	T		LC
Hyla squirella	Squirrel Treefrog	5	4						LC
Hyla versicolor	Gray Treefrog	5	5						LC
Pseudacris brachyphona	Mountain Chorus Frog	5	4	2	2	C			LC
Pseudacris brimleyi	Brimley's Chours Frog	5	4						LC
Pseudacris crucifer	Spring Peeper	5	5						LC
Pseudacris feriarum	Upland Chorus Frog	5	5						LC
Pseudacris kalmi	Mew Jersey Chorus Frog	4	NR	4	4	C			LC
Pseudacris nigrita	Southern Chorus Frog	5	3	4	4	C			LC

APPENDIX continued.

Species	Common name	GR	SR	05	15	OP	ST	ESA	IUCN
Pseudacris ocularis	Little Green Frog	5	3	4	4	C			LC
Gastrophryne carolinensis	Eastern Narrow-mouthed Toad	5	4						LC
Lithobates catesbeianus	American Bullfrog	5	5						LC
Lithobates clamitans	Green Frog	5	5						LC
Lithobates kauffeldi	Atlantic Coast Leopard Frog	NR	NR						NE
Lithobates palustris	Pickerel Frog	5	5						LC
Lithobates sphenocephalus	Southern Leopard Frog	5	4						LC
Lithobates sylvaticus	Wood Frog	5	5						LC
Lithobates virgatipes	Carpenter Frog	4	3	3	3	C			LC
Scaphiopus holbrookii	Eastern Spadefoot	5	4	4	4	C			LC
Ambystoma jeffersonianum	Jefferson Salamander	4	3	4	4	C			LC
Ambystoma mabeei	Mabee's Salamander	4	1/2	2	2	C	T		LC

APPENDIX continued.

Species	Common name	GR	SR	05	15	OP	ST	ESA	IUCN
Ambystoma macuatum	Spotted Salamander	5	5						LC
Ambystoma opacum	Marbled Salamander	5	5						LC
Ambystoma talpoideum	Mole Salamander	5	2	2	2	C			LC
Ambystoma tigrinum	Eastern Tiger Salamander	5	1	2	2	C	E		NE
Amphiuma means	Two-toed Amphiuma	5	4						LC
Cryptobranchus alleganiensis	Eastern Hellbender	3	2/3	2	1	A			NT
Aneides aeneus	Green Salamander	3	3	2	2	C			NT
Desmognathus auriculatus	Southern Dusky Salamander	5	4						LC
Desmognathus fuscus	Northern Dusky Salamander	5	5						NE
Desmognathus marmoratus	Shovel-nosed Salamander	4	2	3	3	C			LC
Desmognathus monticola	Seal Salamander	5	5						LC

APPENDIX continued.

Species	Common name	GR	SR	05	15	OP	ST	ESA	IUCN
Desmognathus ochrophaeus	Alleghany Mountain Dusky Salamander	5	4						LC
Desmognathus orestes	Blue Ridge Dusky Salamander	4	3	4	4	C			LC
Desmognathus wrighti	Northern Pygmy Salamander	3	2	3	3	C			NE
Desmognathus planiceps	Flat-head Salamander	NR	NR						NE
Desmognathus quadramaculatus	Black-bellied Salamander	5	4						LC
Desmognathus welteri	Black Mountain Salamander	4	3						LC
Eurycea bislineata	Northern Two-lined Salamander	5	5						LC
Eurycea cirrigera	Southern Two-lined Salamander	5	5						LC
Eurycea guttolineata	Three-lined Salamander	5	4						LC

APPENDIX continued.

Species	Common name	GR	SR	05	15	OP	ST	ESA	IUCN
Eurycea longicauda	Long-tailed Salamander	5	5						LC
Eurycea lucifuga	Cave Salamander	5	4						LC
Eurycea wilderae	Blue Ridge Two-lined Salamander	5	2	3	3	C			LC
Gyrinophilus porphyriticus danielsi	Blue Ridge Spring Salamander	4	5						LC
Gyrinophilus porphyriticus duryi	Kentucky Spring Salamander	4	2						LC
Gyrinophilus porphyriticus porphyriticus	Northern Spring Salamander	5	5						LC
Hemidactylium scutatum	Four-toed Salamander	5	5						LC
Plethodon chlorobryonis	Atlantic Coast Slimy Salamander	5	NR						NE
Plethodon cinerus	Eastern Red-backed Salamander	5	5						LC

APPENDIX continued.

Species	Common name	GR	SR	05	15	OP	ST	ESA	IUCN
Plethodon cylindraceus	White-spotted Slimy Salamander	5	5						LC
Plethodon glutinosus	Northern Slimy Salamander	5	5						LC
Plethodon hoffmani	Valley and Ridge Salamander	5	4						LC
Plethodon hubrichti	Peaks of Otter Salamander	2	2	2	1	C			VU
Plethodon kentucki	Cumberland Plateau Salamander	4	3	4	4	C			LC
Plethodon montanus	Northern Gray-cheeked Salamander	4	3						LC
Plethodon punctatus	Cow Knob Salamander	3	2	2	1	C			NT
Plethodon richmondi	Southern Ravine Salamander	5	4						LC

APPENDIX continued.

Species	Common name	GR	SR	05	15	OP	ST	ESA	IUCN
Plethodon sherando	Big Levels Salamander	2	2						VU
Plethodon ventralis	Southern Zigzag Salamander	4	1	2	2	C			LC
Plethodon virginia	Shenandoah Mountain Salamander	2	2	3	3	C			NT
Plethodon wehrlei	Wehrle's Salamander	4	4						LC
Plethodon welleri	Weller's Salamander	3	2	2	1	C			EN
Plethodon yonahlossee	Yonahlossee Salamander	4	3	4	4	C			LC
Pseudotriton montanus diasticus	Midland Mud Salamander	5	NR						LC
Pseudotriton montanus montanus	Eastern Mud Salamander	5	5	4	4	C			LC
Pseudotriton ruber nitidus	Blue Ridge Red Salamander	3	NR						LC
Pseudotriton ruber ruber	Northern Red Salamander	5	5						LC

APPENDIX continued.

Species	Common name	GR	SR	05	15	OP	ST	ESA	IUCN
Stereochilus marginatus	Many-lined Salamander	5	3	4	4	C			LC
Necturus maculatus	Common mudpuppy	5	2	3	3	C			LC
Necturus punctatus	Dwarf Waterdog	5	2	3	3	C			LC
Notophthalmus viridescens	Eastern Newt	5	5						LC
Siren intermedia	Lesser Siren	5	2	3	3	C			LC
Siren lacertina	Greater Siren	5	3	4	4	C			LC

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Freshwater Mussels of Virginia (Bivalvia: Unionidae): An Introduction to Their Life History, Status and Conservation

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ABSTRACT

With 77 species, the mussel fauna of Virginia is one of the most diverse in the United States. Fifty-four species or ~70% of the state's mussel fauna occurs in the rivers of the upper Tennessee River basin, especially in the Clinch and Powell rivers of southwestern Virginia. An additional 23 species reside in rivers of the Atlantic Slope, including the Potomac, Rappahannock, York, James and Chowan basins, and in the New River, a major tributary to the Ohio River. A total of 39 species or 51% of Virginia's mussel fauna is listed as federally endangered, state endangered or state threatened. Excess sediment, nutrients and various types of pollutants entering streams from agriculture and industries are the main drivers of imperilment. Freshwater mussels reproduce in a specialized way, one that requires a fish to serve as a host to their larvae, called glochidia, allowing the larvae to metamorphose to the juvenile stage. This extra step in their life cycle uniquely defines mussels among bivalve mollusks worldwide, in freshwater or marine environments, and adds significant complexity to their reproductive biology. Further, they utilize "lures" that mimic prey of fishes to attract their host. Mussels rely on their fish host to provide them with long-distance dispersal and nutrition while they are glochidia, which are small (<0.5 mm) ecto-parasites that attach and encyst on the gills and fins of fishes, typically taking weeks to months to metamorphose, excyst and then drop-away as similar-sized juveniles to the stream bottom where they grow into adults. Adult mussels are mostly sedentary animals living in the benthos, i.e., the bottom of streams and lakes, typically in mixed substrates of sand, gravel and fine sediments. Mussels generally filter suspended organic particles <20 μm from the water column but can also filter deposited particles through the shell-gap when burrowed in the benthos. Further, the adults of most species are long-lived, regularly living 25-50 years or longer in freshwater environments throughout North America. Conservation of freshwater mussels in Virginia will require citizens, non-governmental organizations, local, county, state and federal governments to apply their resources to five main areas: (1) water quality monitoring and regulation enforcement, (2) restoration of stream habitat, (3) restoration of mussel populations, (4) educating the public about the importance and status of mussels, and (5) monitoring and research to understand why mussels are declining and what are the best ways to protect them. Sustained long-term efforts in these five areas offers the greatest potential to conserve freshwater mussels throughout Virginia.

INTRODUCTION

With 77 documented species, the mussel fauna of Virginia is one of the most diverse in the United States — only the states of Alabama (178 species), Tennessee (129 species), Georgia (123 species), Kentucky (104 species) and Mississippi (84) have more species than Virginia (Neves et al. 1997; Paramalee and Bogan 1998; Williams et al. 2008). Virginia's mussel fauna spans two major geographic regions, the southwest region where rivers drain to the Mississippi River and ultimately to the Gulf of Mexico, and the eastern region where rivers drain to the Chesapeake Bay and ultimately to the Atlantic Ocean (Figure 1). The species occurring in these two regions generally are restricted to the major river basins of these areas. Hence, their distributions do not overlap and distinct morphological and biological differences exist between the regional faunas. These differences are in part due to the varied ecological and geological conditions that exist throughout Virginia, and the long-term separation of the Atlantic Slope and Mississippi River basin faunas.

Nationally, freshwater mussels are considered one of the most imperiled groups of animals in the country, with 213 species (72 %) listed as endangered, threatened, or of special concern (Williams et al. 1993). Virginia's fauna is no exception, with more than 50% of its species listed at the federal or state level (Figure 2) (Terwilliger 1991). Most of the endangerment is caused by habitat loss and destruction due to sedimentation, water pollution, dredging, and other anthropogenic factors (Neves et al. 1997). Many of these listed species occur in southwestern Virginia in the Clinch, Powell and Holston rivers, headwater tributaries to the Tennessee River (Figure 1). However, nearly all river systems in the state have mussel species of conservation concern. The rate of mussel imperilment in Virginia and nationally is increasing over time as populations of many species continue to decline and as additional species are listed as endangered by the federal government and state governments.

Population declines and the listing of many mussel species has prompted interest in their conservation (Freshwater Mollusk Conservation Society 2016). State and federal natural resource management agencies, including Virginia Department of Game and Inland Fisheries (VDGIF) and U.S. Fish and Wildlife Service (USFWS), various non-governmental organizations and universities are involved in improving water quality, stream habitat, and increasing abundance and distribution of mussels using population management techniques, such as out-planting hatchery-reared mussels back to native streams, and monitoring populations to determine their status and trends. For example, Virginia Tech, VDGIF and USFWS have been working together to raise mussels in hatcheries and release them to their native streams to build-up populations. Since 2004, this program has released thousands of mussels of numerous species to population restoration sites throughout Virginia.

Most mussels rely on fishes as hosts to metamorphose their larvae to juveniles, and therefore to complete their life cycle. This parasitic relationship uniquely defines

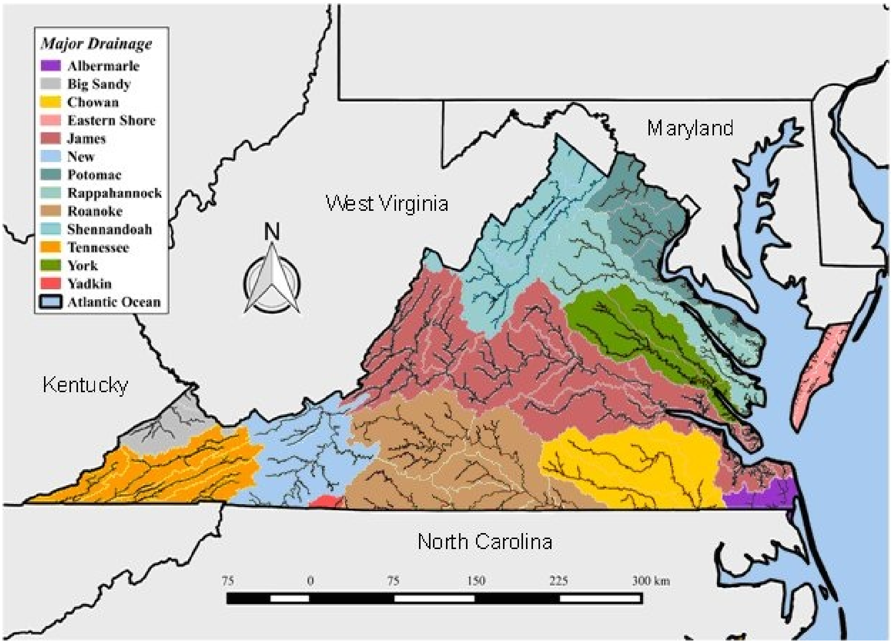

FIGURE 1. Major river drainages of Virginia. Map created by T. Lane, Virginia Tech.

freshwater mussels among bivalve mollusks worldwide, both in freshwater and marine environments. The larvae and newly metamorphosed juveniles are very small, typically less than 0.5 mm long. Hence, these stages are considered weak links in the mussel life cycle, as they are susceptible to loss of host fishes, contaminants in streams, and physical disturbance of stream habitats. However, it is this interaction with fishes that makes mussels unique, and evolutionarily has given rise to some of the most complex and striking mimicry known in the natural world. For students of all ages, mussels are a fascinating portal to understanding streams and the incredible organisms that they contain. Thus, the purpose of this paper is to provide an introduction to the life history, status and conservation of freshwater mussels in Virginia.

METHODS

Occurrence of mussel species in the major river basins of Virginia was determined from publications, reports and personal communications with biologists. However, because mussel surveys and records from the Albemarle, Big Sandy, Eastern Shore and Yadkin basins are sparse to non-existent, species occurrences for these basins were not determined. A mussel species was considered extant in a basin if a live individual was recorded from 1985 to the present. Otherwise, it was considered extirpated or extinct. Species occurrences in the upper Tennessee River basin were determined for the Powell River from Ortmann (1918), Johnson et al. (2012), and Ahlstedt et al. (2016), for the Clinch River from Ortmann (1918), Jones et al. (2014), and Ahlstedt et al. (2016), for the North Fork Holston River from Ortmann (1918), Henley and Neves (1999), and Jones and Neves (2007), for the Middle Fork Holston River from Ortmann (1918),

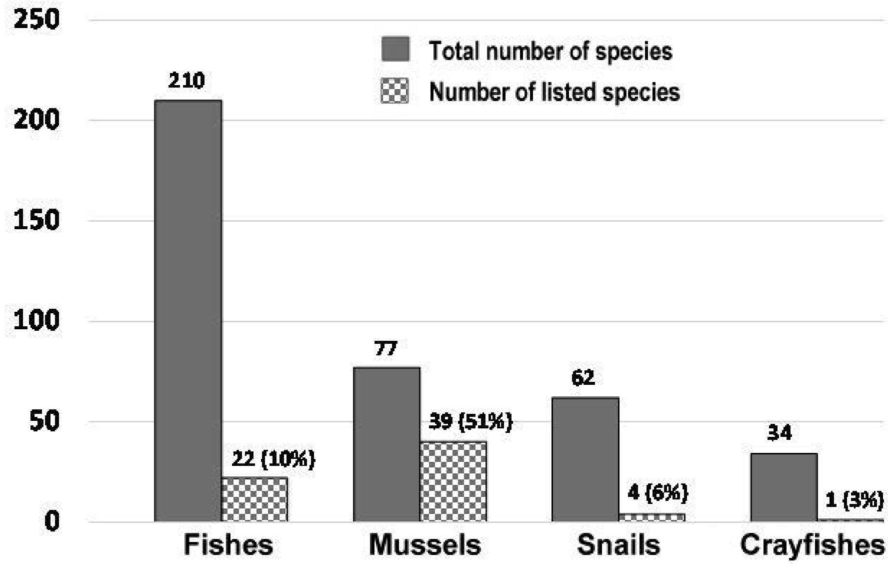

FIGURE 2. Number of species per major aquatic taxon in Virginia. Number of listed species includes species listed as federally endangered, federally threatened, state endangered, and state threatened.

Henley et al. (1999), and Henley et al. (2013), and for the South Fork Holston River from Ortmann (1918) and Pinder and Ferraro (2012). Species occurrences in the New River basin were determined from Pinder et al. (2002). Species occurrences in the major Atlantic Slope river basins were determined for the Roanoke, Chowan, James, York, Rappahannock, and Potomac (including its major tributary the Shenandoah River) river basins from Johnson (1970) and personal communication with VDGIF state malacologist Brian Watson. The legal status of listed species, including federally endangered (FE), federally threatened (FT), federal candidate species (FC), state endangered (SE), state threatened (ST) were accessed from VDGIF's database (last updated on July 18, 2014) and available online at: http://www.dgif.virginia.gov/wildlife/virginiatescspecies.pdf. The number and status of fishes in Virginia was obtained from Jenkins and Burkhead (1993), for snails from Johnson et al. (2013) and for crayfishes based on personal communication with B. Watson. The common and scientific names of freshwater mussels generally follow Turgeon et al. (1998).

RESULTS

A total of 77 mussel species are known from the major river basins of Virginia. Of these, three species (*Epioblasma haysiana*, *E. lenior*, and *Lexingtonia subplana*) and one sub-species (*E. torulosa gubernaculum*) are considered extinct range-wide, and four species (*Anodontoides ferrusacianus*, *Leptodea fragilis*, *L. leptodon*, and *Villosa fabalis*) are considered extirpated from the state, bringing the total extant species in Virginia to 69. From the total species known from the state, 25 are listed as FE, 32 as SE, and six as ST. Since most of the species listed as FE also are listed as SE, the total number of listed mussel species in Virginia is 39, or approximately 51% of the fauna (Figure 2).

The Powell, Clinch and forks of the Holston rivers form part of the upper Tennessee River basin (UTRB), and collectively contain a total of 54 mussel species known from the Virginia sections of these rivers (Table 1). This basin contains the highest diversity of mussel species in the state, especially the faunas of the Clinch and Powell rivers, with 53 and 47 known species, respectively. In the Virginia sections of the Holston, a total of 36 species are known from the North Fork, 22 species from the Middle Fork, and 14 species from the South Fork. Due to the extinction or extirpation of 7 species, a total of 47 species remain extant in the UTRB of Virginia. Again, most of these species occur in the Clinch and Powell rivers, with 46 and 37 extant species, respectively. From the total species known from the UTRB in Virginia, 23 are listed as FE, 29 as SE, and 3 as ST.

The New River flows northwest from North Carolina, through southwestern Virginia, and into West Virginia, where it becomes the Kanawha River just upstream of Charleston, WV. This large, ancient river system has a depauperate mussel fauna of just 12 species (Table 2). Most of the fauna is derived from the Ohio River drainage system, with similarities to the UTRB. However, the pistogrip (*Tritogonia verucossa*), while widespread throughout its range, only occurs in Virginia in the New River. No species that occur in the basin are listed as FE but one species is listed as SE (*Lasmigona holstonia*) and two others as ST (*Lasmigona subviridis* and *T. verucossa*). Further, there are no known mussel species extinctions or extirpations from the basin.

The rivers of the Atlantic Slope of Virginia collectively contain a total of 24 mussel species (Table 3). All species known from the region remain extant, except *L. subplana*, which has not been collected alive in the upper James River basin for decades. The Chowan River basin, specifically its tributary the Nottoway River of Virginia, contains the highest diversity with 20 species, followed by the James River with 19 species. The Roanoke River system has 14 recorded species based on collections in the Virginia section of the Dan River. However, at least five additional species (*Alasmidonta varicosa*, *Elliptio congarea*, *E. fisheriana*, *E. lanceolata*, *Uniomerus carolinianus*) are known from the nearby section of the river and its tributaries in North Carolina. Thus, additional species may occur in the Virginia section of the river.

Two species listed as FE occur in Atlantic Slope rivers of Virginia, *Alasmidonta heterodon* remains extant in the Po River of the upper York River basin and in the Nottoway River, and *Pleurobema collina* is extant in several tributaries to the James River basin and in the Dan and Mayo rivers of the upper Roanoke River basin. Additionally, *Alasmidonta varicosa* (SE) occurs in Broad Run of the Potomac River basin, while *Fusconaia masoni* (ST) occurs in the James River and several river systems to the south and *L. subviridis* (ST) is more broadly distributed, known from all major Atlantic Slope river basins in the state.

TABLE 1. Scientific and common names of freshwater mussel species occurring in major tributaries to the upper Tennessee River basin in Virginia, where FE=federally endangered, SE=state endangered, ST=state threatened and - =no federal or state status, ✓=extant, *=very rare in river, X=known from the system but possibly extinct, EX=known from system but possibly extirpated, and NR=no records of species from river system.

Scientific Name	Common Name	Status	Powell	Clinch	Holston		
					North Fork	Middle Fork	South Fork
Actinonaias ligamentina	Mucket	-	✓	✓	EX	✓	NR
Actinonaias pectorosa	Pheasantshell	-	✓	✓	✓	✓	✓
Alasmidonta marginata	Elktoe	-	✓*	✓*	EX	✓	EX
Alasmidonta viridis	Slippershell	SE	NR	✓*	✓*	EX	EX
Amblema plicata	Threeridge	-	✓	✓	EX	NR	NR
Anodontoides ferrusacianus	Cylindrical papershell	-	EX	NR	NR	NR	NR
Cumberlandia monodonta	Spectaclecase	FE, SE	✓*	✓	NR	NR	NR
Cyclonaias tuberculata	Purple wartyback	-	✓	✓	✓*	✓	NR
Cyprogenia stegaria	Fanshell	FE, SE	EX	✓	NR	NR	NR
Dromus dromas	Dromedary pearlymussel	FE, SE	✓	✓	NR	NR	NR
Elliptio crassidens	Elephantear	SE	✓*	✓*	EX	NR	NR
Elliptio dilatata	Spike	-	✓	✓	EX	✓	EX
Epioblasma brevidens	Cumberlandian combshell	FE, SE	✓	✓	EX	NR	NR
Epioblasma capsaeformis	Oyster mussel	FE, SE	✓	✓	EX	NR	NR
Epioblasma florentina aureola	Golden riffleshell	FE, SE	NR	✓	NR	EX	EX
Epioblasma haysiana	Acornshell	-	X	X	X	NR	NR
Epioblasma lenior	Narrow catspaw	-	X	X	NR	NR	NR
Epioblasma torulosa gubernaculum	Green blossom	FE, SE	X	X	X	NR	NR
Epioblasma triquetra	Snuffbox	FE, SE	✓*	✓	EX	NR	NR

TABLE 1. Continued.

Scientific Name	Common Name	Status	Powell	Clinch	Holston North Fork	Holston Middle Fork	Holston South Fork
Fusconaia cor	Shiny pigtoe	FE, SE	✓*	✓	✓	EX	NR
Fusconaia cuneolus	Finerayed pigtoe	FE, SE	✓	✓	✓	NR	NR
Fusconaia subrotunda	Longsolid	-	✓	✓	EX	NR	NR
Hemistena lata	Cracking pearlymussel	FE, SE	EX	✓	NR	NR	NR
Lampsilis abrupta	Pink mucket	FE, SE	NR	✓	NR	NR	NR
Lampsilis fasciola	Wavyrayed lampmussel	-	✓	✓	✓	✓	✓
Lampsilis ovata	Pocketbook	-	✓	✓	✓	✓	NR
Lasmigona costata	Flutedshell	-	✓	✓	✓	✓	✓
Lasmigona holstonia	Tennessee heelsplitter	SE	✓	✓	✓*	✓	NR
Lemiox rimosus	Birdwing pearlymussel	FE, SE	✓*	✓	EX	NR	NR
Leptodea fragilis	Fragile papershell	ST	EX	EX	NR	NR	NR
Leptodea leptodon	Scaleshell	FE	NR	EX	NR	NR	NR
Ligumia recta	Black sandshell	ST	✓*	✓	NR	EX	NR
Medionidus conradicus	Cumberland moccasinshell	-	✓	✓	✓	✓	✓
Pegias fabula	Littlewing pearlymussel	FE, SE	EX	✓*	✓*	EX	EX
Plethobasus cyphyus	Sheepnose	FE, SE	✓	✓	NR	NR	NR
Pleurobema cordatum	Ohio pigtoe	SE	NR	✓	NR	NR	NR
Pleurobema oviforme	Tennessee clubshell	-	✓*	✓	✓	✓	✓
Pleurobema rubrum	Pyramid pigtoe	SE	NR	✓	NR	NR	NR

TABLE 1. Continued.

Scientific Name	Common Name	Status	Powell	Clinch	Holston North Fork	Holston Middle Fork	Holston South Fork
Pleuronaia barnesiana	Tennessee pigtoe	-	✓*	✓	✓	✓	EX
Pleuronaia dolabelloides	Slabside pearlymussel	FE, SE	✓*	✓	✓	✓	NR
Potamilus alatus	Pink heelsplitter	-	✓*	✓	NR	NR	NR
Ptychobranchus fasciolaris	Kidneyshell	-	✓	✓	✓	✓	NR
Ptychobranchus subtentum	Fluted kidneyshell	FE, SE	✓	✓	✓	✓	EX
Quadrula cylindrica strigillata	Rough rabbitsfoot	FE, SE	✓	✓	EX	NR	NR
Quadrula intermedia	Cumberland monkeyface	FE, SE	✓	EX	EX	NR	NR
Quadrula pustulosa	Pimpleback	ST	✓*	✓	NR	NR	NR
Quadrula sparsa	Appalachian monkeyface	FE, SE	✓*	✓*	NR	NR	NR
Strophitus undulatus	Creeper	-	✓*	✓*	✓*	NR	NR
Toxolasma lividum	Purple lilliput	SE	EX	✓*	✓*	NR	NR
Truncilla truncata	Deertoe	SE	✓*	✓*	NR	NR	NR
Villosa fabalis	Rayed bean	FE, SE	NR	EX	EX	NR	NR
Villosa iris	Rainbow mussel	-	✓	✓	✓	✓	✓
Villosa trabalis	Tennessee bean	FE, SE	EX	✓	EX	NR	NR
Villosa vanuxemensis	Mountain creekshell	-	✓	✓	✓	✓	✓
TOTAL SPECIES KNOWN (54)			47	53	36	22	14
TOTAL SPECIES EXTANT (47)			37	46	20	17	7

TABLE 2. Scientific and common names of freshwater mussel species occurring in the New River basin of Virginia, where SE=state endangered, ST=state threatened and -=no state status, ✓=extant.

Scientific Name	Common Name	Status	New
Actinonaias ligamentina	Mucket	-	✓
Alasmidonta marginata	Elktoe	-	✓
Cyclonaias tuberculata	Purple wartyback	-	✓
Elliptio complanata	Eastern elliptio	-	✓
Elliptio dilatata	Spike	-	✓
Lampsilis fasciola	Wavy-rayed lampmussel	-	✓
Lampsilis ovata	Pocketbook	-	✓
Lasmigona holstonia	Tennessee heelsplitter	SE	✓
Lasmigona subviridis	Green floater	ST	✓
Tritogonia verucossa	Pistol-grip	ST	✓
Pyganodon grandis	Floater	-	✓
Utterbackia imbecillis	Paper pondshell	-	✓
TOTAL SPECIES KNOWN (12)			12
TOTAL SPECIES EXTANT (12)			12

DISCUSSION

Complexity of the mussel life cycle and traits of vulnerability

Freshwater mussels reproduce in a specialized way, one that requires a fish to serve as a host to their larvae, called glochidia, allowing the larvae to metamorphose to the juvenile stage. This extra step in their life cycle uniquely defines mussels among bivalve mollusks worldwide, in freshwater or marine environments, and adds significant complexity to their reproductive biology. Eggs of female mussels are fertilized internally by sperm released by males into the water and taken in during siphoning. The embryos then develop or "brood" in the gills of the female until becoming mature glochidia. Depending on the species, mussel glochidia brood in the gills of females during either winter or summer. Winter-brooders typically spawn in late summer to early fall, brood their larvae through the winter and then release glochidia the following spring and summer. Summer-brooders typically spawn in spring to early summer, and then brood and release their glochidia in the same summer period. Once mature, female mussels release glochidia out into the water, where they must attach and encyst on a suitable host fish for the transformation of larvae to juvenile mussels. Mussels rely on their fish host to provide them with long-distance dispersal and nutrition to metamorphose to juveniles while they are glochidia, which are small (<0.5 mm) ecto-parasites that attach and encyst on the gills and fins of fishes, typically taking weeks to months to metamorphose, excyst and then drop-away as similar-sized juveniles to the stream bottom where they grow into adults. However, for several species, including Green floater (*Lasmigona subviridis*), Creeper (*Strophitus undulatus*), and Paper pondshell (*Utterbackia imbecillis*), the glochidia can

Table 3. Scientific and common names of freshwater mussel species occurring in major Atlantic Slope river basins of Virginia, where FE=federally endangered, SE=state endangered, ST=state threatened and - =no federal or state status, ✓=extant, X=known from the system but possibly extinct, EX=known from system but possibly extirpated, and NR=no records of species from river system. Roanoke=1, Chowan=2, James=3, York=4, Rappahannock=5, and Potomac=6.

Scientific Name	Common Name	Status	1	2	3	4	5	6
Alasmidonta heterodon	Dwarf wedgemussel	FE, SE	NR	✓*	EX	✓	EX	EX
Alasmidonta undulata	Triangle floater	-	✓	✓	✓	✓	✓	✓
Alasmidonta varicosa	Brook floater	SE	NR	NR	✓	NR	NR	✓
Elliptio complanata	Eastern elliptio	-	✓	✓	✓	✓	✓	✓
Elliptio congaraea	Carolina slabshell	-	NR	✓	NR	✓	NR	NR
Elliptio fisheriana	Northern lance	-	NR	✓	✓	✓	✓	NR
Elliptio lanceolata	Yellow lance	-	NR	✓	✓	✓	✓	NR
Elliptio roanokensis	Roanoke slabshell	-	✓	✓	NR	✓	NR	NR
Fusconaia masoni	Atlantic pigtoe	ST	✓	✓	✓	NR	NR	NR
Lampsilis cariosa	Yellow lampmussel	-	✓	✓	✓	✓	NR	✓
Lampsilis cardium/ovata	Pocketbook	-	NR	NR	NR	NR	NR	✓
Lampsilis radiata	Eastern lampmussel	-	NR	✓	NR	✓	NR	✓
Lasmigona subviridis	Green floater	ST	✓	✓	✓	✓	✓	✓
Leptodea ochracea	Tidewater mucket	-	✓	✓	✓	✓	✓	✓
Lexingtonia subplana	Virginia pigtoe	-	NR	NR	X	NR	NR	NR
Ligumia nasuta	Eastern pondmussel	-	NR	✓	✓	✓	NR	✓
Pleurobema collina	James spinymussel	FE, SE	✓	NR	✓	NR	NR	NR
Pyganodon cataracta	Eastern floater	-	✓	✓	✓	✓	✓	✓

TABLE 3. Continued.

Scientific Name	Common Name	Status	1	2	3	4	5	6
Pyganodon grandis	Floater	-	✓	✓	✓	✓	✓	✓
Pyganodon implicata	Alewife floater	-	✓	✓	✓	✓	✓	✓
Strophitus undulatus	Creeper	-	✓	✓	✓	✓	✓	✓
Uniomerus carolinianus	Florida pondhorn	-	NR	✓	NR	NR	NR	NR
Utterbackia imbecillis	Paper pondshell	-	✓	✓	✓	✓	✓	✓
Villosa constricta	Notched rainbow	-	✓	✓	✓	NR	NR	NR
TOTAL SPECIES KNOWN (24)			14	20	19	17	12	16
TOTAL SPECIES EXTANT (23)			14	20	17	17	11	15

metamorphose to the juvenile stage inside the gill of the female parent mussel without parasitizing a host fish (Lefevre and Curtis 1911; Howard 1915; Barfield and Watters 1998; Cliff et al. 2001; Dickinson and Seitman 2008).

Many mussel species have elaborate adaptations to attract their fish hosts. To facilitate attachment of glochidia to their hosts, mussels have evolved highly modified mantle tissues to serve as lures or they produce packets called conglutinates that contain glochidia (Barnhart et al. 2008). Mantle lures and conglutinates closely resemble and mimic prey of fish, such as worms, insect larvae and pupae, leeches, crayfish and even other fish. This mimicry is among the most complex and striking known in the natural world! For example, the mantle lure of the Cumberlandian combshell (*Epioblasma brevidens*) mimics insect larvae and that of oyster mussel (*E. capsaeformis*) is brightly colored blue (Figure 3, photographs A and B); both lures attract their fish host and then capture them like a “venus flytrap” to infest their glochidia directly on fish (Jones et al. 2006a). Mantle lures of other mussels may resemble legs of aquatic insects, such as the lure of Mountain creekshell (*Villosa vanuxemensis*) or that of a large insect larvae, such as the lure of Wavy-rayed lampmussel (*Lampsilis fasciola*) (Figure 3, photographs C and D). Perhaps even more remarkable than these mantle lures, are conglutinates of the kidneyshell (*Ptychobranchus fasciolaris*) that resemble larvae of the black fly (Simuliidae), and conglutinates of the fluted kidneyshell (*P. subtentum*) that resemble pupae (Figure 4, photographs A and B) (Jones et al. 2006b). Conglutinates of the creeper (*Strophitus undulatus*) encase triangular shaped glochidia within individual compartments that are kinetically released by contact with host fish (Watters et al. 2002) and conglutinates of the dromedary pearlymussel (*Dromus dromas*) mimic freshwater leaches (Figure 4, photographs C and D) (Jones et al. 2004). All of these mussels live in rivers of Virginia.

Adult mussels are mostly sedentary, living in the benthos, i.e., the bottom of streams and lakes, typically in mixed substrates of gravel, sand, and silt. Mussels generally filter suspended organic particles <20 µm from the water column to eat but can also filter deposited particles through the shell-gap when burrowed in the benthos (Strayer et al. 2004). Further, the adults of most species are long-lived, regularly living 25-50 years or longer in freshwaters throughout North America (Haag and Rypel 2011). The kidneyshell (*Ptychobranchus fasciolaris*) has been aged to as old as 85 years in the upper Clinch River, Virginia (Henley et al. 2002). Because they are long-lived, their population growth rates tend to be slow, and stable population sizes are sustained by modest to low levels of annual recruitment by juveniles. Collectively, these life history traits, such as dependency on fish to metamorphose their larvae, a small sensitive juvenile stage, filter-feeding, and long-lived benthic-dwelling adults, make mussels vulnerable to various natural and anthropogenic impacts, including severe floods and droughts, habitat alteration from dams, various types of pollution entering rivers and streams, sedimentation from agriculture and urban environments and many other factors (Neves et al. 1997; Strayer et al. 2004).

Distribution and diversity of mussels in Virginia

With 77 species, the mussel fauna of Virginia is one of the most diverse in the United States. However, due to the varied physiography of the state, including the Appalachia Mountains to the west, the rolling hills of the central Piedmont, and the flat coastal plain of the east, Virginia’s mussel fauna has a complex distribution and

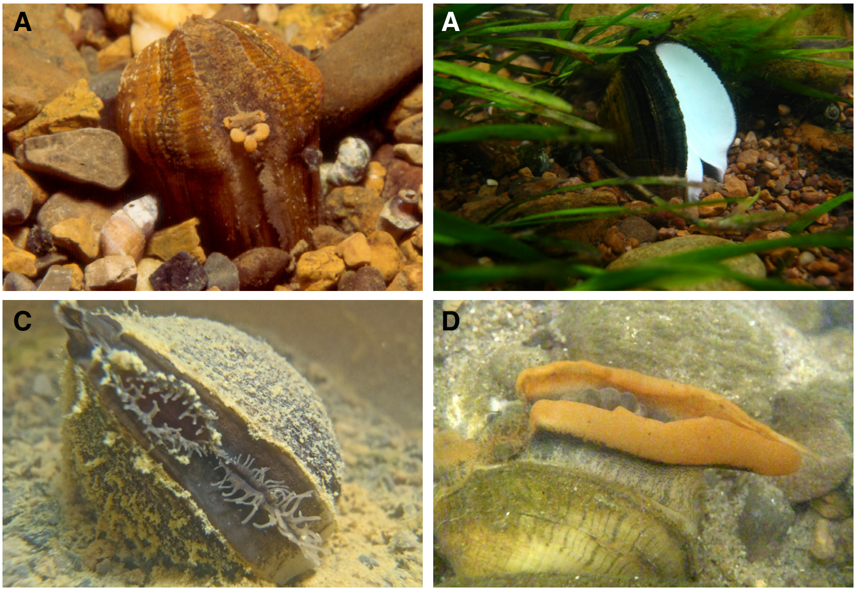

FIGURE 3. Mantle-lure displays of female mussels: (**A**) Cumberlandian combshell (*Epioblasma brevidens*), Clinch River, Hancock County, Tennessee (Photo by J. Jones); (**B**) Oyster mussel (*Epioblasma capsaeformis*), Clinch River, Hancock County, Tennessee (Photo by N. King, Virginia Tech); (**C**) Mountain creekshell (*Villosa vanuxemensis*), Clinch River, Russell County, Virginia (Photo by T. Lane, Virginia Tech); (**D**) Wavy-rayed lampmussel (*Lampsilis fasciola*), Nolichucky River, Hamblen County, Tennessee (Photo by T. Lane, Virginia Tech).

origins. Mussel diversity is not evenly distributed throughout the state, with a major phylo-geographic break occurring between rivers of the UTRB of western Virginia and those draining the Atlantic Slope. The faunas of these two regions are quite different in their species compositions. Because the rivers of these two geographic areas flow in different directions, those of the former into the Mississippi River valley (=Interior Basin) and ultimately to the Gulf of Mexico, and those of the latter to the Atlantic Ocean, the evolutionary histories and the sources or origins of these faunas are quite different. Further, the rivers of Virginia flow through varied gradient, geology, soils, and vegetative cover, creating a range of environmental conditions suitable to mussel growth and survival. Hence, Virginia's rivers have given rise to a unique mussel fauna, one that contains some of the rarest freshwater species in the country, and is in need of continued scientific study and conservation.

Of course, a majority (70%) of the state's mussel fauna resides in rivers of the UTRB, especially the Clinch and Powell rivers. Several factors account for the high species diversity of this region. First, Virginia as a whole was not glaciated during the last ice-age more than 20,000 years ago. Both terrestrial and aquatic biota were

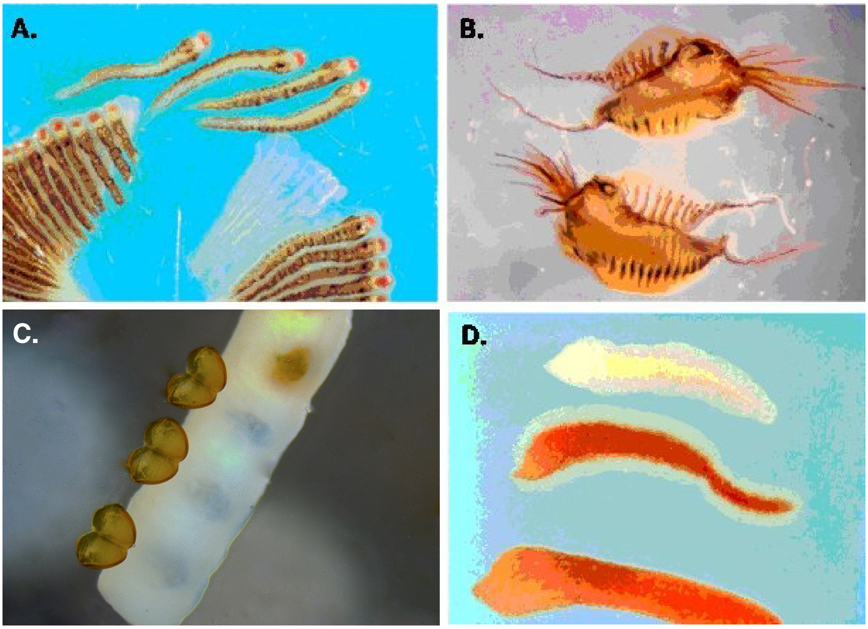

FIGURE 4. Conglutinates of female mussels: (**A**) Kidneyshell (*Ptychobranchus fasciolaris*) Clinch River, Hancock County, Tennessee; (**B**) Fluted kidneyshell (*Ptychobranchus subtentum*), Clinch River, Russell County, Virginia; (**C**) Creeper mussel (*Strophitus undulatus*) Clinch River, Hancock County, Tennessee (Photo by T. Lane, Virginia Tech); (**D**) Dromedary pearlymussel (*Dromus dromas*), Clinch River, Hancock County, Tennessee. Photographs A and B originally published by Jones et al. 2006 and D by Jones et al. 2004.

therefore not destroyed by massive ice sheets that covered large sections of North America north of Virginia. The UTRB served as a glacial refuge area for mussels, fishes and many other aquatic species. Second, the UTRB is connected to and is a part of the Mississippi River basin fauna, which is naturally diverse and where many species are widely distributed throughout its tributary streams and ecoregions. The interconnected nature of this river valley promotes high fish host diversity for mussels. For example, the Clinch River alone contains more than 120 species of fish (Jenkins and Burkhead 1993). High host-fish diversity in turn promotes high mussel diversity (Watters 1994). Third, the rivers of the UTRB in Virginia mostly flow through the Valley and Ridge physiographic province, where geologic rock strata are predominately limestone-based and rich in calcium and other minerals, which enhances shell growth and survival of mussels. These rivers also contain abundant and high quality habitat for mussels. Shoals are shallow areas in streams where cobble, gravel and sand substrate collect and remain stable over time. This type of habitat is critical to mussels because they need it to burrow into to protect themselves during floods, and to feed and reproduce effectively in stream environments. Thus, the UTRB's excellent habitat and its connection to the rich aquatic fauna of the Mississippi River basin have acted together to sustain a high diversity of mussels and fishes.

In contrast, mussel diversity in the New River of Virginia is low, with only twelve species recorded. This basin lies between the UTRB and rivers of the Atlantic Slope and has faunal elements of both. For example, the Tennessee heelsplitter (*Lasmigona holstonia*) is native to the Tennessee River basin but now occurs in two tributaries, upper Big Walker Creek and upper Wolf Creek, Bland County (Pinder et al. 2002). Although most of the species that occur in this river originated from streams of the Mississippi River valley, the green floater (*Lasmigona subviridis*) and the eastern elliptio (*Elliptio complanata*) are of Atlantic Slope origin (Clarke 1985; Johnson 1970). The latter species has been recently documented in Claytor Lake, Pulaski County and is considered introduced in the last ten years (B. Watson, VDGIF pers. comm.). The New River was not glaciated but for millennia it has been isolated from the Ohio River and hence the much richer aquatic fauna of the Mississippi River basin by Kanawha Falls, located just upstream of Charleston, West Virginia. These large falls are 20 to 30 feet high and span the river, blocking upstream migration of fish hosts; therefore, preventing many mussel species from colonizing the river above the falls. Of the 89 fish species known from the New River in Virginia, only 46 species are considered native, the remainder having been introduced over the last 50 to 100 years (Jenkins and Burkhead 1993). Hence, its low mussel diversity is mirrored by low native fish diversity. The majority of the New River basin drains the Blue Ridge physiographic province, where geologic rock strata are predominately crystalline based (granite and gneiss) and poor in minerals, including calcium. Mussel shells often appear eroded and of poor quality in the river, indicating shell growth is compromised by the naturally soft water of the basin. Despite ample shoal habitat, mussel abundance is low, further indicating growing conditions are not ideal.

The mussel fauna of the Atlantic Slope contains numerous species unique to the region. Many species that occur here have no direct analogue to species occurring in the Mississippi River basin. For example, *Elliptio complanata* is widely distributed from Florida to New Brunswick and is one of the most abundant species on the Atlantic Slope. However, it does not occur naturally in the Mississippi River basin nor is there a taxonomic equivalent to it in this basin. Mussels such as dwarf wedgemussel (*Alasmidonta heterodon*), yellow lance (*Elliptio lanceolata*), tidewater mucket (*Leptodea ochracea*), James spinymussel (*Pleurobema collina*) and other species also are unique to the Atlantic Slope. Further, a phylogeographic break occurs in the mussel fauna north and south of the James River basin (Johnson 1970). North of this river the fauna contains less species and most are not endemic to the northern half of the Atlantic Slope, i.e., they also occur in the James River basin and south of it. However, the river contains several species such as *P. collina*, Atlantic pigtoe (*Fusconaia masoni*), and notched rainbow (*Villosa constricta*) where the northern limit of their range is the James River (Fuller 1973; Hove and Neves 1994; Eads et al. 2006). To the south, these species and many others are unique to the southern half of the Atlantic Slope. This half of the region contains more mussel species, suggesting that colonization of the Atlantic Slope has occurred from the southern fauna and then moved northward through time. Streams of the Atlantic Slope in Virginia contain excellent habitat for mussels, flowing through varied geology of the Valley and Ridge, Blue Ridge, Piedmont Plateau, and

Coastal Plain physiographic provinces. Habitat in these creeks and rivers can range from rocky-bottom shoals typical of montane streams, sandy-bottom streams of the Piedmont, and the organic-rich, almost swamp-like conditions of the lower Coastal Plain. Mussel populations can reach high abundance in all of these habitat types, especially the ubiquitous *E. complanata*.

While the species compositions of the UTRB, New River, and Atlantic Slope rivers are distinct from each other, species exchanges have occurred among these basins over time. These exchanges have taken place over millennial to contemporary timescales, and are most likely the result of natural stream capture events between basins and from humans introducing host fishes naturally infected with mussel glochidia. There are a suite of species considered native to the Atlantic Slope of Virginia and other east coast states that have very recognizable Interior Basin (namely, UTRB, New, upper Ohio River) forms or analogues; for example, *Alasmidonta varicosa* (=*Alasmidonta marginata*), *Fusconaia masoni* (=*Fusconaia flava*), *Ligumia nasuta* (=*Ligumia recta*), *Lampsilis siliquoidea* (=*Lampsilis radiata*), and *Villosa constricta* (=*Villosa vanuxemensis*). These species are morphologically diverged enough from their Interior Basin counterparts and distributed widely enough on the Atlantic Slope to suggest that faunal exchanges occurred through stream captures millennia ago. Further, given the ubiquitous and widespread nature of these species throughout the Interior Basin, the direction of the exchange likely was from this basin to the Atlantic Slope. *Lampsilis ovata* is native to the Mississippi River valley but its presence and now common occurrence in the Potomac River system indicates a recent introduction. The species is restricted to just this basin on the Atlantic Slope and Johnson (1970) states that it was first introduced here through the Shenandoah River from fish stockings conducted in the late 1800s. The New River has at least three species that are not native to the system, *Lasmigona subviridis* and *Elliptio complanata* originating from the Atlantic Slope, and *L. holstonia* from the UTRB. Other species likely introduced to the system include *Lampsilis ovata* and *L. fasciola*. How and when these species came to the basin is unknown, but similarly, fish stockings and stream captures offer the best explanations.

Over ecological time, species exchanges and dispersal of mussels from one basin to another is seemingly a rare but natural process. More recently, humans have been responsible for introducing species outside their known ranges. Effects on the native or receiving fauna are unknown, but in most cases, it appears that the introduced species is simply incorporated into the native mussel assemblage with minimal consequences. However, research is needed to determine how such introductions can negatively affect native species through competition and hybridization. For example, genetic techniques could be used to determine if hybridization is occurring between *L. ovata* and *L. cariosa* in the Potomac River. Negative consequences potentially are greatest between closely related species that possibly can interbreed and compete for fish hosts and habitat.

Mussel Taxonomy and Cryptic Species Diversity

Within the freshwater mussel order Unionoida, the families Unionidae and Margaritiferidae contain the species that occur throughout Virginia, North America and even in other regions of the world (Table 4). In Virginia, the spectaclecase (*Cumberlandia monodonta*) is the only representative of the Margaritiferidae, while all other species in the state belong to the Unionidae. For North American species, the

TABLE 4. Scientific classification of freshwater mussels, including all sub-families, tribes, and genera known from Virginia. Classification scheme is based on Campbell et al. (2005). The number of species in each genera is in parentheses; total is 77 species.

Kingdom:	Animalia
Phylum:	Mollusca
Class:	Bivalvia
Order:	Unionoida
Family:	Margaritiferidae
Genera:	Cumberlandia (1)
Family:	Unionidae
Sub-family:	Ambleminae
Tribe:	Lampsilini
Genera:	Actinonaias (2)
	Amblema (1)
	Cyprogenia (1)
	Dromus (1)
	Elliptio (7)
	Epioblasma (7)
	Lampsilis (5)
	Lemiox (1)
	Leptodea (3)
	Ligumia (2)
	Medionidus (1)
	Potamilus (1)
	Ptychobranchus (2)
	Toxolasma (1)
	Truncilla (1)
	Villosa (6)
Tribe:	Pleurobemini
Genera:	Cyclonaias (1)
	Fusconaia (4)
	Hemistena (1)
	Lexingtonia (1)
	Plethobasus (1)
	Pleurobema (4)
	Pleuronaia (2)
	Uniomerus (1)
Tribe:	Quadrulini
Genera:	Quadrula (4)
	Tritogonia (1)
Sub-family:	Anodontinae
Genera:	Alasmidonta (5)
	Anodontoides (1)
	Lasmigona (3)
	Pegias (1)
	Pyganodon (3)
	Strophitus (1)
	Utterbackia (1)

Unionidae is divided into two subfamilies, the Anodontinae and Ambleminae, with the later subfamily further subdivided in three tribes, Quadrulini, Lampsilini, and Pleurobemini (Campbell et al. 2005). Key mussel life history and anatomical traits are reflected in these taxonomic groups. For example, the Quadrulini and Pleurobemini mussels generally are summer brooders, whereas the Lampsilini and Anodontinae mussels generally are winter brooders. Lampsilini mussels in the genera *Epioblasma*, *Lampsilis*, and *Villosa* have complex mantle lures and those in the genera *Dromus*, *Cyprogenia*, and *Ptychobranchus* produce intricate conglutinates that mimic invertebrate prey of fishes (Jones and Neves 2002; Jones et al. 2004; Jones et al. 2006a; Jones et al. 2006b; Barnhart et al. 2008). Species in the Lampsilini are considered some of the most anatomically advanced species in North America. Quadrulini and Pleurobemini mussels have rudimentary mantle lures or none at all, and generally release simple conglutinates. The Anodontinae mussels have large triangular shaped glochidia with hooks at the tip of each valve, which allows the glochidia of these species to attach to and metamorphose on a wide variety of fish hosts (Clarke 1981; Clarke 1985; Hoggarth 1999). Thus, each of these four taxonomic groups of mussels have life history and anatomical features that uniquely defines them.

While 77 mussel species currently are known from Virginia, the recognized taxa and species names are likely to change over time. For example, a recent molecular genetics study conducted by Lane et al. (2016) showed that purple bean (*Villosa perpurpurea*) and Cumberland bean (*V. trabalis*) in the UTRB are the same species. Since the latter scientific name has priority it was unchanged but the authors changed the common name to "Tennessee bean" (see Table 1). Further mussels in the genus *Elliptio* on the Atlantic Slope are not well understood genetically and taxonomically. The shell shape and color of these species are phentotypically variable. Many of the currently recognized species in this genus look quite similar in their shell morphology, prompting biologists to question the taxonomic validity of some *Elliptio* species. The lanceolate *Elliptio* mussels on the Atlantic Slope of Virginia previously included four nominal species: *E. angustata*, *E. fisheriana*, *E. lanceolata*, and *E. producta*. Recently, Bogan et al. (2009) used mitochondrial DNA sequence analysis to show that only *E. fisheriana* and *E. lanceolata* actually occur in the state. At least in Virginia, the other two lanceolate species were shown to be genetically the same species as *E. fisheriana*. These finding reduced the number of recognized taxa in the state from 80 to 77.

The eastern elliptio (*E. complanata*) is widely distributed in Virginia from mountain to coastal plain streams. Hence, the shape and color of its shell can be quite variable depending on local stream conditions. Over 180 species names for *E. complanata* were synonymized by Johnson (1970) because the species was excessively over-described by earlier taxonomists, in part due to its highly variable shell morphology. In addition, *Elliptio congarea*, *E. roanokensis*, and *Uniomerus tetralasmus* all can resemble *E. complanata*; therefore, research is needed to determine the taxonomic validity of these three species in the Virginia portion of their ranges.

The taxonomy of Virginia pigtoe (*Lexingtonia subplana*) in the upper James River basin also has been questioned by biologists. Is this species simply a morphological variant of *Fusconaia masoni* which it closely resembles? Possibly, but Ortmann (1914) and Fuller (1973) have argued that it is a valid species because only the outer two gills are charged in gravid females, versus four charged gills in gravid females of *F. masoni*. Similarly, the shell morphology of Tennessee clubshell (*Pleurobema oviforme*) and Tennessee pigtoe (*Pleuronaia barnesiana*) in the UTRB are nearly indistinguishable but females of the former have two charged gills and those of the later four charged gills. These two similar looking species are genetically distinct based on DNA sequences (Campbell et al. 2005). The Virginia pigtoe was last collected alive in lower Craig Creek in Botetourt and Craig counties (Gerberich 1991). Thus, the taxonomic validity of *L. subplana* should not be discounted until scientific data become available to dispute Conrad's (1836) original description and Ortmann's (1914) observations on its gravid condition.

Conservation of mussels in Virginia

Conservation of freshwater mussels in Virginia will require citizens, non-governmental organizations, local, county, state and federal governments to apply their resources to five main areas: (1) water quality monitoring and regulation enforcement,

(2) restoration of stream habitat, (3) restoration of mussel populations, (4) educating the public about the importance and status of mussels, and (5) monitoring and research to understand why mussels are declining and what are the best ways to protect them (Freshwater Mollusk Conservation Society 2016). Sustained long-term efforts in these five areas offer the greatest potential to conserve freshwater mussels throughout the state.

The federal Clean Water Act (CWA) of 1972 and applicable water laws of Virginia govern water quality monitoring and enforcement in the state; the rules and regulations of these laws can be obtained by conducting a key word internet search (e.g., CWA 1972). Especially for those streams in Virginia with important mussel resources, such as in the Powell, Clinch, and Holston rivers of the UTRB and the James and Nottoway rivers of the Atlantic Slope, it is imperative that good water quality be maintained so mussel populations can survive long-term (Jones et al. 2014; Price et al. 2014; Zipper et al. 2014).

Stream restoration is one of the best ways to improve water quality and habitat conditions, especially in tributaries to main rivers. Tributary streams are vital arteries contributing to the health of a river. If they are clogged by excessive sediments from stream-bank erosion for example, habitat quality will decline in the main river where mussels are most diverse and abundant. Hence, projects that create riparian corridors filled with trees, shrubs and grasses can go a long way toward controlling sediment erosion, and in turn, help protect mussels. Fencing out cattle and other livestock from streams and their respective riparian corridors is especially effective in improving the health and condition of streams important to mussels.

Restoration of mussel populations by stocking hatchery-reared or translocated mussels is now technically feasible and the quickest way to boost population size of imperiled species or those lost via toxic spills or other anthropogenic impacts (Carey et al. 2015). To alleviate the immediate risk of extinction, population restoration will play a critical role in mussel conservation. In Virginia, three hatcheries currently produce mussels for restoration purposes: the Freshwater Mollusk Conservation Center at Virginia Tech in Blacksburg, the VDGIF Aquatic Wildlife Conservation Center near Marion, and the U.S. Fish and Wildlife Service's Harrison Lake National Fish Hatchery near Charles City. Collectively, these mussel hatcheries have produced thousands of mussels of more than two dozen species and that have subsequently been stocked in Virginia river's, including the Powell and Clinch of the UTRB, and on the Atlantic Slope in the upper James and Nottoway.

Environmental outreach to K-12 students is critical to increasing awareness and respect for streams and freshwater mussels in future generations. In 2010 the VDGIF stocked several thousand mussels at Cleveland Islands on the Clinch River, Russell County. Biologists invited more than a dozen students from Cleveland Elementary School to attend and participate in stocking and searching for mussels at the event. The students learned about what mussels do in streams and had a great time wading into the river to help stock them. Read about the event at: http://www.fws.gov/endangered/map/ESA_success_stories/VA/VA_story2/index.html. Events like these directly connect kids with nature and can make lasting impressions on them to increase their appreciation for mussels and the importance of healthy streams.

Monitoring and research to understand mussel population trends

Monitoring rare and endangered mussel species is critical to determining if their populations are declining, stable, or increasing over time. Assessing population trends is an important first step in understanding the reasons for declines, such as identifying various sources of industrial, agricultural and urban pollution. Therefore, when considering the traits that make mussels vulnerable, they make ideal organisms to monitor how contaminants in freshwater systems might influence their population trends. Because mussels are considered one of the most imperiled animal groups in the United States, state and federal natural resource agencies are initiating population monitoring programs for species of conservation concern in selected river and stream locations (Strayer et al. 2004). Long-term monitoring programs in the Clinch and Powell Rivers are good examples (Johnson et al. 2012; Jones et al. 2014; Ahlstedt et al. 2016). Since mussels are filter feeders and relatively immobile, they can uptake and accumulate toxins from the environment into their vital organs, including the foot, gonads, digestive gland and kidney. Thus, focused research efforts to concurrently monitor trends in population abundance, contaminants in stream networks, toxin accumulation in vital organs, and the transport, fate and toxicity of chemicals in the aquatic environment are needed to protect mussels in rivers and streams throughout Virginia. In addition, research is needed to understand the roles of excess fine sediments and nutrients, disease, altered temperature regimes, and fish host availability on mussel reproduction and survival. Finally, several areas and watersheds in Virginia have not been surveyed for mussels, including Dismal Swamp of the Albemarle basin, Levisa and Russell forks of the Big Sandy River basin, the Ararat River of the Yadkin basin, and freshwater streams of the Eastern Shore (Figure 1). Surveys in these areas may add new species and records of occurrence for freshwater mussels in Virginia.

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Forest Diversity and Disturbance: Changing Influences and the Future of Virginia's Forests

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ABSTRACT

The Virginia landscape supports a remarkable diversity of forests, from maritime dune woodlands, swamp forests, and pine savannas of the Atlantic Coastal Plain, to post-agricultural pine-hardwood forests of the Piedmont, to mixed oak, mesophytic, northern hardwood, and high elevation spruce-fir forests across three mountain provinces in western parts of the state. Virginia's forests also have been profoundly shaped by disturbance. Chestnut blight, hemlock woolly adelgid, emerald ash borer, and other pests have caused declines or functional extirpation of foundation species. Invasive plants like multiflora rose, Oriental bittersweet, and Japanese stiltgrass threaten both disturbed and intact forests. Oaks and other fire-dependent species have declined with prolonged fire suppression, encouraging compositional shifts to maple, beech, and other mesophytic species. Agriculture has left lasting impacts on soil and microsite variations, and atmospheric nitrogen deposition has led to soil acidification, nutrient loss, and diversity declines. Future changes associated with climate warming are expected to influence species distributions and habitat quality, particularly for hemlock-northern hardwood and spruce-fir forests. These and other disturbances will continue to shape Virginia's forests, influencing species interactions, successional trajectories, and susceptibility to invasive plants and secondary stressors, and initiating broader impacts on forest diversity, ecosystem processes, and habitat resources for associated species and neighboring ecosystems.

DIVERSITY OF VIRGINIA'S FORESTS

Biodiversity losses affect ecosystems throughout the world, but forests have been particularly affected. Like most forests in eastern North America, those in Virginia have undergone centuries of change, shaped by natural and cultural disturbances. Pollen records suggest that Appalachian oak forests have changed more rapidly over

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the past 150 years than at any other time in the past 4,000 years (Delcourt and Delcourt 1998). Across Virginia, these rapid changes have resulted largely from agricultural clearing, timber harvesting, and burning; invasive species impacts; intensive herbivory by white-tailed deer; and atmospheric influences (Gilliam 2007; Fleming 2012). Habitat loss, degradation, and fragmentation are considered primary threats to forested ecosystems (Wilson and Tuberville 2003). In less than four decades, Virginia has lost more than 200,000 ha of forest. Annually, this includes an estimated 20,000 ha of forest loss and a comparable area of development throughout the state (Wilson and Tuberville 2003; VA-DOF 2014a). Non-native and invasive plants, insects, and pathogens further threaten Virginia's forests. Nearly half of the species listed as threatened or endangered under the U.S. Endangered Species Act are considered at risk because of non-native invasive species, with damage and control costs for invasive species in Virginia estimated at $1.4 to $3 billion per year (Pimentel et al. 2005).

Virginia leads the nation in vascular plant diversity and diversity of globally rare plants (13th and 14th, respectively) (Wilson and Tuberville 2003). Despite this remarkable diversity, or more likely because of it, Virginia has one of the highest plant and animal extinction rates in the country (8th in the U.S.). Much of Virginia's diversity results from variations in topography, regional climates, soils, and bedrock geology across more than 750 km from the Atlantic Ocean to the Appalachian Mountains, and numerous species at or near northern or southern geographic limits. Virginia spans seven of 20 major "ecoregions" (U.S. EPA 2013) and five major physiographic provinces (Woodward and Hoffman 1991; Fleming 2012) across the eastern U.S. Descriptions of physiographic provinces and associated natural communities used in this manuscript follow Fleming (2012), as presented in the *Flora of Virginia* (Weakley et al. 2012). The Atlantic Coastal Plain in far eastern Virginia makes up approximately one-fifth of the state. This province is dominated by maritime dune woodlands, scrub, and grasslands; tidal marshes; forested swamps; and pine savannas (Fleming 2012). Historically, much of the Coastal Plain was dominated by longleaf pine (*Pinus palustris*) forests and woodlands, with oaks, hickories, and other pine species of greater importance in the northern and inner Coastal Plain. Today, Coastal Plain forests are comprised largely of loblolly and shortleaf pines (*Pinus taeda, P. echinata*) or southern mixed hardwoods. Additional diversity occurs in maritime dune woodlands where live oak (*Quercus virginiana*) and other drought-tolerant coastal oaks and pines are common, and bottomland swamp forests of bald cypress (*Taxodium distichum*), swamp tupelo (*Nyssa aquatica)*, black gum (*N. biflora*), and red maple (*Acer rubrum*) (Fleming 2012; Fleming et al. 2016). West of the Coastal Plain, the Piedmont covers an additional 40% of the state's land area. These rolling, post-agricultural pine-hardwood forests are relatively low in diversity and dominated by mixed oaks, most notably white and black oaks (*Q. alba, Q. velutina*), and Virginia and shortleaf pines (*P. virginiana, P. echinata*). Successional forests include hardwoods such as sweet gum (*Liquidambar styraciflua*), red maple (*Acer rubrum*), tulip poplar (*Liriodendron tulipifera*), and hickories (*Carya* spp.).

Recognition of three distinct mountain provinces emphasizes the topographic and geologic diversity in western parts of the state. In the Ridge and Valley and the Blue

Ridge Provinces, mixed oak forests dominate drier sandstone ridges and upper slopes where American chestnut (*Castanea dentata*) once was common. Chestnut oak (*Q. montana*), white oak, red oak (*Q. rubra*), and hickories are especially common, with understory ericaceous or heath shrubs (esp. blueberries; *Vaccinium* spp.) on drier and more acidic sites. Mesophytic species increase on calcareous substrates, particularly in cool, moist valleys, and reach greatest importance in mesophytic cove forests in far western Virginia, in the Cumberland and Allegheny Mountains of the Appalachian Plateaus province. These mesophytic forests are considered a hotspot of temperate forest diversity and are dominated by an impressive variety of tree species, including sugar maple (*A. saccharum*), American beech (*Fagus grandifolia*), red and white oaks, tulip poplar, basswood (*Tilia americana* var. *heterophylla*), yellow buckeye (*Aesculus flava*), eastern hemlock (*Tsuga canadensis*), and magnolia (*Magnolia* spp.) (Woodward and Hoffman 1991; Fleming 2012). At higher elevations, dominance shifts to northern hardwoods such as sugar maple, American beech, black and yellow birches (*Betula lenta, B. alleghaniensis*), and hemlock. Unique montane forests occur on the highest peaks of the Blue Ridge, above 1,500 m, where spruce-fir (*Picea rubens-Abies fraseri*) forests become prevalent.

Forest disturbances and ecosystem responses are as varied as Virginia's forests themselves. Maritime forests and dune woodlands on the Coastal Plain are considered globally rare natural communities due to restricted range and threats from coastal development, erosion, and other natural and anthropogenic impacts on dune systems. Fire suppression is responsible for structural and compositional changes in fire-dependent coastal woodlands (Fleming et al. 2016). High elevation spruce-fir forests experience greatest threat from the balsam woolly adelgid (*Adelges piceae*), an introduced insect responsible for more than 90% mortality of Fraser fir (*Abies fraseri*), as well as atmospheric pollution and acid deposition, and historical impacts of logging and fire. Alluvial floodplain forests have a long history of agricultural clearing and logging, development, and hydrologic alteration. Moist, nutrient-rich floodplain soils also make these communities particularly susceptible to invasive plants (Spira 2011). Across nearly all parts of the state, vast pre-settlement forests have been largely cleared or degraded for anthropogenic land uses, particularly crops and grazing animals (Stephenson et al. 1993; Fleming 2012). Degradation of Appalachian rich cove forests is of particular concern due to their exceptional biotic diversity and richness of endemic species (Woodward and Hoffman 1991; Spira 2011). In this region, overharvesting also threatens commercially important forest herbs such as American ginseng (*Panax quinquefolius*) and black cohosh (*Actaea racemosa*), and, like floodplain forests, mesic conditions make these sites particularly susceptible to invasive plant encroachment.

LAND USE AND LEGACY EFFECTS

Native American settlements were documented in southeastern Virginia as early as 17,000 years ago, with small-scale agriculture and low-intensity fires increasingly used as management practices. As Native American populations expanded 8,500 to 4,000 years ago, agricultural clearing and burning became more widespread and intensive throughout the state (Egloff and Woodward 2006). Despite this, the Virginia landscape was almost continuously forested when Europeans colonized in the early 1600s. As European settlements grew, forests were cleared rapidly, with nearly 50% of the state's forests were removed by the late-1800s (Fleming 2012). Intensive logging, agriculture, and burning, and opening of mountain regions for timber and coal extraction caused severe landscape degradation by the 1930s. By the mid-1900s, however, many farms were abandoned and much of the eastern landscape returned to forest. In Virginia, approximately 60% of uplands and 75% of remaining wetlands are now forested (Fleming 2012). As a result, eastern forests have been described as more natural today than at any other time in recent centuries (Foster et al. 2003).

Despite agricultural abandonment and reforestation in the early 20th century, today's forests are very different from those of the past. It is becoming clear that modern species distributions and ecosystem dynamics cannot be understood without considering this long-term history of anthropogenic land use, particularly agricultural history. These influences are especially apparent in the herbaceous layer, because of its responsiveness to site conditions and disturbance (Small and McCarthy 2005; Gilliam 2007). Flinn and Vellend (2005) suggest that differences in species composition, diversity, and soil characteristics in post-agricultural forests (compared to forests without agricultural history) may persist for centuries after land abandonment. Loss of diversity occurs through direct elimination of species during land clearing and reduced recruitment, often due to dispersal limitations and low fecundity of forest herbs. Encroachment of opportunistic species during forest recovery also impacts native diversity (Foster et al. 2003; Flinn and Vellend 2005). Cultivation (plowing) has been shown to homogenize upper soils layers, deplete nutrients and organic matter, and remove microsite variation (e.g., pit and mound topography created by tree falls) necessary for the germination of many forest herbs (Beatty 2003; Foster et al. 2003). Soil amendments produce lasting increases in pH and fertility and encourage competitive, nitrogen-demanding species (Foster et al. 2003; Flinn and Vellend 2005). These "legacies" or persistent influences of historical land use practices can equal or outweigh prevailing influences such as topography, soils, and modern disturbances.

Structurally and compositionally, today's forests also are very different from those of pre-settlement periods. Across the U.S., most forests (~85%) are less than 100 years old and just 0.1% are considered old-growth (> 200 years) (Gilliam 2007; Butler et al. 2015). In Virginia, youngest forests occur in the coastal plain and southern piedmont. Throughout the state, forests are highly fragmented, with just 20% in large, contiguous blocks (Fleming 2012; Rose 2013). A regional assessment of land cover change from 1973 to 2000 shows that forest regeneration has now slowed and forest cover is declining across the eastern U.S. (Drummond and Loveland 2010). In 2011, approximately 6.4 million ha in Virginia were forested – similar to 2001 forested area. However, more than 100,000 ha of forest has shifted to non-forested use. Development was responsible for the greatest net loss of forest, except in the inner coastal plain where losses stemmed largely from mechanical clearing for timber and agriculture (Drummond and Loveland 2010; Rose 2013). No major gains in forest area were reported across the region, although Rose (2013) noted that declines in agriculture offset increases in development and clearing over the past decade. As a result of these land conversions, Virginia forests today are relatively even-aged and comprised largely of oak-hickory (*Quercus*-*Carya*), oak-pine, or loblolly-shortleaf pine (*Pinus taeda*-*Pinus echinata*) forest types. A sizable proportion of these forests lie in pine plantations (~13%, esp. loblolly pine) and early-successional pine or pine-hardwood stands (~10%), especially in the piedmont and coastal plain (Fleming 2012; VA-DOF 2014a).

FIRE HISTORY AND FOREST MESOPHICATION

Fire history also has played an important role in shaping eastern forests, including those in Virginia. For thousands of years, Native Americans used low-intensity surface fires to clear the landscape, prepare sites for crops, and encourage fruit production and wild game. This periodic burning and occasional lightning fires created a patchy landscape and strongly favored fire-tolerant trees such as oaks, American chestnut, and pines (Delcourt and Delcourt 1998; Brose et al. 2001). Fire also was key to the formation of open woodlands, savannas, and grasslands in Virginia (Fleming 2012). With European colonization, fires increased in frequency and severity. High-intensity stand-replacing fires became common in the late 19th and early 20th centuries as forests were cleared and burned. Railroads expanded access to forests in remote parts of the state and sparked frequent fires from coal or wood fuel ignitions. These intense fires continued to favor oaks, hickories, chestnut, and coastal fire-tolerant pines such as longleaf and shortleaf pines, and restricted mesophytic species such as beech and maples to moist and protected sites (Ware et al. 1993; Nowacki and Abrams 2008). Concern over the effects of these intense and unregulated fires led to extensive fire suppression campaigns (i.e., Smokey Bear) beginning in the mid-20th century. These efforts were highly effective, nearly eliminating fire from Virginia's natural and managed ecosystems over the next 100 years (Brose et al. 2001; Fleming 2012).

The role of fire in forest development in Virginia and neighboring regions has been well-documented. Studies of fossil pollen and charcoal by Delcourt and Delcourt (1998) illustrate the importance of Native American burning in expanding oak-chestnut forests across the southern Appalachians 3,000 to 1,000 years ago, particularly on ridgetops and upper slopes. Tree rings studies by Aldrich et al. (2014) in pine-oak forests of the Virginia Blue Ridge and Ridge and Valley Provinces report a relatively constant 6 to 8 year fire return interval from the late 1600s through European settlement and early industrialized logging and railroads. By the early 1900s, however, fire scars were almost entirely absent from these trees due to fire suppression efforts. Silver et al. (2013) found similar results in Virginia Ridge and Valley forests, with a typical fire return interval of 14 years from 1850 to 1930, followed by a period of marked fire suppression. In coastal plain forests on Virginia's Eastern Shore, Kirwan and Shugart (2000) reported negative correlations of American beech and red maple, species highly sensitive to fire, to soil charcoal and modeled fire frequencies. They concluded that beech and red maple dominance is indicative of long-term fire absence, whereas scarlet oak (positively correlated with fire history estimators) indicated a long-term history of fire in these coastal plain forests.

Fire prevention efforts beginning in the early 1900s led to dramatic structural and compositional changes in eastern forests. Open woodlands and savannas have been replaced by closed-canopy forests; fire-dependent species have been replaced by those sensitive to fire; and forest understories have become increasingly shaded, encouraging shade-tolerant species (Brose et al. 2001). In Virginia, many fire-dependent communities are declining due to fire suppression, including Pond Pine (*Pinus serotina*) Woodlands and Pocosins and Pine / Scrub Oak Sandhills (historically dominated by longleaf pine) on the coastal plain and Pine-Oak / Health Woodlands in the Appalachian Mountains (Fleming 2012; Fleming et al. 2016). Nowacki and Abrams (2008) coined the term "mesophication" to describe the replacement of oaks, hickories, pines, and other fire-tolerant eastern forest trees by mesophytic and fire-sensitive species such as red maple, American beech, tulip poplar (*Liriodendron tulipifera*), black birch, and Eastern hemlock. These species create dense shade and cool, moist conditions less conducive to fire. These changes reduce oak regeneration and have resulted in widespread declines, particularly of white oak. Once the dominant species across much of the Central Appalachians, Abrams (2003) suggests that virtually no white oak regeneration has occurred in eastern forests over the past 100 years, and little to no regeneration has occurred in other upland oak species over the past 50 years. While oaks tolerate a wide range of growing conditions, higher light, shallow leaf litter, and periodic disturbance are needed for successful germination. In the absence of fire, white oak tends to be a poor competitor and generally gives way to more shade-tolerant species. In pre-settlement forests of Virginia, white oak was one of the most abundant forest species, representing an estimated 18 to 49% of forest cover, with secondary importance of red oak, American chestnut, chestnut oak, hickories, and pines. Today, white oak remains dominant (30% of forest cover) only on xeric, nutrient poor sites but is considerably less abundant (5-9%) on mesic sites (Abrams 2003).

Current forest inventory data emphasize this compositional shift to mesophytic species. Virginia forests contain a diversity of tree species, but just four: tulip poplar, loblolly pine, chestnut oak, and white oak – make up about 50% of the total forest volume (Rose 2013). Since 2001, tulip poplar has increased by more than 20% in Virginia forests. Loblolly pine has increased by 32%, with most increases in the coastal plain and eastern piedmont. Based on tree density (rather than volume), red maple and loblolly pine were by far the most abundant species in 2011, representing almost a quarter of all tree stems in Virginia forests (12% and 10%, respectively). Red maple and loblolly pine each had more than three times the density of the most abundant oaks (white oak = 3.5%, chestnut oak = 3%). These numerous small stems indicate that red maple and loblolly pine make up much of the regeneration layer in our forests (Rose 2013). Efforts to encourage regeneration of oaks and other fire-dependent species focus largely on prescribed burning. Fire has been very effective in restoring some fire-dependent natural communities, although there is little expectation that Virginia's natural areas will return to pre-settlement conditions (Wilson and Tuberville 2003; Fleming 2012).

DIRECT AND INDIRECT EFFECTS OF FOREST PESTS

Forests Pests and Pathogens

Exotic insect pests and fungal pathogens pose a serious threat to Virginia's forests and have been responsible for declines or functional extirpation of many forest species. American chestnut, eastern hemlock, and other forest dominants have been described as "foundation species" for their local abundance, importance to forest structure and microenvironments, and regulation of ecosystem processes for co-occurring species (Ellison et al. 2005). Effects of pests and pathogens on foundation species can be particularly detrimental because of these broader ecosystem impacts. For example, American chestnut once comprised more than 50% of Appalachian forests on drier upland sites, but by the 1940s was largely eliminated by the chestnut blight (*Cryphonectria parasitica*) fungus (Paillet 2002). Today, chestnut occurs almost exclusively as an understory shrub and typically succumbs to the blight before reaching reproductive maturity, resulting in compositional shifts largely to oak or oak-hickory dominance. Compared to oaks, chestnut grows and takes up nutrients more quickly, leaves decompose more rapidly, and high tannin content results in slower wood decomposition. Thus, ecological consequences of losing American chestnut have included, changes in forest productivity, nutrient dynamics, and decomposition rates, as well as reduced quantity and quality of wildlife food. Altered nutrient dynamics also have influenced associated streams and macroinvertebrate and fish assemblages (Ellison et al. 2005).

Like American chestnut, eastern hemlock and Carolina hemlock (*Tsuga caroliniana*) may be functionally eliminated from our forest in coming decades due to an exotic pest. The hemlock woolly adelgid (*Adelges tsugae*; HWA), a Japanese insect, often kills adult trees within just four to ten years (McClure 1991). The HWA has spread to nearly every Virginia county in which eastern and Carolina hemlocks occur (piedmont and mountains) and has caused severe declines in hemlock populations (Fleming 2012; Rose 2013). Abella (2014) reported nearly 50% mortality of eastern hemlock in Shenandoah National Park from 1990-2000, with greater impacts in lower elevation forests. Krapfl et al. (2011) found significant but somewhat lower declines (11% mortality of canopy trees and 34% mortality of understory hemlocks) in higher elevation forests of Great Smoky Mountains National Park from 2003 to 2008-2009. Along streams in the Virginia Ridge and Valley province and West Virginia Appalachian Plateau, Martin and Goebel (2012) reported that hemlock remained dominant but both trees and saplings showed more than 50% defoliation, suggesting that complete mortality is likely within a few years. As one of the only evergreen trees in low- and mid-elevation Appalachian forests, hemlocks support unique ecosystem functions. Their foliage creates dense shade, cool moderate temperatures, and forms a thick layer of acidic and slowly decomposing leaf litter that influences water chemistry, temperature, and flow in associated streams. Hemlock forests also support unique assemblages of understory plants, invertebrates, birds, and mammals (Ellison et al. 2005; Abella 2014). With hemlock mortality, canopy gaps increase understory light availability, soil temperatures and nitrification rates, and decrease moisture (Jenkins et al. 1999), encouraging invasive plants such as Japanese barberry (*Berberis thunbergii*), Oriental bittersweet (*Celastrus orbiculatus*), tree of heaven (*Ailanthus altissima*), garlic mustard (*Alliaria petiolata*), and Japanese stiltgrass (*Microstegium vimineum*) – species typically absent from healthy hemlock forests (Small et al. 2005; Eschtruth et al. 2006; Martin and Goebel 2012). Former hemlock forests often shift to oak, birch, maple, and/or tulip poplar dominance, or thickets of rhododendron (*Rhododendrox maximum*) that are capable of inhibiting forest development. These new communities differ markedly from hemlock-dominated forests in structure, microclimate, nutrient dynamics, and habitat resources for associated species (Jenkins et al. 1999; Small et al. 2005).

Flowering dogwood (*Cornus florida*) has experienced severe declines due to dogwood anthracnose (*Discula destructiva*), a fungal disease. Dogwood anthracnose was first recognized in Virginia in the early 1980s and currently affect dogwood trees throughout the central and southern Appalachians (Suchecki and Gibson 2008). Drought and powdery mildew also contribute to dogwood declines. In Virginia forests, dogwood declined more than 30% from 2001 to 2007, with an additional 25% through 2011 (Rose 2013). Higher elevation moist and shaded sites, including cove and alluvial forests, appear most heavily affected, many reporting more than 90% loss (Jenkins and White 2002; Holzmueller et al. 2006; Suchecki and Gibson 2008). Loss of dogwood as a subcanopy tree has the potential to reduce soil fertility and pH, as its leaf litter is an important contributor of soil calcium, and eliminate an important food source for many associated forest birds (Holzmueller et al. 2006).

The emerald ash borer (*Agrilus planipennis*; EAB), an Asian wood-boring beetle, is a more recent threat to Virginia forests and responsible for widespread declines in ash trees (*Fraxinus* spp.). Larval feeding interrupts sap flow, girdling and killing trees often within 2 to 4 years. Early infestation sites have shown up to 99% mortality of adult trees. All North American ash species are susceptible, including white (*F. americana*) and green ash (*F. pennsylvanica*), those most common in Virginia forests (Herms and McCullough 2014). In Virginia, EAB became established in 2008 and since has been discovered in 23 counties, primarily in central and northern parts of the state (VA-DOF 2014b). Like other forest pests, broader impacts of the EAB include canopy gap formation, increased understory light and reduced moisture levels and nitrification, increased woody debris, and facilitation of non-native invasive plants (Hausman et al. 2010; Herms and McCullough 2014). Ash mortality also is predicted to impact insect species that feed on ash trees, including more than 20 species of North American moths, butterflies, and leaf miners that rely on ash as a primary food source (Wagner 2007). Flower et al. (2013) also suggest substantial declines in regional forest productivity (30% or more) with ash mortality, at least in the short-term, during which time severely infected stands may function as carbon sources rather than sinks.

Other more recent or perhaps less well-known pathogens in Virginia forests include butternut canker disease (*Ophiognomonia clavigignenti-juglandacearum*), which has caused dramatic declines in butternut (*Juglans cinerea*), a species once widespread in the northeast and southward to northern and western parts of Virginia (Clark et al. 2008; Bower et al. 2014). By 1995, nearly 80% butternut mortality was reported in southeastern states, with complete elimination from North and South Carolina forests (Schlarbaum et al. 1998). Other pests not yet affecting Virginia forests but raising considerable concern include black walnut thousand cankers disease (*Geosmithia morbida*), a fungal pathogen spread by the walnut twig beetle (*Pityophthorus juglandis*) and first discovered in Virginia in 2011. Forest Inventory and Analysis data showed that black walnut populations in Virginia remained healthy, with stable crown conditions from 2000 to 2010 (Randolph et al. 2013). However, walnut mortality due to thousand cankers disease in western states and more recent outbreaks in Tennessee have led to careful monitoring and quarantines in Virginia.

Many other insect pests and pathogens threaten Virginia forests. Our intention is not to not present an exhaustive list here, but to emphasize the important role they may play in future Virginia forests. Lovett et al. (2006) suggest that these pests may be the primary driver of ecosystem change in coming decades. Gandhi and Herms (2010) say that these invaders have the potential to "unleash a diverse cascade of direct and indirect effects on ecosystem processes and ecological interactions that can alter community composition and successional trajectories of eastern North American forests". Impacts common to many of these pests and pathogens include tree defoliation, stress, and mortality; increased size and frequency of canopy gaps; altered light, temperature, and moisture environments; increased woody debris; altered litter quality and nutrient cycles; changes in species interactions, composition, and successional trajectories; and facilitation of light-demanding and invasive species.

Non-Native Invasive Plants

Ninety non-native invasive plant species have been identified by the Virginia Department of Conservation and Recreation (VA-DCR) as ecological or economic threats to the Virginia's protected natural areas (Heffernan et al. 2014). These tend to be most abundant in forests of the Virginia piedmont and least in mountain provinces, particularly in the northern Ridge and Valley (Rose 2013). Thirty-eight of the invasive plants recognized by VA-DCR have an invasiveness rank of "high" for their widespread abundance, ability to invade relatively undisturbed habitats, and pronounced impacts on native species and ecosystem processes (Heffernan et al. 2014). Across Virginia, Japanese honeysuckle (*Lonicera japonica*), multiflora rose (*Rosa multiflora*), and tree-of-heaven are considered the most widespread and abundant invasive plant species (Robertson et al. 1994; Rose 2013). Others ranked as highly invasive across the state include shrubs such as autumn olive (*Elaeagnus umbellata*), Chinese privet (*Ligustrum sinense*), and Amur honeysuckle (*Lonicera maackii*); woody vines such as kudzu (*Pueraria montana* var. *lobata*) and Oriental bittersweet; and many herbaceous species, including garlic mustard and Japanese stiltgrass (Heffernan et al. 2014).

Invasive tendencies are much more common among shrubs and herbs, as these species tend to grow more rapidly with higher rates of vegetative and sexual reproduction. However, tree-of-heaven (high invasiveness rank) and princess tree (*Paulownia tomentosa*; medium invasiveness) are of particular concern in Virginia (Heffernan et al. 2014). Both have increased dramatically in Virginia forests in recent years (2007 to 2011: 16% and 14% increases) (Rose 2013). Tree-of-heaven is particularly problematic because of its ability to suppress resident species through allelopathy or chemical inhibition. In southwest Virginia, tree-of-heaven was found to have greater impact on native understory species than associated invasives, suggesting that it may facilitate the spread of other non-native plants (Small et al. 2010). Chemical inhibition also has been noted in garlic mustard, a common invader of moist forest understories in Virginia. Stinson et al. (2006) found that garlic mustard suppresses tree reproduction in beech-maple forests by interrupting beneficial seedling-mycorrhizal fungi associations, helping garlic mustard to invade relatively intact forests. Japanese stiltgrass, also prevalent in shaded and intact forest understories, alters soil chemistry and nutrient cycles and reduces habitat use by soil invertebrates (Ehrenfeld et al. 2001; McGrath and Binkley 2009). Additional species have been listed by the VA-DCR as "early detection species" – those not yet widespread in Virginia but highly invasive in similar habitats of the region (Heffernan et al. 2014). Wavy-leaved basket grass (*Oplismenus undulatifolius*), discovered just recently (late 1990s) in northern Virginia and Maryland, has been listed as a highly invasive early detection species. Predictive models suggest that, like garlic mustard and Japanese stiltgrass, basket grass has the potential to invade intact and deeply shaded forests and negatively affect understory diversity and ecosystem-level processes (Beauchamp et al. 2013).

Recent ecological studies have focused on understanding ecosystem characteristics that promote or inhibit "invasibility". In temperate forests, site disturbance is very often associated with invasive plant abundance. Numerous studies also suggest that forests or forest patches with greater light, moisture, and nutrients, and those with higher native plant diversity, are more susceptible to invasion (Levine and D'Antonio 1999; Stohlgren et al. 2003; Martin et al. 2008). Using Forest Inventory and Analysis (FIA) data from hemlock-white pine-northern hardwood forests in Pennsylvania, Huebner et al. (2009) found consistently higher invasive plant richness in younger, fragmented forests and those with higher soil pH (increasing availability of nutrients such as Ca, Mg, N) and native plant diversity. Lundgren et al. (2004) and Kelly et al. (2009) also reported increased richness and abundance of invasive plants in disturbed central hardwood and hemlock-northern hardwood forests of southern New England, particularly near roads and trails. Historical land use also appears to have lasting influences on invasive plant distributions. Post-agricultural forests typically support greater richness and abundance of invasive species than sites continuously forested over the past 100 to 150 years (Lundgren et al. 2004; Von Holle and Motzkin 2007; Mosher et al. 2009). Japanese barberry (*Berberis thunbergii*), a common invasive shrub in Virginia forests, seems particularly problematic in post-agricultural forests (DeGasperis and Motzkin 2007; Mosher et al. 2009).

Intact or undisturbed forests typically are thought to be more resistant to non-native plant invasions (Luken 2003). For example, McCarthy et al. (2001) reported no non-native species in an old-growth central Appalachian mixed-oak forest, despite dozens of invasive species in surrounding fields and edge habitats. Recent studies, however, suggest that many invasive species are common in intact, shaded forests and have pronounced impacts. Martin et al. (2008) identified 58 species of invasive plants with high shade tolerance in southern U.S. forests. While many also invade open habitats and disturbed forests, these species have the capacity to invade deeply shaded and intact forests. Of those species ranked as highly invasive and widespread in Virginia, Huebner (2003) found multiflora rose, Amur honeysuckle, Oriental bittersweet, and garlic mustard to occur frequently in closed-canopy forests, based on West Virginia herbarium records. Oriental bittersweet and Japanese stiltgrass were especially common in open, disturbed forests, and Morrow's honeysuckle (*Lonicera morrowii*) and Tartarian honeysuckle (*L. tatarica*) occurred in both forest environments. Habitat models for Oriental bittersweet in North Carolina mountains showed preference for mesic tulip poplar (non-oak) forests and sites with canopy and forest floor disturbance (McNab and Loftis 2002). In these forests, prolonged invasion of bush honeysuckles (e.g., *L. maackii, L. morrowii, L. tatarica*) and Oriental bittersweet has been shown to suppress native species, reducing richness and abundance of tree seedlings and understory herbs, and altering vegetation development patterns in developing forests (Fike and Niering 1999; Collier et al. 2002, Hartman and McCarthy 2008). Thus, it is clear that across Virginia's forests, non-native, invasive plants exert broad impacts on native species that range from direct competition for resources to indirect effects such as altered nutrient cycles, light environments, plant-pollinator interactions, and successional trajectories (Butler et al. 2015).

White-Tailed Deer and Forest Regeneration

From the 1930s to the 1990s, white-tailed deer (*Odocoileus virginianus*) populations across Virginia expanded from 25,000 to 900,000 deer – an increase of 3,500%! (Cote et al. 2004). Changes in land use, especially agriculture and forest fragmentation, loss of top predators, and reduced hunting have led to unprecedented increases in deer in eastern North America. Damage to forest plants from excessive herbivory has been shown to occur at densities as low as 4 deer / km^2 (10 / mi^2) (Alverson et al. 1988). In 1988, deer densities were reported at well over 12 / km^2 (30 / mi^2) in many parts of Virginia, most notably northern and southeastern regions (VDGIF 2007). Populations throughout the state are estimated to be beyond forest carrying capacities, except in south central and extreme southwest counties. In managed forests of Virginia and elsewhere, excessive browsing also has been shown to reduce stand height and density and lengthen rotation periods, greatly reducing economic value of timber (Cote et al. 2004).

White-tailed deer have been described as keystone species or ecosystem engineers for their broad influences on forest structure, composition, and diversity (McShea and Rappole 1992; Baiser et al. 2008). Intense herbivory reduces growth, regeneration, and survival of preferred browse species, driving shifts in forest composition and successional pathways (Horsley et al. 2003; Baiser et al. 2008). Preferred species, including oaks and hemlock, are typically uncommon or absent from forest understories outside deer exclosures (McShea and Rappole 1992). There is particular concern for reestablishment of eastern hemlock following hemlock wooly adelgid attack, as seedlings are slow growing and especially susceptible to deer browse (Cote et al. 2004). In coastal oak-beech forests near Washington, D.C., Rossell et al. (2007) reported severe oak decline and predicted that continued deer browse will shift future forests almost exclusively to American beech. In mixed-hardwood forests on the Virginia coastal plain, Kribel et al. (2011) documented similar increases in beech and holly (*Ilex opaca*) and declines in red maple, dogwood, and other hardwoods, suggesting that these changes most likely were driven by selective deer browse. Similar studies in Appalachian forests found increases in American beech and reductions in red maple, sugar maple, white ash, and black cherry in response to excessive browse (Kain et al. 2011). Deer avoidance also has favored hay-scented fern (*Dennstaedtia punctilobula*) in many eastern forests (Horsley et al. 2003). Hay-scented fern is a strong understory competitor and has been shown to reduce germination and survival of red oak, white ash, and birch seedlings (George and Bazzaz 2003)

Plants with slow growth and reproductive rates such as spring ephemerals and other mature, mesic forest herbs and shrubs are particularly susceptible to herbivory, especially in spring and summer when herbaceous plants are a primary component of deer diets and most or all above-ground biomass is consumed. In Smoky Mountains National Park, Thiemann et al. (2009) reported severe declines in richness and cover of forest herbs, including complete loss of 46 species from sample plots. These changes occurred from the late 1970s to 2004, a period when peak deer densities reached 43 deer / km^2. Many forest herbs also delay flowering for several seasons after defoliation or shift to predominantly non-reproductive states. In Trillium (*Trillium* spp.), excessive browsing reduced average plant size, lowered survival rates, and delayed flowering for many years (Augustine and Frelich 1998). Similarly, Canada mayflower (*Maianthemum canadense*) was 40 times less likely to flower when exposed to deer browse (Cote et al. 2004). Furedi and McGraw (2004) found that deer eliminated more than half of all fruit-bearing American ginseng plants from West Virginia forests and consumed 50 to 100% of all seeds in some populations. As a result of deer browse and intense wild harvest pressures, this and other economically valuable Appalachian medicinal herbs may be driven to extinction in the coming century.

Intensive deer browse can initiate far reaching, cascading effects in forested ecosystems. Through direct competition and habitat alteration, deer influence the abundance and distribution of associated animal species. Deer exclosure studies in Shenandoah National Park and elsewhere suggest that removal of understory vegetation increases light and habitat space, facilitating establishment of shade-tolerant invasive plants like garlic mustard, Japanese stiltgrass, and Japanese barberry (Rooney et al. 2004; Knight et al. 2009). Deer-assisted seed dispersal (on hair and hooves) and browse avoidance (preferential browsing on more palatable species) also facilitate spread of these invasives into forest understories. In turn, invasive plants limit regeneration of native trees and herbs through shading and other forms competitive exclusion. Understory removal also eliminates essential habitat resources and causes declines in ground- and midstory-nesting birds and understory insects and spiders (Cote et al. 2004; Baiser et al. 2008). In the fall, deer feed heavily on acorns and other fruits. Competition for food resources has been shown to limit small mammal and other wildlife populations in Virginia forests, particularly during poor mast years (McShea and Rappole 1992). Other broad-ranging ecosystem effects include reduced forest productivity and nutrient cycling, as preferred browse species often are those with nutrient-rich foliage. Remaining unpalatable species or plant components leave lower quality leaf litter for nutrient cycling through the forest ecosystem.

ACID DEPOSITION, CLIMATE CHANGE AND FUTURE FORESTS

Over the past century, industrial and agricultural emissions of nitrogen and sulfur oxides have greatly increased, altering global biogeochemical cycles and increasing concern for the effects of acid deposition on eastern forests. Though Clean Air Act regulations have reduced sulfur emissions and improved air quality in some regions, atmospheric nitrogen and associated deposition continue to increase in many northeast and mid-Atlantic forests (Erisman et al. 2013). Today, some historically nitrogen-limited forests show symptoms of "nitrogen saturation", the availability of nitrogen in excess of biological demand (Aber et al. 1998). Excess nitrogen has been linked to severe ecosystem changes, including increased nitrogen mineralization and nitrate leaching, soil acidification and nutrient loss (esp. calcium and magnesium), aluminum toxicity, and watershed eutrophication. Plant-mycorrhizal associations, important in nutrient absorption for many forest species, also typically decline with nitrogen enrichment (Pardo et al. 2011; Erisman et al. 2013).

Some of the most obvious effects of increased nitrogen deposition are changes in species composition, diversity, and overall forest declines (Bobbink et al. 2010). High elevation spruce-fir forests receive especially high levels of nitrogen deposition due to persistent cloud cover and wet and dry deposition. Effects include reduced tree growth, foliar nutrient imbalances and needle dieback, and increased susceptibility to secondary stressors such as insect pests and diseases, drought, and freezing or frost damage (Bobbink et al. 2010; Gilliam 2014). Fraser fir, a high elevation southern Appalachian endemic, has been largely eliminated from the canopy of these forests by the introduced balsam woolly adelgid and stress from chronic acid deposition (Stehna et al. 2013). Recent studies suggest that nitrogen deposition also negatively affects deciduous forests in the central and southern Appalachians (Boggs et al. 2005; Pardo et al. 2011). Changes in species composition and reduced diversity have been noted repeatedly, as species adapted to nutrient-limited conditions are replaced by species capable of rapid nitrogen utilization or those less affected by soil chemistry and acidification. While specific influences vary, decreased growth and survival of chestnut oak, scarlet oak, yellow birch, and basswood have been reported in northern hardwood forests, as well as increases in faster-growing, mesophytic species such as red maple, black cherry, and invasive plant species (Pardo et al. 2011; Gilliam 2014). In Virginia, effects of increased nitrogen deposition have been well-documented in mountain forests. Piedmont and coastal plain forests receive lower levels of atmospheric nitrogen deposition and have had little associated study. It is expected, however, that eastern Virginia forests will respond to excess nitrogen in much the same way, with nitrate leaching and soil acidification, changes in foliar nutrient concentrations and increased susceptibility to secondary stress, and shifts in community composition and declines in species richness (Gilliam et al. 2011).

In a review of nitrogen saturated forests in eastern North America, Fenn et al. (1998) suggested that young, vigorously growing forests are most efficient in retaining excess nitrogen, whereas mature forests have relatively low nitrogen retention capacities. In addition, changes in composition and diversity tend to be most pronounced on nutrient-poor sites (Fenn et al. 1998; Bobbink et al. 2010). Forest understory communities are particularly sensitive to nutrient dynamics and have shown significant compositional shifts in response to excess nitrogen. Repeated nitrogen enrichment treatments in eastern deciduous forests have resulted in increased tree canopy cover, causing severe shading and reduced richness and abundance of understory herbs (Bobbink et al. 2010). Gilliam et al. (2011) found initial increases in understory herbaceous cover in central Appalachian forests, but again reported declines in species richness. As in the canopy, declines in herbaceous layer diversity were attributed to competitive exclusion by fast growing, nitrophilous or mesophytic species and non-native invasive species, reduced mycorrhizal associations, and increased susceptibility to disease and herbivory (Gilliam 2007; Gilliam et al. 2011).

Climate changes associated with increased nitrates, carbon dioxide, and other greenhouse gases have influenced Central Appalachian forests for decades and are expected to increase throughout this century. A recent climate change vulnerability assessment for central Appalachian forests suggests that regional temperatures will increase year-round, resulting in longer growing seasons and more frequent weather extremes (Butler et al. 2015). Decreased precipitation in summer months will increase the potential for drought-stress, and increased precipitation in winter will increase streamflow and flooding potential. Warming and drought impacts are expected to have greatest effects on northern hardwood, hemlock, and spruce/fir forest types, those typical of cool, moist environments, and reduce habitat quality for associated species such as beech, sugar maple, black cherry (*Prunus serotina*), red spruce, and balsam fir. The forest herbaceous layer also is expected to respond to climate changes, given its sensitivity to moisture and microclimatic variations, including perennial herbs of economic and cultural importance for medicinal use, foods, or crafts (i.e., non-timber forest products) (Butler et al. 2015; See McGraw et al. 2013 for detailed discussion of climate change and American ginseng.). Floodplain and riparian forests also are expected to be vulnerable. In contrast, drier, southern forest types such as dry and dry-mesic oak-hickory and oak-pine forests and woodlands are predicted to be least vulnerable, with potential expansion of species such as shortleaf pine, southern red oak (*Q. falcata*), blackjack oak (*Q. marilandica*) post oak (*Q. stellata*), and shagbark and bitternut hickories (*Carya ovata, C. cordiformis*) under warmer and drier climate conditions (Butler et al. 2015).

Just as climates affect native species and forest communities, climate changes are expected to influence the distribution and overall impacts of forest pests and other disturbances. Warmer climates are likely to support range expansion for a number of invasive species, include some of Virginia's most problematic species (Dukes et al. 2009). For example, the hemlock woolly adelgid has been limited by winter temperature extremes. Expansion of this insect pest northward and into higher elevation sites is expected with warmer climates. Similar increases in geographic range and ecological impacts are predicted for beech bark disease, currently isolated to just a few Virginia forests, and forest tent caterpillars, responsible for severe defoliation of oaks, maples and other canopy species. Several invasive plant species also are predicted to expand with warmer temperatures, including Oriental bittersweet, tree of heaven, kudzu, privet, and bush honeysuckles (Dukes et al. 2009; Butler et al. 2015). More frequent and severe droughts also are expected to increase the intensity and frequency of wildfires, further influencing nutrient cycles, forest regeneration, and resulting successional pathways (Dale et al. 2001).

The composition and diversity of Virginia's forests reflect variations in topography, regional climates, and soil conditions across the state. However, our forests also have experienced, and are continuing to experience, natural and anthropogenic disturbances and subsequent successional changes. Agriculture, timber harvest, and shifting fire regimes have left lasting influences on vegetation and ecosystem properties. Oaks and other fire-dependent species have declined in many forests due to prolonged fire suppression, with compositional shifts to shade tolerant, mesophytic species. Forest fragmentation, exotic plants, insects, and pathogens, and intensive deer browse also shape forest regeneration and herbaceous layer diversity. And, climate changes are predicted to influence both native and invasive species and the timing of pest outbreaks. It is clear that to manage and conserve Virginia's forests in the future, we must work to understand the complex and synergistic effects that influence the remarkable diversity of our forest communities.

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Sea Level Rise in Virginia – Causes, Effects and Response

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ABSTRACT

Sea level rise (SLR) along Virginia's coasts and around the Chesapeake Bay as measured by tide gauges is analyzed and discussed. It is shown that the SLR rates vary between one location to another and in most locations the rates increase over time (i.e., SLR is accelerating). The latest science of SLR is reviewed and the causes of the high SLR rates in Virginia are discussed. The impacts of land subsidence and ocean currents (changes in the Gulf Stream in particular) on sea level are especially notable and important for predicting future SLR in Virginia. The consequences of SLR on increased duration and severity of floods are demonstrated and potential responses are discussed.

INTRODUCTION

One of the environmental consequences of climate change that have been the most visible in Virginia is sea level rise (SLR). While sea level along the coasts of Virginia is slowly rising, the impacts of waves and storm surges increase as waters are pushed farther into previously unaffected coastal areas and low-lying streets. Both natural features such as marshes and barrier islands and also the built features such as docks, shipyards, tunnels, homes and hotels constructed along the shoreline are all affected. People living on the coast do not always recognize sea level rise itself, but they clearly see that there is more frequent flooding and that areas that were not flooded in the past are now becoming new flood-prone areas (Atkinson et al. 2013, Mitchell et al. 2013, Ezer and Atkinson 2014, Sweet and Park 2014).

The relative SLR rate (i.e., local water level relative to land) on Virginia's coasts is one of the highest of all U.S. coasts and the rate appears to be accelerating (Boon 2012, Ezer and Corlett 2012, Ezer 2013, Sallenger et al. 2012, Kopp 2013). SLR rates from tide gauges in Virginia over the past 10-30 years are ~4-6 mm/year, which are higher than the global mean SLR rate of ~1.7 mm/year over the past century as seen from tide gauges and even higher than the ~3.2 mm/year over the past 20 years as seen from satellite altimeter data (Church and White 2011, Ezer 2013). Note that SLR of 3 mm/yr is equivalent to about 1 foot/century. Relative SLR is primarily the result of

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three processes: 1. global SLR due to warming ocean temperatures and melting land ice, 2. local land subsidence (sinking) and 3. ocean dynamics. The impact of land subsidence and ocean dynamics is especially evident in Virginia. The Virginia coast is experiencing subsidence due to human activities such as groundwater extraction and historic geological processes (Boon et al. 2010, Eggleston and Pope 2013). Changes in the flow of offshore currents and the Gulf Stream in particular can result in water level anomalies and flooding (Sweet et al. 2009, Ezer and Atkinson 2014). Since much of Virginia's coastal areas are flat, small amounts of SLR can have dramatic impacts- increased flooding and coastal erosion, and altering marshes. Dealing with these issues requires knowledge on future SLR to design and plan accordingly.

CURRENT TRENDS IN SEA LEVEL RISE

Water level measurements from 13 locations around the Chesapeake Bay and the Virginia coast were analyzed (Figure 1)- 8 stations with long records (~40-110 years) and 5 stations with shorter records (10-20 years). Water levels along the U.S. coast are measured by tide gauges maintained by the National Oceanic and Atmospheric Administration (NOAA) (Zervas 2009). Hourly data are obtained from the NOAA website (www.tidesandcurrents.noaa.gov); these data are used for calculations of potential flooding and storm surge impacts (Atkinson et al. 2013, Ezer and Atkinson 2014, Sweet and Park 2014). Monthly mean data for stations around the globe are archived by the Permanent Service for Mean Sea Level (PSMSL, www.psmsl.org, Woodworth and Player 2003). The PSMSL monthly data were used for the stations with long records, while the NOAA data were used for the stations with short records (Figure 1); monthly means were calculated from hourly data before calculating SLR rates. Note that the statistical accuracy of calculating SLR rates from linear regression (fitting the data with a straight line, the slope of which represents the mean rate) depends on record length. For example, a record of 60 years would yield an error in SLR of less than ±0.5 mm/yr (at 95% confidence level), while a record of 30 years would have an error of less than ±1.5 mm/yr (Zervas 2009, Boon et al. 2010). However, there are only 2 tide gauge stations in Virginia with observations of over 60 years (86 years at Sewells Point in Norfolk and 62 years at Kiptopeake on the eastern shore). Therefore, long records from Maryland and short records from Virginia are analyzed as well.

The analysis of the long records is shown in Figure 2 and that for the shorter records is shown in Figure 3. Also shown (smooth black line in Figure 2) are inter-annual variations after removing high-frequency variations using Empirical Mode Decomposition (EMD, Huang et al. 1998, Ezer and Corlett 2012). SLR rates are calculated for the past 30 years, and the 30 years before that, to see if the rates are constant or changing.

Our results reveal that everywhere within the region sea level is rising faster than the global rates. However, SLR rates are not constant- they vary in time (due to climatic changes in the ocean) and in place (due to local and regional land subsidence, see discussion later). SLR is largest in the lower Chesapeake Bay (Chesapeake Bay Bridge Tunnel (CBBT) and Norfolk), and a little lower in the northern

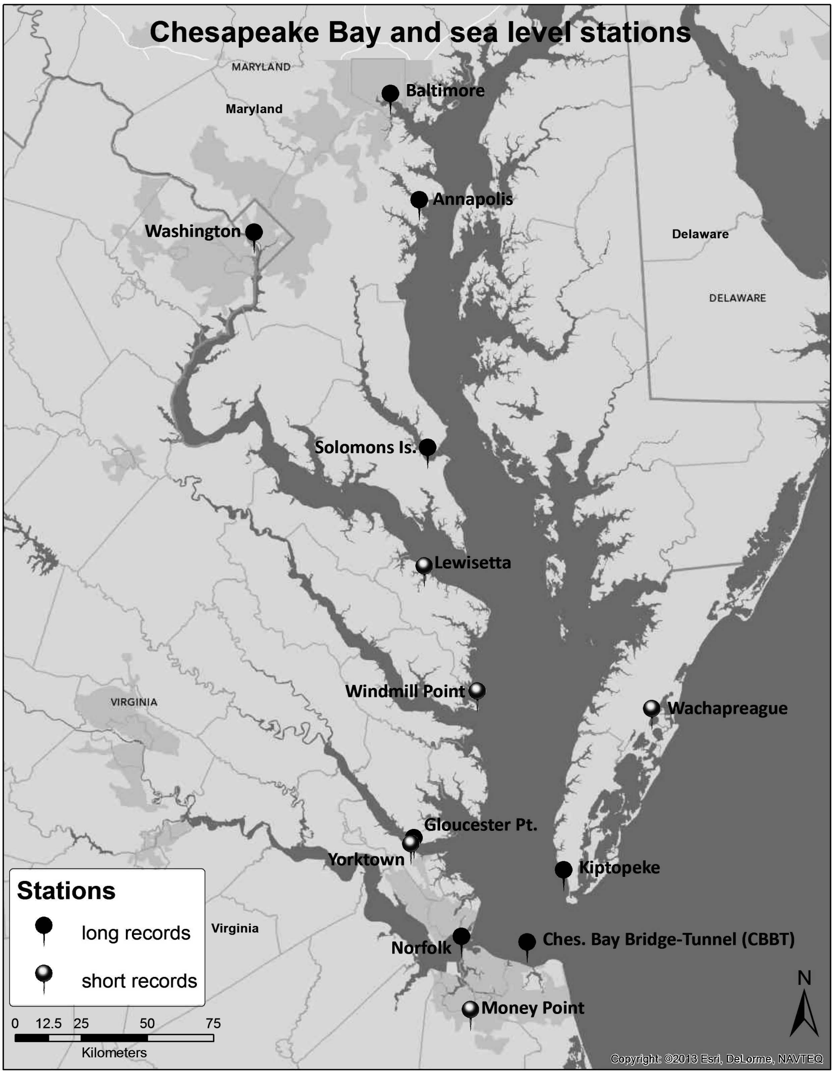

FIGURE 1. Map of the Chesapeake Bay region and location of tide gauge stations. Long and short records are indicated and analyzed separately in figures 2 and 3, respectively.

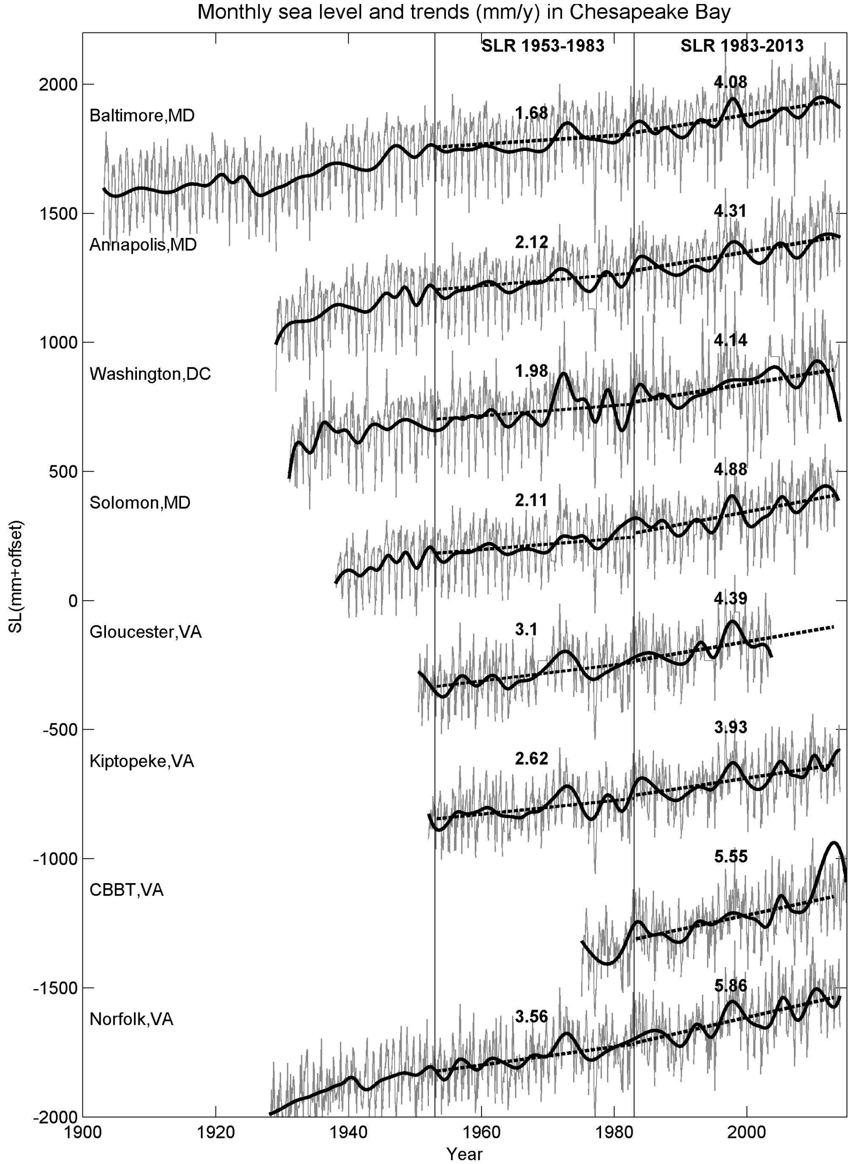

FIGURE 2. Monthly sea level in the Chesapeake Bay for stations with long records (from 40 years in Chesapeake Bay Bridge Tunnel, CBBT, to 110 years in Baltimore). Inter-annual variations are shown by black heavy lines and linear trends by dash lines. SLR rates in mm/yr are shown for two 30-year periods.

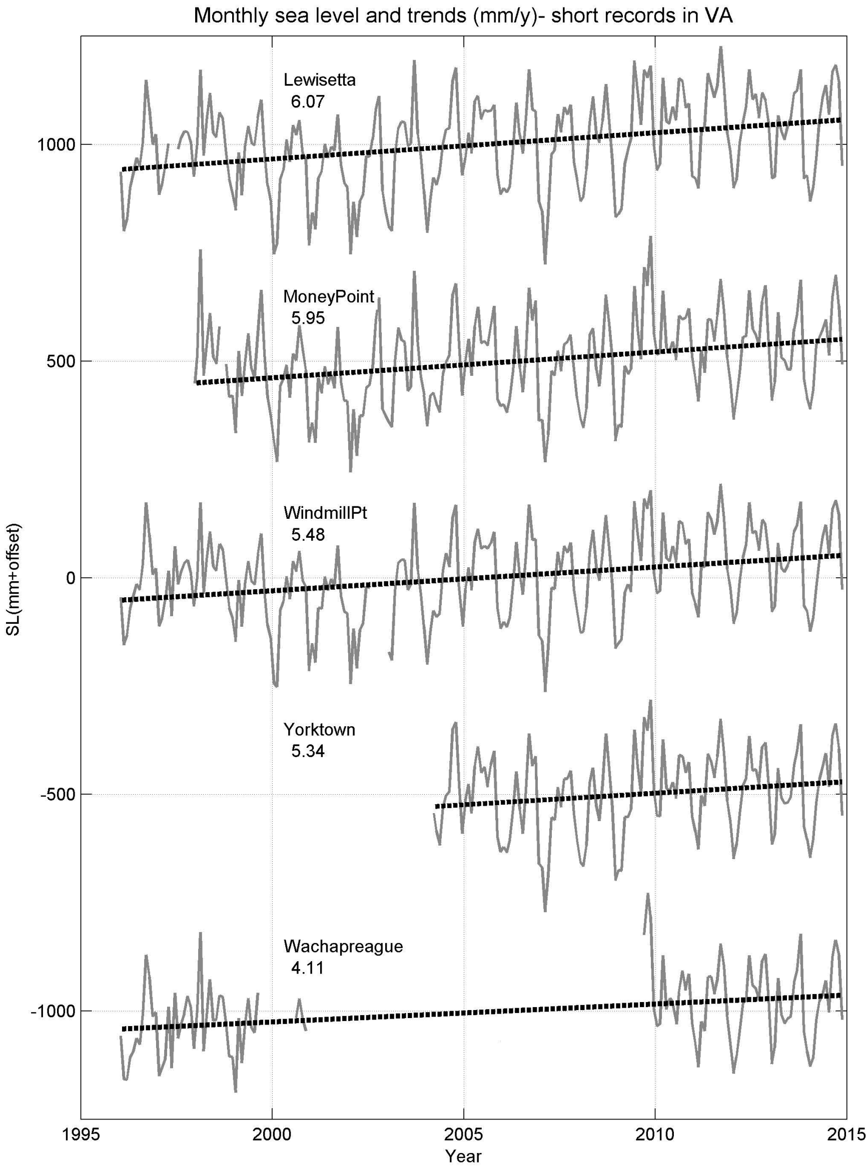

FIGURE 3. Monthly sea level and trends as in Figure 2, but for tide gauge stations in Virginia with relatively short records. The SLR rates in mm/y are listed under the station names.

Bay (Baltimore, MD, and Washington, DC) and in the eastern shore peninsula (Kiptopeke and Wachapreague).

Sea level is persistently accelerating. The average SLR from 30-60 years ago (2.45 mm/y for 1953-1983; Figure 2) has increased to a higher rate over the past 30 years (4.73 mm/y for 1983-2013; Figure 2) and seems even faster in recent years (5.4 mm/y for 1996-2014; Figure 3). The latter calculations for the short records are less accurate, but they are consistent with the same increasing trend of the longer measurements. The findings here support previous studies that identified the Mid-Atlantic region as a "hotspot" for accelerated sea level rise (Boon 2012, Ezer and Corlett 2012, Sallenger et al. 2012, Ezer 2013), but provides more details for Virginia's coasts than previous studies which focused only on long records.

There are coherent inter-annual variations (smooth black lines in Figure 2) that can cause a prolong periods (months to several years) of anomalously high water; such periods are seen for example around 1975 and 2009. These two periods have similar weakening GS (Ezer 2015), increased flooding (Sweet 2009, Mitchell et al. 2013, Sweet and Park 2014, Ezer and Atkinson 2014) and increased coastal erosion (Theuerkauf et al. 2014). The relation between these water level anomalies and changes in ocean currents will be discussion later.

CAUSES OF LOCAL SEA LEVEL RISE

Most discussions of SLR are about the average rise of the global sea level measured by satellites and tide stations (Church and White 2011); the global SLR is mostly attributed to increase in the volume of the ocean due to land-ice melting and thermal expansion due to warming of ocean waters. However, the rate of local SLR can vary significantly from place to place (Ezer 2013). The rate of local SLR can also change more rapidly over time than global SLR does due to decadal, multi-decadal and other long-term changes in ocean circulation (Ezer 2015). A summary of contributions to SLR is given in Table 1. Below, we will thus discuss two aspects that have particularly large impact on local sea level in Virginia.

Land subsidence

Local SLR is the change in sea level relative to the coast. Thus, if the land is sinking (i.e., land subsidence) or rising, the relative sea level can rise faster or slower than the global SLR rate. It turns out that much of the Virginia coast is sinking; there are two main reasons for this subsidence, Glacial Isostatic Adjustment (GIA) and underground water extraction, and they are explained below. Note however, that measuring the exact rate of subsidence at every point is difficult; even the modern Global Positioning System (GPS) that accurately measures land movement has only very few stations in Virginia with relatively short records of only a decade or so (Eggleston and Pope 2013).

The first factor affecting subsidence in Virginia is GIA, which is caused by the earth responding to the disappearance of the Laurentide ice sheet a few tens of thousands years ago. The earth crust is rising in the northern regions of New York and Quebec while sinking occurs in the regions south of New York, including Virginia (Sella et al. 2007). GIA is estimated to cause a subsidence of about 0.6-1.8 mm/yr (1

TABLE 1. Summary of estimated contributions to sea level rise (positive=increase SLR).

SLR Process	Rate mm/y	Reference & notes
Subsidence Glacial Isostatic Adjustment	0.6-1.8 mm/yr	USGS, Engelhart & Horton 2012, Miller et al. 2013
Subsidence Ground water pumping	2-4.8 mm/yr (location dependent)	USGS, Eggleston & Pope 2013
Subsidence Impact crater	Probably small or unknown	USGS, Powars & Bruce 1999, Boon et al. 2010
Ocean circulation	+5-10 mm/yr (includes decadal variations)	Ezer 2013, Ezer et al. 2013
Global scale thermal expansion and land ice melt	1.7-3.2 mm/yr (larger recent rates)	Church & White 2011, Ezer 2013, many others

mm/yr ~ 0.3 feet per century) (Engelhart et al. 2009, Engelhart and Horton 2012). Note however, that subsidence due to GIA is a very slow process over thousands of years, so it cannot contribute to the recent acceleration in SLR seen in tide gauge data. The Chesapeake Bay Impact Crater (Powars and Bruce 1999) affected the geology of the region as well, but is thought to contribute little to the regional subsidence rates (summarized in Eggleston and Pope 2013).

The second factor affecting subsidence in Virginia is groundwater withdrawal, which is a more local effect than GIA. A recent USGS report provided important new information on the subsidence rates related to groundwater withdrawals near two Virginia cities (Eggleston and Pope 2013): Franklin and West Point (Figure 4). Highest subsidence rates at those locations were 3.8 and 4.8 for West Point and Franklin respectively. The extent of this effect extends throughout the lower Bay region with rates of 2.0 to 2.8 in the heavily populated Virginia Beach and Norfolk areas. So ground water pumping can cause a subsidence rate between 2.0 and 4.8 mm/yr and contribute to the higher SLR rates seen in Figure 2 and Figure 3. Updating the subsidence maps using new data from GPS and other sources is needed and is an ongoing process.

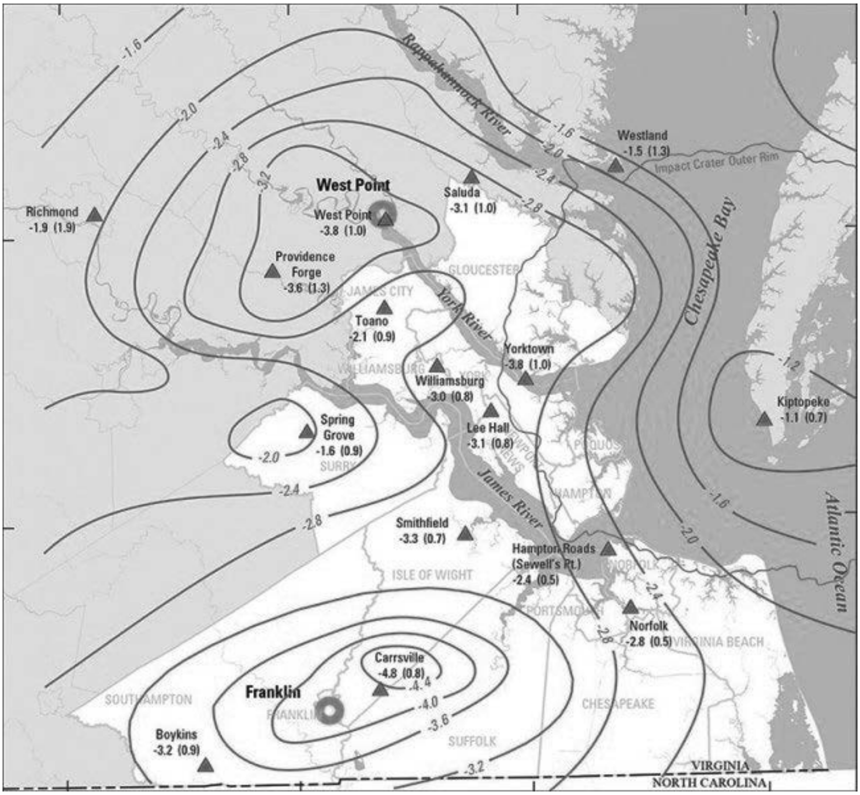

FIGURE 4. Land subsidence in Virginia (negative values represent land sinking in mm/year) from 1940 to 1971. The fastest sinking sites are centered near West Point and Franklin townships, where large paper mills extract underground water from wells. The bull-eye feature in Kiptopeke is near the center of the Impact Crater (source: U.S. Geological Survey).

Ocean dynamics

One of the least understood contributions to SLR is the impact of offshore ocean currents, which can result in spatial variations of SLR along the coast (Ezer 2013) and temporal variations in SLR rates that make predictions more challenging. In particular, recent research focused on the causes for a "hotspot" of accelerated sea level rise along the U.S. East Coast north of Cape Hatteras, North Carolina (Boon 2012, Ezer and Corlett 2012, Sallenger et al. 2012, Kopp 2013, Ezer 2013, Ezer et al. 2013). These studies suggest that the acceleration in SLR may be a dynamic response to climate-related slowdown in ocean circulation, and in particular, weakening of the Atlantic Meridional Overturning Circulation (AMOC, McCarthy et al. 2012, Smeed et al. 2014).

The Gulf Stream (GS) is a crucial part of AMOC (as well as wind-driven and density-driven components, see McCarthy et al. 2012, for details), and recent studies show that when the GS weakens sea level rises along the U.S. East coast (Ezer et al. 2013, Ezer 2013, 2015). The idea that the GS can impact sea level along the U.S. East Coast is not new (Montgomery 1938, Blaha 1984, Maul et al 1985), but the process is still not fully understood despite recent observations and models that captured the GS-SLR connections. The basic mechanism is as follows. Sea level is tilted across the GS (i.e., sea level is ~1-1.5 m lower on the onshore side of the GS than the offshore side) and this tilt depends on the speed of the current (this is called "geostropic" balance), therefore changes in the path and strength of the GS can cause variations in sea level and they evidently do so (Ezer 2001, 2013, 2015, Sweet et al. 2009, Ezer et al. 2013). Climatic changes in large-scale wind patterns may also contribute to coastal sea level anomalies observed along the U.S. East Coast (Woodworth et al. 2014), either directly, or by influencing the Gulf Stream flow. These studies found that inter-annual variations in sea level (such as those seen in Figure 2) are correlated with changes in the GS flow.

Anomalously higher water levels and increased flooding often happens during periods when the GS is weakening (Sweet et al. 2009, Ezer et al. 2013, Ezer and Atkinson 2014). The impact of the GS on sea level can be seen not only on inter-annual and longer time scales, but also on daily, weekly and monthly basis, as seen in Figure 5. The observed hourly water level in Norfolk (Figure 5a) is apparently influenced by the GS flow, which is measured (Meinen et al. 2010) by a cable across the Florida Straits (Figure 5b). For example, at the first half of March, 2014, there were two periods (days 65 and 75 in Figure 5) when water level anomaly was ~0.5 m (~1.5 ft) above the tidal prediction and at the same time the GS transport declined by ~10% (-3 Sv compared to mean flow of ~30 Sv; Sv is 1 million cubic meter per second). How to use this information on changing ocean currents to improve prediction of coastal sea level is a great challenge. Currently, storm surge computer models used by scientists at NOAA and other institutions, are mainly driven by local wind, so they neglect the impact on sea level from offshore changes in ocean currents.

IMPACT OF SEA LEVEL RISE

The impact of sea level rise can already be felt in many low-lying Virginia communities (Mitchell et al. 2013, Atkinson et al. 2013) and in particular, on the streets of Norfolk (Figure 6). The frequency and duration of minor tidal flooding has increased dramatically in recent decades along many U.S. coasts (Ezer and Atkinson 2014, Sweet and Park 2014). This is sometimes called "nuisance" flooding, which is not catastrophic, but causes some streets to be covered with water, blocking traffic and preventing residence from reaching work, hospitals, etc.; in Norfolk for example, this level is about 30-50 cm, or about 1 foot or more above Mean Higher High Water (MHHW). For example, before 1980 Norfolk experienced in average only ~30 hours of minor flooding per year and a year with flooding of more than 50 hours occurred only once every 10 years (black bars in Figure 6). However, since the 1990s, annual flooding of 100-200 hours happens almost every year. In the past, a hurricane or strong nor'easter storm was needed to cause flooding, while today with the additional sea level

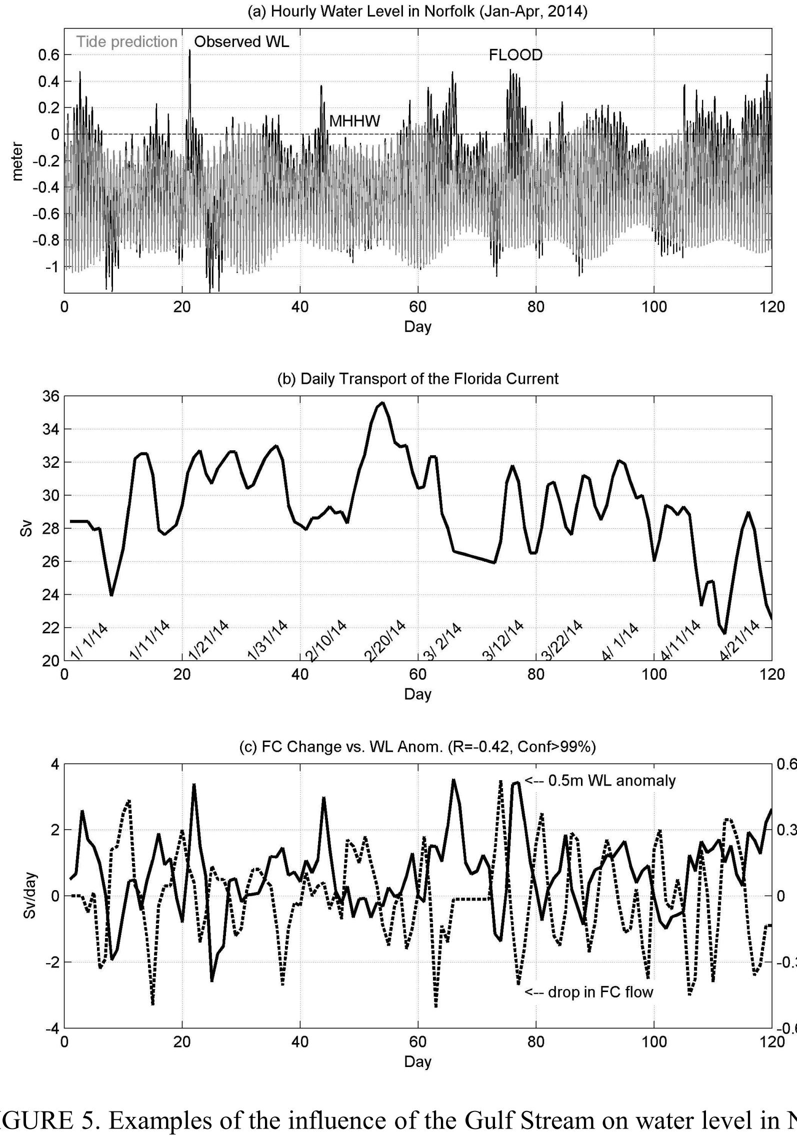

FIGURE 5. Examples of the influence of the Gulf Stream on water level in Norfolk. (a) Tide prediction (gray) and observed (black) water level; water level of ~0.3m above Mean Higher High Water (MHHW) are prone to flooding. (b) Observed flow of the Florida Current (upstream part of the GS) from cable measurements (www.aoml.noaa.gov/phod/floridacurrent/). Transport is in Sverdrup units (1Sv= million cubic meter per second). (c) Water level anomaly (solid) and changes in the GS flow (dash; in Sv/day) are anti-correlated. An example of water level anomaly that resulted in street flooding in mid March is indicated.

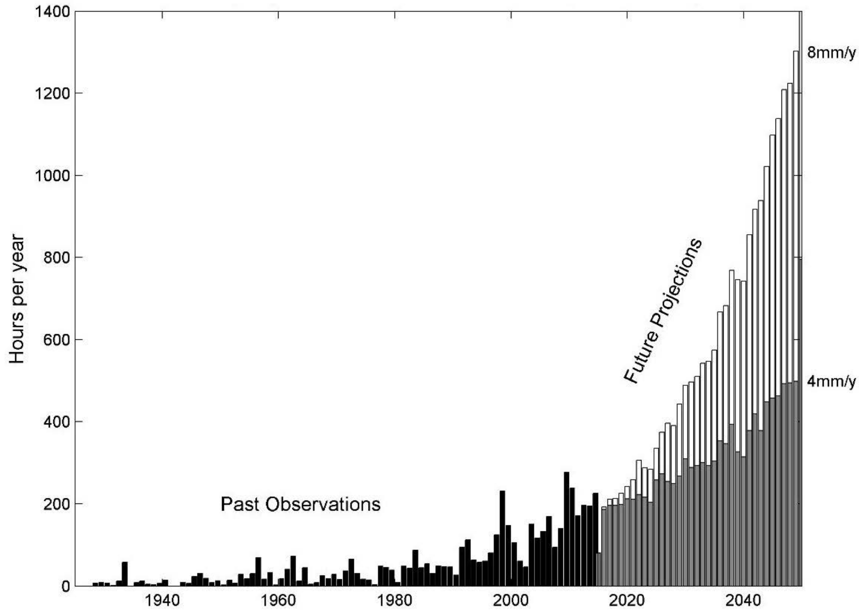

FIGURE 6. Hours per year that minor flooding starts in the streets of the historic Hague district of Norfolk, VA, when water level is ~1 ft (30 cm) above MHHW. Black bars are based on past observations of the tide gauge at Sewells Point; gray and white bars are estimated projections until 2050 for future SLR rates of 4 and 8 mm/y, respectively.

rise a threshold is reached such that even a small weather event or a regular Spring Tide (during full or new moon) can cause flooding. Big storms, such as Sandy in 2012, will cause today much more damage than past storms that happened when sea level was lower.

Projections of future flooding are estimated here from past statistics by using randomly sampled past water level anomalies from the hourly data plus prescribed SLR rates. Two different scenarios are shown in Figure 6, a very conservative SLR rate of 4 mm/y (lower than today's rate in Norfolk) in gray and a larger SLR rate of 8 mm/y in white (assuming an increase in SLR rate over today's rate). The projections demonstrate very dramatic impact of future SLR on the frequency of nuisance floods. By 2050 the annual hours of minor floods will increase from ~200 hours in 2013 to ~500 hours for the low SLR scenario and up to ~1300 hours for the high SLR case (~4 full days of floods per month). This means for example, that many roads along the water will not be passable for long periods of time so people living in some neighborhoods will have to find alternative roads and parking slots away from those streets. The impact of major storms on inundation (not shown) will also increase dramatically.

Various initiatives, from local-, city- and state-level, have been taken already as a response to increased flooding in Virginia in general and in the streets of Norfolk in particular. For example, Old Dominion University (ODU) established in 2010 the Climate Change and Sea Level Rise Initiative (http://www.odu.edu//research/initiatives/ccslri/), which involves education, research and outreach activities in climate studies and the developments of mitigation and adaptation strategies. Virginia Sea Grant, ODU and the Hampton Roads Planning District Commission (HRPDC) plan and host quarterly meetings of the Flood Adaptation Forum, which bring together professionals in adaptation including local municipal government staff, scientific experts, private sector engineers, state and federal agency staff and other stakeholders. The Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Planning Pilot Project (http://www.centerforsealevelrise.org/) was formed to create a plan for coordination across federal, state and local government agencies. Residents in flood-prone streets in the Hampton Roads region can receive flood warning from a local network and from a new Sea Level Rise App for smart phones (developed by the Norfolk-based, environmental non-profit group Wetlands Watch). Houses and roads in flood-prone streets in Norfolk have already been raised, and flood gates and walls protect the business district of downtown Norfolk, but other areas need protection, so various means for mitigation and adaptations are under consideration.

SUMMARY

Sea level will likely continue to rise for decades to come, and local rates in Virginia may continue to rise even faster than the global SLR. Studies need to better understand and quantify the contribution from land subsidence and ocean dynamics using combination of measurements, theory and models. Because of the flat topography of the Virginia coasts and the large population living around the Chesapeake Bay and along the Atlantic coast, the impacts of future sea level rise need to be addressed. The SLR into the far future, say 100 years from now, is predicted by global scales climate models (see for example the reports from the Intergovernmental Panel on Climate Change, IPCC) and has quite large uncertainties. However, local SLR in Virginia for the relatively short term, say 10-30 years, can be estimated from the statistics of the past based on tide gauge stations (Boon 2012, Ezer and Corlett 2012). Since future SLR is predicted to be at least as fast as the current rates (and likely faster), a rough estimate of about 1.5-2.5 ft/century for our region is not unreasonable, based on the data analyzed here. If the Gulf Stream slow down continues the rates may be considerably higher.

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Virginia Air Quality: Trends, Exposure, and Respiratory Health Impacts

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ABSTRACT

Air quality is an important determinant of public health and quality of life. A secondary data analysis was carried out to investigate trends and air quality in Virginia. The analysis included an evaluation of two major air pollution source categories, emission of criteria and hazardous air pollutants, ambient concentrations of criteria pollutants, ozone standard violations and associated meteorology, and hospital admissions for asthma and chronic obstructive pulmonary disease in Virginia. Comparisons were also made to national trends and statistics. Data was gathered from many open reputable on-line sources available through various state and federal agencies. Virginia routinely meets 5 of the 6 criteria air pollutant ambient standards. Ozone does continue to represent a challenge for Virginia, as it does for many other states. Potential focus on further production and consumption of renewable energy, improvement in fuel efficiency among SUV's and light trucks, reduction of the metals content in fuels burned by electric utilities, utilization of emissions inspections for automobiles, utilization of vapor recovery systems at gas stations, and continued emphasis on ozone precursors all have the potential to further improve air quality within Virginia. This is important because the very young and the elderly are particularly vulnerable to the adverse effects of poor air quality.

INTRODUCTION

Poor air quality has long been associated with adverse human and ecological health impacts. For example, poor air quality led King Edward I in 1273 to prohibit the burning of coal due to noxious air emissions (Beck 2007). Although we have made significant progress in controlling air pollution in many developed countries today, concern still exists regarding the impact of air quality on health. In the 1980's and 1990's, several epidemiologic research studies showed that in the United States both particulate matter (Wilson and Spengler 1996) and ozone (Lippmann 1989) were associated with adverse human health effects at levels typical of that time. Additional

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studies were conducted and this body of research is now reflected in the United States Environmental Protection Agency's (USEPA) Criteria Documents required under Title I of the Clean Air Act (USEPA 2014a; USEPA 2010). These Criteria Documents form the basis for the compliance levels set under the National Ambient Air Quality Standards (NAAQS).

Today in the Unites States, the USEPA regulates ambient air quality through six NAAQS. The Criteria Air Pollutants regulated under Title I of the Clean Air Act are particulate matter (PM), carbon monoxide (CO), ozone (O_3), oxides of sulfur (SO_x), oxides of nitrogen (NO_x), and lead (Pb). The particulate matter standards include both particles under 10 microns in aerodynamic diameter (PM10) and particles under 2.5 microns in aerodynamic diameter (PM2.5). Ambient levels of these Criteria Air Pollutants and other ambient air pollutants are measured continuously through several of USEPA's extensive ambient air monitoring networks, including the State and Local Air Monitoring Stations (SLAMS), National Air Monitoring Stations (NAMS), Special Purpose Monitors (SPMS), and Photochemical Assessment Monitoring Stations (PAMS) (USEPA 2015a). In addition, emissions of the six criteria pollutants are tracked through the National Emissions Inventory (NEI). The USEPA utilizes state inventory data to compile the NEI on an annual basis and conducts a more comprehensive NEI review of the state inventories every three years. Hazardous air pollutants (HAPs) are also regulated by the USEPA through several programs. One of these programs created by the Emergency Planning and Community Right-to-Know Act (EPCRA) Section 313 created the Toxic Release Inventory (TRI) program and contains a list of roughly 650 chemical compounds, many of which are HAPs. HAPs, in addition to waste water and solid waste toxics, are tracked through the TRI (USEPA 2015b), which is a multi-media inventory system designed to fulfill requirements under EPCRA. Trends in the release of HAPs can be tracked by industrial sector and by geographic region through the TRI.

In addition to the actual measurement of airborne concentrations of pollutants and an inventory of air pollution releases, significant sources of air pollution can be tracked through various databases. Two industrial sectors that are particularly important contributors to ambient air pollution are the energy sector and the mobile source (e.g. automobiles) sector. The Energy Information Administration (EIA) (www.eia.gov) is a semiautonomous agency within the US Department of Energy that tracks trends and makes projections of energy production and use in the United States and within individual states. Many state Department of Transportation (DOT) agencies carefully track mobile sources by compiling data on automobile and truck use throughout their state. Mobile source data such as the number of vehicles, total vehicle miles traveled, and fuel efficiency statistics of the motor vehicle fleet are compiled by most state DOTs and the EIA. This information can be used to assess the impact of these two important sectors on ambient air quality.

We endeavored to utilize the information described above to investigate trends in important air pollution sources (energy and mobile sources), TRI data, NEI data, and ambient measurements made by SLAMS monitoring sites for the state of Virginia and explore potential contributors to human exposure and risks of chronic respiratory disease.

METHODS

The approach to assessing the current air quality condition and trends in Virginia were accomplished through secondary data analysis. The overall time period covered in this analysis was from 2002 through 2013, but varied by each analysis due to the varying availability of different data sources across different time periods.

Data Collection

Data from the National Emissions Inventory (NEI) and the Toxics Release Inventory (TRI) were directly accessible via the USEPA website. NEI data was downloaded directly from the Office of Air Quality Planning & Standards, Emissions Inventory & Analysis Group, Technology Transfer Network Clearinghouse for Inventories & Emissions Factors data page (USEPA 2015c). The most recent NEI data available was from 2011. The TRI data was searched and downloaded directly using the USEPA TRI Explorer search tool (USEPA 2014b). Data on energy production and use was downloaded directly from EIA via their State Energy Data System (SEDS) search tool accessible on-line (EIA 2015a). Motor vehicle statistics were accessed through official state data reports published by the Virginia Department of Transportation (VADMV 2014) and through the EIA Monthly Energy Reviews (EIA 2015b). Ambient air monitoring data was accessed through Virginia Department of Environmental Quality (VADEQ) official annual air quality data reports (VADEQ 2009, 2010, 2011, 2012, 2013, 2014). In addition, ozone exceedance day data for the years 2008 – 2013 was obtained directly from the VADEQ Air Quality Monitoring branch (VADEQ personal communication, 2/6/15). The VADEQ reports are based on measurements made by the VA SLAMS monitoring sites. Meteorological data for the years 2008 – 2013 was obtained directly for four Quality Controlled Local Climatological Data (QCLCD) NOAA weather stations located throughout the state of Virginia for Central, Southeastern, Southwestern, and Northern areas of the state (Farmville, Hampton, Martinsville, and Manasas, respectively) (NOAA 2014). Data on asthma admissions was abstracted from a state report by the Virginia Department of Health, Division of Environmental Epidemiology pilot project on Environmental Public Health Tracking published in 2012 (VDH 2012). Asthma data was also collected from the Centers for Disease Control and Prevention by analyzing Morbidity and Mortality Weekly Reports (CDC 2011), Data Briefs and raw data through the Chronic Indicator Search Tool (CDC 2011, 2012a, 2012b, 2015). Other key asthma data was collected from the Virginia Asthma Plan 2011 – 2016 report (Kiger 2010), Virginia Department of Health Burden report for 2013, and American Lung Association Report for 2014 (American Lung Assoc 2014).

Data analysis

First, the data was simply described over the time period and observations regarding any patterns or trends were noted. Second, comparisons were made between trends in Virginia and national trends in order to identify differences. Third, the number of days with a violation of the NAAQS for ozone in each “ozone season” for the years 2008 through 2013 was analyzed. A more detailed description of ozone violations was also described in relation to the meteorology measured in central Virginia. The meteorological parameters investigated included dry bulb temperature and % relative humidity. Comparisons between the seasonal average of the meteorological parameters and the number of NAAQS ozone violations from 2008 through 2013 was assessed.

Fourth, we described data on hospital admissions for asthma and chronic obstructive pulmonary disease (COPD). Detailed description of asthma admissions by age group, with a particular focus on the elderly (> 65 years of age) and young children (<5 years of age) was also performed. This analysis was descriptive in nature and further statistical assessment will be conducted in the future.

RESULTS & DISCUSSION

Sources of Ambient Air Pollution

a) Energy Sector

Analysis demonstrated that for many energy sources, Virginia reflected the national trends. Overall energy consumption measured in terms of either British Thermal Units (BTUs) or in terms of physical quantities (e.g. short tons for coal) had similar trends and showed a decline in the 2008 – 2009 time frame in both the statewide and national consumption trends. This is likely the result of changes in the economy and the impact of the recession that began in 2007. Energy consumption has since returned to pre-recession levels and will likely continue to increase. Nuclear energy consumption has remained relatively flat and unchanged since 2002 in both the statewide and national data as the number of nuclear power plants has remained the same over many years. However, there are plans to potentially build more nuclear power plants in the future and if these plants were built, it would impact the available energy from this sector. Coal exhibits similar trends to overall energy consumption, with the exception that after the recession and recovery in 2010 there was an increase in consumption but this increase began to wane in 2012. At the same time, as hydraulic fracturing has made natural gas more plentiful and hence cheaper, there has been an increase nationally in natural gas consumption and this may have displaced some of the coal used nationally and statewide. The upward trend for natural gas consumption is even more pronounced in Virginia (Figure 1). The percent change from baseline in Figure 1 is approximately an 11% increase from baseline in consumption of natural gas nationwide, whereas in Virginia there is roughly a 59% percent increase from baseline. This may benefit the air quality nationally and in Virginia because natural gas burns significantly cleaner than coal and is much less carbon intensive on a per BTU basis.

Interestingly, Virginia does lag behind the national trends in terms of renewable energy consumption. There was a dramatic rise in renewable energy consumption on the national level with a substantial increase beginning in 2008 and continuing after the economic recovery. However, Virginia appears to be relative flat across the time frame analyzed (Figure 2). An assessment of Virginia's renewable energy production and consumption shows that while consumption flattens out, there is a decrease in production via renewable energy after 2005 (Figure 3).

b) Automobiles and mobile sources

Mobile sources are very important in air quality inventories. Trends in automobile use in Virginia reflect national trends, where from 2002 through 2012 there has been an increase in the number of registered vehicles and an increase in vehicle miles traveled (VMT) but this trend has not been dramatic and in 2007 (national trend) and 2008 (Virginia) there was an inflection point where VMT seems to have leveled off or even decreased slightly. In Virginia, there were 6,659,560 vehicles registered in 2002 and 7,706,795 vehicles registered in 2012 (VADMV 2014). This represents a growth of approximately one million registered vehicles in Virginia over these 10 years.

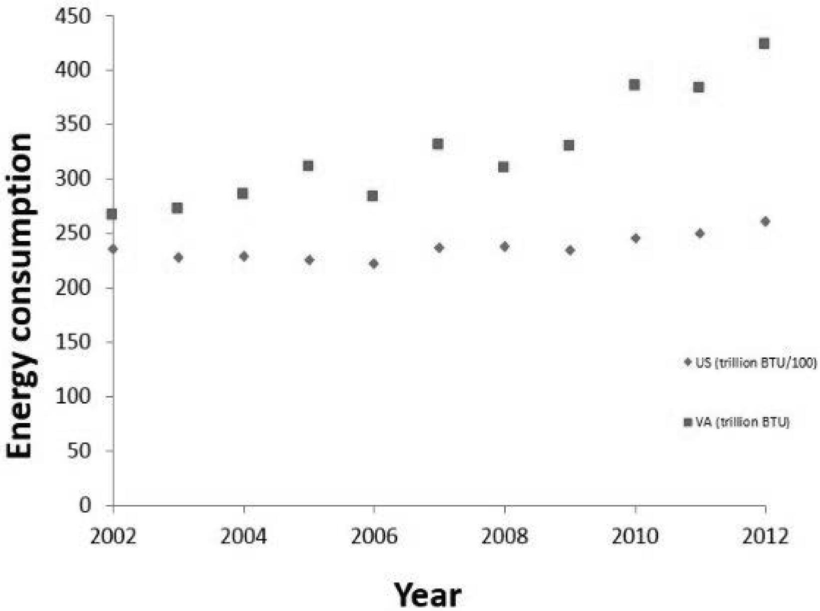

FIGURE 1. Natural Gas Consumption trends for Virginia and Nationally from 2002 - 2012.

Vehicle miles traveled (VMT) is an important parameter to understand the potential contribution of mobile sources to air pollution. In Virginia the peak year for VMT was 2008 with 82 billion miles traveled (VADMV 2014) and 2007 was the peak year nationally with roughly 3 trillion miles traveled (McCahill and Spahr 2013). In Virginia, VMT has leveled off at roughly 81 billion miles. The leveling off of VMT both nationally and statewide is likely related to several important trends that transportation officials believe will continue to retard dramatic growth in VMT with the current technologies. These trends include general economic activity and unemployment rates, the aging of the baby boom generation, saturation of automobile ownership per household, higher costs of car maintenance, decreased desire to drive due to increased traffic congestion and commute times, and changes in attitudes about living in more densely populated communities (McCahill and Spahr 2013). While these changes have taken place, some improvements in fuel efficiency have also taken place. Light duty vehicles (short wheel base, e.g. sedan) have increased their average fuel efficiency from 22 miles per gallon (MPG) in 2002 to 23.3 MPG in 2012 (EIA 2015b). However, light duty vehicles with long wheel bases (e.g. SUVs) have actually seen a slight decrease in their fuel efficiency from 17.5 MPG in 2002 to 17.1 MPG in 2012 (EIA 2015b). Heavy duty trucks have seen a slight increase in fuel efficiency from 5.8 MPG in 2002 to 6.4 MPG in 2012 (EIA 2015b).

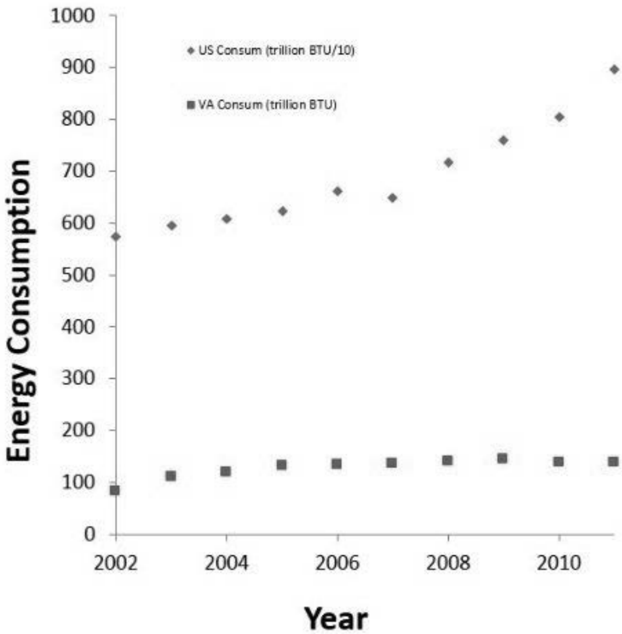

FIGURE 2. Renewable energy consumption trends in Virginia and Nationally from 2002 - 2011.

This data represents a mixed result in terms of benefits for air quality. Leveling off of VMT is beneficial and certainly improvements in fuel efficiency standards for light duty short wheelbase vehicles will result in reduced air pollution from mobile sources. However, the popularity of light duty long wheelbase vehicles (SUVs, light duty trucks) and their relative decrease in fuel efficiency will likely offset some of the air quality gains made in the mobile source sector.

c) Toxic Release Inventory (TRI)

Data gathered from the USEPA TRI demonstrated that in general the trends of total Hazardous Air Pollutants (HAPs) emitted among different industries in Virginia were similar to national trends. The only exceptions were North American Industrial Classification System (NAICS) code 313/314 Textiles, NAICS 333 Machinery, and NAICS 4247 Petroleum Bulk Terminals, which appeared to show a drop in Virginia and yet a relatively flat pattern nationally. In particular, the NAICS 333 Machinery industrial sector showed a significant drop in HAP emissions after the start of the recession in Virginia and has not returned to pre-recession levels.

Analysis of this TRI data showed that in both Virginia and nationally the electric utilities industry (NAICS 2211) emitted the highest amount of TRI-listed hazardous air pollutants. A total of 4,580,961,573 lbs of TRI-listed HAPs were released off-site from electric utilities nationally from 2003 through 2012 and a total of 120,890,122 lbs were

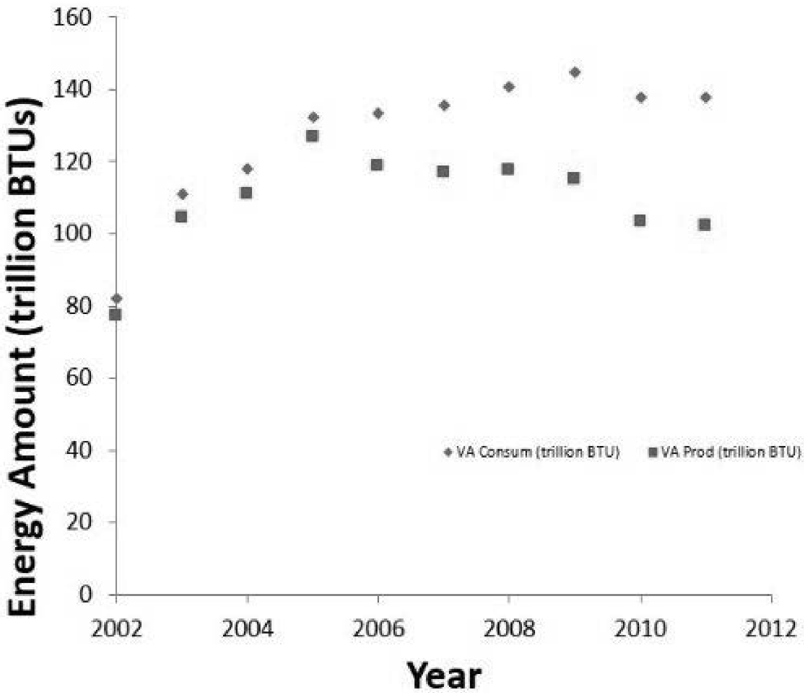

FIGURE 3. Virginia renewable energy consumption versus production 2002 - 2011.

released from Virginia utilities over the same time period. The EIA has a data utility tool available on-line (EIA 2015c) which produces estimates of the net generation capacity at electric utilities. It was found that 17,719,561,000 megawatts was the net generation of all US electric power utilities in NAICS category 22 from 2003 through 2012 and 333,683,000 was the net capacity produced in Virginia over the same time frame. By extension, it was found that the TRI-listed HAPs emission rate averaged over the period from 2003 through 2012 on a per megawatt basis can be calculated as 259 lbs of HAPs per megawatt in the US overall and 362 lbs of HAPs per megawatt in Virginia. As a result, it appears for the 10 year period cited that Virginia had a higher HAPs emission rate on a per megawatt basis compared to the country as a whole. It is important to note that this analysis was conducted only considering fossil fuels and biomass, in other words only fuels that are burned to generate electricity. Nuclear and renewable sources were not included because it was believed that they would not contribute significantly to the TRI-listed HAP emission rate and therefore their exclusion provides a more accurate accounting of the true per megawatt emission rate from electric utilities that are likely to have TRI-listed HAP emissions. The mix of combustible fuels in the energy portfolio for Virginia electric utilities closely mirrors that of the US as a whole and therefore differences in fuel mix are not likely an explanation for the higher emission rate in Virginia (Figure 4).

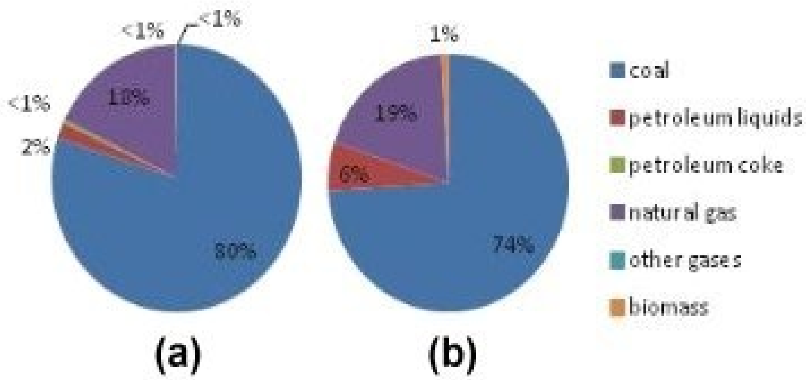

FIGURE 4. Average combustible fuel mix for the United States (a) and Virginia (b) as a percent of total Megawatts generated from 2003 - 2012.

The combustible fuel mix likely explains the finding that the two most abundant TRI-listed HAPs released in Virginia are "magnesium and its compounds" and "lead and its compounds". Overall, magnesium, lead, and their related compounds represented 52 % to 77% of the total mass of TRI-related emissions from 2003 through 2013. TRI data showed that there were anywhere from 79 to 90 different compounds in the TRI database over this time period, but that in many cases, the top 5 compounds on the TRI list for Virginia were metals. This likely resulted from the fact that these metals frequently are present in trace quantities in the fuels burned by electric utilities. A trace concentration in fuels can translate into a large amount of the TRI-listed material being emitted over time because of the massive quantity of fuel that is burned by utilities. The most common organic compounds reported were solvents or additives and the exact chemical varied year to year but included methanol, toluene, 2,4-dinitrotoluene, ethylene glycol, and n-hexane. Toluene was the most common organic in Virginia and was reported in the third or fourth largest quantity of all TRI-listed HAPs for 6 of the 10 years analyzed.

d) National Emissions Inventory (NEI)

The NEI demonstrated several interesting characteristics about air quality trends. The relative contribution of the different source categories were similar from the 2008 inventory to the 2011 inventory and relative source contributions were similar for SO_2 and NO_x in Virginia and the United States overall. The NEI demonstrated the importance of the transportation sector in contributing to NO_x emissions both statewide and nationally.

Differences were observed between Virginia and national trends in the relative contributions among sources of both PM10 and PM2.5. For example, the stationary source combustion sector (e.g. electric utilities), transportation, and industrial processes contributed a higher percentage of emissions in Virginia compared to the national inventory (Figure 5). In addition, the NEI also demonstrated that the relative source contribution from the transportation sector was more substantial for the CO and volatile

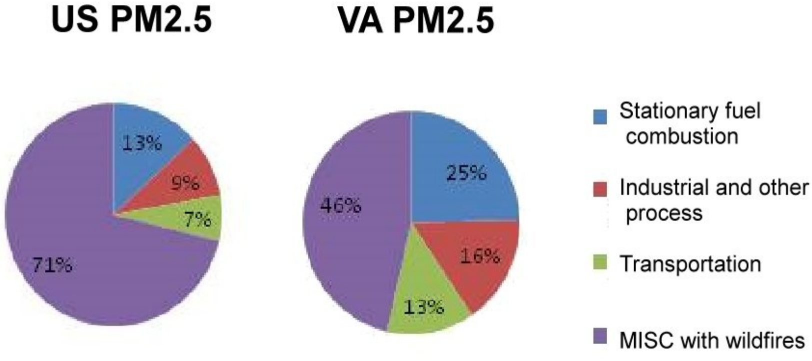

FIGURE 5. Source contribution to PM 2.5 emissions in 2011 for the United States and Virginia based on NEI. Includes both filterable and condensable particulate matter.

organic compound (VOC) emissions in Virginia compared to the overall national trend. (Figure 6) This may be a consequence of the lack of emissions testing for motor vehicles, including fuel system leaks and tail pipe testing, and the lack of vapor recovery systems at gas stations in Virginia. Alternatively, this simply could be an artifact of the inventory where there was a smaller contribution from wildfires in VA compared to the United States as a whole.

National Ambient Air Quality Standards (NAAQS) Compliance

a) Overview – Criteria Air Pollutants in Virginia

A review of the annual ambient air quality monitoring reports from the Virginia Department of Environmental Quality (VADEQ 2009, 2010, 2011, 2012, 2013, 2014) reveals that between 2008 and 2013 the state was in compliance with the NAAQS for carbon monoxide, nitrogen dioxide, and sulfur dioxide. Virginia was in compliance with the particulate matter NAAQS for PM10 from 2008 through 2013 and had only one violation of the PM2.5 twenty four hour standard in 2013. However, it is important to also note that Virginia applied for and received an exceptional event exemption in 2008 and 2011 because high particle concentrations were caused by the coastal North Carolina and Dismal Swamp wildfires. Therefore, these events are not recorded as violations of the NAAQS because the USEPA excluded these particle exceedances from consideration. Despite this petition, it is important to note that these wildfires resulted in significantly elevated particle concentrations and future wildfires may impact public health.

Ozone is the criteria pollutant where there is a persistent challenge in meeting the NAAQS standard for Virginia, as is the case for many areas in the United States. Northern Virginia, Richmond, and the Hampton Roads areas are generally the most problematic areas and experience the highest number of days with a violation of the NAAQS, commonly termed an exceedance day. Ozone is a secondary pollutant and as such its formation is greatly affected by the meteorological conditions and the

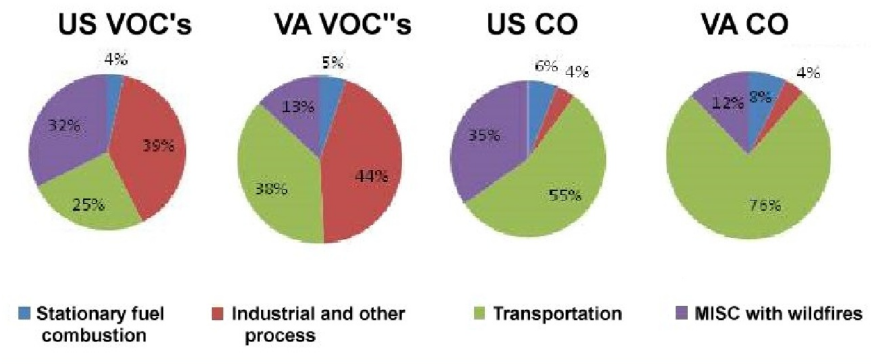

FIGURE 6. Contribution of transportation sector to carbon monoxide (CO) and volatile organic compound (VOC) emissions in the Unities States and Virginia based on 2011 NEI.

concentrations of precursor chemicals. As a result, it is suspected that the differences in the ozone exceedance trends observed across Virginia for the years 2008 through 2013 are significantly related to these factors, which has some similarities to national trends. (Figure 7)

b) Ozone excursions 2008 – 2013

For the period of 2008 through 2013, there were 95 days where at least one monitor in Virginia exceeded the NAAQS for ozone. The data in Figure 7 represents a total of 171 "hits" for the 95 days where there were ozone exceedances, where a "hit" is a day recorded in a given region where there was at least one monitor in the region that exceeded the 8-hour average NAAQS of 0.075 ppm of ozone. There are many days where more than one region exceeded the standard on the same day, so each exceedance day can have more than one "hit". Ozone is a regional pollutant with highly correlated concentrations across different regions and therefore it is not unusual to have multiple "hits" on one day. In addition, there are multiple monitors in each region, so the 171 "hits" represents a total of 358 measurements among all monitors in all regions that recorded an ozone concentration value above the NAAQS standard for the period 2008 through 2013. As a result, each statewide exceedance day often has multiple hits across different regions with many different monitor measurements. The ozone daily standard also records ozone as an 8 hour rolling average based on 8 hourly average measurements from continuous monitors. In other words, the time period from 00:00 to 08:00 is one rolling average, then 01:00 to 09:00 is the next 8 hour rolling average in the 24 hour period, and so on. There are a total of 24 eight hour rolling averages in any given 24 hour period as EPA includes averages over the nighttime as well as daytime. If there are multiple 8 hour rolling averages that exceed the standard, EPA NAAQS stipulate that that this only constituents one exceedance day recorded as the highest 8 hour rolling average of all measurements in the 24 hour period.

Air monitoring data shows that of the 95 ozone exceedance days in Virginia between 2008-2013, 85% of all exceedance days occurred between the months of June

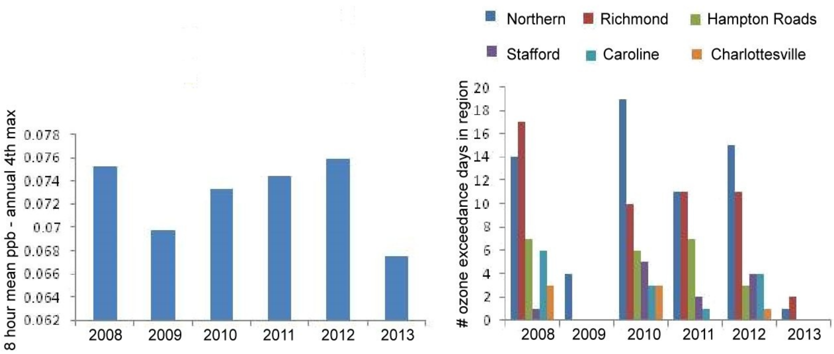

FIGURE 7. National trends in ozone concentrations by year (left) and # ozone exceedance days in Virginia (right) from 2008 through 2013. Note decrease in 2009 and 2013 in both national trends and Virginia trends.

through August and the peak month was July (Figure 8). The highest concentration of ozone measured between 2008 – 2013 was 0.110 ppm at the Henrico monitoring site in Central Virginia (Richmond area) and occurred on June 6, 2008.

If the exceedance data is broken down and summarized by the daily period for which the 8 hour rolling average is calculated, it can be shown that the critical window for ozone exceedance is from 9 am through 7 pm during the day, where more than roughly 98% of the exceedance measurements had at least some percentage of their measured time in this critical window. This is not surprising because ozone is a photochemical oxidant formed in the presence of sunlight. However, there were a small percentage of measurements (~1.5%) collected overnight that were completely outside this critical window. This finding suggests that the persistence of ozone on high concentration days can occur from the lag time associated with transport of ozone generated during the daytime to other regions after dusk resulting in a small number of violations during the night. In fact, one of the ozone violations that occurred from 11 pm through 7 am occurred on April 18, 2008 at the monitoring station in Madison County Virginia, which is a town close to Charlottesville at the foothills of the Blue Ridge Mountains. Data shows earlier in the day on April 18th that there were widespread violations of the standard across all regions of Virginia as the day was unusually warm (avg daily temp 84 ^{0}F) and weather data from the meteorological station at Charlottesville-Albemarle airport (approx 24 miles from Madison) shows that the predominate wind direction for the day and specific periods overnight was from the south-southeast, suggesting that ozone generated during the day throughout Virginia was transported north to Madison County Virginia resulting in the violation overnight. It can be speculated that while ozone is not generated in the absence of sunlight, that it does take some time for ozone that is generated during the day to degrade and therefore it can persist into the evening.

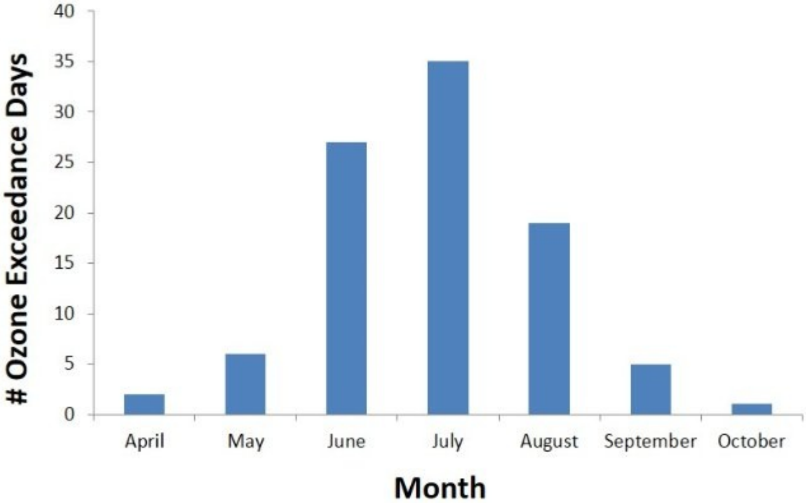

FIGURE 8. Ozone exceedance days in Virginia by month for 2008 through 2013.

c) Meteorological Assessment 2008 – 2013

Meteorological data captured by the NOAA Quality Controlled Local Climatological Data (QCLCD) system was summarized from May to September for the years 2008 – 2013 in the central Virginia region (Farmville meteorological station; approximate center of state). In this descriptive analysis, average daily temperatures between 8 am and 8 pm and the average percent relative humidity (% RH) were calculated for each year's May through September period. Data on ozone violation data in central Virginia was also summarized by including all central Virginia air quality monitors, which were located in Albemarle County, Rockbridge County, Chesterfield County, Henrico County, Hanover County, Charles City County, and Caroline County. The recording of ozone violations are highly correlated among these different monitors because ozone is a regional pollutant and they are all located in the same approximate region. The ozone exceedances for the period were then characterized by using the data from the monitor with the maximum number of ozone exceedance days during the period. This was compared over each year of analysis (Table I). Correlation coefficients calculated for the maximum number of exceedance days in a period versus the number of days where the temperature was greater than 90 ^{0}F was 0.59 and for days with high relative humidity was -0.73. Days that are greater than 90 ^{0}F are associated with intense sunlight and likely associated with factors conducive to photochemical reactions and likely explains the positive correlation coefficient. Days that have a high relative humidity, defined here as between 80% and 95%, are likely to occur when weather conditions are less conducive to photochemical reactions, and hence explains the negative correlation coefficient. In fact if the %RH goes above these values it will most likely produce a rain event.

TABLE 1. Ozone violation data in Central Virginia and corresponding average meteorologic conditions for the May through September time period from 2008 – 2013.

Year	Max # vio* measured by any given monitor	# 90^0F days	# days RH 80-95%
2008	11	62	71
2009	0	44	115
2010	6	88	71
2011	7	62	105
2012	5	69	75
2013	1	37	112

* - violation days

Exposure & Health Effects

a) Overview

Chronic respiratory disease trends in Virginia and Hampton Roads

The prevalence of asthma is a concern nationwide, given that an estimated 8% of Americans have asthma (CDC 2011a). This percentage translates to around 25 million individuals in the United States (US) who are known to have asthma. Of these 25 million individuals, 7 million are children (VDH 2013). Asthma cost the US $56 billion dollars in 2010. However, the estimated prevalence of asthma is higher in Virginia and, even more so, in Hampton Roads. The most recent data available indicate that over 9 percent of Virginians have asthma (Kiger 2010) which translates to an estimated 163,252 pediatric asthma cases and 553,864 cases of adult asthma (American Lung Association 2014.). From 2000-2008, the adult female rate of 11.9 percent surpassed adult male rate of 6.5 percent (consistent with national trends). In addition, those with the lowest income and education had the highest rates of asthma. An increase in lifetime asthma rose from 9.3 percent in 2003 to 14.4 percent in 2008 for children of Virginia. (CDC 2012a, 2012b)

Prevalence rates in Norfolk, Chesapeake, and the Peninsula are much higher and range from 11% to 12%. Hospitalizations for the condition result in a length of stay of 4 days and cost nearly $13,000 on average. Such asthma related hospitalizations represent the fourth leading cause of hospitalization among children in Virginia (Kiger, 2010).

COPD

The prevalence of COPD in Virginia is 5.7 percent, which was equal to the national rate in 2012 among adults ≥18 year of age. The prevalence of COPD in 2012 among those adults ≥45 years of age and older in Virginia is 9.3 percent, which was greater than the national rate 9.0 percent. Prevalence of current smoking among adults ≥18 years of age with diagnosed COPD in 2012, was 48.3 percent for Virginia and 47.0 percent for the national rate. Prevalence of current smoking among adults ≥45 years of age with diagnosed COPD in 2012, was 42.0 percent for Virginia and 38.6 percent for the national rate. The following groups were more likely to report COPD: persons aged 65–74 years, non-Hispanic whites, women, individuals who were unemployed, retired, or unable to work, individuals with less than a high school education, people with lower incomes, individuals who were divorced, widowed, or separated, current or former smokers, and those with a history of asthma (CDC 2011b, 2015).

b) Asthma admissions in Central VA by age group

A pilot Environmental Public Health Tracking (EPHT) project conducted by the Virginia Department of Health in 2011 investigated the relationship between weather patterns and asthma admissions in the metro Richmond area (VDH 2012). This project found that there was an association between daily diurnal temperature and asthma admissions but this relationship had a negative correlation coefficient (VDH 2012), likely due to the fact that the peak in asthma admissions to the hospital occurred in September and October (cooler months) and was the lowest in the middle of the summer (hottest months). It is well documented that asthma hospital admissions peak, especially for children, in the early fall due to the on-set of molds from decaying plant matter and also due the increase in the transmission of respiratory infections among children returning to school (NJDHSS 2006). While the overall rate of hospital asthma admissions is lowest in the summer, studies conducted in locations outside of Virginia have estimated that summer time ED admissions are likely to be 28% higher on summer days with elevated ozone concentrations (Weisel and Cody 1995). Further study that distills the effects of multiple triggers of asthma exacerbation needs to be conducted in Virginia to determine the true relationship between hospital admission and ambient air quality.

The VDPH pilot project also documented the hospital admission rate for asthma as a primary diagnosis among different age groups. Their data analysis showed that children under the age of 5 have the highest admission rate for asthma followed by children between the ages of 5 and 9 (VDH 2012). They also showed that the elderly, especially those over 70 years old, had an elevated incidence of asthma admissions (VDH 2012). This suggests that those most at risk for hospital admission due to asthma are likely the young and old in the population. By extension, an argument could be made that these are also the most at risk from the adverse effects of poor ambient air quality. Differences in asthma admission rates are noted between the years 2008 (high ozone year) and 2009 (low ozone year) in Virginia but it is variable, with 0-4 year olds having a higher rate in 2008 versus 2009 and 5-9 year olds having a higher rate in 2009 versus 2008 (VDH 2012). One could speculate that the rate among school age children is more influenced by triggers like respiratory infections and toddlers who are not yet attending school may have their rates more strongly impacted by ambient air quality triggers. A more detailed investigation of this data is warranted.

SUMMARY

This secondary data analysis helped to demonstrate several characteristics about the condition of Virginia's ambient air quality and factors that impact this quality. The large increase in use of natural gas for energy in Virginia will likely contribute to improved air quality. The national trend in decreasing fuel efficiency for popular long wheelbase vehicles, such as SUVs and light trucks, will likely negatively impact all states, including Virginia. Some additional improvements that may contribute to better air quality in Virginia could include an enhanced focus on better production and consumption of renewable energy, consideration of vapor recovery systems on automobile fueling stations throughout the entire state, emissions inspections for vehicles in Virginia, and additional focus on HAP emission from electric utilities to reduce the metal content of fuels burned.

In addition, Virginia is generally in compliance with the NAAQS for all criteria pollutants with the exception of ozone. Days with strong sunlight and higher temperatures will represent the highest likelihood of elevated ozone concentrations. Although there have been exceedances of the ozone standard between April and October, the peak months having ozone violations in Virginia have been June through August between 9 am and 7 pm. Additional research investigating ozone and respiratory health in Virginia is warranted. In addition, this secondary analysis demonstrated that although weather patterns significantly impact ozone exceedance days, continued focus on ozone precursors will likely improve attainment with the ozone NAAQS. Health data support the need for further analysis and detailed study, however, it appears that the very young (0-4 years of age) and the elderly (>65 years of age) may be the most susceptible to the adverse effects of poor air quality. A comprehensive plan should also be in place to minimize the risks associated with wildfires since they occur occasionally in the Southeastern area of Virginia. During these wildfire events, it is important to make information widely available to residents in areas that may be impacted, such as Hampton Roads.

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