EASTERN HEMLOCK CONSERVATION PLAN

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PENNSYLVANIA DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES
BUREAU OF FORESTRY

COMPILED BY:

MARK FAULKENBERRY Ph.D.
DONALD A. EGGEN Ph.D.
ELLEN SHULTZABARGER

pennsylvania
DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES

Executive Summary

With its rich history in the state's economy and its importance in riparian ecosystems, it is fitting that eastern hemlock (*Tsuga canadensis*) is the state tree of Pennsylvania. In recent years, eastern hemlock has been threatened by a non-native insect, the hemlock woolly adelgid (*Adelges tsugae*). In an effort to conserve eastern hemlock in Pennsylvania the Bureau of Forestry has developed a conservation plan for the species.

The purpose of this plan is to provide a sustainable conservation strategy for eastern hemlock, integrating all available information regarding the species and its associated threats into a comprehensive and science-based approach. The information provided is not solely meant for State Forests and is equally applicable to public and private land. Although written for a broad audience, citations are provided throughout the document for those wishing to further explore any topics covered. The document is organized into three main sections:

1. Eastern hemlock biology, life history, and significance
2. Stressors, threats, and control tools
3. Conservation strategy for eastern hemlock in Pennsylvania

Private landowners will find the majority of the conservation strategy applicable, with only a few objectives specific to public land. Landowners can follow the hemlock conservation strategy by assessing the extent and health of hemlock on-site, prioritizing hemlock for treatment, surveying and monitoring hemlock health and pests, conducting appropriate insecticide treatments, and documenting and reporting any hemlock that appears resistant to hemlock woolly adelgid.

This conservation plan will be periodically updated and evaluated as new information becomes available.

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Introduction

Eastern hemlock (*Tsuga canadensis*), the state tree of Pennsylvania, has a long history with the Commonwealth. Although first recognized for its commercial value to tanneries, it is now seen as a vital component in many riparian areas. As a foundation species for these areas, eastern hemlock influences countless processes affecting stream quality and site conditions, and provides habitat or food to a wide range of plants and animals. Eastern hemlock is facing a critical threat from the non-native hemlock woolly adelgid (HWA) (*Adelges tsugae*), and without intervention, most trees in natural settings will die. Because of the difficulty in controlling HWA in forested settings, even intervention will not prevent many hemlocks from dying or their niche being reduced to a fraction of what it was “pre-infestation”. Although HWA is difficult to treat and there are challenges in protecting hemlock stands not yet affected, conservation of this species is still possible. Through a concerted, comprehensive effort, there is an opportunity to save eastern hemlock from widespread elimination. A strategy focusing on both short-term (chemical control) and long-term (biological control, host resistance, site regeneration) management techniques and an incorporation of extensive field investigation and site prioritization has the best chance for success.

The Bureau of Forestry is the Commonwealth’s lead forestry agency, managing 2.2 million acres (~890,000 ha) of State Forest lands through sound ecosystem management, and providing guidance and technical assistance on forest management to private landowners (three fourths of forest ownership in the state). One of the manners in which the Bureau accomplishes its mission of “ensuring the long-term health, viability, and productivity of the Commonwealth’s forests and conserving native wild plants” is through protection of private and public forestlands from damage by insects, disease, and other agents. Adhering to this mission, the Bureau has developed a conservation plan for eastern hemlock.

The purpose of this plan is to provide a sustainable conservation strategy for eastern hemlock, integrating all available information regarding the species and its associated threats into a comprehensive and science-based approach.

I. Eastern Hemlock

Hemlock Biology/Life History

The genus *Tsuga*, a member of the pine family (Pinaceae), was once widely distributed throughout North America, Europe, and Asia from the Late Cretaceous (99-65 million years ago) to approximately 1.5 million years ago (i.e., the Plio-Pleistocene), with 24 described species, 15 of these extinct. *Tsuga* now consists of nine existing species, four native to North America and five native to Asia. [1, 2] The North American species are split, with eastern hemlock and Carolina hemlock (*Tsuga caroliniana*) occurring in the east, and mountain hemlock (*Tsuga martensiana*) and western hemlock (*Tsuga heterophylla*) native to the west. [3]

The native range of eastern hemlock in the United States is from New England and New York down the Appalachian Mountains to northern Georgia and Alabama. It is typically limited to regions with cool humid climates, and moist to very moist soils with good drainage. [4]

In Pennsylvania, eastern hemlock commonly occurs on steep

[1] As cited in (Lepage, 2003)
[2] (Lepage, 2003)
[3] (Burns & Barbara, 1990)
[4] (Burns & Barbara, 1990)

north or east facing slopes along streams in the southern portion of the state, and in the northern portion of the state homogenous stands of the species can be found in moist ravines, stream valleys, wooded swamps, and steep slopes. Hemlock is also associated with the northern hardwood forest type, and commonly occurs with white pine, beech, birch, maple, and to a lesser degree, oaks. It often occurs as an understory or mid-story component in mixed hardwood stands.

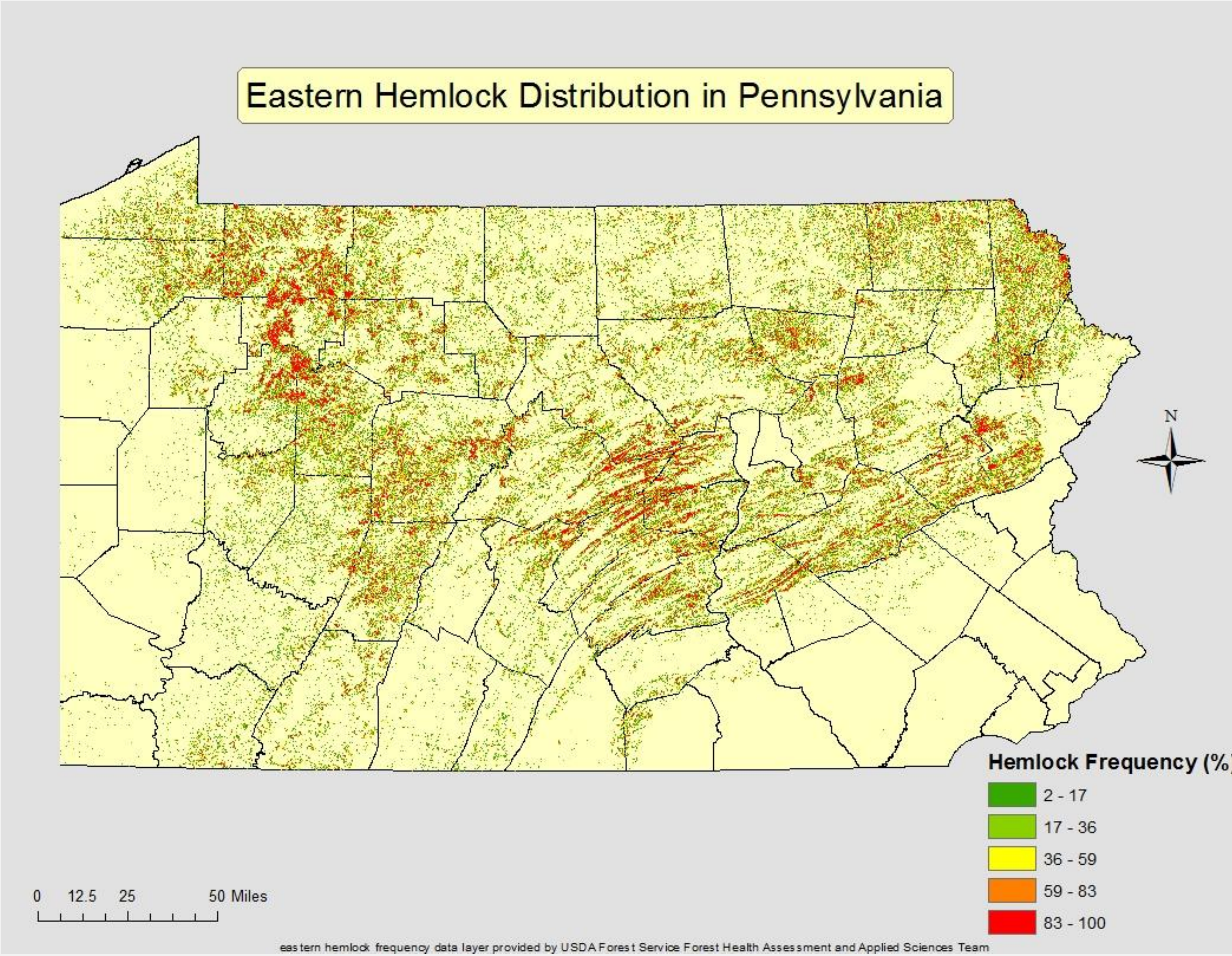
To facilitate management, all Bureau of Forestry lands in Pennsylvania have been classified (i.e., assigned a stand type) by the dominant vegetation type occurring in each area. Of the 38 stand types assigned, eight can contain a significant hemlock component. These are:

- Hemlock (White Pine) Forest
- Dry White Pine (Hemlock) - Oak Forest
- Hemlock (White Pine) - Northern Hardwood Forest
- Hemlock (White Pine) - Red Oak – Mixed Hardwood Forest
- Hemlock - Tuliptree -Birch Forest
- Hemlock - Rich Mesic Hardwood Forest
- Hemlock Palustrine Forest
- Hemlock – Mixed Hardwood Palustrine Forest

A full description of all eight hemlock associated stand types can be found in the Appendix. The table below summarizes the acreage of each hemlock stand type by State Forest District. The map that follows illustrates eastern hemlock distribution throughout Pennsylvania. The methodology used to create the hemlock distribution data can also be found in the Appendix.

Acreage of Hemlock Stand Types for Each State Forest District

State Forest District	Dry White Pine (Hemlock) - Oak	Hemlock (White Pine) - Northern Hardwood	Hemlock (White Pine)	Hemlock - Rich Mesic Hardwood	Hemlock (White Pine) - Red Oak - Mixed Hardwood	Hemlock - Tulip Tree - Birch	Hemlock - Mixed Hardwood Palustrine	Hemlock Palustrine
Michaux	1,067		860	126	1,203	59	305	95
Buchanan	564		160	101	269	275		
Tuscarora	868	238	167		3,060	233	16	5
Forbes		31	6	204	253	90	18	
Rothrock	2,269	512	988	20	3,190	504	106	
Gallitzin		219			35	34		
Bald Eagle	4,613	5,813	1,046		1,718	1,141	852	554
Clear Creek	334	118	325	52	1,330		16	3
Moshannon	794	2,404	211	49	1,133	133	73	18
Sproul	3,128	2,872	3,062	25	2,591	351		
Lackawanna			109					
Tiadaghton	3,032	2,867	1,543		1,067	8	54	85
Elk	2,217	8,816	429		982		247	116
Cornplanter					117		10	
Susquehannock	158	2,111	1,057		729		1,533	354
Tioga	718	3,869	269		868		563	1,074
Weiser	254	33	44	26	253	13	427	
Delaware	721	37	604	346	87		2,700	531
Loyalsock	95	6,420	574		794	216	525	96
Grand Total	20,832	36,360	11,454	948	19,678	3,058	7,445	2,930


Eastern Hemlock Distribution in Pennsylvania
N
Hemlock Frequency (%)
2 - 17
17 - 36
36 - 59
59 - 83
83 - 100
0 12.5 25 50 Miles
eastern hemlock frequency data layer provided by USDA Forest Service Forest Health Assessment and Applied Sciences Team

Eastern hemlock is monoecious, meaning male and female flowers occur in separate clusters on the same branch. Flowering and pollination times range from late April to early June, and fertilization takes about six weeks. Pollen and seeds are wind dispersed, with seed dispersal extending from mid-October through winter. Cones begin opening in mid-October, and can persist on the tree for a little over a year. Cone production of eastern hemlock is among the highest for conifers in the eastern United States and trees over 450 years old have been reported to produce cones. Seed viability is usually low, with germination rates of less than 25%. Desiccation can easily damage eastern hemlock seed, and post germination drying causes high root mortality. Seedlings develop slowly for the first two years until their roots reach a greater soil depth, and are then not as susceptible to surface soil desiccation. In a typical eastern hemlock stand, overstory trees average 400 years in age, are 35-40 inches (89 to 102 cm) in diameter, and over 98 feet (30 m) tall. Eastern hemlock is the most shade tolerant tree species in North America, and is capable of withstanding suppression from overstory trees for 400 years. [5]

Ecological Significance

Eastern hemlock provides vital winter cover habitat for numerous wildlife species, including deer, ruffed grouse, and wild turkey, and the seeds provide a winter food source for birds including, juncos, pine siskins, and crossbills, in addition to small mammals such as mice, voles, and red squirrels. [6, 7, 8] Birds such as the blue-headed vireo, black-throated green warbler, blackburnian warbler, dark eyed junco, hermit thrush, magnolia warbler, Swainson’s thrush, Acadian flycatcher, hermit thrush, yellow-bellied flycatcher, winter wren, solitary vireo, and the blackpoll warbler are strongly associated with eastern hemlock. [9, 10, 11, 12]

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[5] (Burns & Barbara, 1990)
[6] (Burns & Barbara, 1990)
[7] (Rhoads & Block, 2005)
[8] (Yamasaki, DeGraaf, & Lanier, 2000)
[9] (Yamasaki, DeGraaf, & Lanier, 2000)
[10] (Gross, 2009)
[11] (Brown & Weinkam, 2014)
[12] (Sargent, Yeany, Michel, & Zimmerman, 2017)

White-tailed deer (*Odocoileus virginianus* Zimmermann), snowshoe hare (*Lepus americanus* Erxleben), and cottontail (*Sylvilagus* spp.) will all browse eastern hemlock, and porcupines will occasionally chew on the bark. [13] Brook trout (*Salvelinus fontinalis* Mitchill) were found to be three times more likely to occur and four times more abundant in streams draining hemlock forests than those draining hardwood forests. [14] Greater spider abundance and species richness have been observed in eastern hemlock versus deciduous tree canopies, and hemlock also appears to support up to 215 species of insects and 33 species of mites, all of which serve specific roles in food web dynamics. [15, 16] The loss of the coniferous hemlock and its replacement by hardwood trees may lead to changes in terrestrial arthropod biodiversity (e.g., insects, spiders, centipedes, millipedes) as species associated with hemlock dominated ecosystems decline and those associated with hardwoods increase. [17]

Eastern hemlocks influence nutrient and water cycling on-site, likely altering local ecosystem conditions if removed. These include soil temperature, soil moisture, water flow increases to streams, greater stream level oscillations, nitrate increases to streams, and earlier snow melt. [18, 19, 20, 21] The decline of hemlock within watersheds, as with trees in general, will result in less evapotranspiration and an increase in stream discharge. Forested watersheds in the northeastern United States are an important source of water for the region. [22] Maintaining watersheds in a forested condition can reduce the impacts of hemlock decline.

The loss of hemlock would also affect the composition of habitats it currently dominates throughout the eastern United States. Sweet birch (*Betula lenta*), American

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[13] (Burns & Barbara, 1990)
[14] (Snyder, Young, Ross, & Smith, 2005)
[15] (Mallis & Rieske, 2011)
[16] (Turcotte, 2008)
[17] (Rohr, Mahan, & Kim, 2009)
[18] (Jenkins, Aber, & Canham, 1999)
[19] (Yorks, Jenkins, Leopold, Raynal, & Orwig, 2000)
[20] (Ford & Vose, 2007)
[21] (Cessna & Nielsen, 2012)
[22] (Kim, et al., 2017)

beech (*Fagus grandifolia*), and river birch (*Betula nigra*) increases have been observed in stands where HWA induced mortality has occurred, and red maple (*Acer rubrum*) is predicted to increase in the longer term. [23, 24, 25, 26 27] American beech and birch species took similar advantage from a major die off of eastern hemlocks in northeastern North America approximately 5,500 and 6,000 years ago. [28, 29] Replacement of eastern hemlock with sweet birch may have implications to the water balance of these ecosystems due to increased water use observed for sweet birch, especially during the growing season. This would affect the flow of water to streams and groundwater, possibly leading to the drying-up of small streams that previously maintained light or moderate flow during the growing season. [30] The replacement of hemlock by birch and other hardwood species will likely alter several local ecosystem functions (e.g., litter decomposition, nutrient exchange), in addition to changing the composition of stream macroinvertebrate communities, affecting the trophic structure of fish and invertebrates in that habitat. [31, 32, 33, 34, 35, 36] Since hardwoods expose streams to greater sunlight (even in leaf-on conditions) this changeover may increase stream temperatures, in addition to periphyton (i.e., algae) growth, further illustrating potential trophic cascade and compositional changes. [37, 38, 39]

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[23] (Orwig & Foster, Forest response to the introduced hemlock woolly adelgid in southern New England, 1998)
[24] (Jenkins, Aber, & Canham, 1999)
[25] (Kizlinski, Orwig, Cobb, & Foster, 2002)
[26] (Cessna & Nielsen, 2012)
[27] (Krebs, Pontius, & Schaberg, 2017)
[28] (Fuller, 1998)
[29] (Oswald & Foster, 2011)
[30] (Daley, Phillips, Pettijohn, & Hadley, 2000)
[31] (Snyder, Young, Ross, & Smith, 2005)
[32] (Willacker, Sobezak, & Colburn, 2009)
[33] (Stadler, Muller, & Orwig, 2006)
[34] (Cobb, Species shift drives decomposition rates following invasion by hemlock woolly adelgid, 2010)
[35] (Webster, Morkeski, Wojculewski, Niederlehner, & Benfield, 2012)
[36] (Ross, et al., 2003)
[37] (Vannote, Minshall, Cummins, Sedell, & Cushing, 1980)
[38] (Ellison, et al., 2005)
[39] (Rowell & Sobczak, 2008)

Economic Significance

In Pennsylvania, throughout the eighteenth and nineteenth centuries, large amounts of eastern hemlock were harvested for bark and used for tanning leather. The volume of bark harvested was so high that it was more economical for companies to establish tanneries in or near the forests than to incur the considerable costs associated with transportation of the resource. [40]

Hemlock provides several non-market values (e.g., wildlife habitat, recreation, landscape aesthetics) that contribute to its economic value, and the amount of money that individuals would be willing to pay in order to avoid losing these non-market values should be considered when determining the economic benefit of this species. [41]

Cultural Significance

Eastern hemlock provided medicinal uses to Native Americans, including an astringent for stopping blood flow from wounds and promote healing, and a plaster from boiling and pounding the inner bark, in addition to providing a consumptive use to early European explorers and settlers of eastern North America, who used its young branch tips for tea. The early settlers also used eastern hemlock bark to create a reddish-brown dye for wool and cotton. [42]

II. Stressors / Threats & Control Tools

Non-living Stressors and Threats

Eastern hemlock has low fire tolerance, no salinity tolerance, and its shallow rooting system makes it more susceptible to windthrow as stands age. Drought is likely the most severe damaging agent for eastern hemlock, and has been suggested as the main driver for two large scale population crashes of eastern hemlock in northeastern North

[40] (Rhoads & Block, 2005)
[41] (Holmes, Aukema, Von Holle, Liebhold, & Sills, 2009)
[42] (Rhoads & Block, 2005)

America approximately 5,500 and 6,000 years ago. [43, 44, 45] The declines were rapid, taking less than 70 years, and took hemlock roughly 1,500 to 2,000 years to recover. [46, 47] In the northeastern United States annual temperatures have increased an average of 0.14 °F (0.08 °C) per decade for the last century. This rate has nearly tripled over the last thirty years to 0.45 °F (0.25 °C) annually, and predicted to increase 5.22-9.54 °F (2.9-5.3 °C) by 2070 to 2099, depending on the level of emissions used in the climate model (5.22°F; 2.9 °C = lowest emissions level / 9.54 °F; 5.3 °C = highest emissions level). [48] Currently hemlock woolly adelgid populations are limited from greater expansion in the northernmost range of eastern hemlock due to their lack of cold tolerance (i.e., widespread winter induced mortality) and temperature increases and the occurrence of mild winters in the northeastern United States may allow for the insect to expand its range to all eastern hemlock. [49, 50]

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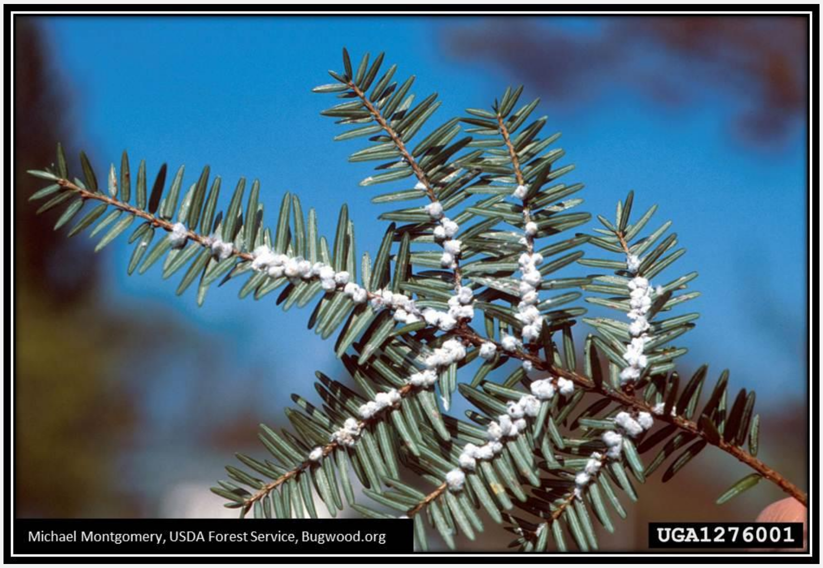
[43] (Burns & Barbara, 1990)
[44] (USDA Natural Resources Conservation Service, n.d.)
[45] (Oswald & Foster, 2011)
[46] (Fuller, 1998)
[47] (Oswald & Foster, 2011)
[48] (Hayhoe, et al., 2006)
[49] (Paradis, Elkinton, Hayhoe, & Buonaccorsi, 2008)
[50] (Dukes, et al., 2009)

Living Stressors and Threats

Hemlock Woolly Adelgid

Hemlock woolly adelgid was first reported in the eastern United States in Richmond, Virginia in the early 1950s, likely originating from a population in southern Japan. [51, 52, 53] Since its introduction, HWA has spread to 17 states in the eastern U.S., with widespread hemlock mortality reported in Tennessee, North Carolina, West Virginia, Virginia, Pennsylvania, Connecticut, and New Jersey. [54, 55, 56, 57] Based on two separate estimates from 1951-2006 and 1990-2006, the average rate of spread of the adelgid is 7.6-7.8 miles (12.3-12.5 km) a year, respectively. [58, 59] Although wind, birds, deer, humans, and insects have all been suggested as potential dispersal agents for the insect, wind and birds are probably the main contributors to its spread. [60, 61] Simulations suggest that even light winds are sufficient for rapidly spreading adelgids throughout a stand, and although the majority of



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[51] (Gouger, 1971)
[52] (Souto & Chianese, 1996)
[53] (Havill N. , Montgomery, Yu, Shigehiko, & Caccone, 2006)
[54] (Knauer, Linnane, Shields, & Bridges, 2002)
[55] (Orwig & Foster, Forest response to the introduced hemlock woolly adelgid in southern New England, 1998)
[56] (Skinner, Young, Ross, & Smith, 2003)
[57] (USDA Forest Service, n.d.)
[58] (Evans & Gregoire, 2007)
[59] (Morin, Liebhold, & Gottschalk, 2009)
[60] (McClure, Role of wind, birds, deer, and humans in the dispersal of hemlock woolly adelgid (Homoptera: Adelgidae), 1990)
[61] (Turner, Fitzpatrick, & Preisser, 2011)

dispersal takes place within 82 feet (25 m) of an infested tree, distances of 1312 feet (400 m) are possible. [62] The capability to spread quickly under light winds, coupled with HWA's potential for long range dispersal and ability to persist and become established at low population densities is of significant concern. [63, 64]

The aphid-like insect feeds on the sap of the tree, disrupting the storage and transfer of nutrients, and tree mortality typically occurs within 10 years. [65, 66, 67, 68, 69, 70, 71, 72, 73] It has been suggested that the rapid decline of hemlock to HWA feeding may be due to a systemic hypersensitive response in which affected plant cells are destroyed from the initial sites of infestation, triggering additional cells to be destroyed throughout the tree. [74, 75]

Both of the native hemlock species from the eastern United States, the eastern hemlock and Carolina hemlock, are susceptible to HWA attack, while the native hemlock species in the western United States, the mountain hemlock and western hemlock, are resistant.

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[62] (Turner, Fitzpatrick, & Preisser, 2011)
[63] (Miller-Pierce, Orwig, & Preisser, 2010)
[64] (Turner, Fitzpatrick, & Preisser, 2011)
[65] (McClure, Biology and control of hemlock woolly adelgid, 1987)
[66] (Young, Shields, & Berlyn, 1995)
[67] (McClure, Biological control of hemlock woolly adelgid in the eastern United States, 2001)
[68] (McClure, Biology and control of hemlock woolly adelgid, 1987)
[69] (Young, Shields, & Berlyn, 1995)
[70] (McClure, Biological control of hemlock woolly adelgid in the eastern United States, 2001)
[71] (Orwig, Foster, & Mausel, Landscape patterns of hemlock decline in New England due to the introduced hemlock woolly adelgid, 2002)
[72] (Trotter & Shields, 2009)
[73] (Miller-Pierce, Orwig, & Preisser, 2010)
[74] (Radville, Chaves, & Preisser, 2011)
[75] (Oten, Cohen, & Hain, 2014)

Elongate hemlock scale

Elongate hemlock scale (*Fiorinia externa*) is another non-native insect pest of eastern hemlock in the United States. Originally from Japan, it was first discovered in the United States in Long Island, New York in 1908. [76, 77] The elongate hemlock scale is established in 14 states in the eastern United States. [78] Although elongate hemlock scale also feeds on sap within the tree (like HWA), its population densities are slower to build and its negative effects to eastern hemlock are slower acting than those of HWA. Feeding by the scale has not been shown to induce the damaging hypersensitive response in hemlocks seen from HWA feeding. [79, 80, 81] Interestingly, hemlock health of individuals infested with elongate hemlock scale and HWA together have been shown to decline slower than those infested with the HWA alone, although more research is needed to determine if this is due to a simple reduction in HWA density/feeding, or more complex causes. [82] It's also been proposed that feeding by HWA may allow elongate hemlock scale to reach damaging levels in hemlock stands, thus hastening the decline of already weakened trees. [83]

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[76] (Ferris, 1942)
[77] (Abell & Driesche, 2008)
[78] (Lambdin, et al., 2005)
[79] (Abell & Driesche, 2008)
[80] (Miller-Pierce, Orwig, & Preisser, 2010)
[81] (Preisser & Elkington, Exploitative competition between invasive herbivores benefits a native host plant, 2008)
[82] (Preisser & Elkington, Exploitative competition between invasive herbivores benefits a native host plant, 2008)
[83] (Danoff-Burg & Bird, 2000)

Cryptomeria scale

Cryptomeria scale (*Aspidiotus cryptomeriae*), an insect native to Japan, can be a pest of eastern hemlock in the mid-Atlantic United States, although it currently appears to be more of a problem with Christmas tree plantations. [84, 85, 86, 87]

Shortneedle conifer scale

Shortneedle conifer scale or shortneedle evergreen scale (*Nuculaspis tsugae*) is a scale insect pest for eastern hemlocks in the northeastern and mid-Atlantic areas of the United States. Like elongate hemlock scale, hemlock woolly adelgid, and cryptomeria scale, it was also introduced to the eastern United States from Japan. This scale is considered an occasional but serious pest of eastern hemlock. [88, 89, 90]

[84] (Stimmel, 1986)
[85] (Gardosik, 2001)
[86] (Raupp, et al., 2008)
[87] (Penn State Cooperative Extension, n.d.)
[88] (McClure, Adelgid and scale insect guilds on hemlock and pine, 1991)
[89] (Miller & Davidson, 2005)
[90] (Raupp, et al., 2008)

Hemlock looper

Hemlock looper (*Lambina fiscellaria*) is a native butterfly to North America and its larvae can be serious pests of eastern hemlock, with severe defoliations causing tree mortality after one year. [91, 92] Eastern hemlock's own chemical plant defenses appear to be more specialized for combating leaf-eating insects, such as loopers, than those of sap feeding insects such as the HWA and elongate hemlock scale. [93, 94] This may be due to the fact that the hemlock looper is native, allowing for coevolution of the eastern hemlock's plant defenses with the insect. Hemlock looper has been linked to a major crash of eastern hemlock populations in northeastern North America approximately 5,500 years ago. [95, 96] There has been some dispute over whether the looper was the main driver of the decline or an exacerbating factor. [97]

Hemlock borer

Hemlock borer (*Melanophila fulvoguttata*) is a native beetle of North America that is considered a secondary pest of eastern hemlock, typically becoming established after an initial disturbance (e.g., drought, other insect pests, excessive openings) weakens the trees. The larval or immature stage of the insect is considered the pest stage, in which it feeds on plant sap. Indicators of attack from hemlock borer include 0.12 inch (3 mm) diameter oval holes in the bark and larval galleries beneath the outer bark. [98]

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[91] (USDA Forest Service)
[92] (Johnson & Lyon, 1988)
[93] (Lagalante, Montgomery, Calvosa, & Mirzabeigi, 2007)
[94] (Miller-Pierce, Orwig, & Preisser, 2010)
[95] (Bhiry & Filion, 1996)
[96] (Fuller, 1998)
[97] (Oswald & Foster, 2011)
[98] (USDA Forest Service)

Spruce spider mites

In addition to other conifer tree species, spruce spider mites (*Oligonychus ununguis*) do commonly feed on eastern hemlock. The spider-like arthropods feed on plant sap, causing foliage to look bronzed or bleached, and premature leaf drop can occur. In cases where high populations are present, webbing created by the mites can be seen surrounding needles. The mites thrive in cool weather or spring and fall, and become dormant during the summer. [99]

Armillaria root rot

Armillaria root rot is a fungal disease that affects hundreds of species of woody plants, including forest and shade trees. *Armillaria* actually refers to several different species of fungi, with *Armillaria gallica* and *Armillaria solidipes* being the most common species found in eastern hemlock forests in the northeastern United States. [100] The fungus primarily spreads through root-to-root transmission, and common symptoms include reduced growth, yellowish leaves smaller than normal, and dieback of twigs and branches, with death of the tree being either sudden or gradual. [101] The *Armillaria* species most often occurring in eastern hemlock forests in the northeastern United States are normally not considered pests, but this may change as the health of these forests decline due to HWA. [102] Eastern hemlock normally exhibit resistance to *Armillaria*, but when weakened by other stressors they are unable to fight off the pathogen, and can die more rapidly. [103, 104]

Fabrella needle blight

Fabrella needle blight (*Fabrella tsugae*) is a leaf disease of eastern hemlock. It was first discovered in Pennsylvania in 1974 and is now reported in approximately 35 counties in the state. The pathogen of the disease is a fungus that enters through the stomates, eventually causing needles to turn brown and drop off in late summer,

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[99] (Penn State Cooperative Extension, 2002)
[100] (Brazee & Wick, 2011)
[101] (Agrios, 2005)
[102] (Brazee & Wick, 2011)
[103] (Brazee & Wick, 2011)
[104] (Wargo & Fagan, 2000)

particularly in the lower crown. [105, 106] Damage from the disease is much more significant during prolonged cool wet periods in the spring into the summer. Some twig and branch dieback in the lower crown may be evident but usually is not lethal to the tree. However, when other stress factors including HWA, or drought come into play, significant dieback and mortality is likely. [107]

Sirococcus tip blight

Sirococcus tip blight (*Sirococcus tsugae*) was been observed in the eastern United States in Maine in 2006. The fungal disease affects young shoots and twigs less than a year old, causing them to droop, withering and browning within weeks. [108], [109] Needle loss and shoot death occur through the summer. Cool, wet Springs create ideal conditions for the pathogen to increase.

Hemlock twig rust

Hemlock twig rust (*Melampsora farlowii*) is a disease common to eastern hemlock. It rarely causes concerning damage to hemlock in forests, and is known more as a pest of commercial tree nurseries. Wet years favor the establishment of the fungus that causes hemlock twig rust, and it is more common in the lower crown of the tree. New growth is targeted, causing the shoots to lose their needles and curl up. Infested trees usually do recover. [110]

Control Tools

Three main tools utilized for controlling hemlock pests and impacts are:

1. Insecticides
2. Biological control agents
3. Cultural practices

This plan addresses each and in the subsequent chapter presents a conservation strategy incorporating these tools into management.

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[105] (Forestry)
[106] (Agrios, 2005)
[107] (Forestry)
[108] (Sinclair & Lyon, 2005)
[109] (USDA Forest Service, 2010)
[110] (Kenaley & Hudler, 2010)

Insecticides

Horticultural oils and insecticidal soaps

Horticultural oils and insecticidal soaps are typically non-toxic and kill the insect by smothering it. Trees must be covered as much as possible with these products for maximum efficacy and treatments are likely needed annually. Treatments should be applied from August until frost, to target when the insect is susceptible and to prevent leaf burn from the hot weather of summer. [111] These products are not appropriate for treating very large hemlock trees. Although horticultural oils or insecticidal soaps are not able to sufficiently control some armored scales (a group that includes the three scale pests of hemlock), research has shown horticultural oil to be effective against elongate hemlock scale. [112, 113] Armored scales derive their name from the hard secretions they produce that protect them from many insecticides and natural enemies. [114]

Neonicotinoids

Imidacloprid, dinotefuran, and acetamiprid all belong to the same insecticide class (neonicotinoids), and have a similar mode of action for killing insects. They are all systemic insecticides, meaning the chemicals are taken up by the plant and transported through its tissues. Due to this characteristic, treatments can be made via leaves, soil, or bark. Soil and bark treatments are recommended in forested areas due to reduced likelihood of negative effects to non-target organisms and water resources. Please follow all label requirements for any insecticide.

Imidacloprid

Imidacloprid is one of the most widely used insecticides in the world, and it is effective against a wide variety of insects, including hemlock woolly adelgid. [115] Although imidacloprid has been detected downstream from known treatment sites for HWA, concentrations were well below the benchmark for chronic toxicity to aquatic invertebrates set by the U.S. Environmental Protection Agency. [116] While this should not

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[111] (North Carolina Cooperative Extension Service, 2009)
[112] (Smith, Cowles, & Hiskes)
[113] (Raupp, et al., 2008)
[114] (Smith, Cowles, & Hiskes)
[115] (Silcox, 2002)
[116] (Benton E. , Grant, Mueller, Webster, & Nichols, 2016)

be seen as a free-pass for imidacloprid, it should alleviate concerns from land managers that are weighing stream impacts of treatments versus mortality of untreated hemlock. In the previous edition of the Hemlock Conservation Plan, a formula was provided to determine the lowest dose of imidacloprid possible to control around 90% of HWA and it is still accurate. [117] Research now suggests that concentrations of imidacloprid found in hemlock can vary by tree diameter. While applying imidacloprid concentrations uniformly regardless of tree size is effective, it may waste limited resources, since some trees are receiving more insecticide than necessary to control HWA. A diameter based approach has been developed, optimizing treatment rates by tree size.

Diameter based dosage can be calculated with the following formula:

> Optimum dose = $0.3 \times \log(dbh)^{1.745}$ (where dosage is grams of the active ingredient imidacloprid per 2.5 cm of trunk dbh, and dbh is measured in centimeters). [118]

Imidacloprid has been reported to be more slow acting than dinotefuran for control of HWA, but it also provides multi-year control of the insect. [119, 120] Due to its lack of mobility through the plant, imidacloprid is not considered to be effective at controlling armored scales, a category in which all three of the mentioned scale pests of hemlock fall. [121] Although there has been research reporting control of elongate hemlock scale with imidacloprid, more extensive studies are needed before any additional conclusions can be made regarding its efficacy at controlling this insect, and likely all three of these armored scale pests. [122]

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[117] (Cowles R. , 2009)
[118] (Benton E. , et al., 2016)
[119] (Silcox, 2002)
[120] (Cowles, Montgomery, & Cheah, Activity and residues of imidacloprid applied to soil and tree trunks to control hemlock woolly adelgid (Hemiptera: Adelgidae) in forests, 2006)
[121] (Smith, Cowles, & Hiskes)
[122] (Raupp, et al., 2008)

Dinotefuran

Dinotefuran is highly water soluble, facilitating its uptake and distribution through plants. [123] Research has shown it to be more rapidly taken up by hemlock trees than imidacloprid, and almost complete mortality of HWA has been reported 50 days after treatments were applied. [124, 125, 126] This insecticide is known for its quick knockdown ability, but not as long lasting as imidacloprid, and control past the second year of treatment is not likely. [127, 128] Also, due to the greater mobility of this insecticide through the plant, it is also considered to be effective against armored scales, hence the three scale pests of hemlock can be controlled. [129] Some research did find dinotefuran trunk injections ineffective at controlling elongate hemlock scale however. [130]

[123] (Cowles, Montgomery, & Cheah, Activity and residues of imidacloprid applied to soil and tree trunks to control hemlock woolly adelgid (Hemiptera: Adelgidae) in forests, 2006)
[124] (Corbel, Duchon, Morteza, & Hougard, 2004)
[125] (Cowles, Montgomery, & Cheah, Activity and residues of imidacloprid applied to soil and tree trunks to control hemlock woolly adelgid (Hemiptera: Adelgidae) in forests, 2006)
[126] (Faulkenberry, Culin, Jeffers, Riley, & Bridges, 2012)
[127] (Cowles & Lagalante, Activity and persistence of systemic insecticides for managing hemlock woolly adelgids, 2009)
[128] (Joseph, Braman, Quick, & Hanula, 2011)
[129] (Smith, Cowles, & Hiskes)
[130] (Raupp, et al., 2008)

Biological Control Agents

Biological control (coupled with genetic resistance) is the most viable alternative for HWA management in forested settings. Although insecticides are effective at controlling the pest, it is not economically sustainable to periodically treat entire forests or stands as would be necessary. Although considerable funding and effort goes into research and rearing of biological control agents, little investment is needed once they become established, are reproducing in the field, and their populations are high enough to control the pest. If this process is successful it would present a sustainable control tool for HWA.

Due to a lack of well-suited native or previously introduced insects that either fed on or parasitized HWA, researchers had to search elsewhere for non-native predatory insects and parasitoids that could be introduced as biological control agents. [131] It should be noted that there are three different types of biological control. All but one of the cases described below refer to "classical biological control", in which an organism is introduced to an area where it is not native, in hopes to combat a specific pest of interest.

Sasajiscymnus tsugae

One early potential biological control candidate discovered (in Japan) was *Sasajiscymnus tsugae* (formerly *Pseudoscymnus tsugae*). [132, 133, 134] This beetle had several qualities which made it a promising candidate for biological control, including a life cycle highly synchronized with HWA, multiple generations per year, and the ability to be mass reared in an insectary. From 1999-2011, more than 2.5 million *S. tsugae* beetles have been reared and released in 15 states in the eastern United States. [135] Establishment and spread of these beetles has been documented at some release sites, but field recoveries as well as impacts against HWA have been inconsistent. [136] Although

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[131] (Wallace & Hain, 2000)
[132] (Cheah & McClure, 1996)
[133] (McClure, Biological control of hemlock woolly adelgid in the eastern United States, 2001)
[134] (Zilahi-Balogh, Loke, & Salom, A review of world wide biological control efforts for the family Adelgidae, 2002)
[135] (Onken & Reardon, 2011)
[136] (Onken & Reardon, 2011)

large scale rearing and release of this agent is ending, its presence and impacts against the adelgid will continue to be monitored. [137]

Laricobius nigrinus

Laricobius nigrinus, a native predatory beetle to the Pacific Northwest, is a potential candidate for biological control of the adelgid. This beetle lays its eggs on and feeds on HWA, and its life cycle is highly synchronized with that of the insect pest. [138, 139, 140] Over 150,000 *L. nigrinus* have been released in 11 states (in plant hardiness zones 6a and 6b), and have successfully established to the point where they can be collected from their original sites and released in other locations. [141]

Laricobius osakensis

Laricobius osakensis is another beetle that was discovered (in Japan) in 2005, has been shown to consume more HWA and produce more offspring than *Laricobius nigrinus*, and is well suited to adapt to the wide climate ranges it will encounter in the United States. Another interesting fact about this beetle is that it is from the same region in Japan as the original HWA population introduced to the eastern United States, hinting at a closer link to the insect pest, due to coevolution. *L. osakensis* was approved for release from quarantine in the United States in 2010, with initial releases in 2012, and work toward large scale operational releases are underway. [142, 143]

Leucopis

Two fly species that have been identified are *Leucopis argenticollis* and *Leucopis piniperda*. These insects were collected from HWA infested western hemlock in Washington and Oregon from 2005-2006. More research is needed on various biological

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[137] (Havill, Vieira, & Salom, Biology and Control of Hemlock Woolly Adelgid, 2014)
[138] (Zilahi-Balogh, Loke, & Salom, A review of world wide biological control efforts for the family Adelgidae, 2002)
[139] (Zilahi-Balogh, Humble, Lamb, Salom, & Kok, 2003)
[140] (Zilahi-Balogh, Kok, & Salom, Host specificity of Laricobius nigrinus Fender (Coleoptera: Derontidae), a potential biological control agent of the hemlock woolly adelgid, Adelges tsugae Annand (Homoptera: Adelgidae), 2003)
[141] (Onken & Reardon, 2011)
[142] (Onken & Reardon, 2011)
[143] (Havill, Vieira, & Salom, Biology and Control of Hemlock Woolly Adelgid, 2014)

and ecological aspects of these insects, but promising signs include a highly synchronized life cycle to HWA, with two generations of fly larvae (which is the feeding stage) being most abundant in both times of the year that HWA eggs are produced. Similarly related species of flies have also been used successfully to control other adelgid species in Hawaii, New Zealand, and Chile. [144]

Cultural Practices

Reducing environmental stresses on hemlock can enable it to better tolerate HWA infestations. Mulching and irrigating during drought are two measures that minimize water stresses on the tree and help maintain its vigor. [145] Silvicultural treatments designed to remove unhealthy hemlocks and enhance vigor of other hemlocks and hardwoods, may help reduce stress and allow hemlocks to better tolerate infestations. Infested trees should not be fertilized with nitrogen, as this will also boost adelgid health and numbers.

[144] (Ross, Gaimari, Kohler, Wallin, & Grubin, 2011)
[145] (Ward, J., Cheah, C., Montgomery, M., Onken, B., Cowles, R., 2004)

III. Conservation Strategy for Eastern Hemlock in Pennsylvania

An integration of the pest management techniques mentioned in previous sections is the most practical and sustainable method for conserving eastern hemlock in Pennsylvania. Hemlock woolly adelgid is currently the largest threat to eastern hemlock in North America. Infestations across the state must be regularly monitored, in order to determine their extent and distribution. Infested sites and individual trees must be prioritized in order of importance for treatments. For areas that will not receive treatments, or are lower priority, thoughts should be given about influencing what species of tree will be replacing hemlock, either through planting or site manipulation.

Several components of the eastern hemlock conservation strategy are made possible through funding from the USDA Forest Service's Hemlock Woolly Adelgid Initiative (e.g., suppression, training and outreach, data reporting, technical support, surveying, biological control). This program was initiated in 2003 and renewed in 2008 and 2014, and has integrated efforts from four federal agencies, 20 state agencies, 24 universities, seven institutions in China and Japan, and over nine private industries. Focus of the program is on rapidly developing and implementing management options to reduce the spread and impact of hemlock woolly adelgid.

Threat 1: Hemlock Pests

Of the hemlock pests mentioned in this document, only HWA, elongate hemlock scale, cryptomeria scale, and shortneedle conifer scale would typically need control. These insects are not native to hemlock forests in eastern North America, lacking a suite of natural predators, parasitoids, pathogens, and plant defenses that would normally keep them in check. The hemlock looper and spruce spider mite are native to North America, and outbreaks will typically be controlled through the natural methods described above. Hemlock borer and *Armillaria* also generally attack weakened or stressed trees, so keeping the trees healthy is the appropriate way to minimize infestations or outbreaks from these organisms.

Strategies for managing insect pests of hemlock should utilize the following suite of components in order to be sustainable.

1. Assessment and Prioritization of Sites

Individuals must perform landscape level hemlock assessments to determine the extent and health of hemlock on their property. Since it is not feasible to treat all hemlock, landowners and land managers must assess their sites and prioritize them for treatment. Several site characteristics will aid in this assessment. The following criteria are meant to aid in determining treatment priority. Landowners and land managers with prime recreational and aesthetic areas are provided with a supplemental set of criteria to consider when identifying high priority sites.

Low Priority Sites	High Priority Sites	High Priority Sites (recreational/aesthetic)
1. areas that have already suffered heavy insect pest induced mortality or decline (~ >70% defoliation)	1. old growth present	1. old growth present
2. hemlock growing in shallow, excessively drained soils are highly susceptible to drought stress	2. potential habitat of refuge for hemlock	2. hemlock of historical or cultural significance
3. hemlock growing on waterlogged soils	3. hemlock providing habitat for species or resources of greatest conservation need	3. areas known for or defined by their characteristic hemlocks
4. sites not easily accessible for treatment	4. hemlock shading exceptional value (EV) streams	4. hemlock in high use areas such as hiking trails or campgrounds

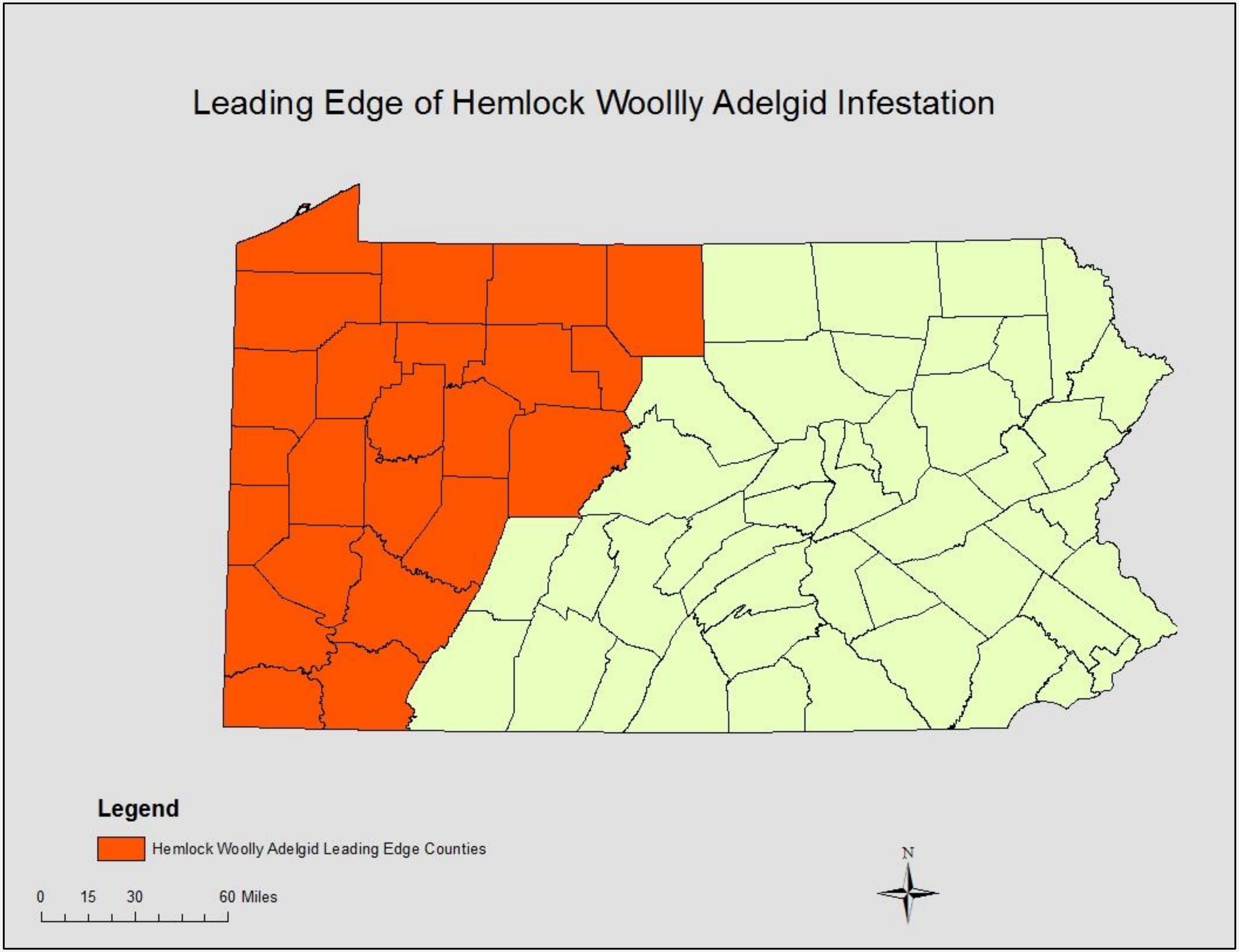
2. Surveying, Monitoring, Mapping

Public lands

It is important that infestations be identified as early as possible. Hemlock stands on Bureau of Forestry land should be mapped and monitored, including presence/absence of pests, and tree health. This will enable efficient delineations and tracking of infestations. The Bureau of Forestry is currently conducting two simultaneous programs for surveying, monitoring, and mapping hemlock and hemlock pest infestations in Pennsylvania.

Permanent plots: In areas where infestations have historic impacts permanent plots are established and inspected for insect pests annually. Data about hemlock health in these plots is collected every three years.

General hemlock surveys: Temporary plots will be established annually to survey for a wide variety of components, including hemlock volume, hemlock health, presence and level of pest infestation (including HWA and elongate hemlock scale). Although general hemlock surveys were originally conducted throughout the range of hemlock in Pennsylvania, they are now confined to the advancing leading edge of the hemlock woolly adelgid infestation (see map below). Hemlock woolly adelgid has existed in these leading-edge counties for a shorter amount of time and is not as widely distributed, so continued presence and absence surveys are needed.


Leading Edge of Hemlock Woollly Adelgid Infestation
Legend
Hemlock Woolly Adelgid Leading Edge Counties
0
15
30
60 Miles
N

Survey and monitoring for Private lands

The Bureau of Forestry can coordinate training on detection and monitoring of other hemlock pests but the following methodology is for surveying and monitoring HWA. Hemlock woolly adelgid needs specific mention due to the level of threat it poses.

Landowners and land managers should inspect their hemlock annually for hemlock woolly adelgid. A good time-frame for inspections is from November to May when the white woolly material produced by the adelgid is more apparent. Ten to 25 trees for a stand of a few acres, and two to four branches per tree should be sufficient. [146] Individuals should note the presence or absence of HWA on each branch inspected. Once the proportion of infested branches reaches a specific threshold, treatments should be applied. It has been noted that hemlock growth is hampered or halted when the proportion of infested branches reaches 45%. [147] [148]

3. Focus Areas

Focus areas are ecologically unique sites for hemlock that are closely monitored for hemlock woolly adelgid and prioritized for HWA control.

Please note that the areas on this list appear in no specific order

A. Cook Forest State Park is located in northwestern Pennsylvania and comprises 11,536 acres (4,668 ha). Old growth forests cover 2,353 acres (890 ha) here, including the "Forest Cathedral", a National Natural Landmark. With the demise of many old growth hemlock in the southern Appalachians, Cook Forest State Park is now home to the greatest concentration of tall old growth hemlock in the eastern United States. John Cook bought the first acreage that eventually became Cook Forest in 1826 and the Cook family continued to acquire additional timber holdings in the area afterwards. Seeing the value in preserving a portion of the land John's son Anthony Cook set aside 3,000 acres (1,214 ha) of the forest for which no timber activities could occur. Efforts from his son Anthony Wayne Cook Jr. eventually led to it being

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[146] (Ward, J., Cheah, C., Montgomery, M., Onken, B., Cowles, R., 2004)
[147] (Ward, J., Cheah, C., Montgomery, M., Onken, B., Cowles, R., 2004)
[148] (Evans R. , 2002)

preserved for the public. The Commonwealth acquired the land to become Cook Forest from Anthony W. Cook in 1928 fulfilling his and his late father's goal of preserving it as a national landmark. This was the first land in the state to have this designation. [149] Hemlock woolly adelgid was found in Cook Forest State Park in the spring of 2013. Chemical treatments were promptly planned and are being carried out by the Bureau of Forestry and Bureau of State Parks.

B. Tionesta Scenic and Research Areas are located in Allegheny National Forest. Over 4000 acres (1,619 ha) of original forest can be found here. With 3000 acres (1,214 ha) of old growth, this makes it the largest intact old growth forest in Pennsylvania. This area is a remnant of the hemlock beech forests that spanned 6 million acres (2,428,114 ha) of the Allegheny Plateau in Pennsylvania and New York, and is designated as a National Natural Landmark. Originally part of a colonial grant to the Holland Land Company, the land changed hands several times, from tanneries in Sheffield Pennsylvania, to the US Leather Company, to the Central Pennsylvania Lumber Company. The last remnant of this uncut hemlock beech forest was purchased by the Federal Government in 1936. In 1940 the northern half of the forest (2018 ac; 817 ha) was designated Tionesta Scenic Area, while the southern half (2113 ac; 855 ha) was designated as Tionesta Research Natural Area. Tionesta Scenic Area is maintained as an undisturbed climax hemlock beech forest. Tionesta Research Natural Area was set aside for research of the ecology of the climax hemlock beech forest, with one study spanning at least 35 years. [150] HWA was discovered in Tionesta Research Natural Area in November, 2013. In addition to the Bureau of Forestry, who conducts the aerial surveys, USDA Forest Service staff at Allegheny National Forest closely monitors this area for HWA and will coordinate any control treatments necessary.

[149] (Cook, 1997)
[150] (Bjorkbom & Larson, 1977)

C. Heart's Content Scenic Area is located within Allegheny National Forest and is another National Natural Landmark. It originated as a 20 acre (8 ha) parcel that the Wheeler and Dusenbury Lumber Company purchased in 1897 and donated to the US Forest Service in 1926. [151] This parcel, which is old growth forest, and surrounding 102 acres (41 ha) were designated as a Scenic Area in 1934. [152] It is an old growth hemlock-northern hardwood forest, with eastern hemlock as the dominant tree in the area followed distantly by American beech (*Fagus grandifolia*), and yellow birch (*Betula alleghaniensis*). [153,154] Hemlock woolly adelgid has not been discovered in Heart's Content. In addition to the Bureau of Forestry, who conducts the aerial surveys, USDA Forest Service staff at Allegheny National Forest closely monitors this area for HWA and will coordinate any control treatments necessary.

D. Snyder Middleswarth Natural Area is a 250 acre (101 ha) old growth forest within Bald Eagle State Forest, and is another National Natural Landmark. Eastern hemlock is the dominant species in the forest, followed by black birch (*Betula lenta*), yellow birch, chestnut oak (*Quercus prinus*), and red maple (*Acer rubrum*). [155] Hemlock woolly adelgid has been reported in this natural area for several years. It was an early release site for biological control, and some of the streamside hemlocks have been treated chemically. Some old growth hemlocks have suffered HWA related mortality in this area. Given that black birch is abundant and well distributed in the area, it's likely that this species will increase in dominance, rapidly taking advantage of the openings created from hemlock mortality. [156]

E. Alan Seeger Natural Area is also located in Rothrock State Forest. It consists of 390 acres (158 ha), the core of which is old growth forest. This 25 acre (10 ha) old growth core was spared from cutting due to a boundary dispute

[151] (Lutz, 1930)
[152] (Management, n.d.)
[153] (Lutz, 1930)
[154] (Whitney, 1984)
[155] (Zawadzkas & Abrahamson, 2003)
[156] (Zawadzkas & Abrahamson, 2003)

between two logging companies and eventually acquired by the Commonwealth and designated a natural area in 1970. [157] Hemlock woolly adelgid has been reported in Alan Seeger Natural Area and chemical treatments have been conducted.

F. Bear Meadows Natural Area is an 890 acre (360 ha) National Natural Landmark in Rothrock State Forest. Within Bear Meadows is a 390 acre (158 ha) boreal bog that it is a remnant of glacial retreat from the Holocene (10,000 years before present) when most northern tree species in the mid-Atlantic migrated northward. [158,159] The bog at Bear Meadows has unique features that allowed black spruce (*Picea mariana*) and balsam fir (*Abies balsamea*) two northern tree species, to remain, forming populations far south of their natural range. Interestingly there are several old growth black gum (*Nyssa sylvatica*) present, some of which are over 400 years old, and a 257 year old yellow birch. [160] Although there isn't a large population of hemlock old growth present, hemlock is the dominant tree in the outermost ring of the bog, and it is an ecologically unique and uncommon habitat for this species. Hemlock woolly adelgid has been reported in Bear Meadows Natural Area.

The priority areas above were primarily chosen due to their populations of old growth hemlock. A landscape based GIS analysis was also performed to identify potential hemlock stands of ecological importance, which may lead to additional focus areas in the future. (Appendix)

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[157] (Nowacki & Abrams, 1994)
[158] (DCNR, 2013)
[159] (Abrams, Copenheaver, Black, & van de Gevel, 2001)
[160] (Abrams, Copenheaver, Black, & van de Gevel, 2001)

4. Chemical Control

Chemical treatments should be utilized until a long-term solution via biological control or host resistance is developed. Pockets of priority hemlocks should be chemically treated either with imidacloprid or dinotefuran. Application methods (soil drench, soil injection, soil tablet, bark spray) will depend on site conditions, such as soil characteristics, accessibility, and proximity to sensitive resources. Label directions for insecticides must be carefully followed. Insecticides will need to be reapplied periodically, and the time frame will depend on which product is used. Imidacloprid treatments may persist up to five years while dinotefuran may need reapplication on the third year. Horticultural oil may be used for HWA control in ornamental settings also, but is not practical for large trees. Armored scales can be difficult to control chemically, and in order to be effective, care must be made to apply approved insecticides at specific times of the year. Dinotefuran and horticultural oils are both approved for control of elongate hemlock scale. Chemical and biological controls should not be seen as mutually exclusive, with research showing that they may be mixed in areas without diminishing effects. [161]

5. Biological Control

The Bureau of Forestry will continue to release biological control agents on public land, and maintain cooperative ties with government agencies and universities that are researching, collecting, or rearing them. If populations of a suitable biological control agent (or suite of agents) are capable of establishing at release sites and dispersing to new areas, this will be a promising break-through in long term, sustainable HWA control in forested settings. The best possible outcome would be that a suite of predators becomes established throughout the region. Currently, biological control agents that are available to private landowners are prohibitively expensive and have not been confirmed to control HWA in their new habitats. The Bureau of Forestry is currently releasing the biological control agents *Laricobius nigrinus*, and *Laricobius osakensis* in State Forests.

[161] (Mayfield, et al., 2015)

6. Hemlock Resistance

Research by the University of Rhode Island focused on identifying eastern hemlock in the wild that may be resistant to hemlock woolly adelgid. For any trees found, cuttings were taken and brought back to lab greenhouses for artificial infestation by HWA to test for resistance. Cuttings from a stand in New Jersey nicknamed the bullet proof stand may exhibit resistance to HWA and test plots have been planted in several northeastern US states, including Pennsylvania. [162, 163] There is also research focused on identifying any unusual features on these trees that may be responsible for impeding the establishment and survival of HWA.

The Bureau of Forestry is co-funding research with the University of Rhode Island to continue looking for resistant hemlock in Pennsylvania, in addition to developing lab surveys that can quickly identify specific chemical or biological features of a resistant tree. Anyone encountering a healthy hemlock that has not been treated with insecticide, or a healthier hemlock than surrounding neighbors in an infested stand should immediately contact DCNR Bureau of Forestry.

7. Silviculture

For hemlock forests in heavy decline from hemlock woolly adelgid, and where no chemical or biological controls are planned, rapidly initiating regeneration to desired tree species has been suggested, possibly mitigating many of the anticipated stream impacts from loss of hemlock. [164, 165] Establishing another conifer species may better mimic site conditions (i.e., microclimate) that existed when the hemlock was the dominant tree on site. [166]

While reforestation with a HWA resistant eastern hemlock should be the ultimate goal, this may be many years from fruition, if ever. In areas with dying or heavily damaged hemlock thought should be made on influencing regeneration, preferably of native conifers. It will be more practical and cost effective to manage for tree species that are already present in the canopy or understory of the site, and supplement with some underplanting. Attention should be made to promote conditions that favor the establishment of desired and appropriately adapted tree species

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162 (Caswell, Casagrande, Maynard, & Preisser, 2008)
163 (Preisser, Maynard, & Casagrande, Hemlock Woolly Adelgid Resistance, 2011)
164 (Roberts, Tankersley, & Orvis, 2009)
165 (Cessna & Nielsen, 2012)
166 (Cessna & Nielsen, 2012)

in the understory. Potential conifer species for replanting can be found in the following table, which was compiled by the USDA Forest Service staff in Allegheny National Forest.

Potential Replacement Species for Eastern Hemlock [167, 168, 169, 170]

Species	Habitat Characteristics	Site Requirements	Shade Tolerance / Growth	Deer Palatability / Browse Tolerance	Other Considerations
Red Spruce *Picea rubens*	Lacking lower limb structure and thermal characteristics of hemlock. Best replacement species for northern flying squirrel, as it supports lichens (Bryoria fremontii) required by northern flying squirrel for food and nesting material.	Higher elevation, good moisture regime. Grows well on poor sites, acidic and shallow soils preferred.	Tolerant-Very Tolerant. Long-lived (350-400 years), slow growing.	Browsing occurs, but not preferred browse.	Suitable habitat projected to occur north of Allegheny National Forest (ANF) in climate change models.
White Spruce *Picea glauca*	Retains lower limbs.	Tolerant of wide range of sites in northern North America, from moist to dry, alkaline and acidic.	Intermediate shade tolerance. Long lived (250-300 years)	Not preferred as browse.	Considered a hardy tree. Strong affinity to local environments. Suitable habitat projected to occur in northern New York state and New England in climate change models.

[167] (Burns & Barbara, 1990)
[168] (Latham, et al., 2005)
[169] (USDA Natural Resources Conservation Service, n.d.)
[170] (Prasad, Iverson, Matthews, & Peters, 2007)

Potential Replacement Species for Eastern Hemlock [167, 168, 169, 170]

Species	Habitat Characteristics	Site Requirements	Shade Tolerance / Growth	Deer Palatability / Browse Tolerance	Other Considerations
Black Spruce *Picea mariana*	Small dbh at maturity, retains lower limbs, shallow rooting.	Moisture regime important, prefers dark brown peat, boggy areas and wet organic soils. Common in swamps or bogs. Pioneer species.	Tolerant. 200 year lifespan typical.	Not preferred as browse.	Not a large tree, usually planted in pure stands. Suitable habitat projected to occur north of Canadian border in climate change models.
Balsam Fir *Abies balsamea*	Retains Lower Limbs, Fairly small crown area. Provides food and cover for wildlife. Second best species for northern flying squirrel.	Abundant moisture required, slightly acidic sites.	Very Tolerant. Slow growing, 80 year lifespan typical.	Browsing occurs, but not preferred browse.	Suitable habitat projected to occur north of ANF region in climate change models.

Potential Replacement Species for Eastern Hemlock [167, 168, 169, 170]

Species	Habitat Characteristics	Site Requirements	Shade Tolerance / Growth	Deer Palatability / Browse Tolerance	Other Considerations
Northern white-cedar ***Thuja occidentalis***	General Bush-like appearance, may lose lower limbs in forest grown areas. Provides an abundance of food in cover for wildlife, especially in winter.	Moist, nutrient rich sites, such as those along streams. Prefers calcareous soils.	Tolerant. Slow-growing, persistent. 300 year lifespan typical.	Preferred/ \ Not Tolerant	Can withstand suppression for long time periods. Suitable habitat projected to occur north of Canadian border in climate change models.
Eastern White Pine ***Pinus strobus***	Lacking lower limb structure and thermal characteristics of hemlock.	Well drained, drier sites, with coarse textured soils.	Intermediate. 200 year lifespan typical, but can be long-lived (450 years).	Preferred/ Not tolerant.	Grows rapidly and is considered an excellent tree for reforestation projects. White pine needle litter has a similar decay rate to eastern hemlock, possibly preserving some of the ecosystem function of the site [171] Suitable habitat projected to migrate northward but still remain ANF region in climate change models (could consider more southerly genotypes).

[171] (Cobb & Orwig, Changes in decomposition dynamics in hemlock forests impacted by hemlock woolly adelgid: restoration and conservation of hemlock ecosystem function, 2008)

If landowners or land managers wish to remove heavily damaged hemlocks, live crown ratio can be used as an indicator of which trees to target for removal. Hemlocks with higher live crown ratios (i.e., tree vigor) have been shown to better survive hemlock woolly adelgid infestations. [172] Please note that hemlock health/vigor does not predict susceptibility to hemlock woolly adelgid attack, but may enable the trees to survive longer once infested. Trees with live crown ratios of 30% and less should be targeted for removal. For more information on live crown ratio and how to measure it please see the following report from the US Forest Service . [173] Individuals should also anticipate increased hemlock mortality (in HWA infested stands) following a mild winter the previous year, followed by a dry summer the year of, as research has shown these factors to be highly linked. [174] In general, there is a higher likelihood of hemlock dying within a year if crown dieback exceeds 30% or if foliar transparency exceeds 35%. Research is also being conducted on whether preemptive thinning of un-infested hemlock stands may boost tree vigor. [175]

8. Preservation of Hemlock Genetic Material

In attempts to preserve the species and allow for reintroduction if practical adelgid controls are developed for forests, eastern hemlock and Carolina hemlock seeds have been collected and are being used to establish hemlock plantations in areas far removed from the pest, and where no native populations of hemlocks exist. This work has been conducted by Camcore with funding provided by the US Forest Service. In addition to tree improvement programs through breeding, Camcore also works to conserve imperiled tree species such as eastern hemlock and Carolina hemlock through ex situ (i.e., off-site) plantings. Since 2003, Camcore and the US Forest Service have collected seed from 407 families across 59 populations of eastern hemlock and 134 families across 19 populations of Carolina hemlock and are establishing them in central Chile, southern Brazil, and Ozark Mountains in Arkansas. [176,177] The Bureau of Forestry has aided Camcore to collect hemlock genetic material from Pennsylvania and will continue to do so if requested.

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[172] (Fajvan & Wood, GTR-NRS-P-64, 2009)
[173] (Schomaker, et al., 2007)
[174] (Eschtruth, Evans, & Battles, 2013)
[175] (Fajvan, The role of silvicultural thinning in eastern forests threatened by hemlock woolly adelgid (Adelges tsugae), 2007)
[176] (Jetton, Whittier, Dvorak, & Potter, 2008)
[177] (Camcore, 2012)

Threat 2: Climate Change

Climate change is a two-way threat for eastern hemlock in North America. First it may permit the expansion of hemlock woolly adelgid into the more northern range of eastern hemlock, where cold winter temperatures have been able to suppress the pest. Secondly, a warming climate is likely to cause a decline in hemlock by reducing the amount of suitable habitat for it to thrive. Land owners and managers should anticipate both outcomes and take any available measures. These include:

1. Identifying and Maintaining Refugia

Refugia are areas that are able to resist environmental changes that have otherwise decimated species in most of their former habitat. This allows for these formerly widespread species to persist in small relict populations, preventing complete disappearance. [178] Land owners should identify likely areas or refuge for hemlock where would be able to persist, despite climate change. Focus should be made on identifying cooler, wetter sites, such as riparian areas, north facing slopes, lake edges, and wetlands. [179] These sites would have to be monitored and treated long term for hemlock woolly adelgid and any other threatening pests.

2. Adapting Control Measures

If the hemlock woolly adelgid does expand its range, control measures will have to be increased above current levels. This may mean more insecticide applications, in addition to higher numbers of biological control agent releases.

3. Adapted Replacement Species

If underplanting or promotion of alternative tree species to replace hemlock, care should be taken to choose tree species that will be more suitable for the anticipated climate conditions in the future. See Table of Potential Replacement Species for Eastern Hemlock

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[178] (Millar, Stephenson, & Stephens, 2007)
[179] (Swanston, et al., 2012)

Appendix

Appendix A: Plant Community Types Associated with Eastern Hemlock

FF **Hemlock (White Pine) Forest:** *Tsuga canadensis* (eastern hemlock), *Pinus strobus* (eastern white pine), or more often a combination of the two dominates these forests. Conifer cover generally exceeds 75% of the canopy. Associate species include a variety of northern hardwoods and oaks. Typical representatives include *Betula lenta* (black birch), *B. alleghaniensis* (yellow birch), *Acer saccharum* (sugar maple), *A. rubrum* (red maple), *Quercus rubra* (red oak), *Q. velutina* (black oak), *Fagus grandifolia* (American beech), and *Liriodendron tulipifera* (tuliptree). Representative shrubs include *Rhododendron maximum* (rosebay), *Viburnum lantanoides* (witch-hobble), *V. acerifolium* (maple-leaved viburnum), and *Hamamelis virginiana* (witch-hazel). Typical herbs and creeping shrubs include *Maianthemum canadense* (Canada mayflower), *Mitchella repens* (partridge-berry), *Lycopodium* spp. (ground pine), *Gaultheria procumbens* (teaberry), *Thelypteris novaboracensis* (New York fern), *Medeola virginiana* (Indian cucumber root), and *Polystichum acrostichoides* (Christmas fern).

Related types: If the conifer component is less than 75% relative cover, review the mixed conifer - broadleaf terrestrial forests.

Range: Glaciated NE, Glaciated NW, Pocono Plateau, Unglaciated Allegheny Plateau.

FA **Dry White Pine (Hemlock) - Oak Forest:** This type occurs on fairly dry sites, often with 25% or more of the forest floor covered by rocks, boulders and/or exposed bedrock. The canopy may be somewhat open and tree growth somewhat suppressed. The tree stratum is dominated by a mixture of *Pinus strobus* (eastern white pine), or occasionally *Tsuga canadensis* (eastern hemlock), and a mixture of dry-site hardwoods, predominantly oaks. On most sites, the conifer and the hardwood component both range between 25% and 75% of the canopy. The oak species most often associated with this type are *Quercus montana* (chestnut oak), and *Q. alba* (white oak), although *Q. velutina* (black oak), *Q. coccinea* (scarlet oak), or *Q. rubra* (northern red oak) may also occur. Other associated trees include *Nyssa sylvatica* (black-gum), *Betula lenta* (sweet birch), *Fraxinus americana* (white ash), *Prunus serotina* (black cherry), and *Castanea dentata* (American chestnut) sprouts. There is often a heath-dominated shrub layer with *Kalmia latifolia* (mountain laurel) being especially important; *Gaylussacia baccata* (black huckleberry), *Vaccinium* spp. (blueberries), and *Kalmia angustifolia* (sheep laurel) are also common. Other shrubs, like *Cornus florida* (flowering dogwood), *Hamamelis virginiana* (witch hazel), *Viburnum acerifolium* (maple-leaved viburnum) may also occur on less acidic sites. There is typically a sparse herbaceous layer with a northern affinity; *Aralia nudicaulis* (wild sarsaparilla), *Pteridium aquilinum* (bracken fern), *Maianthemum canadense* (Canada mayflower), *Gaultheria procumbens* (teaberry), *Trientalis borealis* (star-flower), and *Medeola virginiana* (Indian cumber root) are typical. The successional status of this type seems variable, in some cases, especially on harsher sites, it appears relatively stable, in other cases it appears to be transitional.

Related types: If the total conifer cover is less than 25%, see the "Broadleaf terrestrial forests" types. This forest type shares several species with the "Hemlock (white pine) -red oak - mixed hardwood" forest type. The latter is more mesic; *Q. montana* (chestnut oak), *Pteridium aquilinum* (bracken fern) and *Aralia nudicaulis* (wild sarsaparilla) are more often associated with the dry type, while *Q. rubra* (red oak), *Podophyllum peltatum* (may-apple) and *Smilacina racemosa* (false Solomon's seal) are more characteristic of the mesic type.

Range: Most typical of the Ridge and Valley, also occurs on South Mountain, Glaciated NE, Glaciated NW, Pittsburgh Plateau.

FB **Hemlock (White Pine) - Northern Hardwood Forest:** Any of the three named components may be dominant; at least two are present in some amount. Conifers and hardwoods each contribute between 25% and 75% of the canopy. Characteristic hardwood species include *Fagus grandifolia* (American beech), *Acer saccharum* (sugar maple), *A. rubrum* (red maple), *Betula lenta* (sweet birch), and *B. alleghaniensis* (yellow birch). The conifer component may be *Pinus strobus* (eastern white pine), *Tsuga canadensis* (eastern hemlock), or a combination of the two. These forests occur mostly on mesic sites, often north-facing, sometimes rocky and steep. This type is fairly widespread in northern Pennsylvania. *Rhododendron maximum* (rosebay) may be locally abundant. Other common shrubs include *Hamamelis virginiana* (witch-hazel), *Acer pensylvanicum* (striped maple), and Viburnums (*Viburnum* spp.). The herbaceous layer is generally sparse and reflects a northern affinity; common components include *Maianthemum canadense* (Canada mayflower), *Trientalis borealis* (star-flower), *Thelypteris novaboracensis* (New York fern), *Medeola virginiana* (Indian cucumber-root), *Lycopodium lucidulum* (shining clubmoss), *Mitchella repens* (partridge-berry), and *Clintonia borealis* (bluebead lily). There is often a rich bryophyte layer.

Related types: The "Northern hardwood forest" type has less than 25% combined relative cover by conifers. The "Hemlock (white pine) - red oak - mixed hardwood forest" type is generally dominated by a combination of various oaks—characteristically *Quercus rubra* (red oak), and *Tsuga canadensis* (eastern hemlock) and/or *Pinus strobus* (white pine). In the type being described here, the same conifers usually share dominance with *Fagus grandifolia* (American beech), *Betula* spp. (birches), and *Acer saccharum* (sugar maple). The understory species associated with this type are likewise more northern in affinity.

Range: Entire state except the Coastal Plain, Piedmont, and South Mountain.

FR **Hemlock (White Pine) - Red Oak – Mixed Hardwood Forest:** This type is similar to the "Red oak - mixed hardwood forest" type but with *Tsuga canadensis* (eastern hemlock) and/or *Pinus strobus* (eastern white pine) contributing more than 25% relative cover. Conifers may be scattered, locally abundant, may dominate the subcanopy, or may occur as a relict supra-canopy (*Pinus strobus*), or in large former canopy gaps (*Pinus strobus*). *Quercus rubra* (northern red oak) is usually present, often dominant/codominant, most often with *Acer rubrum* (red maple), *Quercus velutina* (black oak), *Q. alba* (white oak), *Carya tomentosa* (mockernut hickory), *Betula lenta* (black birch), *Fraxinus americana* (white ash), *Fagus grandifolia* (American beech), and/or *Liriodendron tulipifera* (tuliptree). Shrubs include *Viburnum acerifolium* (maple-leaved viburnum), *Rhododendron periclymenoides* (pinxter-flower), *Amelanchier laevis* (smooth serviceberry), *A. arborea* (shadbush), *Carpinus caroliniana* (hornbeam), *Ostrya virginiana* (hop-hornbeam), *Hamamelis virginiana* (witch-hazel), and *Lindera benzoin* (spicebush). Herbaceous species include *Smilacina racemosa* (false Solomon's-seal), *Polygonatum biflorum* (Solomon's seal), *Gaultheria procumbens* (teaberry), *Maianthemum canadense* (Canada mayflower), and *Podophyllum peltatum* (may-apple).

Related types: The "Red oak - mixed hardwood forest" type has less than 25% combined relative cover by conifers. The type described here is generally dominated by a combination of various oaks—characteristically *Quercus rubra* (red oak), and *Tsuga canadensis* (eastern hemlock) and/or *Pinus strobus* (eastern white pine). In the "Hemlock (white pine) - northern hardwood forest," the same conifers usually share dominance with *Fagus grandifolia* (American beech), *Betula* spp. (birches), and *Acer saccharum* (sugar maple). The understory species associated with the "Hemlock (white pine) - northern hardwood forest" type are likewise more northern in affinity.

Range: Entire state except the Coastal Plain.

FT **Hemlock - Tuliptree -Birch Forest:** The presence of tuliptree and a mix of somewhat more southern species distinguish this type from the "Hemlock/white pine - northern hardwood" type. This is generally a lower slope or cove type. *Tsuga canadensis* (eastern hemlock) usually contributes at least 25% of the canopy. *Liriodendron tulipifera* (tuliptree), *Betula alleghaniensis* (yellow birch), and *B. lenta* (black birch) are the most characteristic hardwood species. Other tree species commonly found on these sites are *Acer rubrum* (red maple), *A. saccharum* (sugar maple), *Quercus* spp. (oaks)—usually *Q. rubra* (northern red oak), as well as *Fagus grandifolia* (American beech), *Fraxinus americana* (white ash), *Prunus serotina* (black cherry), *Tilia americana* (basswood), *Pinus strobus* (eastern white pine), and in western Pennsylvania, *Magnolia acuminata* (cucumber-tree). Shrubs include *Hamamelis virginiana* (witch-hazel), *Rhododendron maximum* (rosebay) and others. The herbaceous layer is highly variable; characteristic species include *Maianthemum canadense* (Canada mayflower)—especially under hemlock, *Podophyllum peltatum* (may-apple), *Dryopteris marginalis* (evergreen wood fern), *Botrychium virginianum* (rattlesnake fern), *Arisaema triphyllum* (jack-in-the-pulpit), *Aster divaricatus* (white wood aster), and *Polystichum acrostichoides* (Christmas fern).

Related types: If hemlock contributes less than 25% of the canopy cover, read the description of the "Tuliptree - (beech) - maple forest." This type is in some ways intermediate between the "Hemlock (white pine) - northern hardwoods forest," which has a more northern species composition and range, and the "Hemlock - rich mesic hardwoods forest," which has a richer, more southern species composition and a more southerly range. This type is also closely related to the "Hemlock (white pine) - red oak forest," which usually occurs on dryer sites, and generally has *Quercus rubra* (red oak) as a major canopy component.

<u>Range</u>: Piedmont, Pittsburgh Plateau, Ridge and Valley.

FM **<u>Hemlock - Rich Mesic Hardwood Forest:</u>** These are species-rich, lower slope forests, reminiscent of the "Mixed mesophytic forest" type in the southwestern part of the state, but usually with a strong *Tsuga canadensis* (eastern hemlock) component. The hardwood species vary; typical representatives include *Liriodendron tulipifera* (tuliptree), *Fagus grandifolia* (American beech), *Quercus rubra* (northern red oak), *Acer rubrum* (red maple), *A. saccharum* (sugar maple), *Betula lenta* (sweet birch), *B. alleghaniensis* (yellow birch), *Fraxinus americana* (white ash), *Tilia americana* (basswood) and *Carya ovata* (shagbark hickory). Hemlock cover is often patchy. Under hardwood cover, the herbaceous diversity approaches that of the richer "Mixed mesophytic" type, while under dense hemlock cover, the herbaceous stratum reflects a more northern flora. *Magnolia tripetala* [S] (umbrella magnolia) is not uncommon. Other southern shrubs such as *Asimina triloba* (pawpaw) and *Staphylea trifolia* (bladdernut) may also occur, although *Rhododendron maximum* (rosebay), *Hamamelis virginiana* (witch-hazel), and *Lindera benzoin* (spicebush) are more abundant on most sites. Herbaceous species include *Adiantum pedatum* (maidenhair fern), *Erythronium americanum* (trout-lily), *Anemone quinquefolia* (wood anemone), *Dicentra canadensis* (squirrel-corn), *D. cucullaria* (dutchman's-breeches), *Cimicifuga racemosa* (black snakeroot), *Geranium maculatum* (wood geranium), *Caulophyllum thalictroides* (blue cohosh), *Hepatica nobilis* (liverleaf), *Arisaema triphyllum* (jack-in-the-pulpit), *Allium tricoccum* (wild leek), *Sanguinaria canadensis* (bloodroot), *Corydalis flavula* (yellow fumewort), *Asplenium* spp. (spleenworts), *Botrychium virginianum* (rattlesnake fern), *Claytonia virginica* (spring-beauty), *Cardamine concatenata* (cut-leaved toothwort), *Mitella diphylla* (bishop's-cap), and *Asarum canadense* (wild ginger). In areas without a strong *Tsuga canadensis* (eastern hemlock) component, there may be complete annual litter turnover. This type may occur in a variety of lower slope/ravine situations, including some moist, often north-facing slopes in the Ridge and Valley.

<u>Related types:</u> This community type resembles a somewhat depauperate version of the "Mixed mesophytic forest" type, with the addition of *Tsuga canadensis* (eastern hemlock) usually with at least 25% relative cover. It is much richer in species composition than the most closely related mixed conifer/broadleaf forest type, the "Hemlock - tuliptree - birch forest." Species like *Magnolia tripetala* [S] (umbrella magnolia), *Asimina triloba* (pawpaw),

Staphylea trifolia (bladdernut), *Corydalis flavula* (yellow fumewort), *Sanguinaria canadensis* (bloodroot), and *Dicentra* spp. (dutchman's breeches and squirrel corn) are more typical of this richer, more southern type.

Range: Piedmont, Pittsburgh Plateau, southeastern portion of Ridge and Valley.

UF **Hemlock Palustrine Forest:** These are wetland forests dominated or codominated by *Tsuga canadensis* (eastern hemlock). The canopy may also contain a mixture of other conifers, e.g. *Picea rubens* (red spruce), *Larix laricina* (tamarack), and *Pinus strobus* (eastern white pine). Hardwoods may contribute up to 25% of the tree stratum; common species include *Acer rubrum* (red maple), *Betula alleghaniensis* (yellow birch), and *Fraxinus nigra* (black ash). There is generally a pronounced mound and pool topography. This community type may occur as a zone around a wetter community type of a more northern affinity. It may also occur in basins or on slopes fed by groundwater seepage. *Rhododendron maximum* (rosebay) is often present, sometimes quite dense. *Viburnum cassinoides* (withe-rod), *Rhododendron viscosum* (swamp azalea), *Ilex verticillata* (winterberry), and *Vaccinium corymbosum* (highbush blueberry) are also commonly associated with this type. Herbs include *Osmunda cinnamomea* (cinnamon fern), *Symplocarpus foetidus* (skunk-cabbage), *Onoclea sensibilis* (sensitive fern), *Mitchella repens* (partridge-berry), *Maianthemum canadense* (Canada mayflower), *Coptis trifolia* (goldthread), *Viola* spp. (violets), *Dalibarda repens* (false-violet), *Trientalis borealis* (star-flower), and various grasses and sedges. There may be a strong bryophyte component, usually dominated by sphagnum.

Related types: Where total conifer cover is less than 75% of the canopy, this type becomes the "Hemlock - mixed hardwood palustrine forest."

Range: Great Lakes Region, Glaciated NE, Glaciated NW, Pittsburgh Plateau, Pocono Plateau, Ridge and Valley, Unglaciated Allegheny Plateau.

UB **Hemlock – Mixed Hardwood Palustrine Forest:** This describes a group of wetland forests that are dominated by a mixture of conifers and hardwood species. The substrate is usually mineral soil or muck over mineral soil. There is generally some groundwater enrichment in these systems. *Tsuga canadensis* (eastern hemlock) contributes between 25% and 75% of the canopy. Other conifer species that may occur with hemlock include *Pinus strobus* (eastern white pine), *Picea rubens* (red spruce), and *Larix laricina* (tamarack). The most common hardwood species are *Betula alleghaniensis* (yellow birch), *Acer rubrum* (red maple), *Fraxinus nigra* (black ash), *Nyssa sylvatica* (black-gum), and *Betula populifolia* (gray birch). *Rhododendron maximum* (rosebay) often forms a dense understory; other shrubs include *Vaccinium corymbosum* (highbush blueberry), *Ilex verticillata* (winterberry), *Rhododendron viscosum* (swamp azalea) and *Viburnum cassinoides* (withe-rod). Herbaceous species include *Osmunda cinnamomea* (cinnamon fern), *Carex folliculata* (a sedge), *Viola* spp. (violets), *C. trisperma* (a sedge), *Symplocarpus foetidus* (skunk-cabbage), *Veratrum viride* (false hellebore), *Onoclea sensibilis* (sensitive fern), and *Aster puniceus* (purple-stemmed aster). The bryophyte layer is usually well developed and dominated by sphagnum.

<u>Related types:</u> Where the conifer component is less than 25% of the canopy, see the "Broadleaf palustrine forests" section, and where the conifer component is greater than 75%, see the "Hemlock palustrine forest" type under "Coniferous palustrine forests."

<u>Range:</u> Glaciated NE, Glaciated NW, Pocono Plateau, Ridge and Valley, Unglaciated Allegheny Plateau.

Appendix B: Methodology for determining hemlock distribution

BUILDING A NATIONWIDE 30-METER FOREST PARAMETER DATASET FOR FOREST HEALTH RISK ASSESSMENTS

James R. ELLENWOOD and Frank J. KRIST

FHTET; USDA Forest Service, 2150 Centre Ave., Bldg A, Ste. 331, Fort Collins, CO 80526, jellenwood@fs.fed.us

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ABSTRACT

Although useful at a national scale, the 1-km resolution 2006 National Insect and Disease Risk Map (NIDRM) has limited utility at the local and regional levels. The USFS has begun work on a 'next-generation' national risk map at a 30-meter resolution to facilitate local and regional planning efforts. In support of this project, forest parameter datasets of basal area and trees per acre are being developed for more than 175 tree species using ground inventory data and 52 national data layers ranging from three-season Landsat 7 imagery to local soil information. To develop models of forest parameters by tree species, USFS Forest Inventory and Analysis (FIA) data are linked to each national data layer and analyzed within Cubist data mining software (Rulequest 2007). Model outputs are converted to a 30-meter spatial dataset using ERDAS Imagine software. Forest parameter models representing less dominant tree species were not well-correlated. In order to improve model results, a new technique called extirpolation was developed in which models are assembled for an individual species from the total parameter values of all remaining species. Early results have been promising based upon field validation.

Keywords: Cubist, Landsat, Forest Parameters, Extirpolation

1 INTRODUCTION

The National Insect and Disease Risk Map (NIDRM) is a tool to provide policy makers, USFS officials, and federal and state land managers with a periodic strategic assessment of risk of tree mortality due to major forest insects and diseases (Krist et. al. 2007b). Limitations of the most recent risk assessment were evaluated and opportunities for improvement were identified for the 2010 assessment. One of the key findings of this evaluation was to create base layers depicting forest host parameters at a higher spatial resolution. The purpose of this paper is to document the procedures used to develop these improved forest host parameter layers.

1.1 BACKGROUND

For the 2006 risk assessment, field specialists formulated 188 multi-criterion pest models to assess the risk of mortality on individual tree species over a 15-year period (Krist et. al. 2007a). Each of these models required one or more tree species-specific forest parameters including basal area (over 1" dbh), mean diameter, and tree density (over 1" dbh). These parameters were modeled on a 1-km cell basis, allowing for broad-scale analysis; however, forest pests inherently operate at a local-scale making local and regional assessments difficult. Therefore, the goal of the 2010 NIDRM is to utilize forest parameter base-layers at 30-meter ground resolution to produce a product that can be used at the local, regional, and national levels.

1.2 AVAILABLE NATIONAL DATASETS

The USGS has recently completed the 2001 National Land Cover Dataset (Homer, 2007) encompassing the continental United States and Alaska. This 30-meter dataset consists of 3 primary products: a landcover layer representing 18 different classes, a forest-canopy cover layer, and an impervious surface layer. In addition to these products, the NLCD project has made available a set of terrain data, and radiometrically corrected and mosaicked three-season Landsat 7 scenes for each of the 78 USGS mapping zones (Figure 1).

Figure 1. USGS Mapping Zones

The USDA-NRCS is currently coordinating the National Cooperative Soil Survey (NCSS), which is a nationwide partnership of federal, regional, state, and local agencies and institutions. Two products are being developed as part of the NCSS: a broad-scale product known as the US General Soil Map or STATSGO and a local-scale product known as the SSURGO (NRCS, 2007).

Climate data were derived from the University of Montana Numerical Terradynamic Simulation Group (NTSG) which produces the Daymet climate datasets at 1-km resolution (Thornton et. Al. 1997, Daymet 2007).

The USDA Forest Service FIA conducts annual inventories of forested lands for all ownerships in each state across the United States. This dataset provides a nationally consistent measurement of individual trees for determining various forest parameters (Becthold and Patterson, 2005). The FIA data is the only ground survey data used to produce the model parameters for this project.

2 PROCEDURES

2.1 NLCD DERIVATIVES

Since the NLCD project undertook the daunting task of creating radiometrically-corrected, Landsat-7 scenes for each of the 78 USGS mapping zones, the opportunity existed to extract more information from this intermediate product. Each mapping zone contains a mosaicked dataset consisting of reflectance corrected Landsat imagery (6 bands) for 3-seasons plus three tasseled-cap transformed bands comprising a total of 27 image bands. For each season, a date-band thematic image was created. In addition to the thematic date-band, a Julian day image was created as a continuous band so the modeling process can better distinguish the temporal differences between the plot data and the imagery. Including the core NLCD products of land cover, impervious surface, and canopy cover, a total of 36 predictor layers were assembled from the NLCD project.

2.2 SOIL DATA PREPARATION

The SSURGO data is a vector-based dataset developed from 1:12,000 or 1:24,000 orthophotos for each county or soil survey area within a given state. Each individual soil map unit within a survey area contains one or more soil components. To reduce the data complexity, the majority soil component was selected for analysis. Since a multitude of variables are associated with each soil component, a process was needed to reduce the variables into a meaningful measure for incorporation in the forest parameter modeling effort. A soil drainage index (DI) was developed to allow for the incorporation of a measure of the long-term wetness of a soil, which is a key variable related to tree growth (Schaetzl et. al. 2007).

Originally named the “natural soil wetness index” (Schaetzl 1986), DI is an ordinal measure of the relative amount of water that a soil contains and makes available to plants under normal climatic conditions. The main factors affecting DI are the depth to the water table, soil moisture regime and volume available for rooting, and (lastly) texture. Therefore, the DI is calculated from the soil’s taxonomic subgroup classification in the US system of soil taxonomy, along with its textural family and slope class. DI values range from 0 to 99. The higher the DI the more water a soil can supply to plants. Sites with a DI of 99 are almost continually waterlogged while a soil with a DI value of zero is thin and dry enough to almost be bare rock or raw sand. A DI value was assigned to each majority soil component within the SSURGO and STATSGO databases.

In addition, soil component dominance and diversity were determined for each soil map unit and incorporated in the predictor layers. In areas where SSURGO data is not available, the majority soil components from the STATSGO data were utilized. From these two data sources, a single 30-meter soil layer was created for each USGS map zone.

2.3 CLIMATE DATA PREPARATION

From the Daymet data, eight layers were utilized: frost free days, growing degree days, average annual precipitation, short wave radiation, average annual temperature, average maximum temperature, average minimum temperature, and water vapor pressure. For each Daymet layer, the first principle component of the 12-monthly averages (1980-1997) was rescaled using the ArcGRID SLICE routine with the equal area option to reduce the dataset and to maximize the variation for the modeling process.

An additional layer was developed to represent seasonal moisture by combining the USGS NDVI seasonal metric data, 1989 to 2001 (Swets, 1999), with a summation of the corresponding average monthly precipitation data.

The native resolution of the Daymet layers is 1-kilometer. A 30-meter modeled surface generated from these datasets would result in a product that has large blocks of pixels which effectively reduces the ground resolution of the data. In order to make the climate data more comparable to other predictor layers, the native raster layers were disaggregated into point datasets and then resampled to a finer resolution utilizing the Arc/Info TOPOGRID function.

2.4 TERRAIN DATA PREPARATION

The terrain data is derived from the 30-meter National Elevation Dataset (NED) utilized in the NLCD production (USGS 2007). In addition to the digital elevation model (DEM) and position index obtained from the NLCD project, slope was recomputed to percent and aspect was recomputed into two phases based upon the sin and cosine, and a slope percent weight (Stage 1976). Slope curvature was also computed and included in the analysis. A total of six continuous terrain variables were generated from this source.

2.5 FIA DATA PREPARATION

Ground data is derived from continuous forest inventory data collected by the USFS Forest Inventory and Analysis (FIA) unit. The standard national FIA plot design consists of 3-subplots centered on a central sub-plot (Bechtold and Patterson 2005). Only the central subplot has geographic coordinates recorded. The locations of the remaining 3-subplots were calculated from the plot design. The subplot installation design orients the plots utilizing magnetic north. Subplot locations were calculated using the subplot design and the magnetic declination at the time the plots were installed. Magnetic declination was determined from the 1995 magnetic declination (Tarr 2000a) and adjusted by the secular variation (Tarr 2000b) based upon the installation date.

Since FIA is a continuous inventory, plot data was selected by individual state inventories that were within 2-3 years of the imagery date. From these cycles, all live trees greater than or equal to 1 inch in diameter were isolated and forest parameters for basal area and trees per area were computed for each individual sub-plot. Plots which were determined to be sampled but with no sample trees were assigned a value of 0 basal area and trees per acre. Plots that were not sampled, designated status code 3 (USFS 2007), as well as plots without geographic coordinates or coordinates that were deemed inaccurate were removed from the sample.

2.6 MODEL BUILDING

A total of 52-predictor layers were sampled utilizing the FIA subplot locations. For continuous variables bilinear sampling was utilized and for thematic variables nearest neighbor sampling was employed. Bilinear sampling was selected to account for mis-alignment between pixel and subplot locations. Once a table containing FIA tree records and predictor layer values was assembled, a separate model was generated for basal area and trees per acre for each USGS mapping zone.

Cubist software (Rulequest 2007) was used to fit models for each tree species with a typical mapping zone. Cubist produces a set of rules, each associated with a multivariate linear model. The rule-based output is used to produce a geo-spatial data set using freely distributable code that was integrated with ERDAS Imagine Software (Ruefenacht et. al. 2007). The resultant geo-spatial data is a 30-meter raster dataset depicting a continuous range of either basal area or trees per acre values.

2.7 EXTIRPOLATED MODELS

For most individual species, subplot occurrence is infrequent and difficult to model. The resultant models typically only have a few values. For this reason, a new technique was used on models with r-values of less than 0.50. The forest parameter of interest (basal area, trees per acre) is subtracted from the total for all species and then modeled through cubist, $BA_{t\text{-}si} = BA_t - BA_{si}$. A geospatial product is built from the resulting model. This product is then subtracted from the total of all species geospatial product to calculate the original species parameter, $Y_{si} = Y_t - Y_{t\text{-}si}$. For ease of discussion, it is proposed to term this procedure as an "extirpolated" model. An example of the normal model versus the extirpolated model is illustrated in the first two panels of Figure 2.

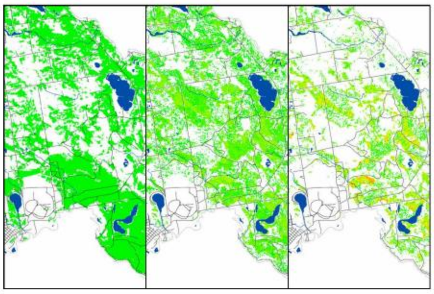

Figure 2. Normal vs extirpolated vs adjusted models

3 RESULTS

The overall purpose of this project is to produce a 30-meter species level forest parameter dataset for use in the 2010 National Insect and Disease Risk Map. Interim goals for regional projects have been tasked. To date three regional forest parameter modeling projects have been completed and resultant maps have been produced for 26 of the 78 mapping zones as of September 30, 2007.

3.1 CUBIST MODELS

Over 10,000 individual cubist models have been produced in the 26 completed mapping zones. Of these, 5,429 models have been selected for geospatial product generation (Table 1). The strongest models are typically the total basal area with r-values ranging from 0.58 to 0.77. For total trees per acre, r-values range from 0.35 to 0.61. Models for individual tree species rarely exceed r-values of 0.50 and most need the extirpolated model to produce a valid modeled parameter. Extirpolated model r-values typically match the corresponding total parameter model.

Table 1. R-value summary of models

Parameter	Max	Min	Avg	Total
Basal area	0.77	0.58	0.68	27
Trees per acre	0.61	0.35	0.50	27
# of models per zone	304	58	201	5429
# of species per zone	151	28	100	2688

3.2 GEOSPATIAL PRODUCTS

Only about 350 forest parameter surfaces have been computed so far, due to the required computing hours. Some of these models were validated against the original ground samples and additional field datasets during local stand exams. Though most of the geospatial products captured the variable density for a species parameter, the overall parameter variation seemed to be somewhat under-represented, as regressions tend to "smooth" the data around the mean. In order to mitigate this tendency, for each of the forest parameter layers generated, a histogram balance-adjustment is performed to scale the product to match the distribution of FIA plot data (Lister and Lister, 2006). An example is illustrated in the third panel of Figure 2.

3.3 FIELD VALIDATION

Several zones were analyzed to meet immediate needs for deployment of survey strategies for recent insect outbreaks. Species parameter maps were used to narrow sampling areas for the sirex woodwasp in central New York and emerald ash borer in Michigan, Ohio, and Indiana. Feedback from survey efforts suggests the forest parameter maps did increase survey efficiency and effectiveness.

Southern pine beetle (SPB) is a key threat to the pine forests of the southern United States. Efforts to control the impact of the southern pine beetle require extensive preventative treatments. In order to prioritize treatment areas, a hazard assessment was developed across 11 ecological mapping zones. Forest parameter mapping was essential to this assessment. Figure 3 illustrates Loblolly pine basal area, which is one of 11 host-species that were modeled in the 11 USGS mapping zones. Field validation showed very high correspondence among the dominant pine species. Some of the less common pine species also showed good correspondence where SSURGO soil data and recent FIA data were available.

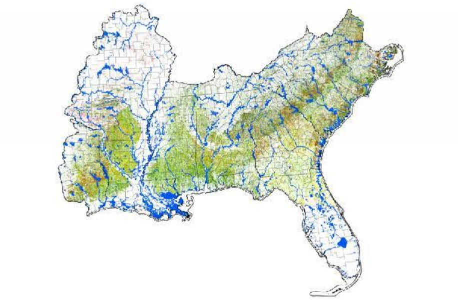

Figure 3. Southern pine basal area

3.4 COMPLETION

For select species within the completed zones, draft forest parameter geospatial products are currently available. Completion of the remaining zones and species is anticipated by 2009.

4 SUMMARY

The final products will provide better representation of forest parameters and support the 'next-generation' risk mapping effort. This will help to bridge the gap between national-scale planning and on-the-ground conditions. The risk map has been a tool through which to communicate national forest health concerns to policy makers. With finer resolution data, it can now be a tool for land management planners to better represent forest health concerns in the forest planning process. Through these mechanisms, better and more effective treatments can be implemented. Caution must be applied when utilizing these products at resolutions smaller than 30-meters, such as would be necessary for project level planning. The 30-meter pixel does not represent individual trees, though there may be utility for application at the stand level by aggregating 30-meter pixels for stand-level summaries. Aggregation for multiple species can be utilized for creating dynamic type maps depending upon end-user needs.

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Continuing Developments in Building a Nationwide 30-meter Forest Parameter Dataset for Forest Health Risk Assessments [TS-10-2]

J. Ellenwood[a], F. Krist[a], F. Sapio[a]

[a] Forest Health Technology Enterprise Team (FHTET), USDA Forest Service, Fort Collins, CO, USA – (jellenwood, fkrist, fsapio)@fs.fed.us

Abstract – FHTET continues production of a nationwide 30-meter forest parameter dataset for the 2010 national forest health risk assessment. Forest parameter datasets of basal area, stand density index, and trees per acre are being developed for 371 tree species. Using USFS Forest Inventory and Analysis (FIA) dataset for ground inventory data, the models incorporate predictor variables generated from the National Land Cover Database (NLCD) three-season Landsat 7 imagery from the NLCD dataset, soils data from the national soil data mart (NRCS), terrain data derived from the National Elevation Dataset (USGS), and 30-m climate data derived from the monthly station normals dataset from the National Climate Data Center (NOAA). This spatial dataset was analyzed utilizing a combination of statistical techniques which involved randomForests and Cubist data mining software (Rulequest, Inc.). Models were developed for 73 USGS mapping zone, each forest parameter (basal area and stand density index), and each species for a total of 8,402 models. As expected, less dominant tree species produce poorly correlated models. In order to better model these tree species, a new technique called extirpolation has been developed (Ellenwood, et. al. 2007b) which is applied to individual species models with correlation r-values of less than 0.71. An adjustment is made to the final geospatial product by matching the inventory histogram to the geospatial product histogram. Results for each of the zones have generated correlation r-values ranging from 0.58 to 0.94 for total basal area and 0.63 to 0.96 for stand density index in each map zone. Correlation for most individual species extirpolated models range comparably with the zone parameter models. Geospatial products for each of the species are anticipated to be completed by August 2009.

Keywords: RandomForests, Landsat, Forest Parameters, Extirpolation.

1. INTRODUCTION

The USFS identified a need to conduct an objective analysis of forest health conditions to support forest, regional, and national planning. The purpose of this project is to develop improved forest host parameters to assist the USFS in meeting this need for analysis through the next generation risk map for 2010 (Krist et. al. 2007). Initial procedures and preliminary output were previously reported in the 32nd ISRSE symposium (Ellenwood et. al. 2007a). As a continuation project, the purpose of this paper is to provide additional details and results from the initial product generation.

1.1 Scope of Effort

Since the USGS developed an extensive imagery data set for the entire United States, these mapping zones were adopted for the individual modeled units. Of the 78 mapping zones for the 50 sates, 73 were determined to have adequate field sampling to represent forest conditions. The zones not analyzed were four mapping zones along the northern and western coasts of Alaska and Hawaii map zone.

1.2 Predictor Datasets

Landsat imagery prepared for the USGS National Landcover Dataset was utilized for this project as detailed in (Ellenwood 2007a). An additional procedure was added to model texture based upon an alternative vegetation index ratio for Landsat bands 5 and 2 for each of the three seasons. This small-scale spatial component was computed using a 3x3 standard deviation kernel around a normalized difference of the Landsat reflectance bands 5 and 2 for each season of the NLCD imagery. The purpose of the texture bands was to assist in better modeling areas near non-census water.

The original project utilized downscaled versions of climate from PRISM and Daymet. Though very significant in each of the species parameter models, the over-fitting of data was commonplace. In attempt to alleviate the over-fitting problems, a new climate layer was investigated. The techniques developed by Rehfeld (2006) were utilized with modification to accommodate fine-scaled needs. Climate data for 7939 monthly station normals were extracted from NOAA-NCDC (2002) clim81 30-year climate normal dataset (1971-2000). The coordinates in this dataset are stored as 2-digit decimal degrees. For the 30-meter dataset, this was deemed to be inadequate. Higher resolution station coordinates were extracted from the 99,369 NCDC COOP station database. Coordinates were computed to extract location information to at least 5 decimal places and converted to the USGS Albers projection (lower 48 and Alaska). This information was linked and a dataset was built for use in the ANUSPLIN climate modeling software (ANU 2008). Surfaces at 30-meter ground resolution were generated for precipitation, temperature minimum, maximum, and average. Derived climate variables utilizing techniques from Crookston were extracted from the ANUSPLIN generated dataset. Seasonal moisture was summarized for the period starting with the month of the first frost-free day to the month of the last frost-free day, with a period minimum of 1-month. The dataset was separated into two sets, one for the lower-48 and the other for Alaska.

NRCS soil data is nearly complete for the lower-48 states with most of the incomplete data occurring on many National Forest System Lands. Much of the spatial data for NFS lands has been acquired data but rectifying individual databases has been difficult and has not been included in the current models. Subsequent data development intends to incorporate this data along with a soil productivity index.

Additional terrain variables were added to the predictor dataset to account for solar radiation and topography. Potential annual direct solar radiation was computed from latitude and elevation using equations by McCune (2002). Additional solar radiation variables were computed utilizing techniques recommended by Zimmermann (2007). Accumulated direct and indirect solar radiation were computed for Julian day 172 (summer solstice) for two-hour periods based upon equations from Kumar (1997). Zimmermann's topographic scale was computed for 3-windows: 5, 10, and 15 cell radii. This predictor layer may be more sensitive than the position index as it looks at multiple windows for topography.

1.3 Training Datasets

New inventory data was added to complete the coverage for Texas. Additionally, for the 49 states included in the training datasets, 19 had incomplete inventory panels. The new data panels were included for these incomplete inventory units for the years 2006 and 2007. A total of 1,300,000 subplots were included in the analysis.

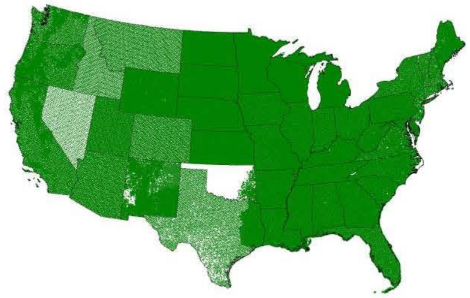

Figure 1. Approximate USFS FIA Plot Network

There is a mismatch between the 30-meter data (0.09 hectares per pixel) and the FIA subplots which are approximately 0.017 hec for trees greater than 12.5 cm and 0.0013 hec for trees between 2.5 and 12.5 cm. Since variation is a function of plot size, one could expect higher variation on the subplot compared to the variation of the imagery. A plot size which would match the imagery would probably have a proportionally higher number of trees. Given the distribution of tree occurrence there would be a lower chance of "zero" count plots.

To compensate for this mismatch, tree count measurements for each subplot were adjusted utilizing a Poisson distribution. An expected subplot tree count (lambda) was determined based upon the overall plot tree count divided by the number of subplots. Using 0.68 two-tail cutoffs (the equivalent of 1-standard deviation in the more familiar Gaussian distribution), actual tree count values which exceeded the cutoff values were set to the cutoff value. Individual parameters were computed based upon a proportion of the tree count and the parameter. Approximately 10 percent of the subplots had adjusted values utilizing this method with 1.1% of the subplots becoming non-zero and 8.9% of remaining subplots being adjusted. A 0.50 cutoff was attempted and a larger percentage of subplots changed (~18%), however due to the unprecedented nature of this procedure, the more conservative 0.68 cutoff was selected. The effect of this procedure reduces the extreme values one would expect from the smaller subplot size, and would be more in line with values from a subplot size which would match the 30-meter imagery.

2. PROCEDURES

2.1 Modeling Techniques

The original project utilized 57 predictor layers using cubist models to generate raster products. Overfitting of models was problematic for many of the species parameter models. In attempt to reduce this problem, several data reduction techniques were investigated to mitigated the overfitting and achieve an efficient process for production.

Variance inflation factor was computed for each of the zone datasets to reduce autocollinearity which would be required for ordinary least square regression. Though somewhat different for each dataset, commonly selected variables were chosen for a global reduced dataset. This reduced the number of predictor layers to 41 for each zone greatly reducing the image processing time.

A second reduction was implemented on the zone reduced predictor dataset by conducting a stepwise-AIC regression for each of the species parameters. The selected predictor variables were subsequently utilized in the cubist modeling process. This resulted in reducing the original predictor dataset from 76 variables to approximate 20-25 variables with minimal change in the model correlation.

Though a significant performance was achieved in producing the reduced predictor datasets, overfitting of many of the models were experienced. As a result, the data reduction techniques were utilized in a secondary modeling scenario. The primary modeling scenario utilized the original dataset without the 24-climate variables, the 3-imagery date meta-data images, and the 2 soil metadata images. The results of the primary modeling technique yielded products with minimal overfitting for a majority of the species parameter models.

2.2 Geospatial Product Generation

The generation of a cubist model is accomplished in a few seconds. For each of these models, the generation of a raster product is approximately 3 hours. For the completion of a nationwide dataset, the equivalent of 3-years of computing time is required. These products were generated on 4 multiprocessor servers which reduced the elapsed time for completion.

2.3 Validation

Each of the generated rasters are visual validated at two scales. For the coarse scale evaluation, a generalized assessment is observed for known species distributions as well as a check on overfitting. Fine scale evaluation is assessed by utilizing high resolution imagery as a backdrop to see if the resulting product visually fits the terrain and vegetation. If the raster fails on either of the evaluations, then the secondary modeling scenario is utilized.

2.4 Histogram Adjustment
For each of the species parameter rasters, a histogram matching routine is conducted to match the predicted parameter with the inventoried parameter. This rescaling of the data helps to eliminate some of the modelling biases that may be inherent in the process.

2.5 Supplemental Masking and Scaling Adjustments
Since trees may occur in landcover areas that are classified as non-forest, the NLCD landcover dataset does not adequately represent the modeling areas. To compensate for this limitation, masks were broadened to prevent the excessive reduction of treed areas. Supplemental masking is being utilized to assist in the over-classification of certain areas associated with non-census waters by utilizing the National Hydrography Dataset.

3. RESULTS

3.1 Results
A total of 15,782 cubist models were created for the 73 mapping zones. Extirpolated models were built for 7,380 of the species parameters or 89.1% of the total number of models. The number of extirpolated models is an indication of the difficulty of producing individual species parameter models and may have not otherwise been achieved. From the cubist models, 8,402 models were utilized to generate individual species parameter raster products.

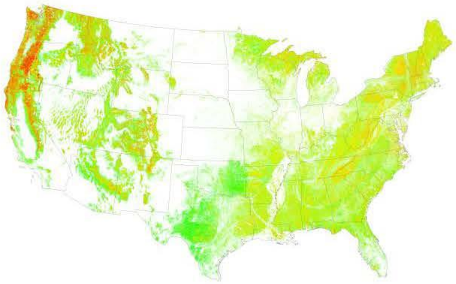

Figure 1. Total Basal Area – Lower 48 – 30m Resolution

3.2 Model Accuracy
Results for each of the zones have generated correlation r-values ranging from 0.58 to 0.94 for total basal area and 0.63 to 0.96 for stand density index in each map zone. The strongest models are typically the stand density index. It should be noted that the zones with a significant diversity of species have the lowest r-values. Nearly 11% of the individual tree species exceeded r-values of 0.71 with the remaining species parameter models utilizing extirpolated models to produce a valid modeled parameter.

Parameter	Min	1st Qtl	2nd Qtl	3rd Qtl	Max
Basal Area	0.58	0.74	0.78	0.83	0.94
Stand Density Index	0.63	0.76	0.80	0.84	0.96

Table A. Summary of Cubist Models

3.3 Validation
Visual and field validations are on-going. Visual validation confirms if the original model produced a viable product. For "failed" models, secondary and tertiary techniques will be implemented. Since the training dataset was fully utilized to create each of the species parameter models, a true accuracy assessment can not be conducted other than the model correlation. Field validation will quantitatively assess a given area through the use of a localized ancillary dataset. This will achieve an affirmation of the generated products for use a dataset for intended risk assessment.

3.4 Delivery
Due to the resultant size of the generated dataset, all of the products generated will be delivered through an image server environment for access by field specialists to generate risk maps for intended forest health concerns. In addition to the direct data access, a webpage with a server linkage will allow for the browsing of the data along with other forest health datasets.

4. SUMMARY

The final products will help provide better representation of forest parameters and support the next-generation risk mapping effort. This will help bridge the gap between national-scale planning and on-the-ground conditions. The risk map has been a tool to communication forest health concerns to policy makers. With finer resolution data, it can now be a tool for land management planners to better represent forest health concerns in the forest planning process. Through these mechanisms, better and more effective treatments can be implemented. Caution must be applied when utilizing these products at resolutions smaller than 30-meters, such as would be necessary for project level planning. The 30-meter pixel does not represent individual trees, though there may be utility for application at the stand level by aggregating 30-meter pixels for stand-level summaries.

ACKNOWLEDGEMENTS

We are grateful to the

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Outline:

Predictor Layers

Training Data

Modeling techniques

Validation

Data Distribution
Distributing 2 TB of data – difficult.
Risk assessment results web-based merged with past damage and anomolies for current survey assessments.

Table A. Key Criteria of Top 11 Agents

$$BA_{t-si} = BA_t - BA_{si} \tag{1}$$

$$\hat{Y}_t = Y_{si} - Y_{t-si}$$

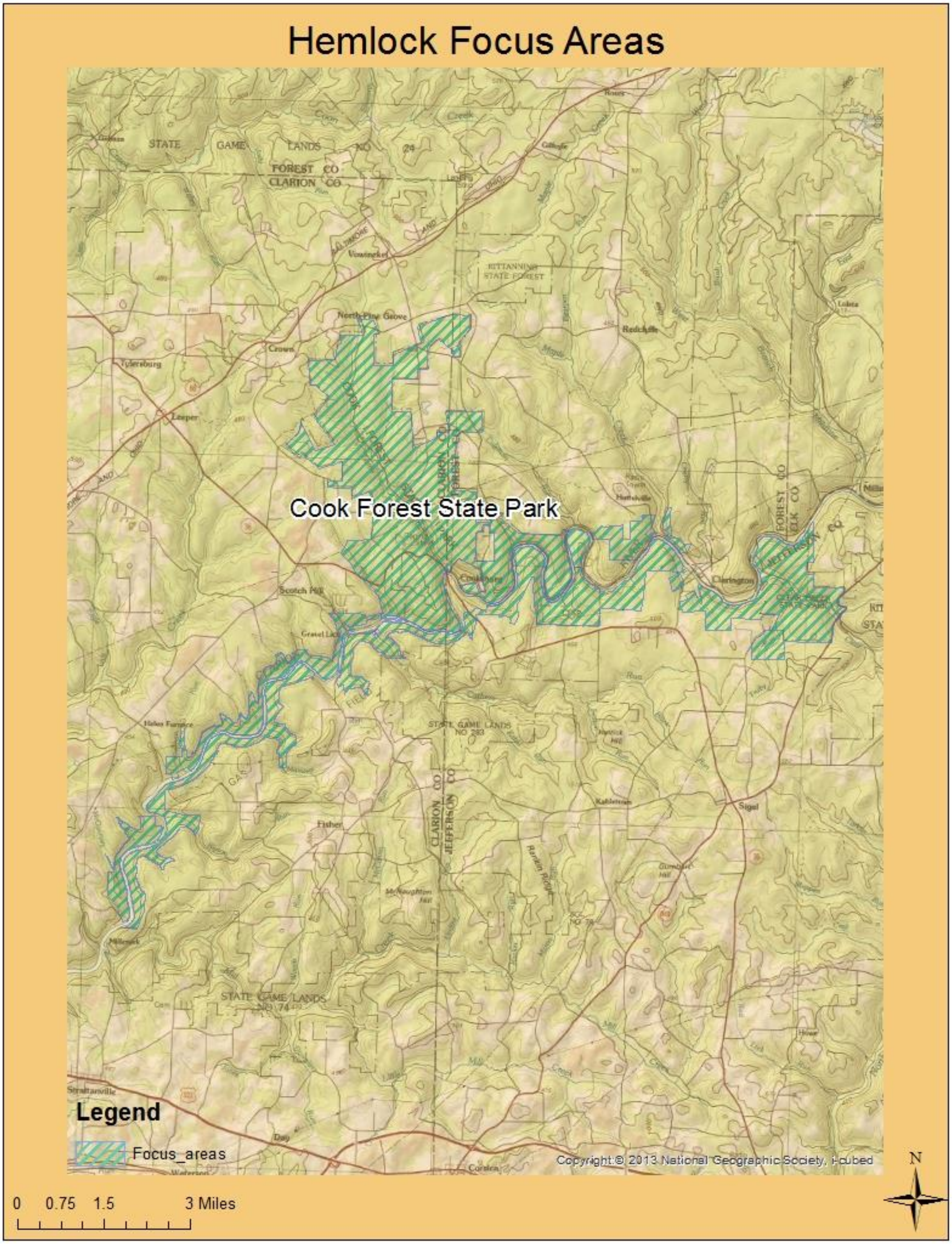
where: BA_t = subplot total basal area for all species
BA_{si} = subplot basal area for $species_i$
BA_{t-si} = subplot extirpolated basal area for $species_i$
Y_{t-si} = modeled extirpolated basal area for $species_i$
Y_t = modeled total basal area for all species
Y_{si} = calculated basal area for $species_i$

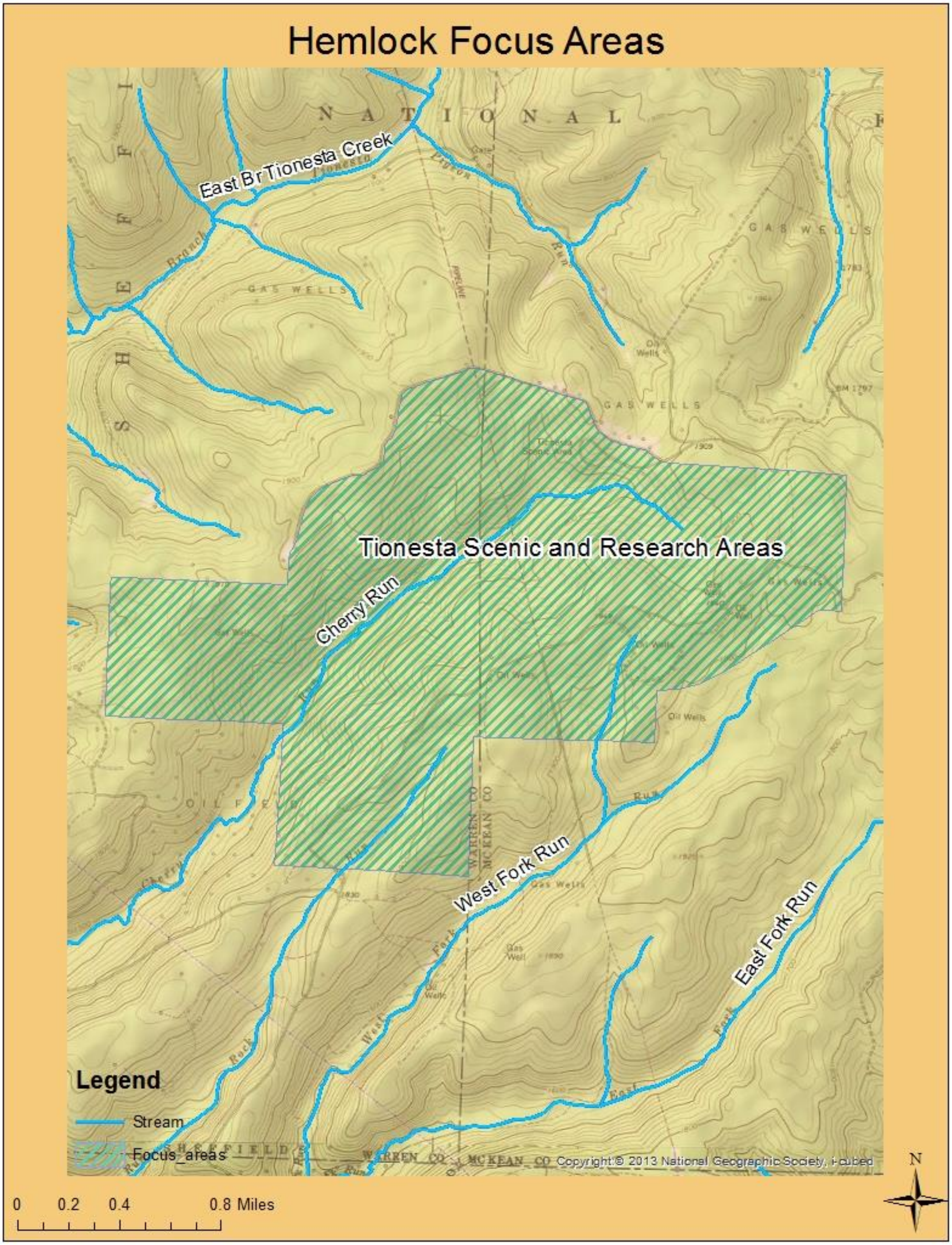
Figure 1. Southern Mapping Zones for Loblolly Pine Basal Area

Figure 2. USGS Mapping Zone 51 Total Basal Area

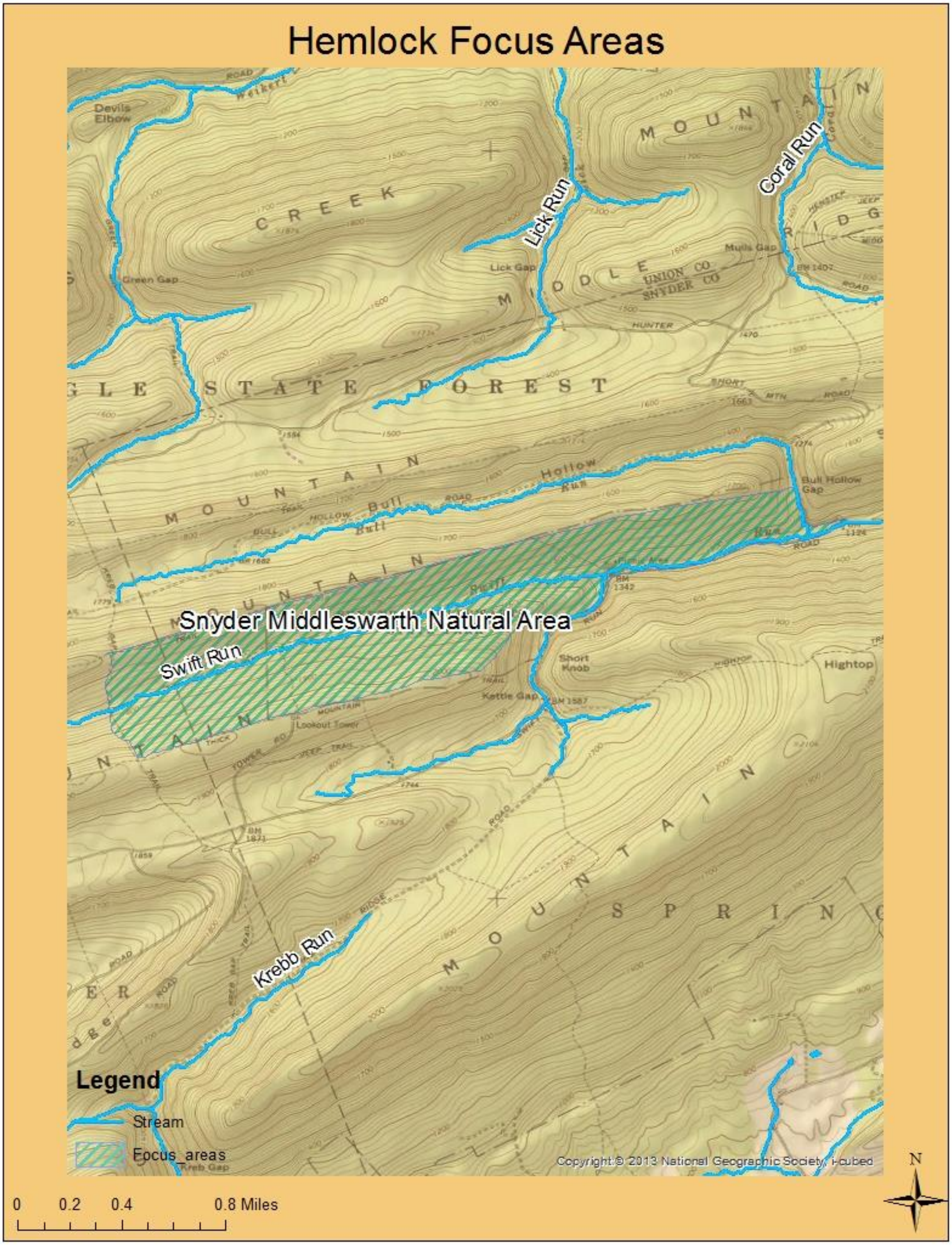
Parameter	Z37	Z44	Z45	Z46	Z48	Z51	Z52
Total BA	0.70	0.72	0.73	0.61	0.69	0.77	0.67
TPA	0.52	0.54	0.61	0.45	0.53	0.58	0.56
# Models	276	230	188	292	260	208	146
	Z54	Z55	Z56	Z57	Z58	Z59	
Total BA	0.64	0.66	0.64	0.67	0.63	0.62	
TPA	0.47	0.46	0.41	0.44	0.45	0.52	
# Models	246	272	146	210	224	204	2902

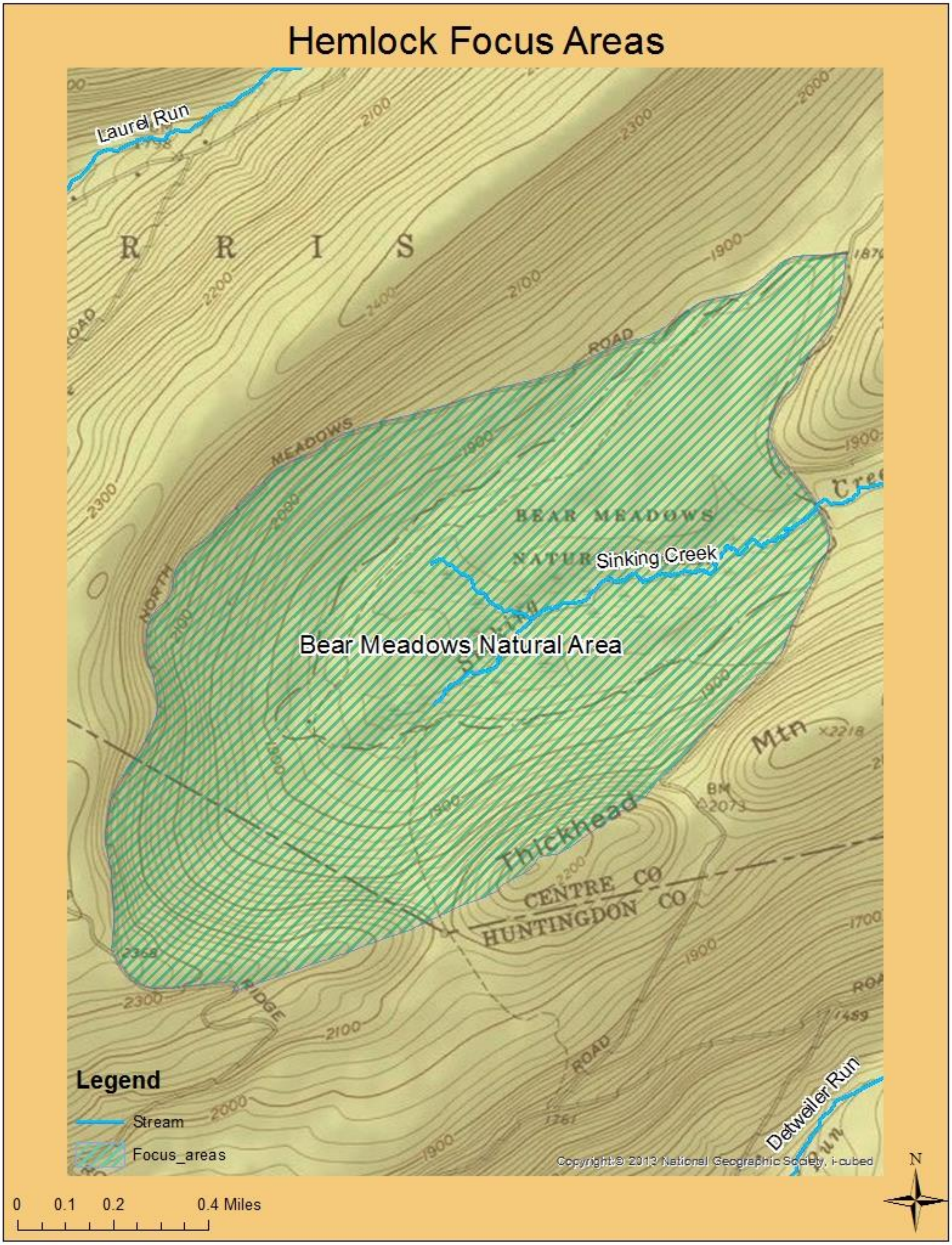
Appendix C: High Priority Hemlock Forests

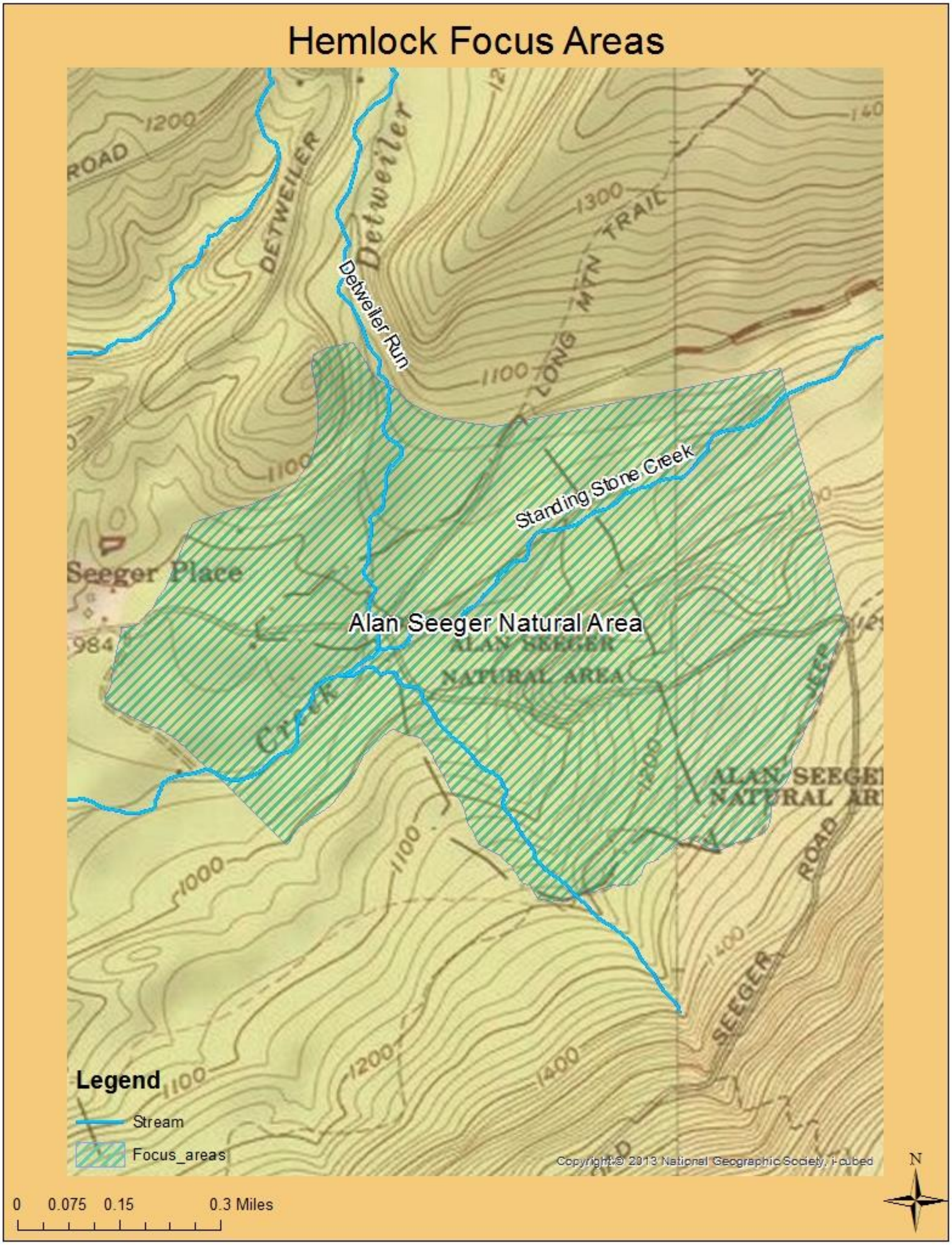

Hemlock Focus Areas
Cook Forest State Park
Legend
Focus_areas
0 0.75 1.5 3 Miles
N
Copyright: © 2013 National Geographic Society, i-cubed


Hemlock Focus Areas
East Br Tionesta Creek
Tionesta Scenic and Research Areas
Cherry Run
West Fork Run
East Fork Run
N A T I O N A L
GAS WELLS
WARREN CO
MC KEAN CO
Legend
Stream
Focus_areas
Copyright © 2013 National Geographic Society, i-cubed
0 0.2 0.4 0.8 Miles
N


Hemlock Focus Areas


Hemlock Focus Areas
Lick Run
Coral Run
Snyder Middleswarth Natural Area
Swift Run
Krebb Run
Legend
Stream
Focus_areas
Copyright:© 2013 National Geographic Society, i-cubed
0 0.2 0.4 0.8 Miles
N


Hemlock Focus Areas
Laurel Run
Sinking Creek
Bear Meadows Natural Area
BEAR MEADOWS
Thickhead
Mtn
CENTRE CO
HUNTINGDON CO
Detweiler Run
Legend
Stream
Focus_areas
0 0.1 0.2 0.4 Miles
N
Copyright© 2013 National Geographic Society, i-cubed


Hemlock Focus Areas
Detweiler Run
Standing Stone Creek
Alan Seeger Natural Area
Seeger Place
ALAN SEEGER NATURAL AREA
LONG MTN TRAIL
DETWEILER
ROAD
Legend
Stream
Focus_areas
Copyright:© 2013 National Geographic Society, i-cubed
0 0.075 0.15 0.3 Miles
N

Appendix D: GIS Analysis Identifying Potential Hemlock Ecological Areas

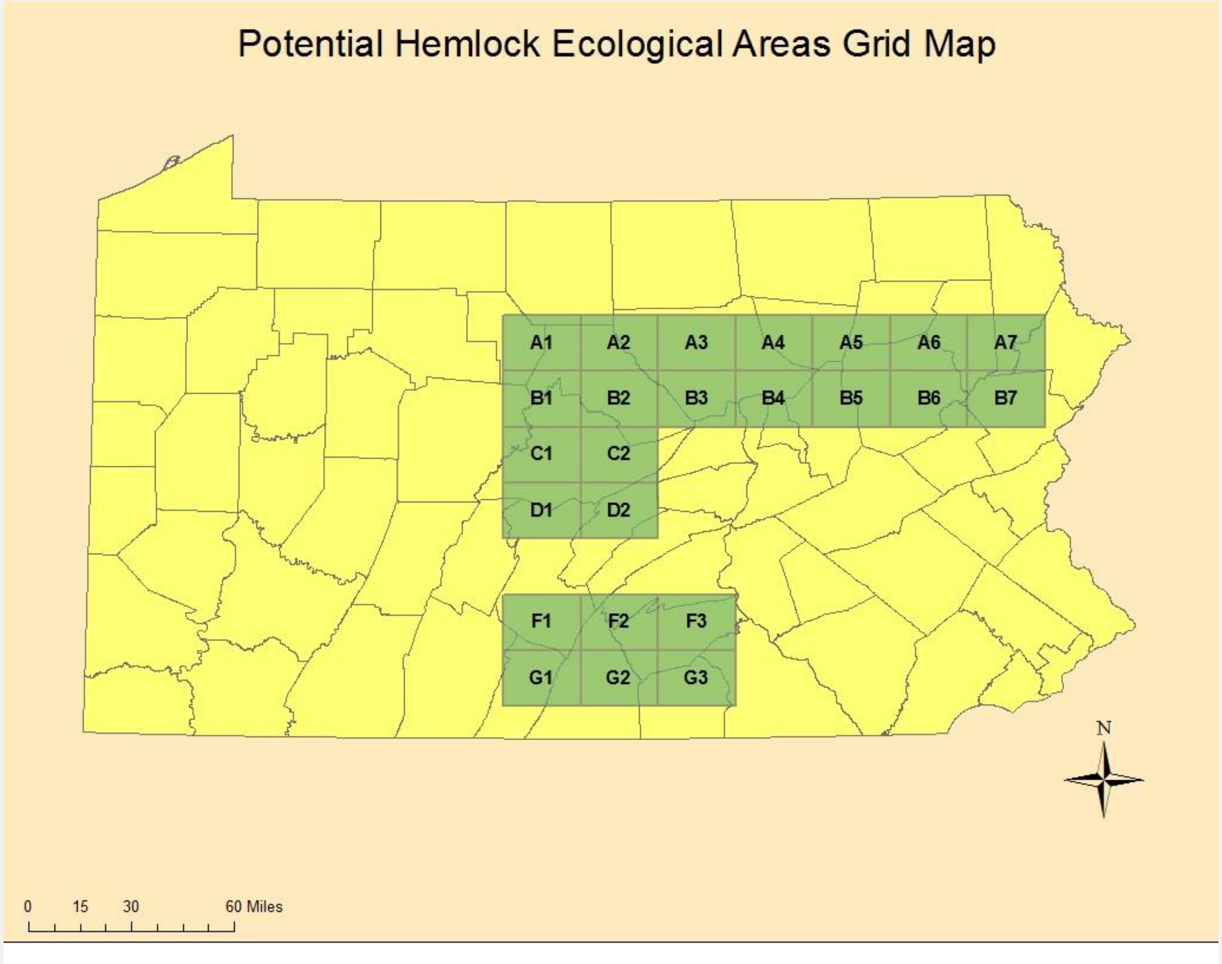
The following criteria were used to identify thirty-six potential hemlock ecological areas. These sites may contain additional hemlock focus areas, upon further evaluation.

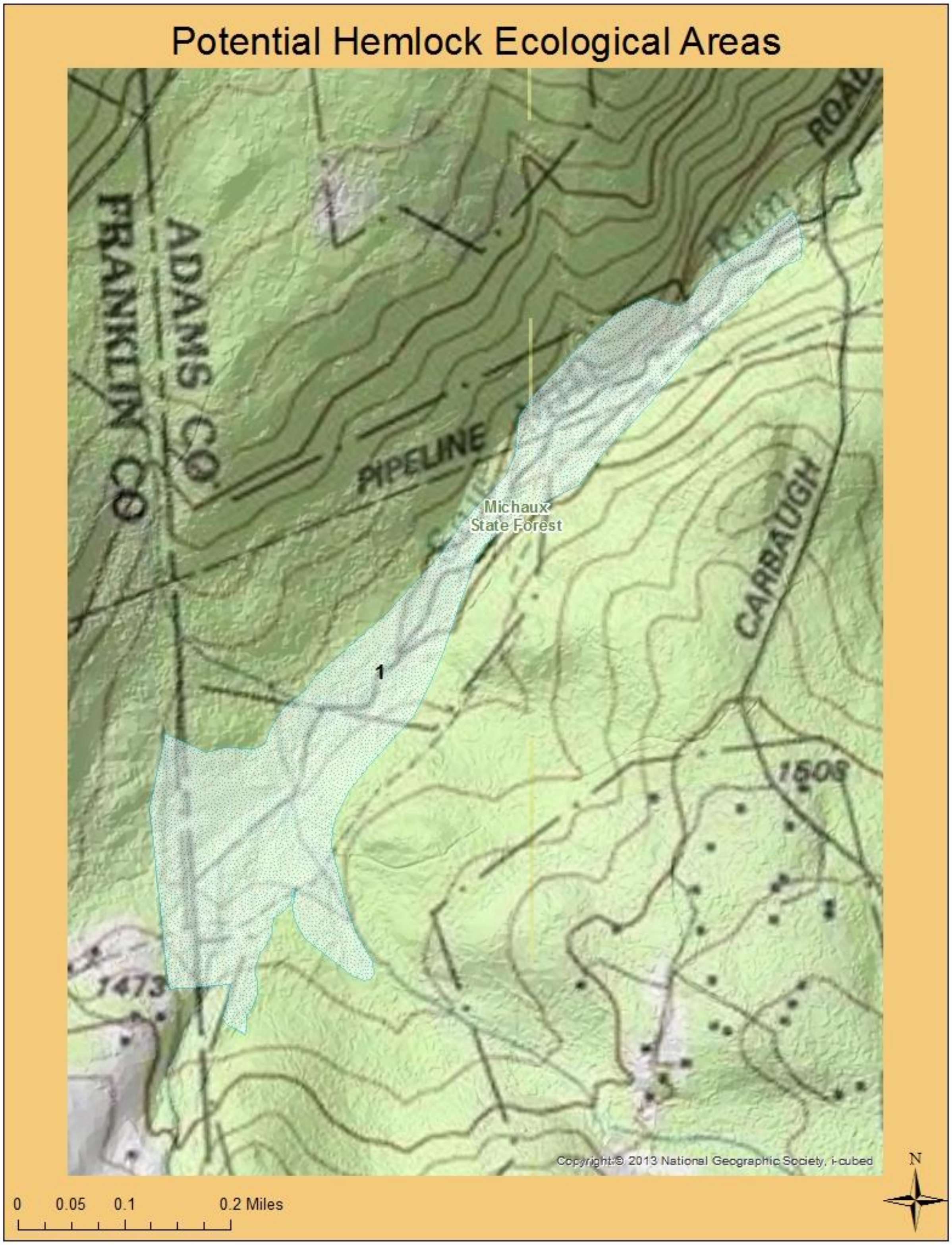
1. Occurs in the following state forests: Loyalsock, Sproul, Moshannon, Tuscarora, Michaux, Delaware
2. A hemlock stand type
3. Equal to or greater than 50 acres
4. Intersects an Exceptional Value Stream
5. Intersects an Important Bird Area

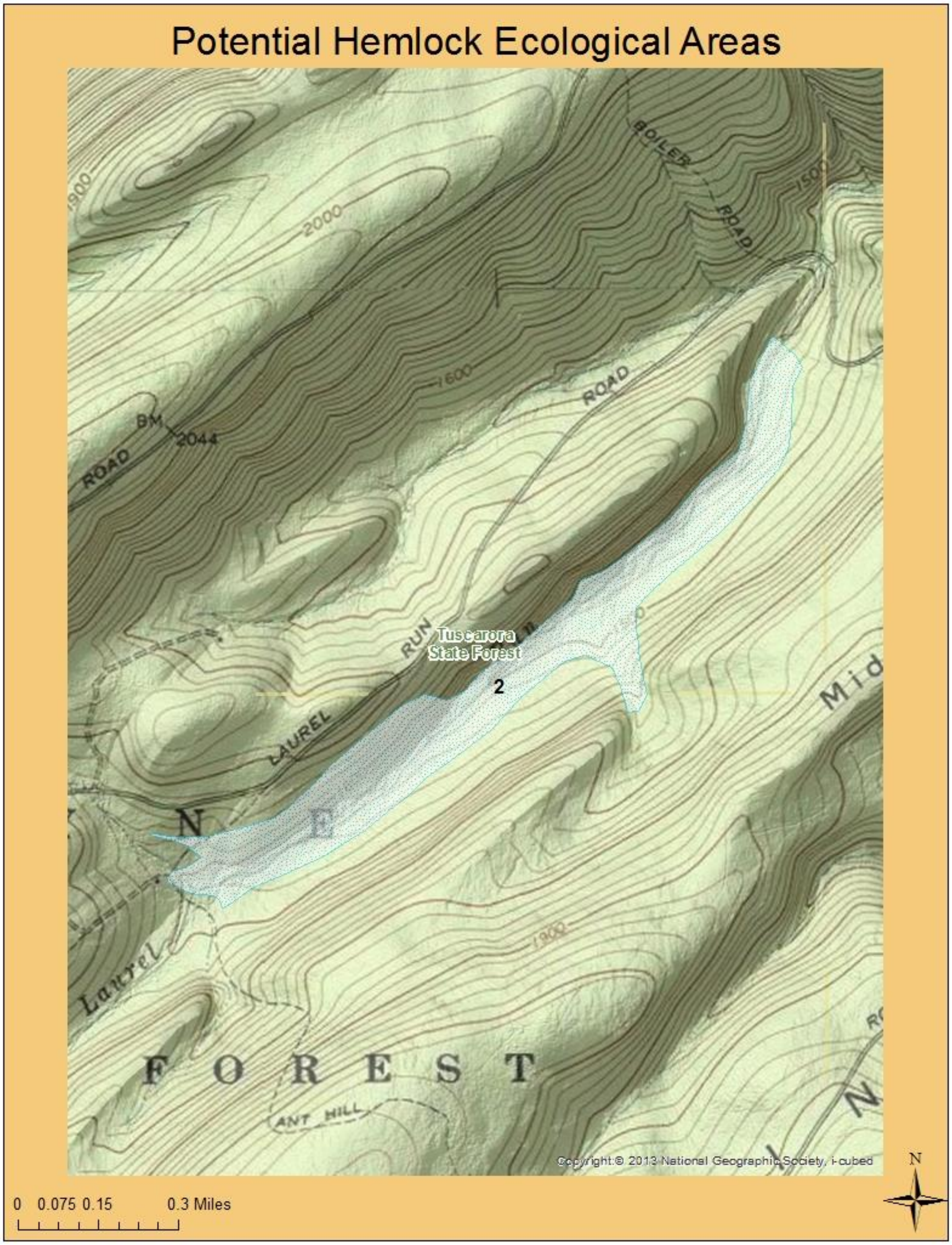
A table exported from the attribute table of the GIS layer can be found below in addition to a map of each area

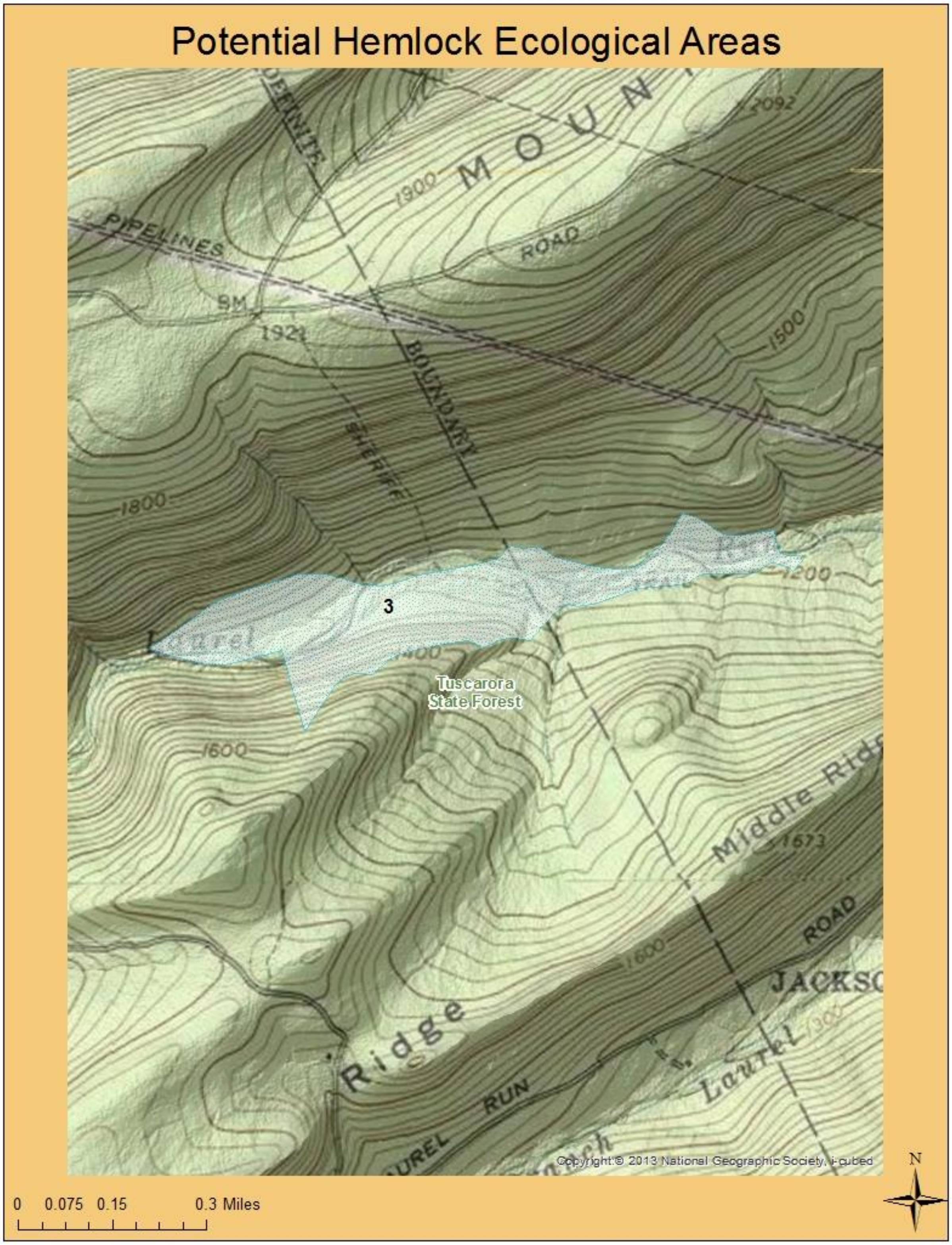
Potential Hemlock Ecological Areas

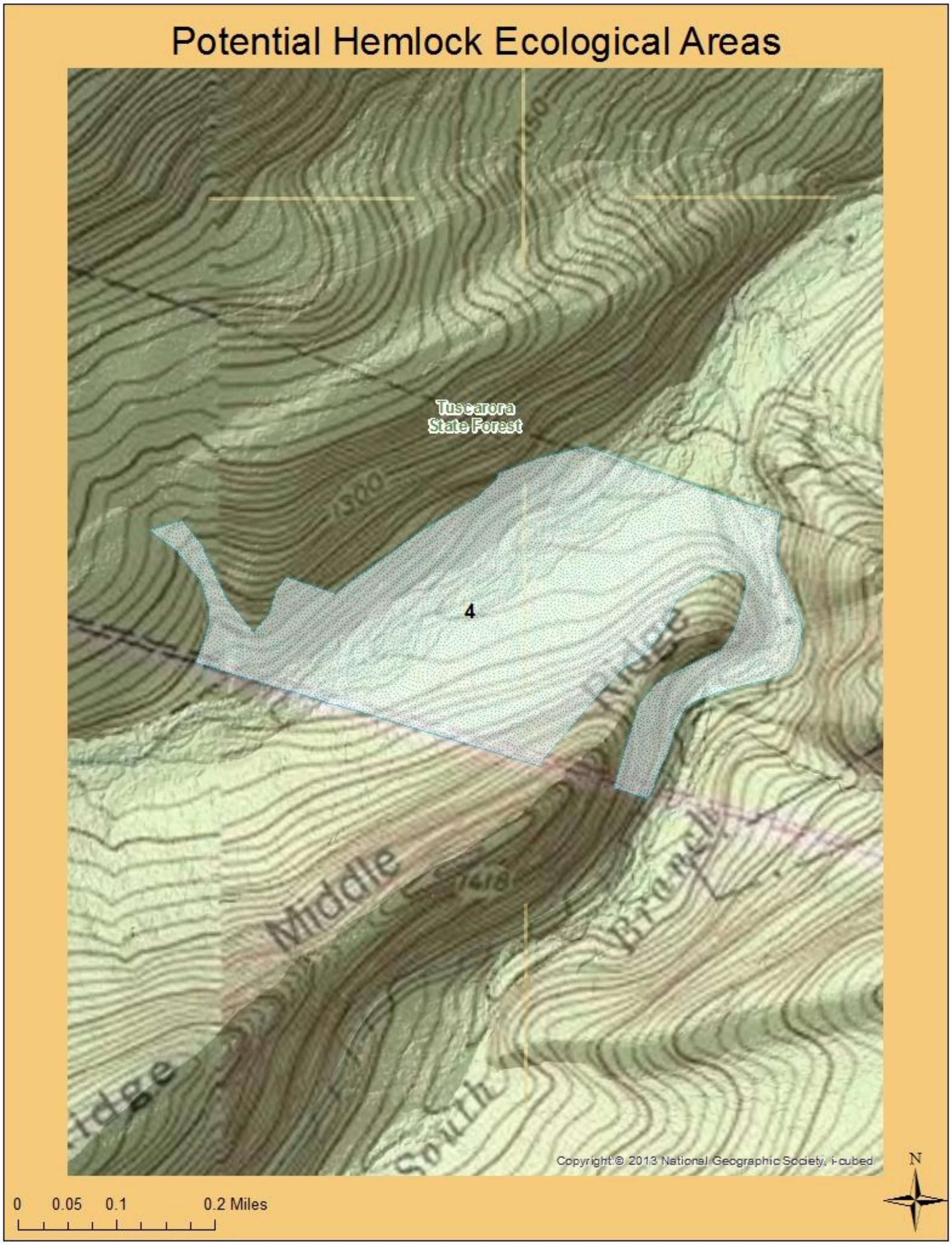
Ecological Area	Grid	District	Compartment	Stand #	Stand ID	Type Code	Acres
1	G2	1	42	19	01042019	LUB12N	51
2	F2	3	30	29	03030029	MFR11C	107
3	F2	3	35	20	03035020	NFR11N	67
4	F2	3	36	19	03036019	LFR11N	73
5	B1	9	72	37	09072037	WFR22N	123
7	C1	9	85	57	09085057	LFB22C	70
10	A2	10	41	37	10041037	LFB22N	67
11	A2	10	41	6	10041006	LFR22N	471
12	A2	10	42	12	10042012	LFF23N	80
13	B2	10	94	24	10094024	LFR22N	130
14	A7	19	48	27	19048027	NUB22N	62
15	A4	20	5	56	20005056	MFB22C	131
16	A4	20	7	33	20007033	MFB22C	152
17	A4	20	9	58	20009058	MFB12C	51
18	A4	20	10	23	20010023	LFB22N	58
19	A4	20	10	16	20010016	LFB22N	141
20	A4	20	11	62	20011062	MFB22C	110
21	A4	20	12	43	20012043	MFB12C	80
22	A4	20	12	59	20012059	MFR22N	68
23	A4	20	20	11	20020011	MFB12C	62
24	A4	20	21	31	20021031	MFB11C	61
25	A4	20	25	18	20025018	MFB12C	94
26	A4	20	25	23	20025023	MFB12N	97
27	A4	20	27	68	20027068	MFB22C	101
28	A4	20	28	24	20028024	MFB22C	98
29	A4	20	29	13	20029013	MFB22C	65
30	A4	20	32	76	20032076	MFB22C	71
31	A4	20	33	182	20033182	MFB22C	105
32	A4	20	33	66	20033066	NFB22N	65
33	A4	20	35	49	20035049	MFB22C	50
34	A4	20	35	58	20035058	MFB22N	161
35	A4, A5	20	38	52	20038052	LFB22N	232
36	A4	20	38	21	20038021	MFB22C	50
37	A3	20	68	37	20068037	LFB22N	65
38	A4	20	70	94	20070094	MFF11N	73
39	B2	10	164	66	10164066	LUB11N	82

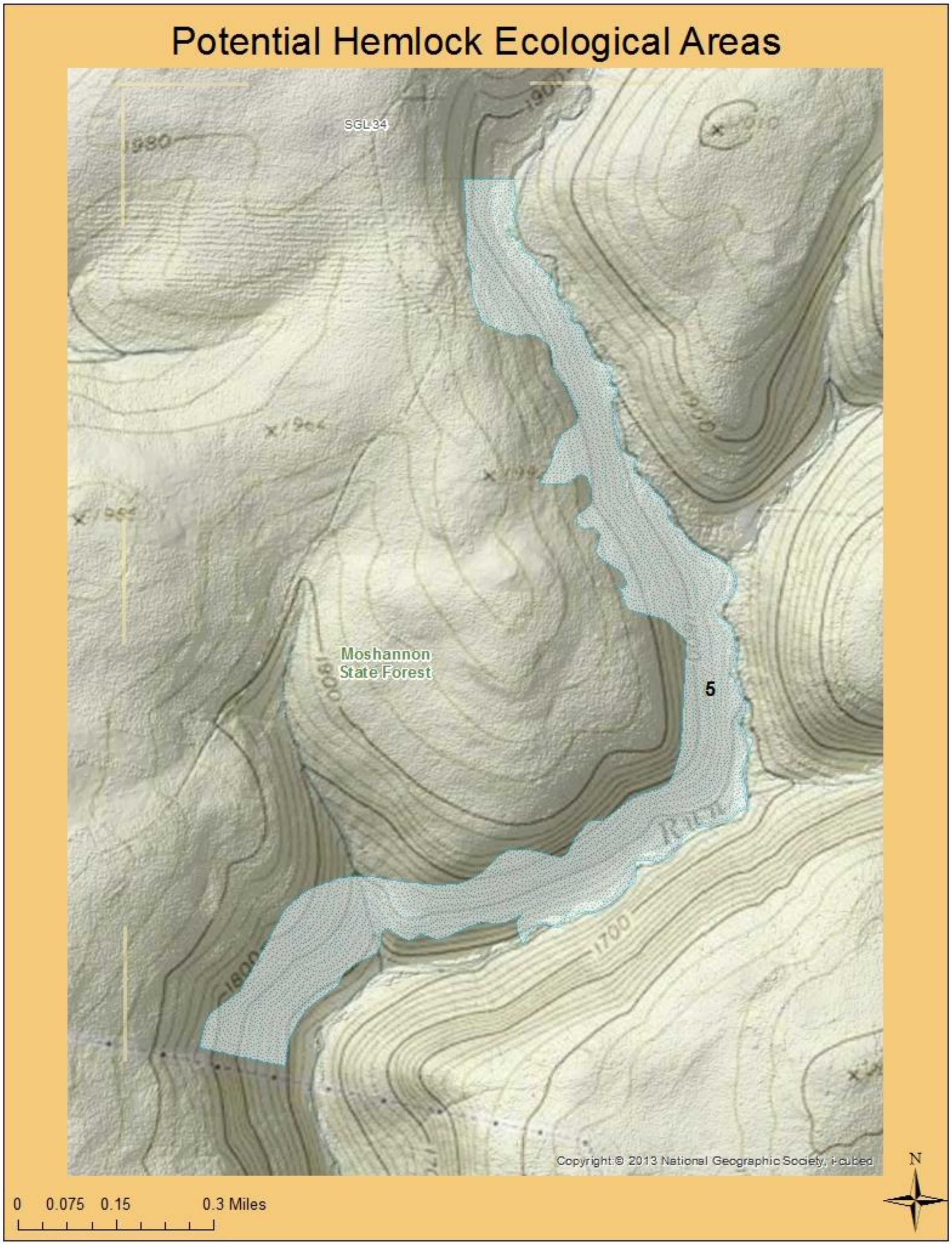

Potential Hemlock Ecological Areas Grid Map
A1
A2
A3
A4
A5
A6
A7
B1
B2
B3
B4
B5
B6
B7
C1
C2
D1
D2
F1
F2
F3
G1
G2
G3
N
0
15
30
60 Miles

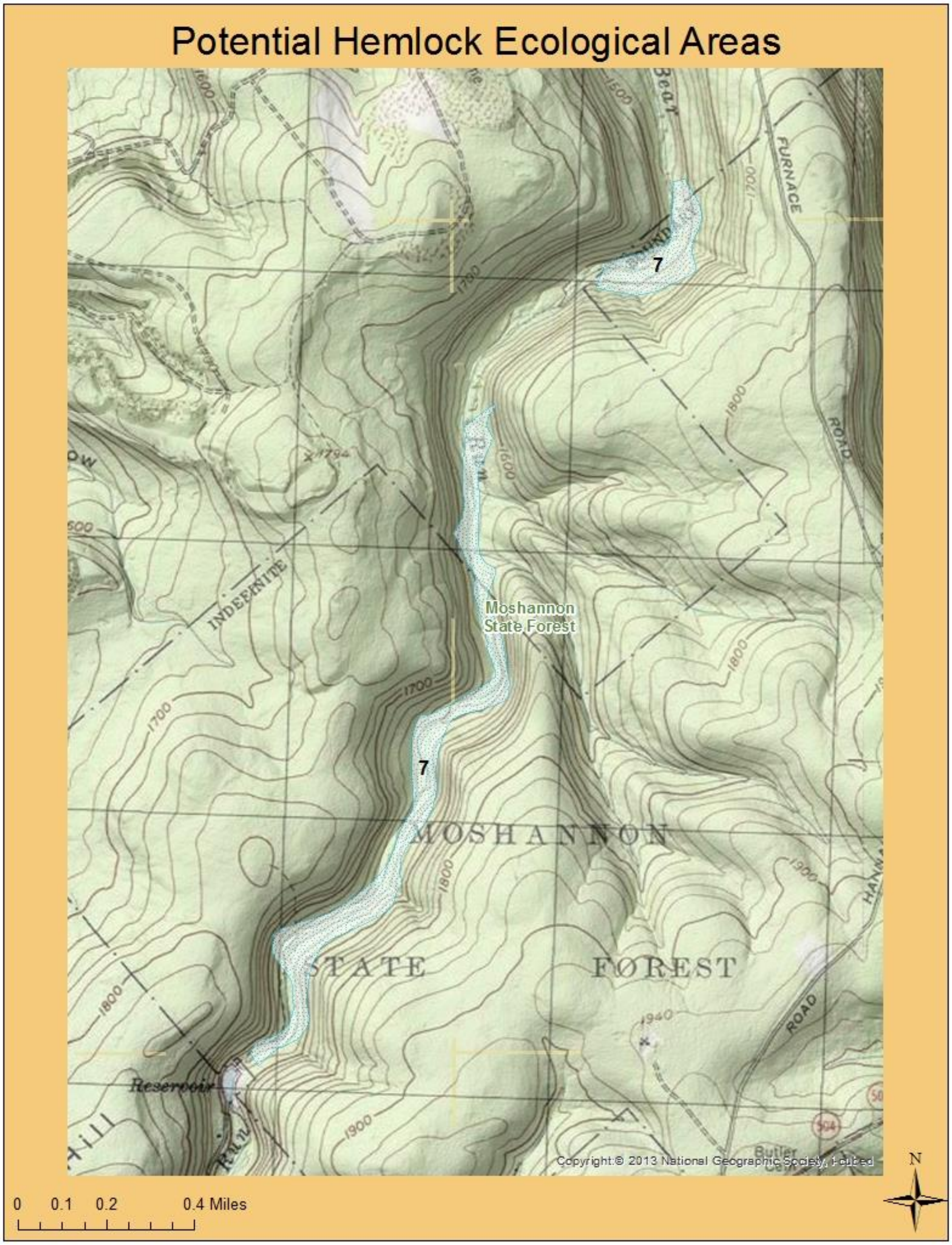

Potential Hemlock Ecological Areas
ROAD
ADAMS CO
FRANKLIN CO
PIPELINE
Michaux
State Forest
CARBAUGH
1
1508
1473
Copyright:© 2013 National Geographic Society, i-cubed
0 0.05 0.1 0.2 Miles
N

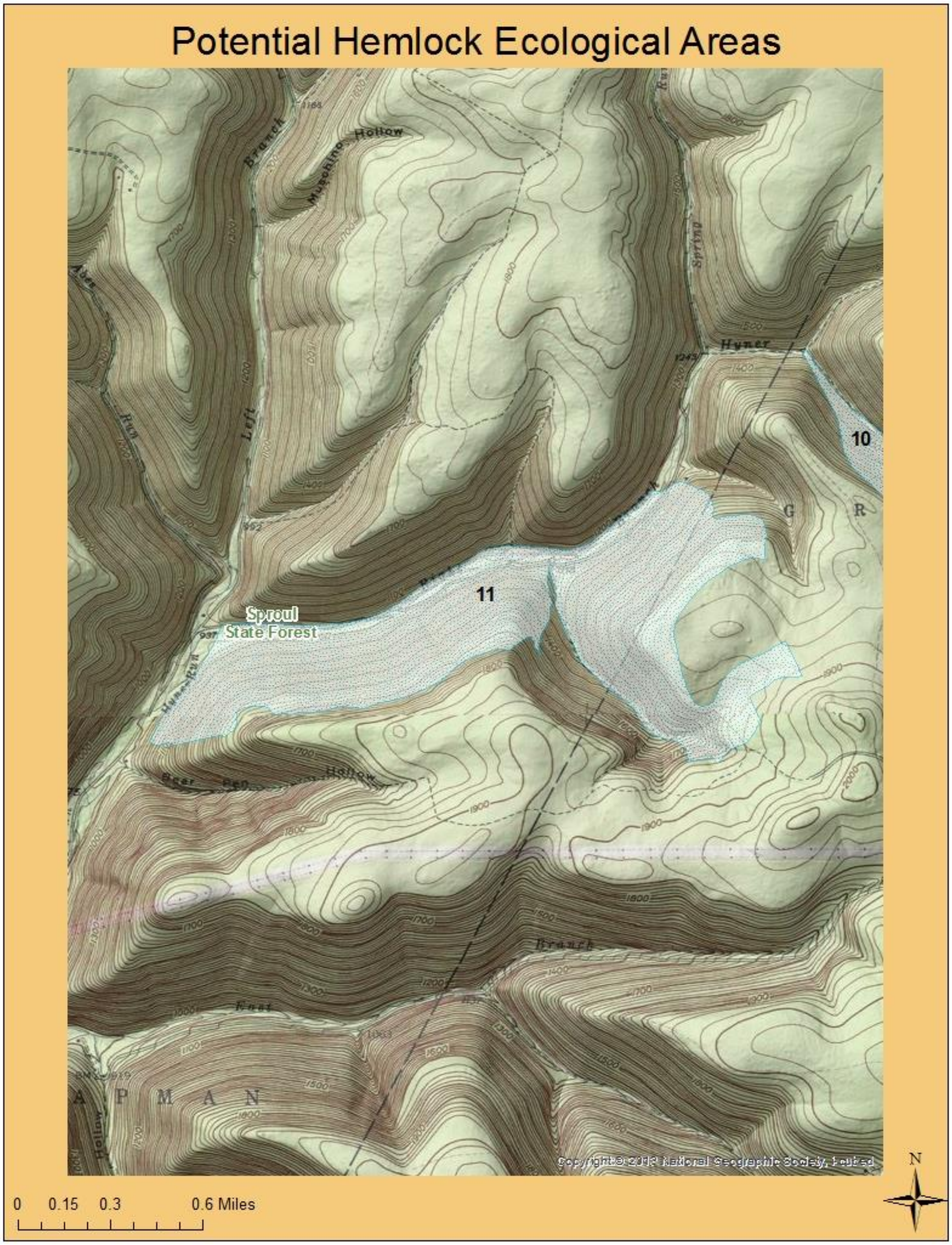

Potential Hemlock Ecological Areas
BOILER
ROAD
1500
1900
2000
1600
ROAD
BM
2044
ROAD
Tuscarora
State Forest
2
RUN
LAUREL
Mid
N
E
Laurel
1900
F O R E S T
ANT HILL
Copyright:© 2013 National Geographic Society, i-cubed
0 0.075 0.15 0.3 Miles
N

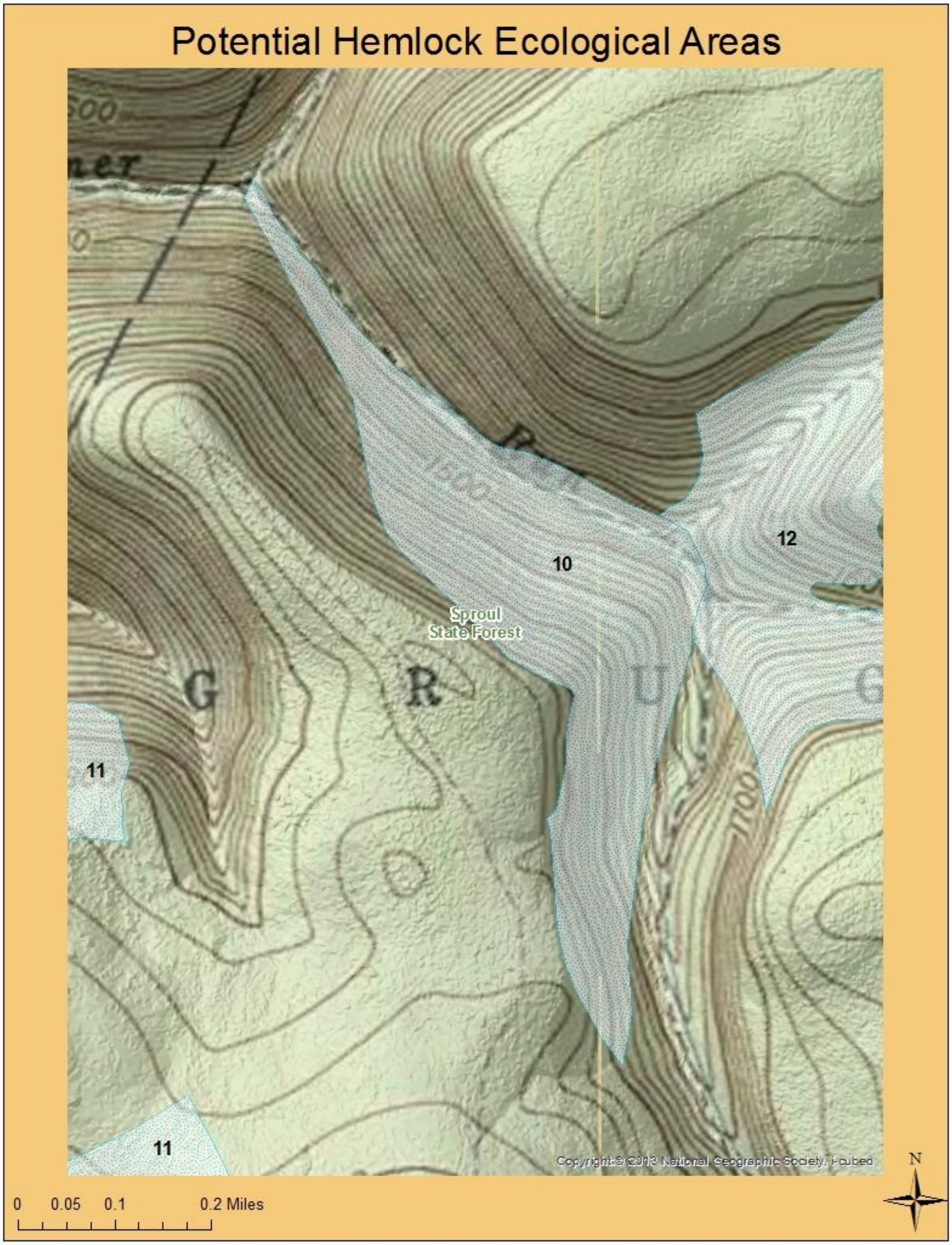

Potential Hemlock Ecological Areas
3
Tuscarora State Forest
PIPELINES
BOUNDARY
SHERIFF
ROAD
Middle Ridge
Ridge
JACKSO
LAUREL
RUN
Laurel
1800
1600
1500
1200
1900
1921
2092
Copyright:© 2013 National Geographic Society, i-cubed
0 0.075 0.15 0.3 Miles
N

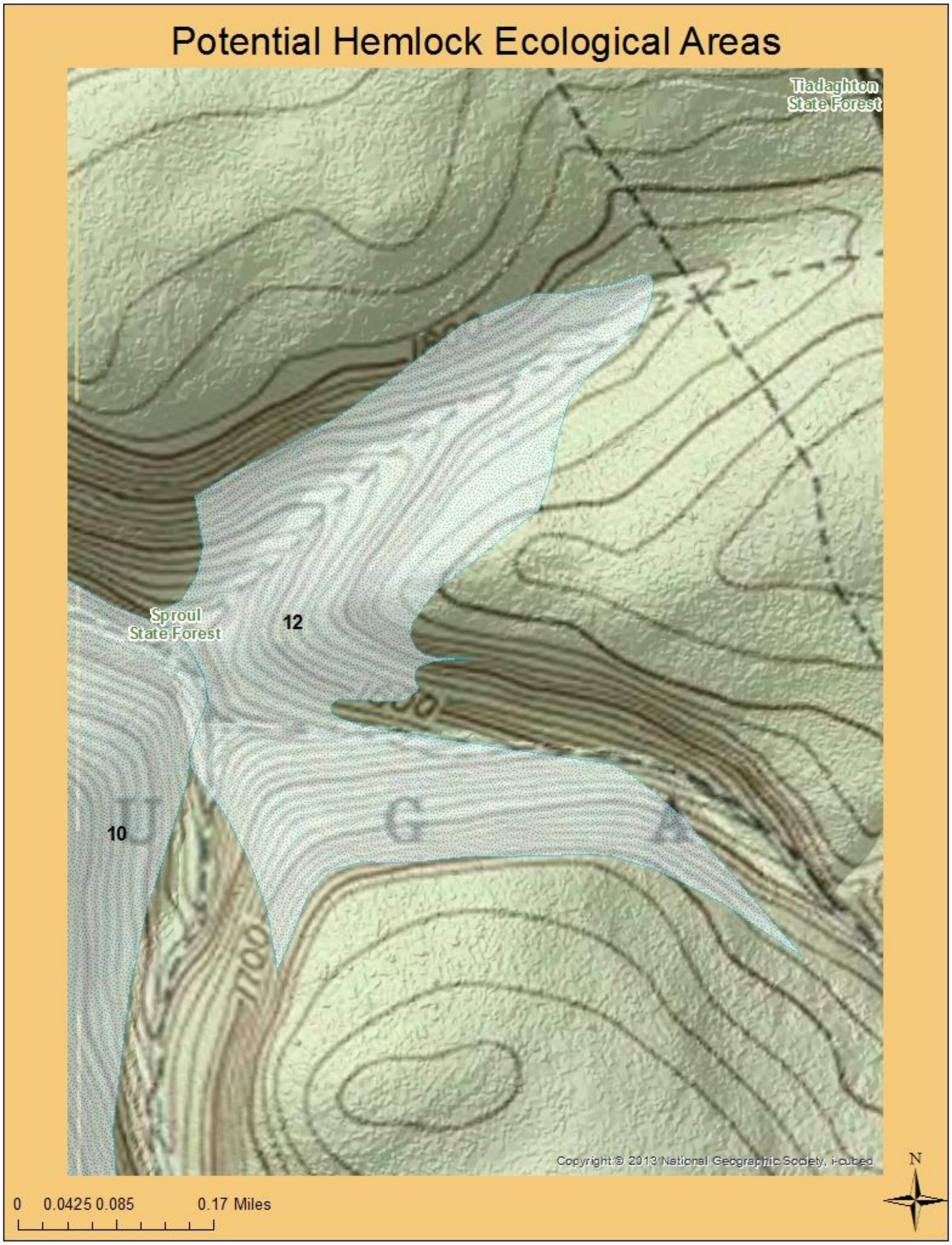

Potential Hemlock Ecological Areas
Tuscarora State Forest
1300
4
Ridge
Middle
Branch
South
Copyright:© 2013 National Geographic Society, i-cubed
0 0.05 0.1 0.2 Miles
N

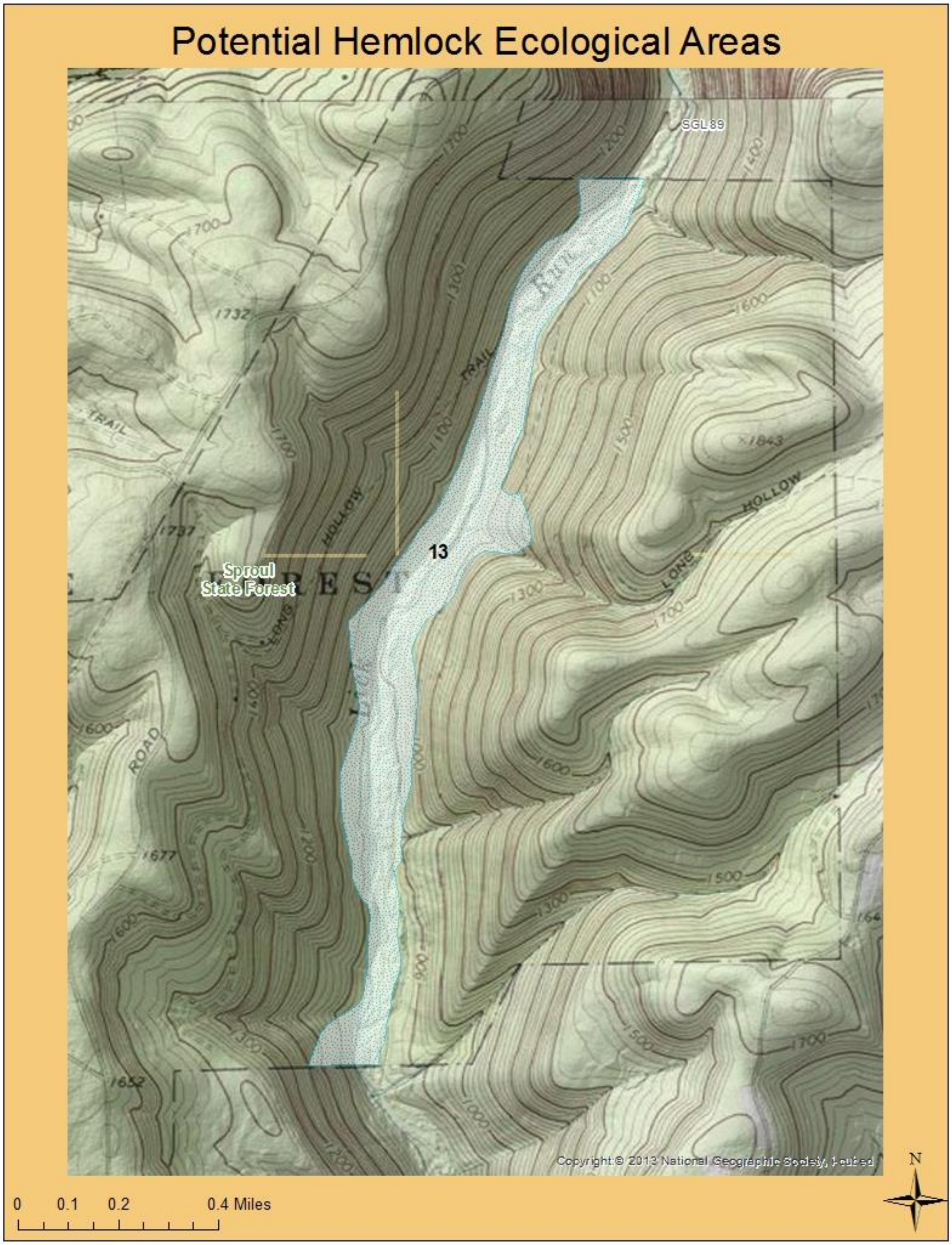

Potential Hemlock Ecological Areas
SGL 34
1980
Moshannon
State Forest
1800
5
1700
1800
Copyright:© 2013 National Geographic Society, i-cubed
0 0.075 0.15 0.3 Miles
N

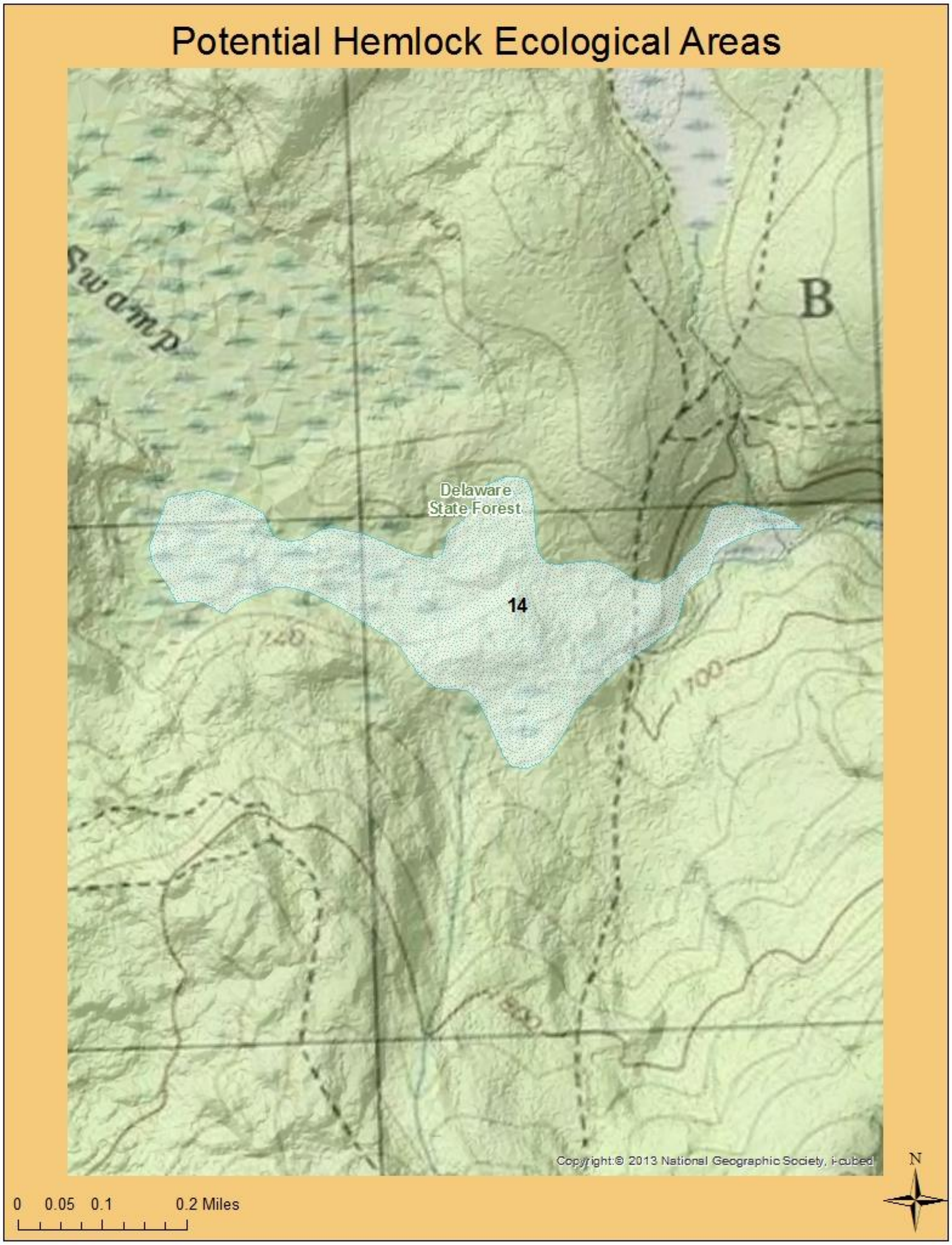

Potential Hemlock Ecological Areas
7
7
Moshannon State Forest
MOSHANNON
STATE
FOREST
INDEFINITE
FURNACE
ROAD
ROAD
Reservoir
Copyright:© 2013 National Geographic Society, i-cubed
0 0.1 0.2 0.4 Miles
N

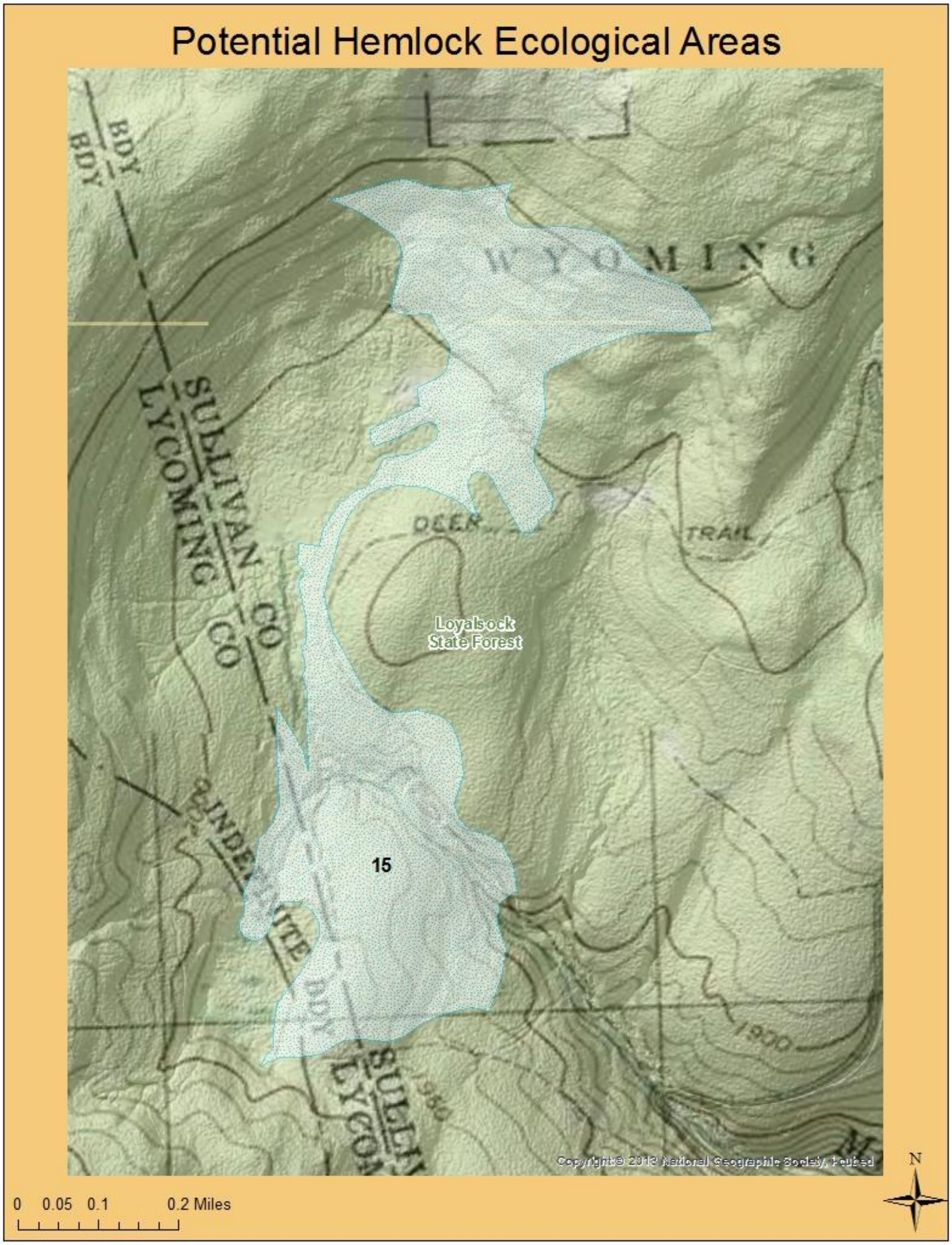

Potential Hemlock Ecological Areas
10
11
Sproul
State Forest
Hollow
Branch
Hyner
Spring
Left
Run
Bear
Hollow
East
Branch
0 0.15 0.3 0.6 Miles
N

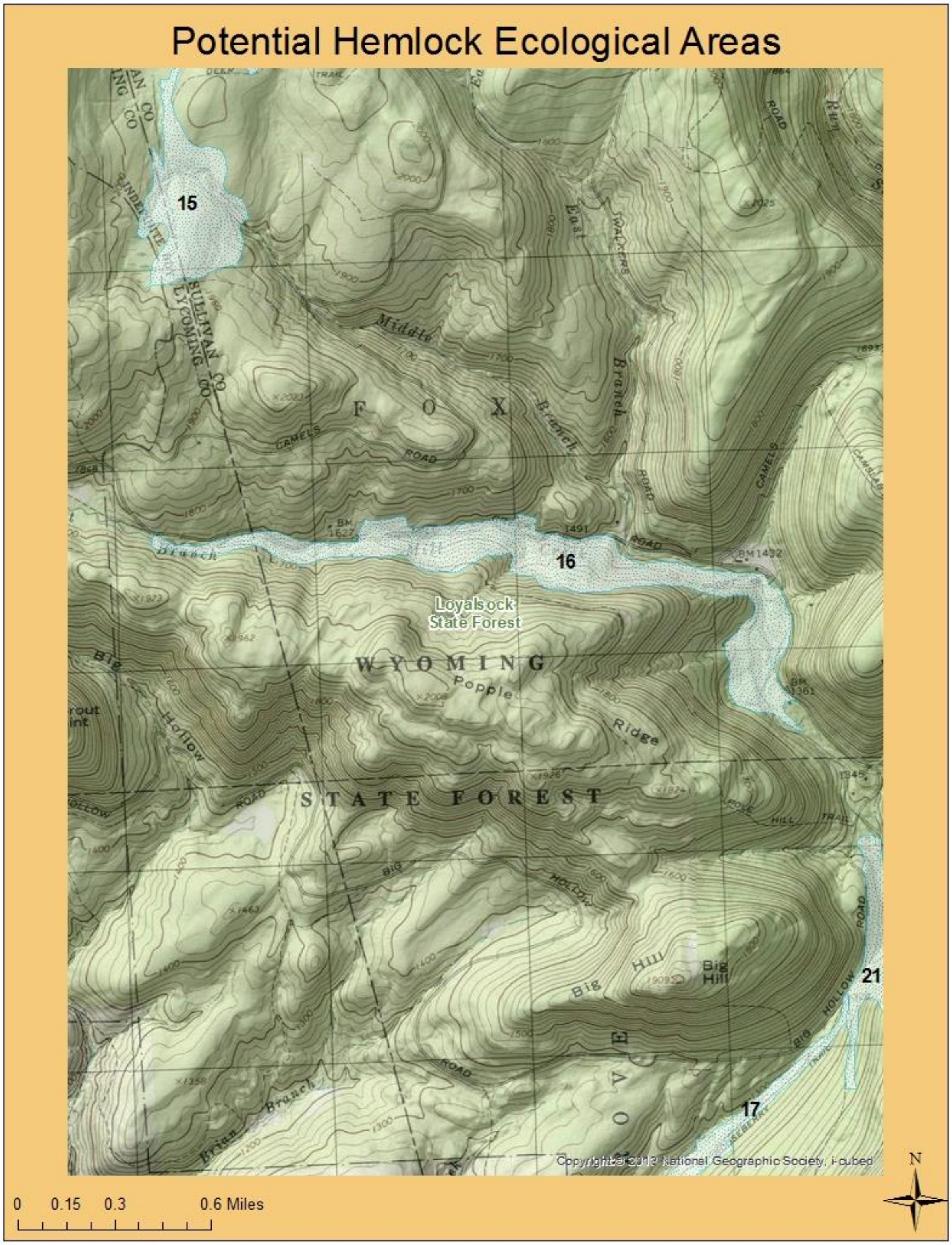

Potential Hemlock Ecological Areas
10
11
11
12
Sproul
State Forest
Copyright© 2013 National Geographic Society, i-cubed
0 0.05 0.1 0.2 Miles
N

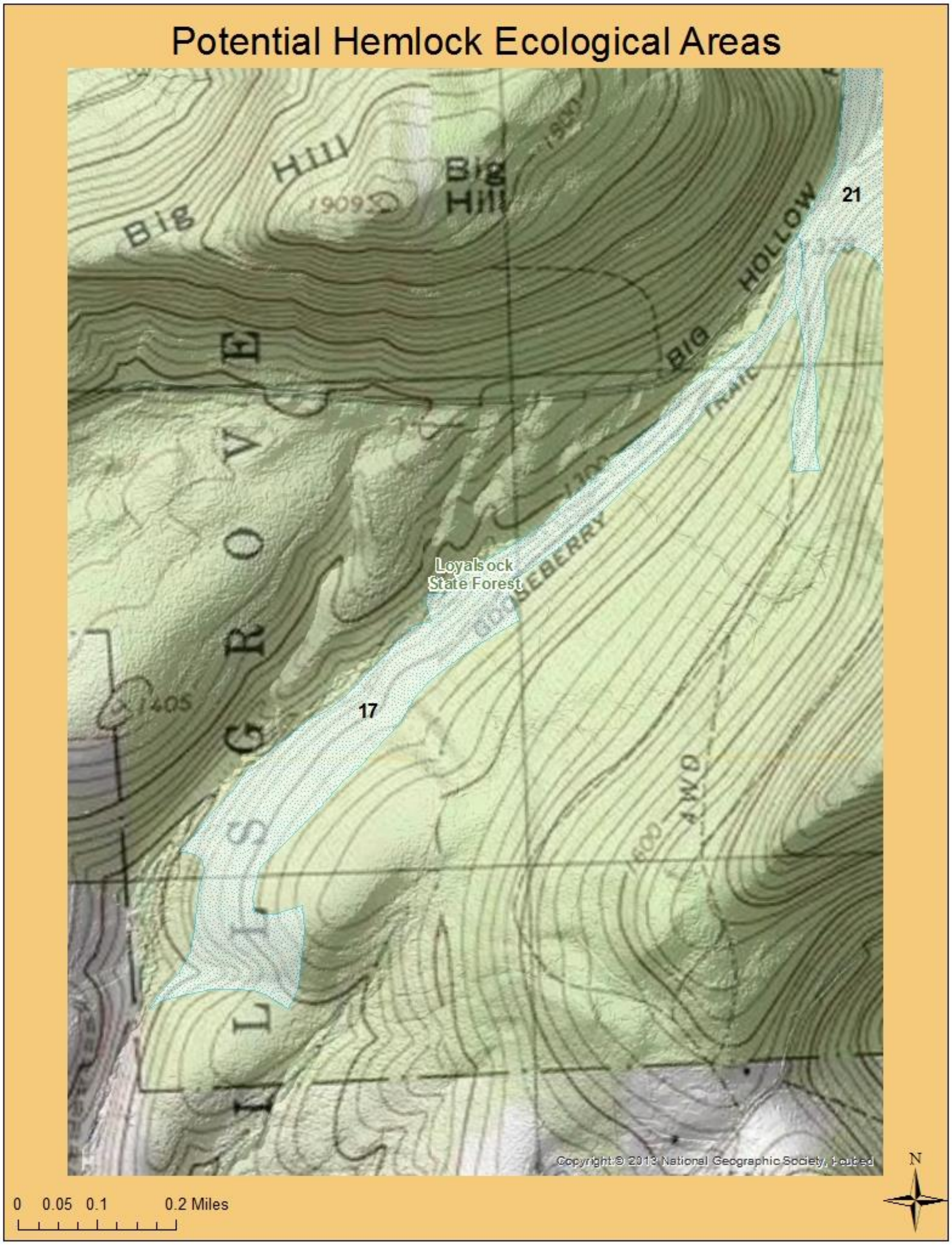

Potential Hemlock Ecological Areas
Tiadaghton State Forest
Sproul State Forest
12
10
Copyright © 2013 National Geographic Society, i-cubed
0 0.0425 0.085 0.17 Miles
N

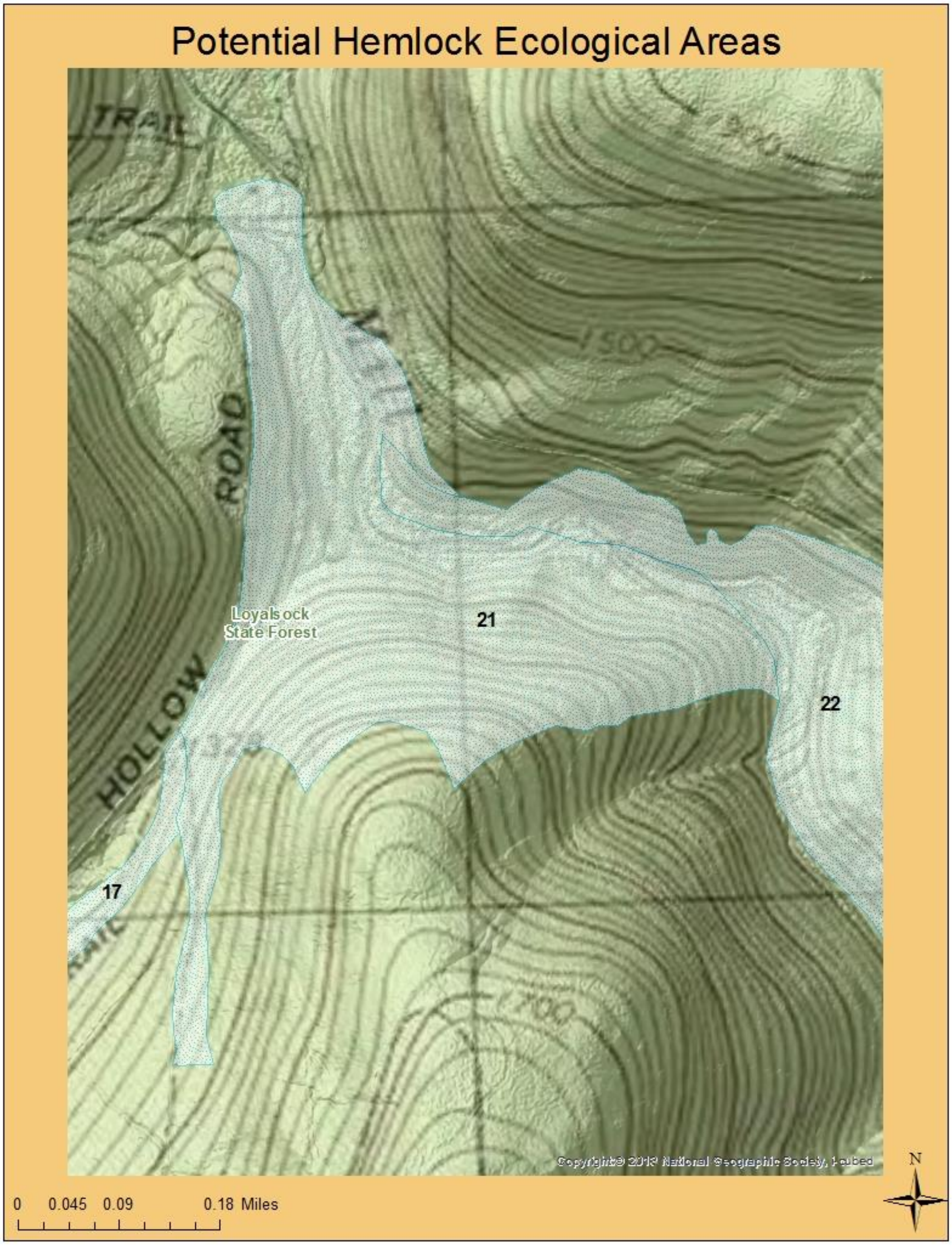

Potential Hemlock Ecological Areas
SGL89
13
Sproul
State Forest
Copyright:© 2013 National Geographic Society, i-cubed
0 0.1 0.2 0.4 Miles
N

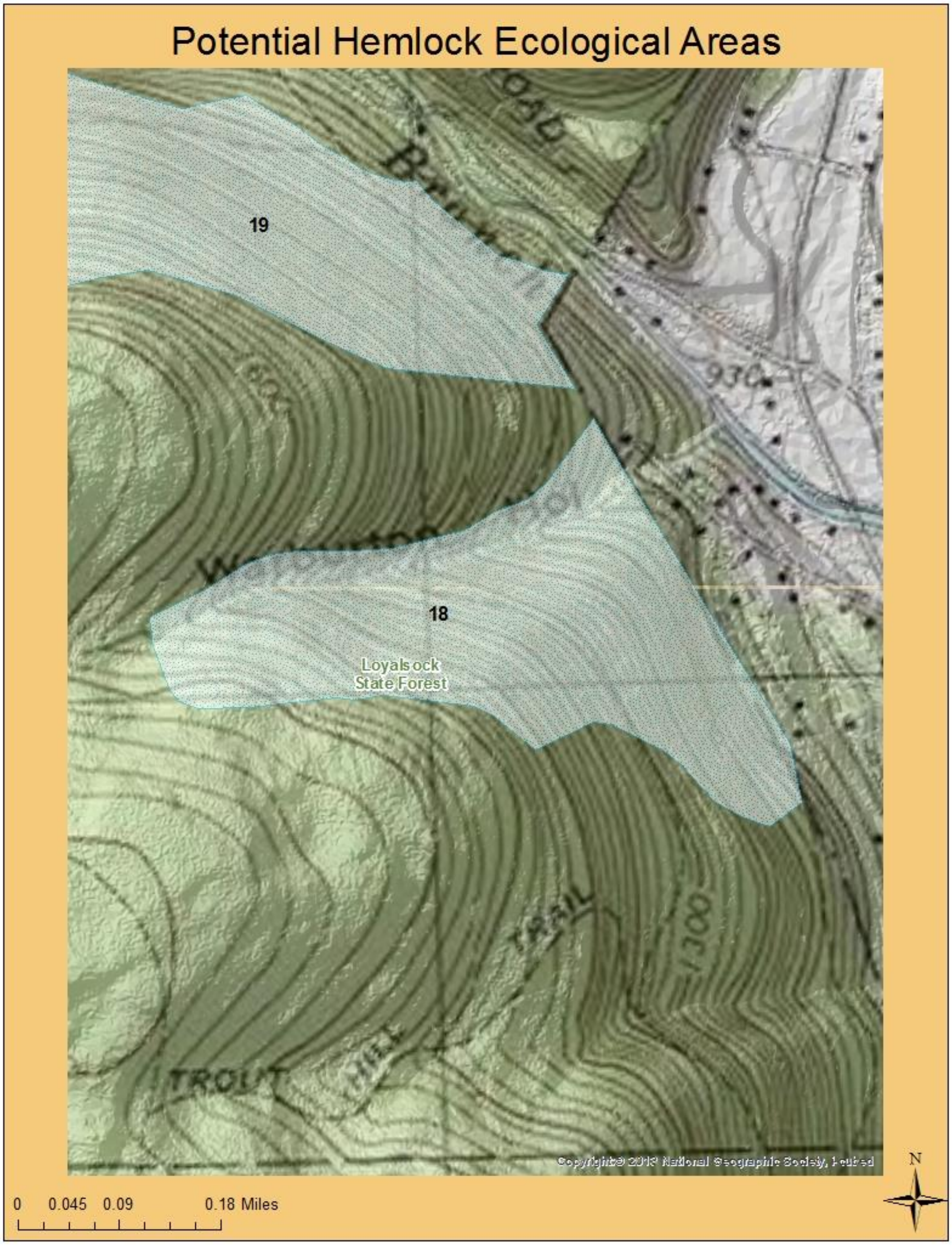

Potential Hemlock Ecological Areas
Swamp
B
Delaware
State Forest
14
1700
Copyright:© 2013 National Geographic Society, i-cubed
N
0 0.05 0.1 0.2 Miles

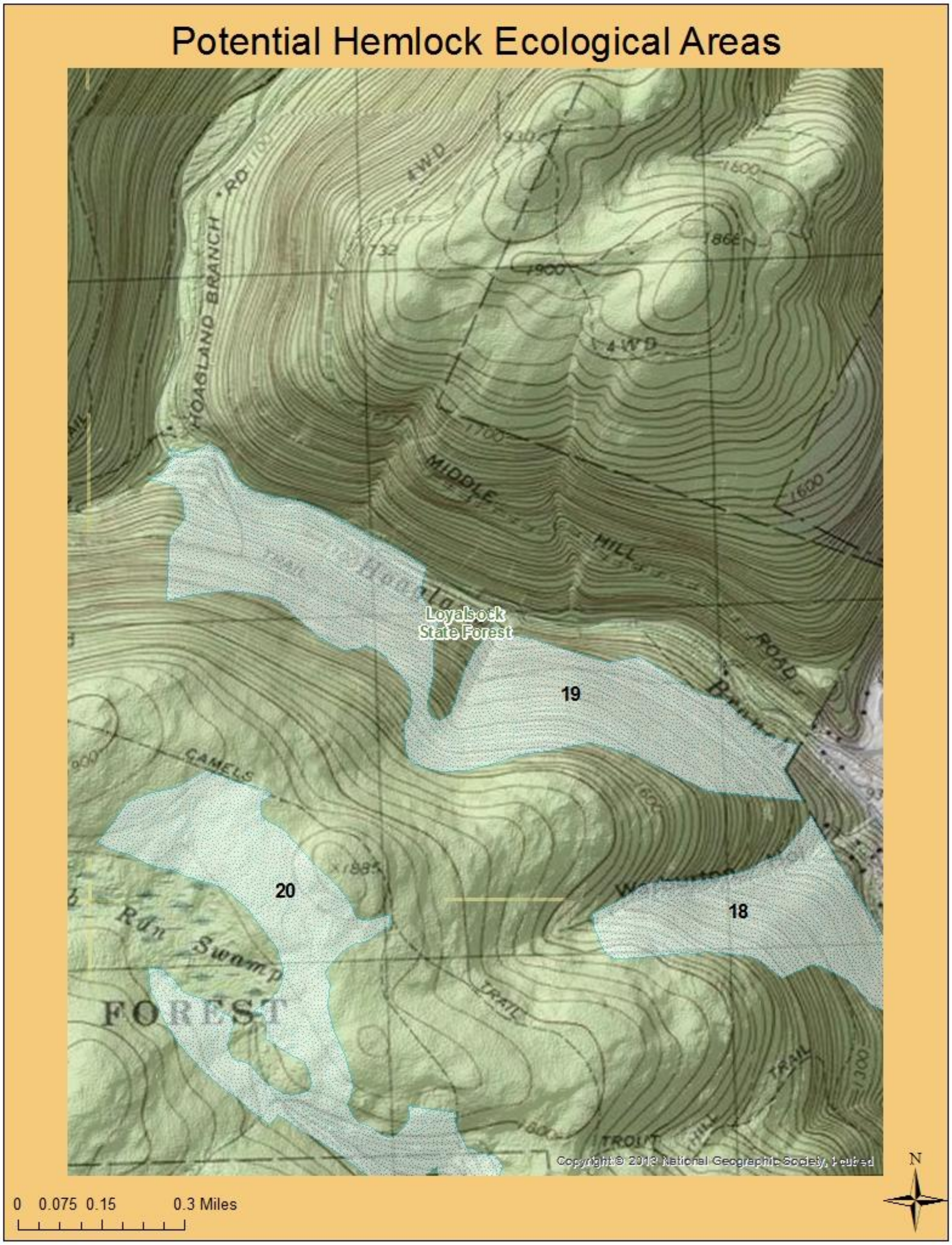

Potential Hemlock Ecological Areas
BDY
BDY
WYOMING
SULLIVAN CO
LYCOMING CO
DEER
TRAIL
Loyalsock State Forest
15
1900
N
0 0.05 0.1 0.2 Miles

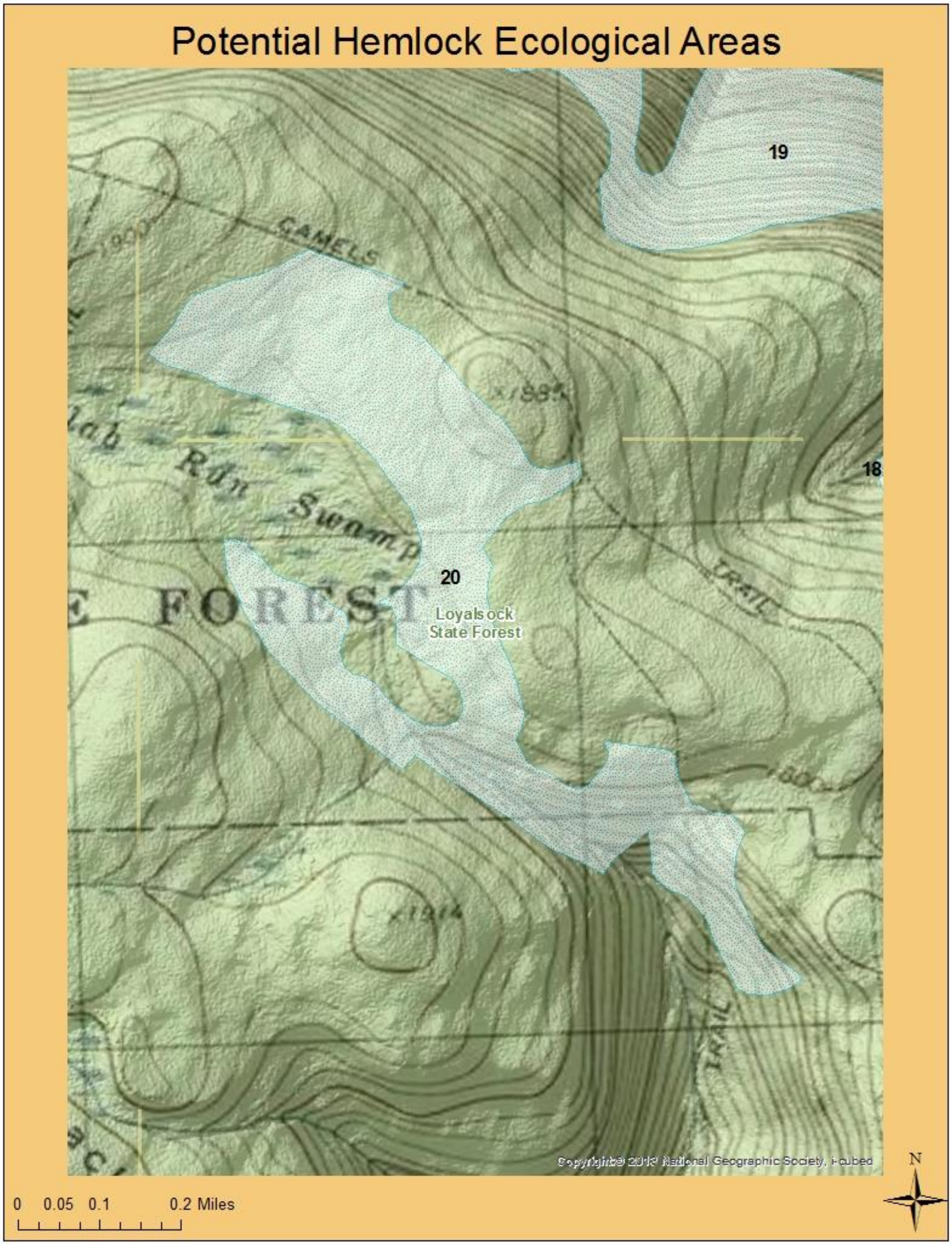

Potential Hemlock Ecological Areas
15
16
17
21
Loyalsock State Forest
F O X
W Y O M I N G
S T A T E F O R E S T
Middle
Branch
East
Popple
Ridge
Big Hill
CAMELS
ROAD
SULLIVAN CO
LYCOMING CO
Copyright:© 2013 National Geographic Society, i-cubed
0 0.15 0.3 0.6 Miles
N

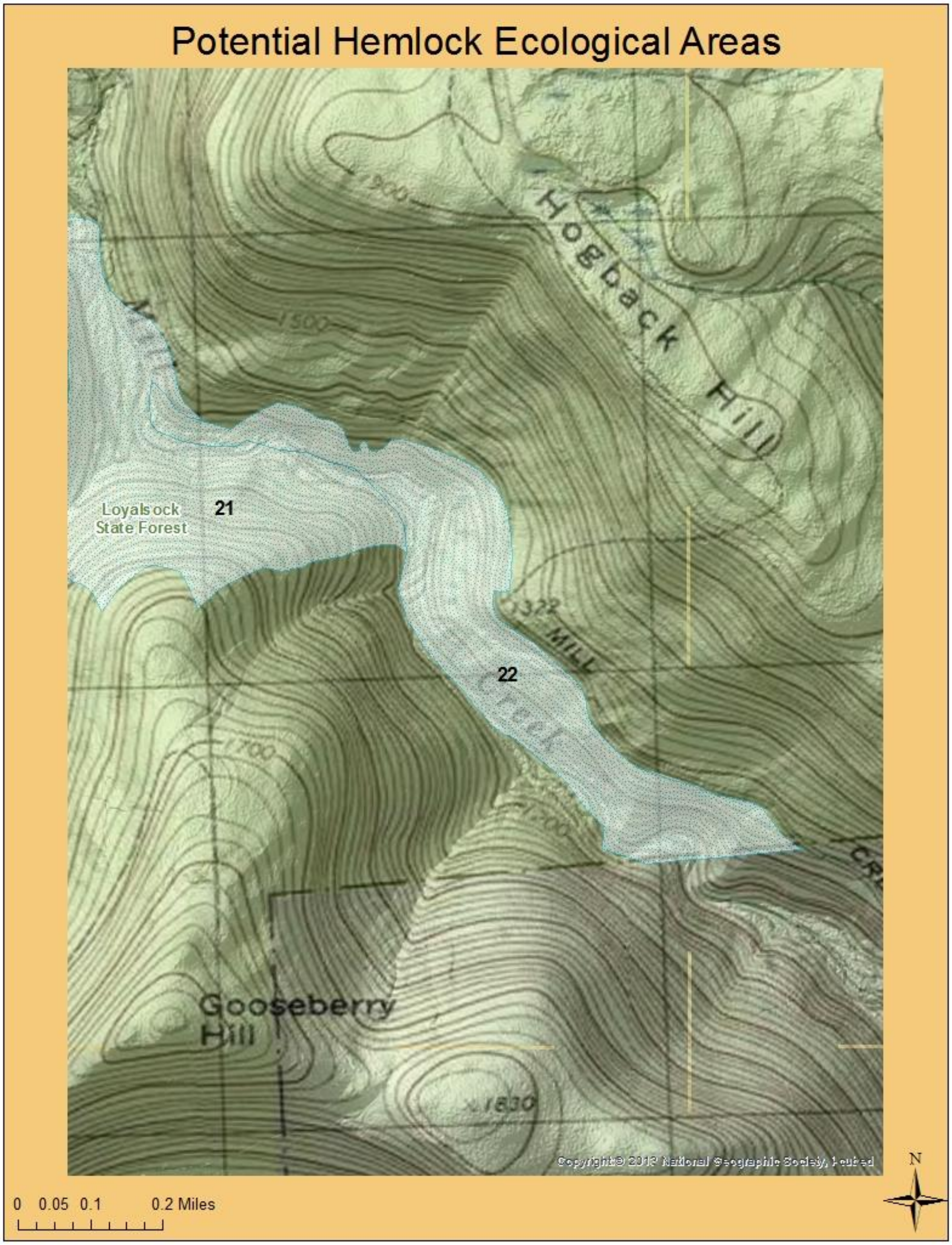

Potential Hemlock Ecological Areas
Big Hill
Big Hill
1909
BIG HOLLOW
21
TRAIL
Loyalsock State Forest
GOOSEBERRY
17
GROVE
1405
1400
Copyright:© 2013 National Geographic Society, i-cubed
0 0.05 0.1 0.2 Miles
N


Potential Hemlock Ecological Areas
TRAIL
ROAD
HOLLOW
1500
1700
Loyalsock State Forest
21
22
17
Copyright© 2013 National Geographic Society, i-cubed
0 0.045 0.09 0.18 Miles
N

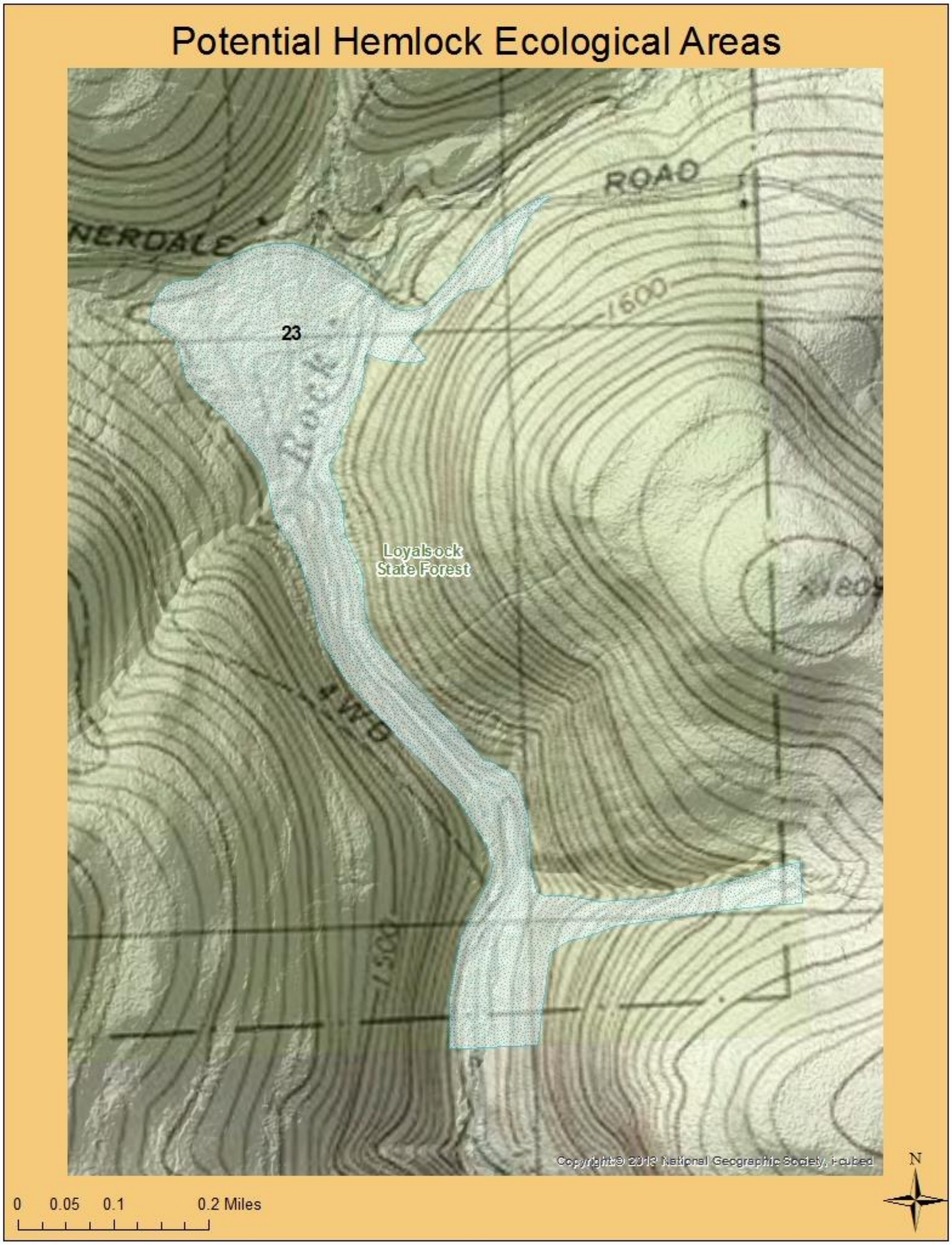

Potential Hemlock Ecological Areas
19
18
Loyalsock
State Forest
930
TRAIL
TROUT
0 0.045 0.09 0.18 Miles
N

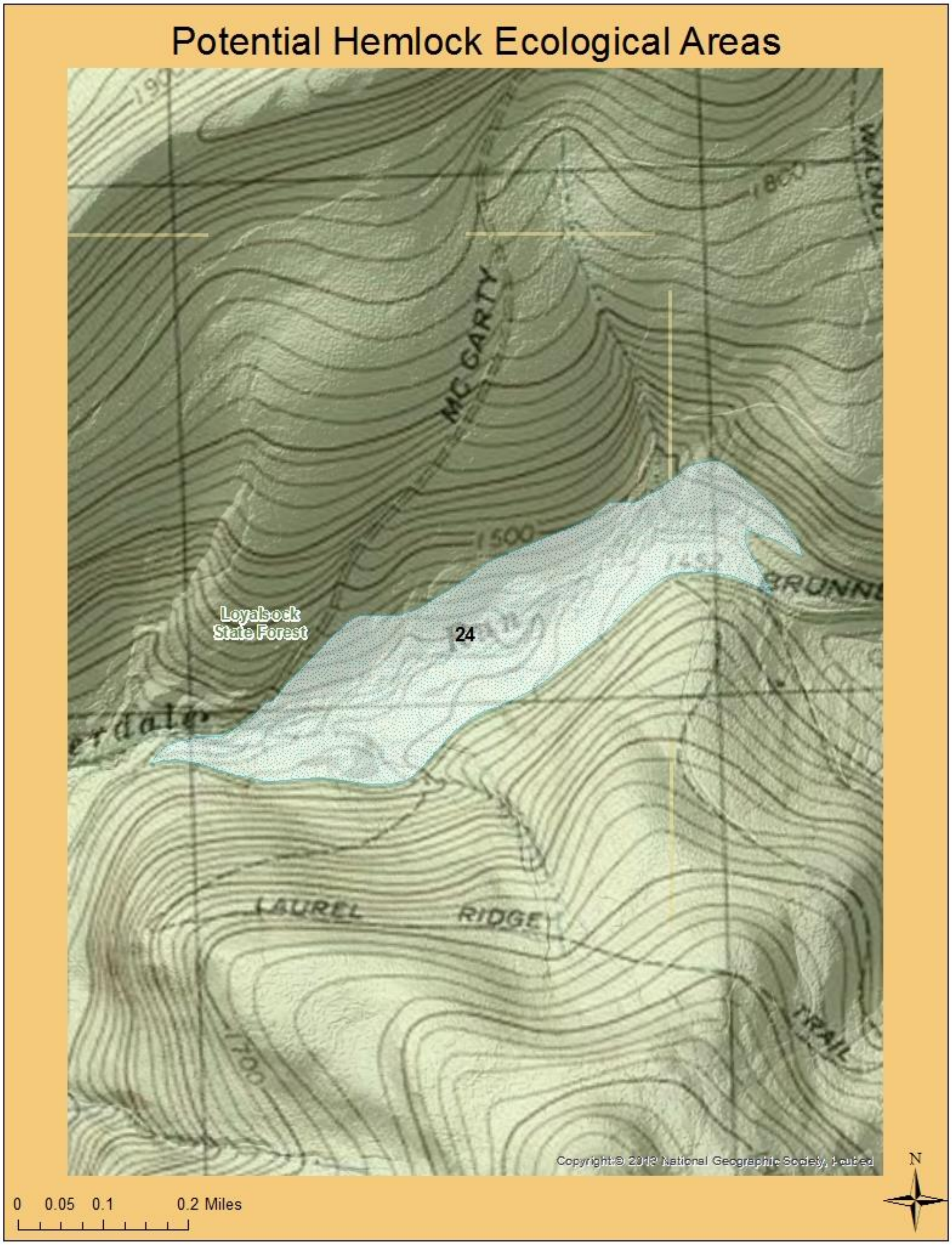

Potential Hemlock Ecological Areas
Loyalsock State Forest
19
20
18
Copyright © 2013 National Geographic Society, i-cubed
N
0 0.075 0.15 0.3 Miles

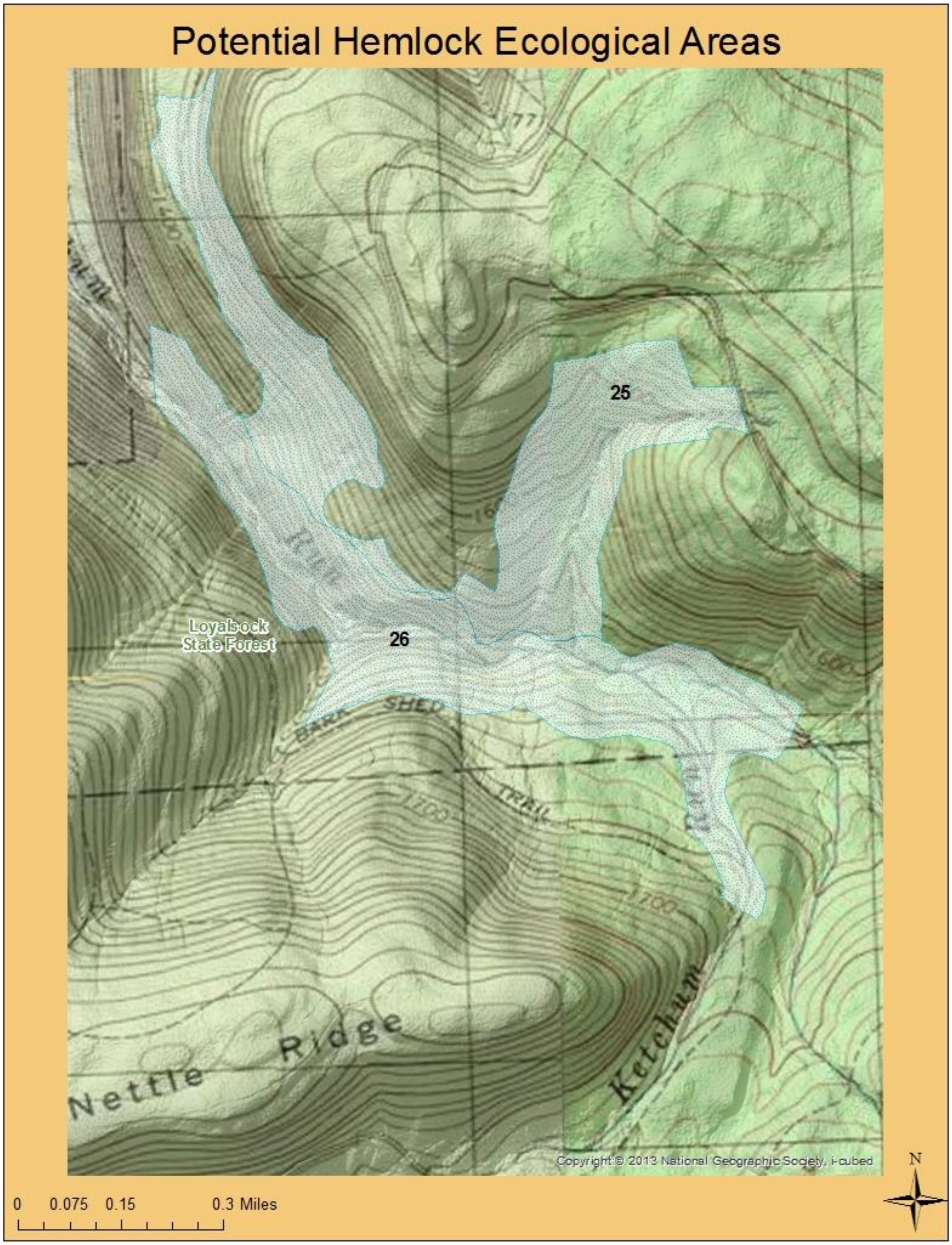

Potential Hemlock Ecological Areas
19
18
20
CAMELS
TRAIL
Swamp
FOREST
Loyalsock
State Forest
Copyright:© 2013 National Geographic Society, i-cubed
0 0.05 0.1 0.2 Miles
N

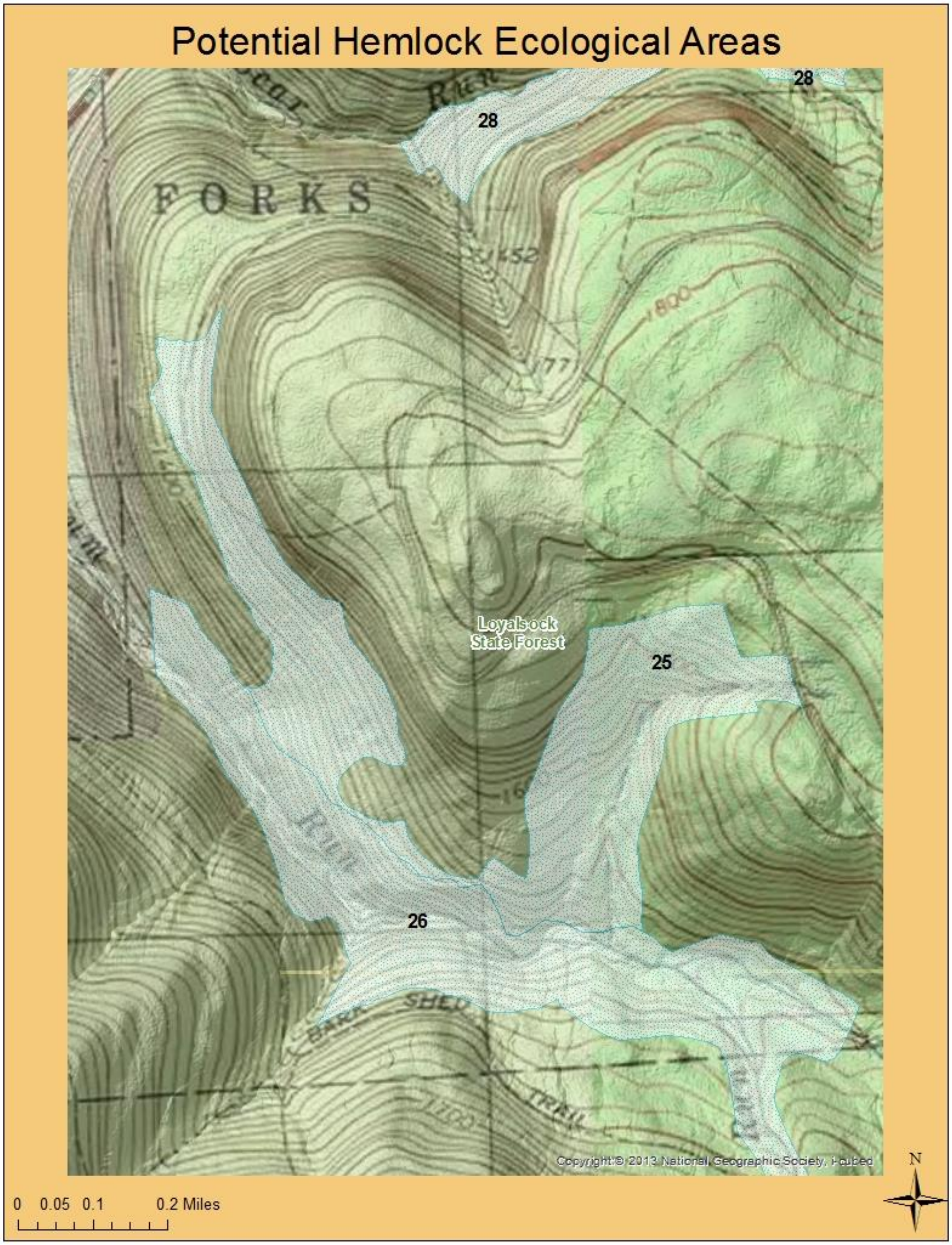


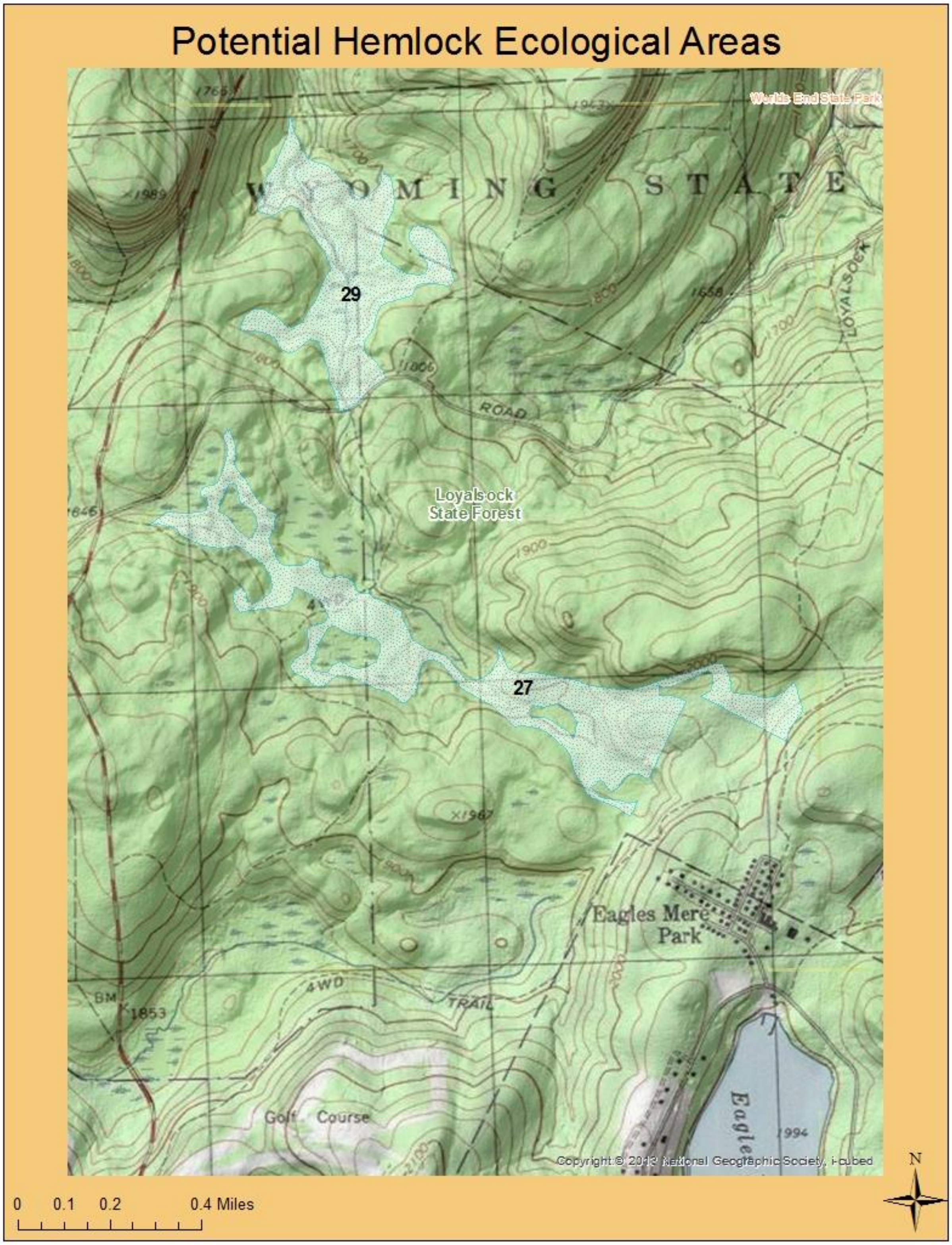
Potential Hemlock Ecological Areas
Hogback Hill
Loyalsock State Forest
21
22
MILL
Creek
Gooseberry Hill
1900
1500
1700
1200
1530
Copyright:© 2013 National Geographic Society, i-cubed
0 0.05 0.1 0.2 Miles
N

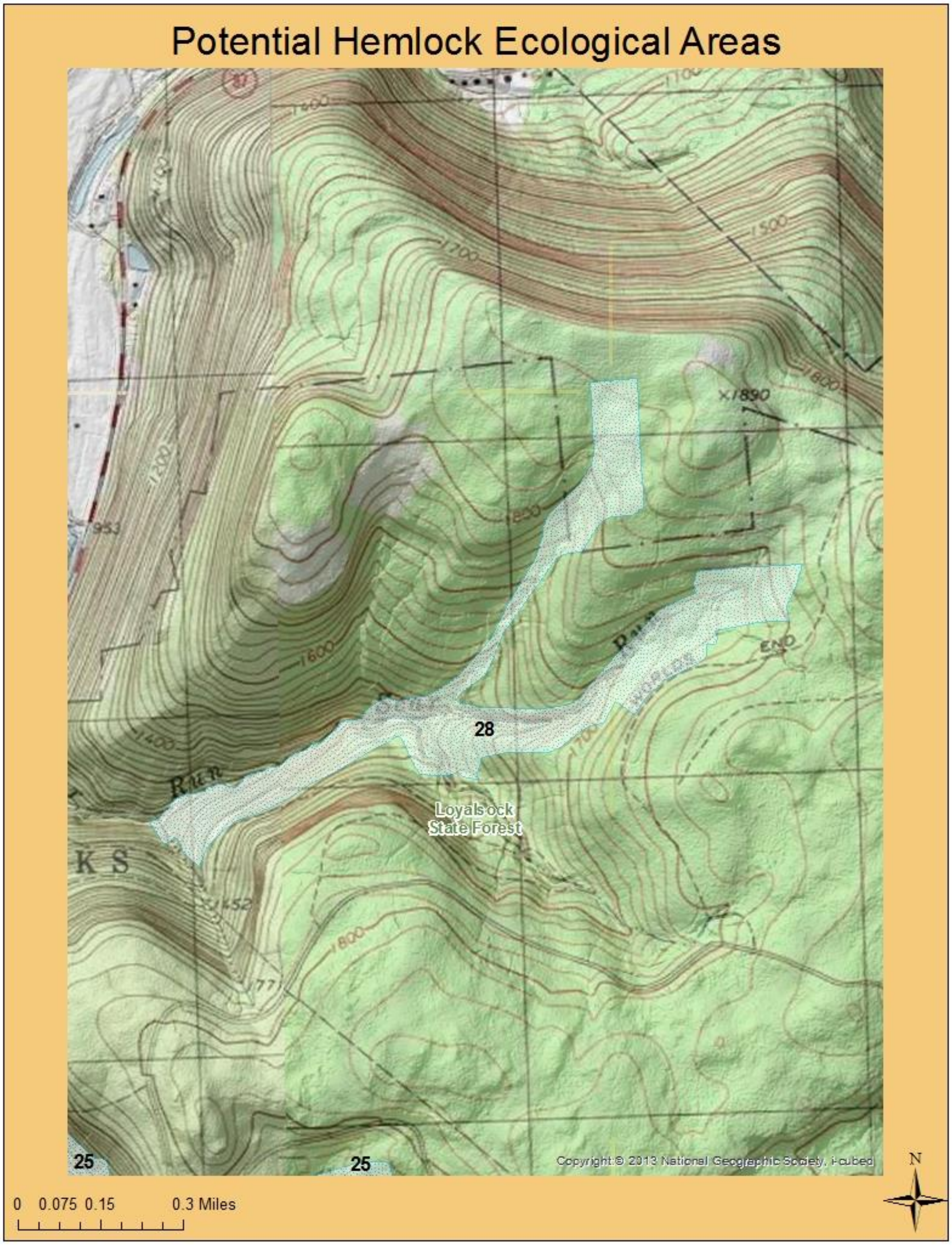

Potential Hemlock Ecological Areas
ROAD
NERDALE
1600
23
Rock
Loyalsock
State Forest
1500
Copyright© 2013 National Geographic Society, i-cubed
N
0 0.05 0.1 0.2 Miles

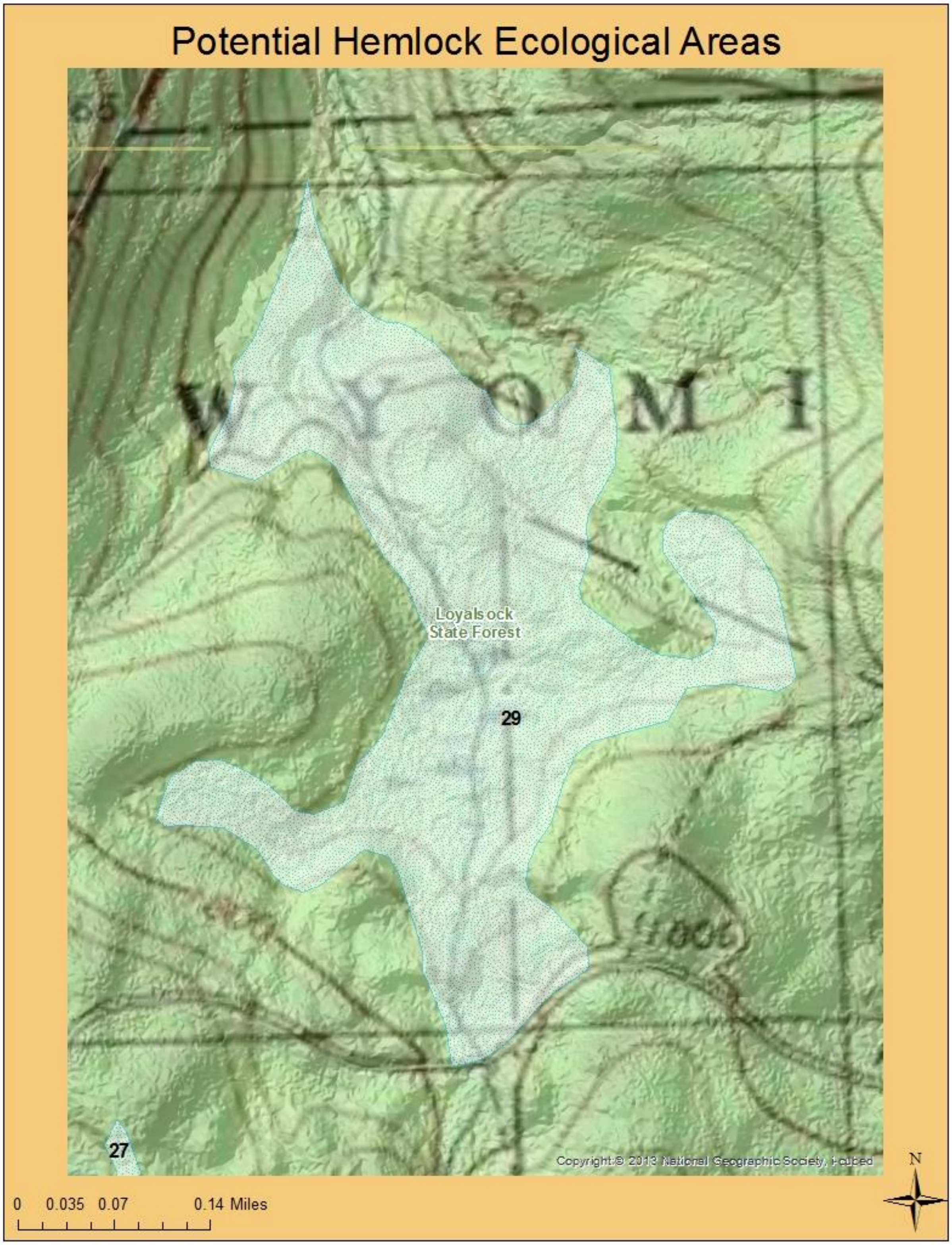

Potential Hemlock Ecological Areas
Loyalsock State Forest
24
MC GARTY
LAUREL
RIDGE
TRAIL
1500
1700
1800
Copyright:© 2013 National Geographic Society, i-cubed
0 0.05 0.1 0.2 Miles
N

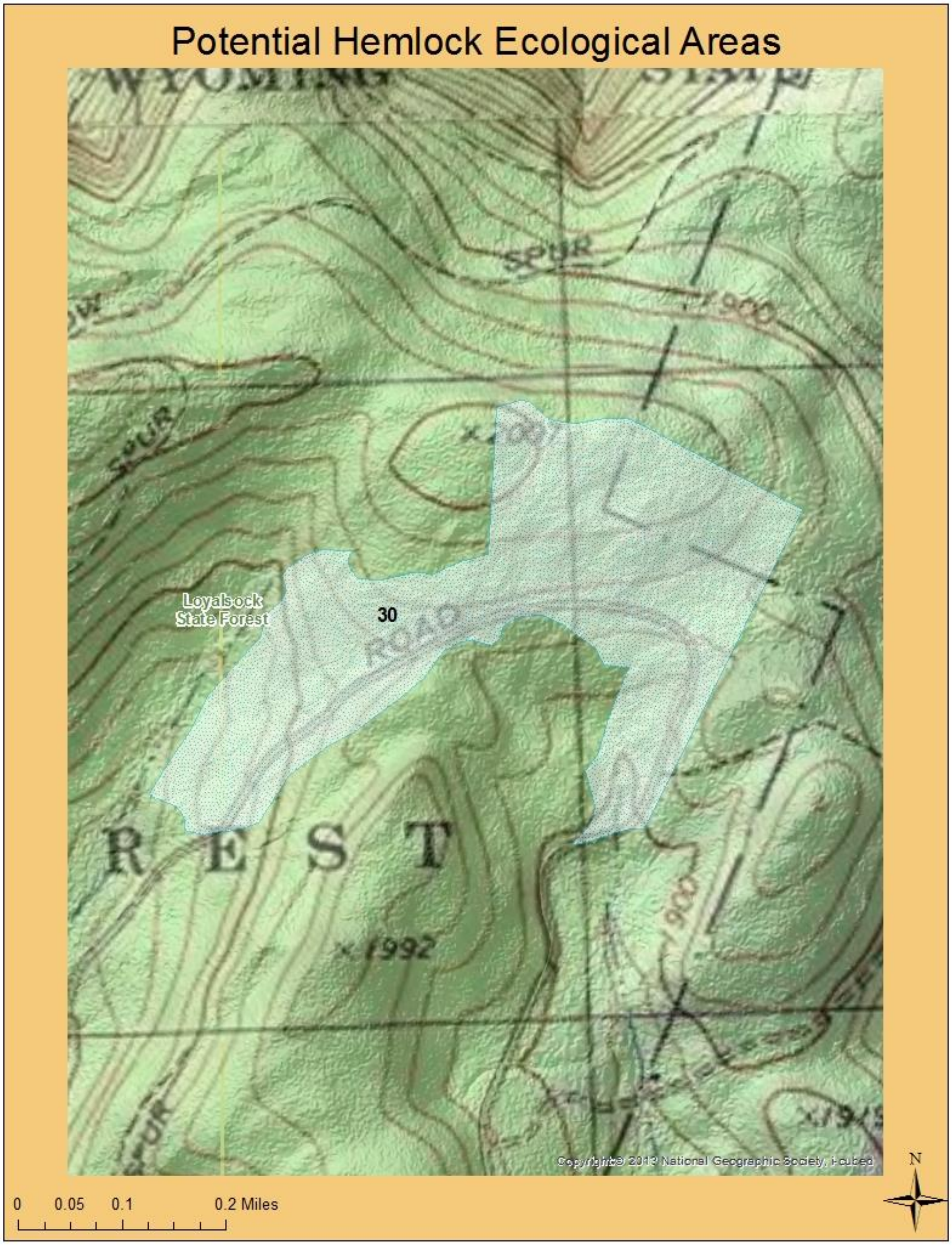

Potential Hemlock Ecological Areas
25
26
Loyalsock State Forest
Nettle Ridge
Ketchum
Copyright © 2013 National Geographic Society, i-cubed
0 0.075 0.15 0.3 Miles
N


Potential Hemlock Ecological Areas
28
28
FORKS
25
26
Loyalsock State Forest
0 0.05 0.1 0.2 Miles
N
Copyright:© 2013 National Geographic Society, i-cubed

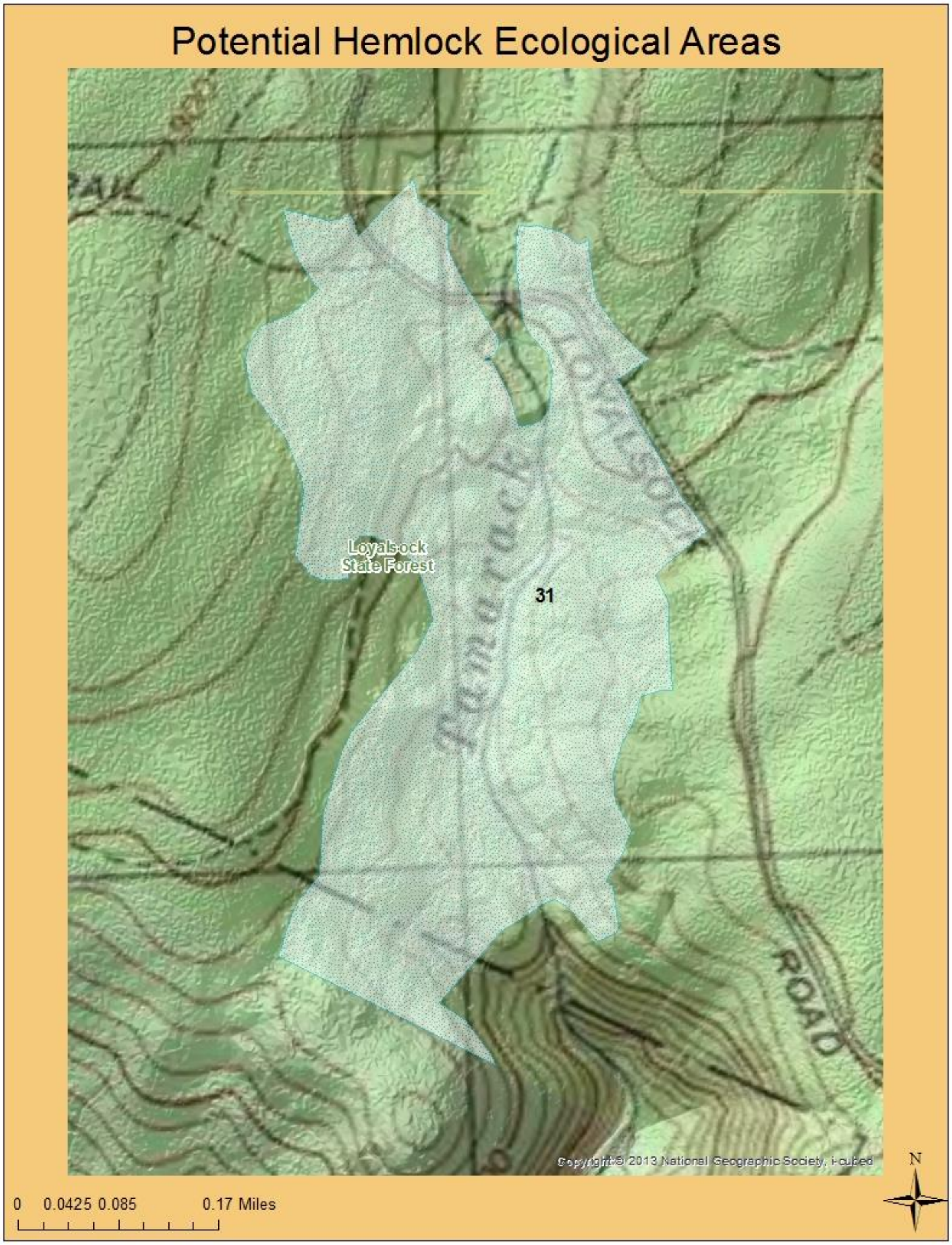

Potential Hemlock Ecological Areas
Worlds End State Park
WYOMING STATE
29
ROAD
LOYALSOCK
Loyalsock
State Forest
27
Eagles Mere
Park
4WD
TRAIL
BM
1853
Golf Course
Eagle
1994
Copyright:© 2013 National Geographic Society, i-cubed
N
0 0.1 0.2 0.4 Miles


Potential Hemlock Ecological Areas
28
Loyalsock
State Forest
x1890
25
25
Copyright © 2013 National Geographic Society, i-cubed
0 0.075 0.15 0.3 Miles
N


Potential Hemlock Ecological Areas
Loyalsock State Forest
29
27
Copyright:© 2013 National Geographic Society, i-cubed
0 0.035 0.07 0.14 Miles
N



Potential Hemlock Ecological Areas
Loyalsock State Forest
30
ROAD
SPUR
R E S T
Copyright © 2013 National Geographic Society, i-cubed
0 0.05 0.1 0.2 Miles
N


Potential Hemlock Ecological Areas
Loyalsock State Forest
31
ROAD
Copyright:© 2013 National Geographic Society, i-cubed
0 0.0425 0.085 0.17 Miles
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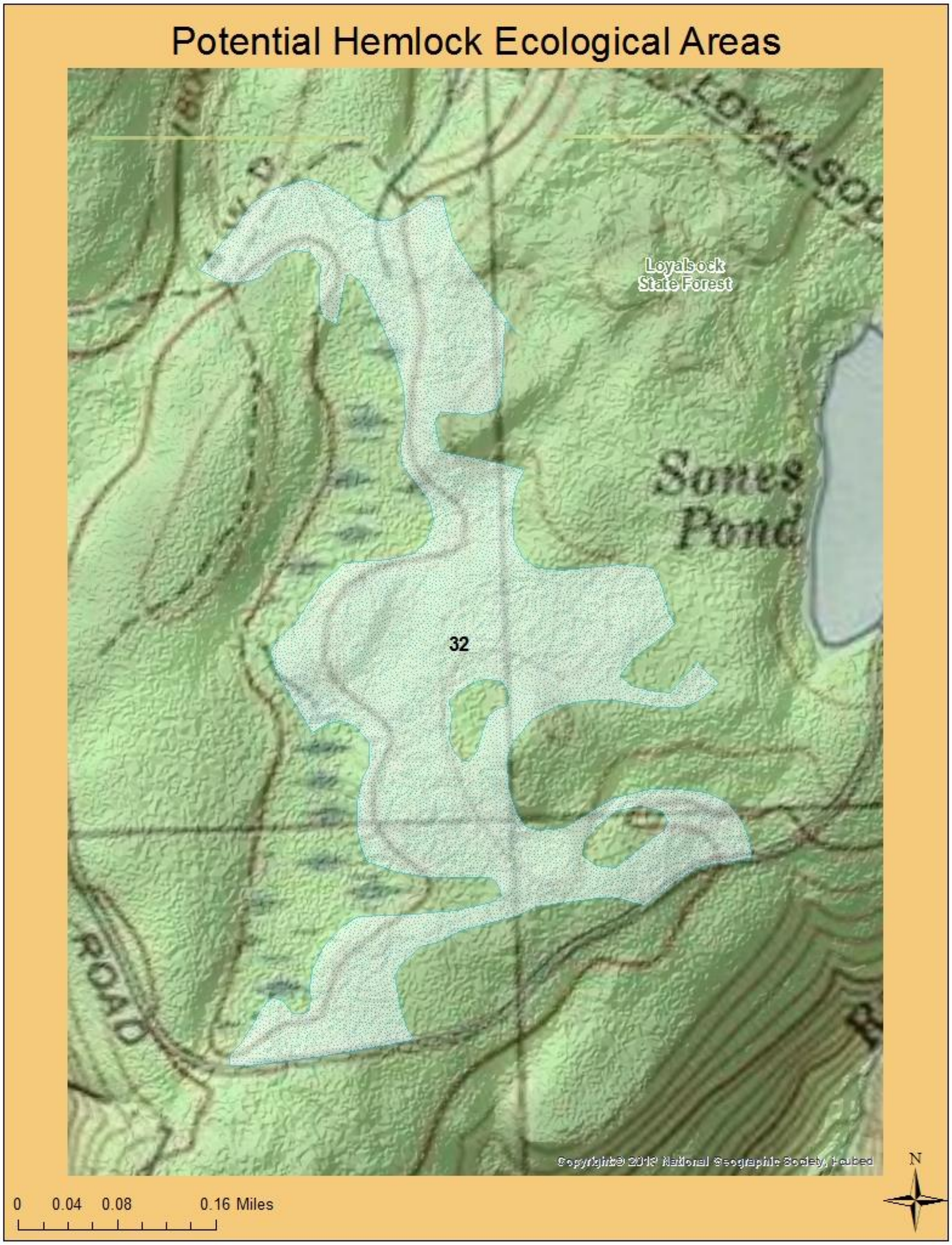
Potential Hemlock Ecological Areas
Loyalsock
State Forest
Sones
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32
ROAD
Copyright:© 2013 National Geographic Society, i-cubed
N
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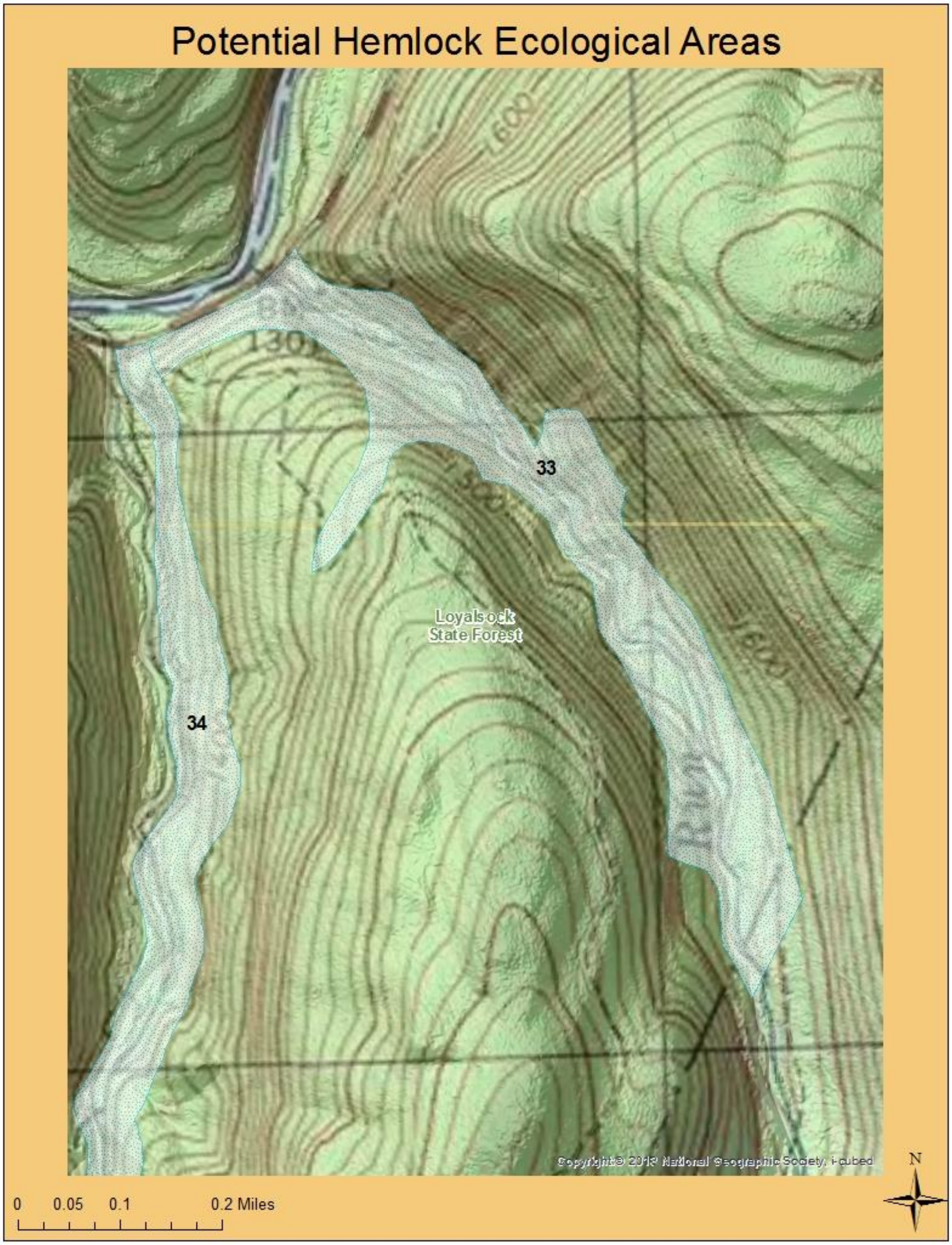
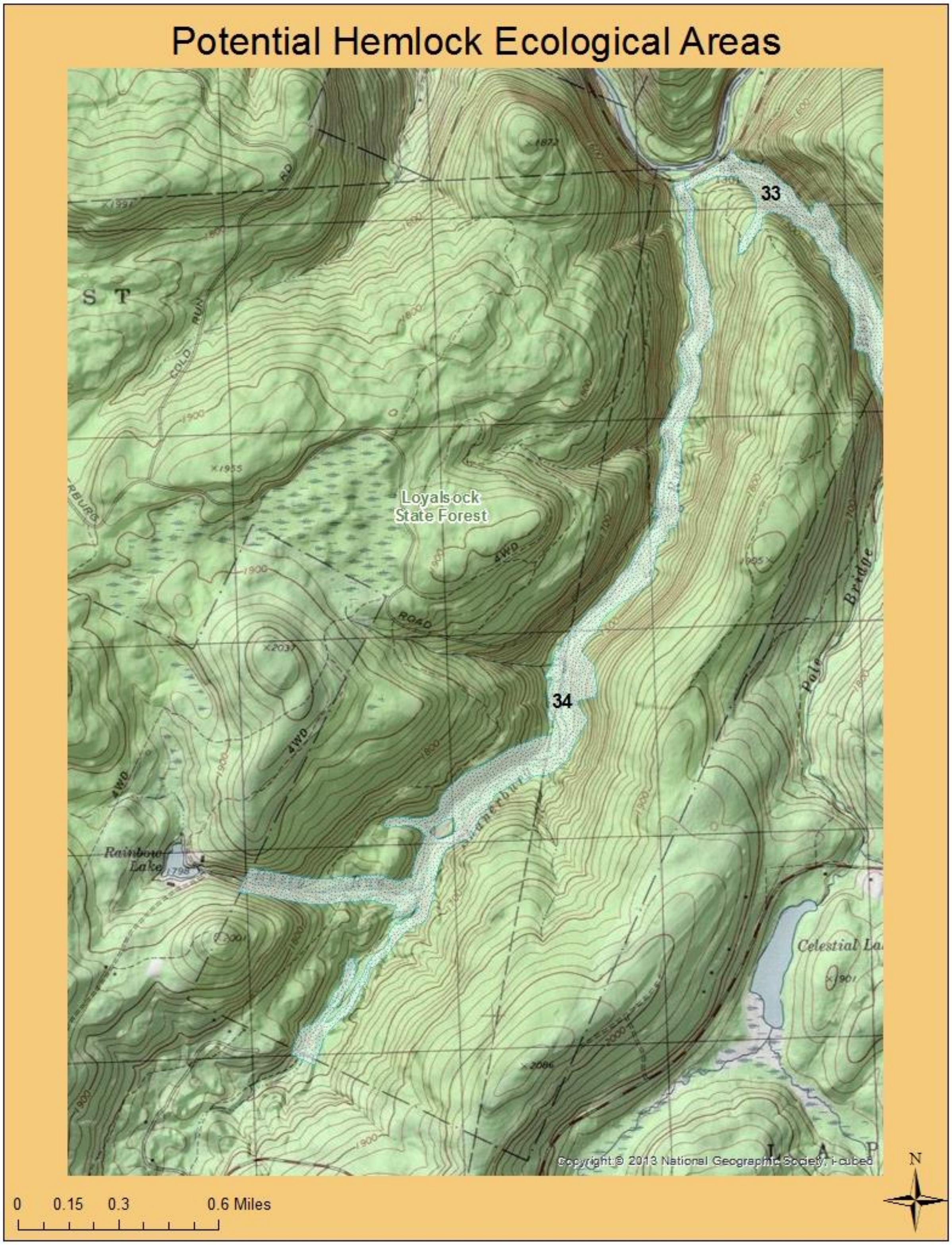
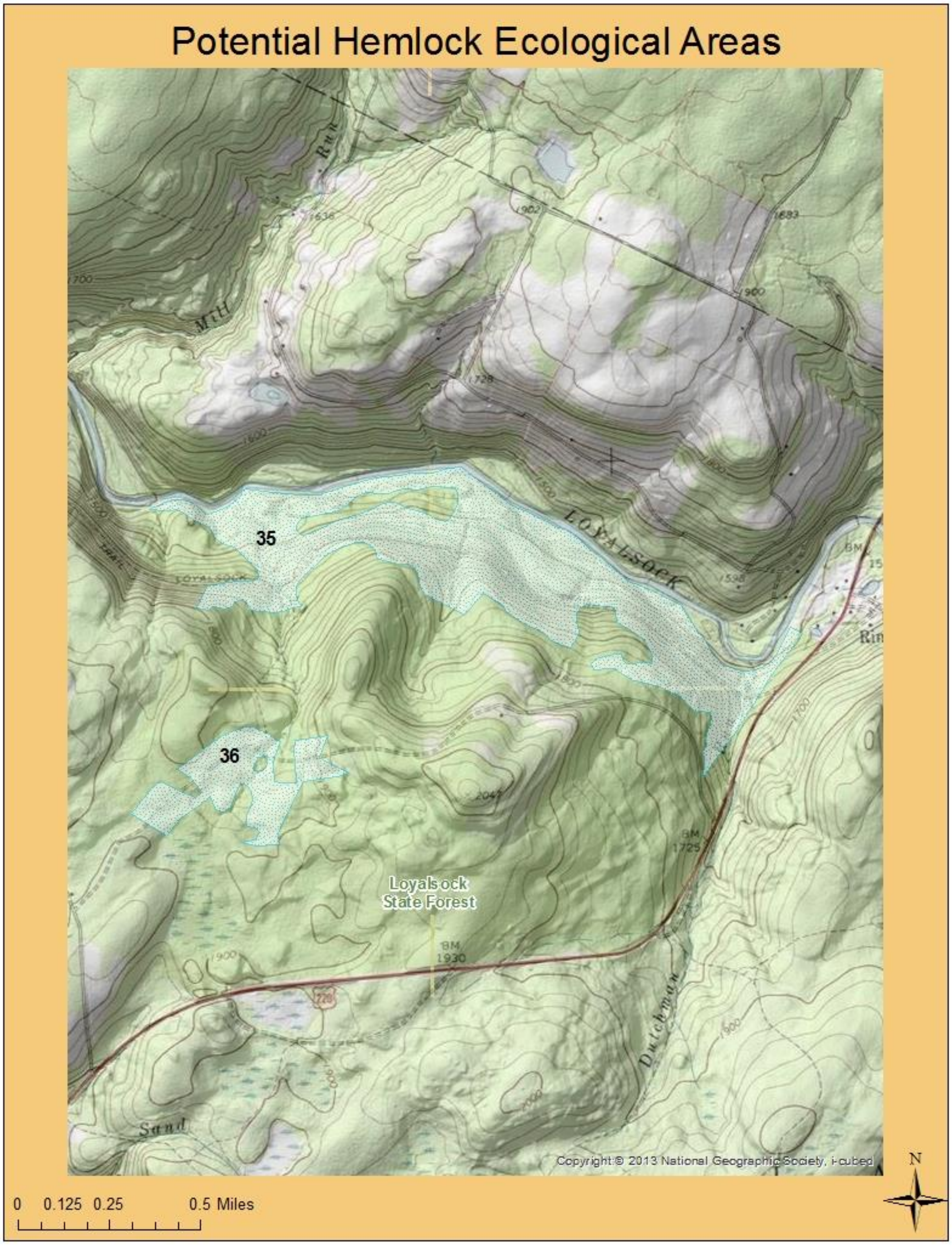

Potential Hemlock Ecological Areas
33
34
Loyalsock State Forest
1600
Copyright© 2013 National Geographic Society, i-cubed
N
0 0.05 0.1 0.2 Miles


Potential Hemlock Ecological Areas
33
34
Loyalsock State Forest
Rainbow Lake
Celestial La
Pole Bridge
COLD RUN
ROAD
4WD
Copyright:© 2013 National Geographic Society, i-cubed
0 0.15 0.3 0.6 Miles
N


Potential Hemlock Ecological Areas
35
36
LOYALSOCK
Loyalsock State Forest
Dutchman
Sand
Copyright:© 2013 National Geographic Society, i-cubed
N
0 0.125 0.25 0.5 Miles

Appendix E: Management Options for Private Landowners

Upland

If maintaining a conifer component is the goal, native alternatives to hemlock include red spruce, white spruce, black spruce, balsam fir, northern white cedar, and eastern white pine (see table). We do not discourage underplanting with eastern hemlock in some areas, in case biological control is successful. This would ensure that these areas retain a hemlock component. We recognize that this may not be practical for all landowners, due to uncertainty and costs. Without actively managing declining hemlock stands, these areas may convert to hardwood stands. The option selected depends on the landowner's management goals.

Among the control options presented in the strategy portion of the conservation plan, insecticide treatments are the most appropriate for the private landowner concerned about individual or groups of trees (see here). If biological control is successful on public lands, the hope is the agents will spread to other areas. Hemlock woolly adelgid resistant hemlock may be an option for planting in the future but development is still being evaluated. Several agencies and organizations are currently researching silvicultural methods for managing hemlock forests.

Mitigating Hemlock Loss in Riparian Areas

Hemlock is an important component of many riparian areas, often in association with yellow birch and red maple. With the decline of hemlock due to the hemlock woolly adelgid, there is concern about the impacts to stream health. Forested riparian areas are important for regulating stream temperatures, leaf litter and terrestrial insect addition to the stream (food for aquatic food web), woody material additions to the stream, nutrient cycling, and wildlife habitat. Terrestrial insects even form around 50% of brook trout diets in the summer when aquatic insects are less abundant (Wilson et al. 2014). Fortunately, native trees, including deciduous trees, can provide these benefits with minimal effects on long-term stream conditions (Roberts et al. 2009, Tallamy 2009).

Many riparian areas will regenerate naturally with a shift away from hemlock dominance as hemlock mortality creates available growing space. Some declining hemlock stands will transition naturally to associated tree species if there is advanced regeneration present. However, other areas may not develop in a desirable manner. The spread of invasive species and dominance of hay-scented fern are serious concerns in these areas (McManus et al. 2000, Orwig and Foster 1998). In these cases, active management can direct the future of declining riparian areas, especially those of cold-water streams. One aspect of headwater streams that contributes to their resiliency is the fact that these stream temperatures are often heavily influenced by groundwater (Siderhurst et al. 2010). An emphasis should be placed on promoting a rapid transition to the new riparian forest, including hardwoods, to minimize the effects of the transition period (Roberts et al. 2009). The following underplanting recommendations can help mitigate the loss of hemlock in our riparian areas.

Underplant declining or understocked hemlock dominated riparian areas with native trees:

- Only underplant **declining** infested stands if desirable natural regeneration is not present
- For best success, plant between early March and early May
- Space plantings at 10' X 10', or where canopy gaps occur
- If tree shelters must be used to protect trees from herbivory, consider 5' woven mesh tree shelters
- Select **native** species that can grow in riparian areas and that benefit the stream
    - **Red maple, yellow birch, white pine, serviceberry, tulip poplar, red spruce** (north of I-80)
    - **Native tamarack** where there is ample light (north of I-80)
    - Replant with **HWA resistant hemlock** given availability
        - Planting resistant hemlock with other natives will allow hemlock to persist
    - Native deciduous trees will shade the streams in **summer** when temperatures rise
    - Native trees support terrestrial insects important to trout in the summer
    - Native conifers can provide shade year around
    - Mountain laurel and rhododendron provide year around shade where present
    - The stream bank can be live-staked with red osier and silky dogwood if there is ample light
- Survey for and treat invasive species that will take advantage of the new growing space
- Norway spruce should not be planted within the stream buffers defined in the AHBG
    - Macro-invertebrates, both aquatic and terrestrial, prefer feeding on foliage of native plants (Sweeney pers. com. 2017, Tallamy 2009)

  - Norway spruce leaf litter increases availability of toxic aluminum, decreases pH, and lessens the buffering capacity of the soil (Brinkley and Valentine 1991)
    - These soil impacts lead to decreased water quality
    - These soil impacts also negatively impact native riparian vegetation (Smith et al. 2007)
  - There are no benefits from Norway spruce that a combination of natives won't provide
  - Monitoring must be done where non-native trees are planted per FSC certification

Do not salvage hemlock in riparian buffer areas:

- Salvaged hemlock typically has low timber value
- Dead hemlock is a source of large woody material, critical for stream habitat
- Standing dead hemlock provides snags for wildlife habitat in the riparian area
- Downed trees in the stream and floodplain slow flood waters and enhance groundwater recharge
- Slower flood waters on the floodplain drop sediment that would otherwise stay in the stream
- Downed trees in the riparian area are utilized by wildlife including amphibians

Although the loss of hemlock from many of our riparian areas will have detrimental impacts, we can ease these impacts and still have healthy riparian forests and streams if we take some proactive steps to accelerate the transition to the new riparian forest.

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