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Review

Northeastern American Forests: Natural Disturbances, Climate Change Impact, and the Utilization of Increasingly Damaged Forest Trees for Biofuel Production

Marvellous Oluwaferanmi Faluyi and Sibel Irmak *

Department of Agricultural and Biological Engineering, The Pennsylvania State University, University Park, PA 16802, USA
* Correspondence: sji5137@psu.edu; Tel.: +1-814-865-3559

Abstract: Forests and forestry-related industries and ecosystem services play a critical role in the daily life of all societies, including in cultural, ecological, social, economic, and environmental aspects. Globally, there are about 4.1 billion hectares of forestland. In the United States, there are about 304 million hectares of forestland, covering about 34% of the total land area, and the forest product industry produces over USD 200 billion worth of forestry products annually. Evidence suggests these precious resources may be negatively impacted by climate change via direct and indirect processes, including wildfires, insect/pest pressure, drought, extreme storm events, increased air temperature, solar radiation, vapor pressure deficit, and other factors and variables that can be detrimental. All these can not only cause significant changes in the health and productivity of the forests, but can also cause the extinction, migration, and/or re-distribution of different tree species. Thus, humankind has the paramount responsibility to take policy, technologic, economic, environmental, and management decisions and actions to protect this vital resource for current and future generations, plants, and animals. This paper provides an overview of some of the important characteristics of forest environmental services, climate–environment–forest interactions with respect to forest health and productivity, climate change's impacts on forest species, and the utilization of forest biomass for high-value products.

Keywords: Northeastern US forests; natural disturbances; climate change; utilization; forest biomass; biofuels

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1. Introduction

Forests are an important component of the environment and ecosystem services and are sources of raw materials, woody biomass, etc. Forests play a critical role in providing food resources and habitats for wildlife [1]; maintaining biodiversity; providing refuge for fauna and flora [2]; protecting land and water resources [3]; minimizing or eliminating flooding [4], soil erosion, and landslides [5]; regulating/moderating air and soil temperatures [6]; and mitigating climate change by acting as a carbon sink [7] through several processes, including photosynthesis; removing carbon dioxide from the atmosphere; reducing the impacts of extreme heat and solar radiation on flora and fauna by intercepting solar radiation at the forest canopy, sheltering the understory vegetation and wildlife habitat; serving as a buffer for improving water quality and reducing the run-off of chemicals that cause environmental degradation; providing biomass for renewable energy production; providing wood materials for heat, construction, and many other purposes; and providing many other important environmental services [8].

Currently, 304 million hectares of the US (approximately 34% of its land area) are covered by forests. Forest lands have gradually changed with time, and these changes in their history cannot be overemphasized [9]. The original American forests covered about 404 million hectares out of the 971 million hectares of the US, approximately 46 percent of the United States' total land area [10]. Since the migration of Native Americans to America after the Ice Age about 10,000 years ago, humans have been fully involved in impacting the American forests (and vice versa) through plant domestication for food, medicine, heat, hunting, and construction. The increase in the human population and development of various industrial and residential complexities has resulted in deforestation that also encouraged settlement, building construction, farm equipment, shipping construction, domestication, and food gathering [11]. All these activities profoundly influenced the American forest ecosystems, affecting the soil, tree species, landscape, and wildlife, and gradually molding them into what they have become today [12]. There was an extreme decline in American forests from about 404 million hectares to approximately 283 million hectares by the 1970s, followed by a cessation of decline. After World War II, there was a gradual increase in forestland, which has continued until today [10]. Therefore, American forest ecosystems are known to be resilient, with a lifelong ability to renew their potency, complexity, and diversity. However, past, current, and projected climate change can have significant negative impacts on forest health, productivity, and its many ecosystem services; these negative impacts can vary substantially with tree species and geographic location and other factors, and the Northeastern American forests are no exception to these variations. The Northeastern America region is a heavily forested area that provides important forest-based services to society and a great contribution to the overall economy. Because of its high population, this region of the US has an increasing demand for energy, and the forests are promising resources for fulfilling this need. The purposes of this review paper are to provide an overview of Northeastern American forests, as they are vitally important to our social, economic, and environmental well-being, by presenting their past and current status and to discuss the effect of natural disturbances and climate change on these forest tree species and how the increased numbers of forest dead trees can be utilized for the production of biofuel/bioenergy.

2. Distribution of Forests in United States

The American forests are astounding resources, comprising approximately 323 million hectares of natural forests, planted forests, and woodlands, with about 16.2 million hectares being virgin old-growth forests. Due to this large area of forestland, there are vastly diverse vegetation species as well [13]. Because of human activities, significant changes in forest tree species have occurred. European settlement into the US was accompanied by the introduction of various trees species, either deliberately or accidentally, some of which became established, some being invasive while others are benign [14]. The US Forest Inventory and Analysis (FIA) identified more than 400 different tree species in the US forests. According to this identification, the majority of the hardwood trees are found in the midwestern and northeastern forests, while softwood trees are predominant in the southeastern and western forests of the US [13].

The distribution of the US forest is a result of various factors, including climatic change, dispersal and disturbances, and other natural causes. Temperate, tropical, and taiga or boreal forests are the main forests found in the US Tropical forests, which are evergreen with lots of rainfall, are only found in Puerto Rico and Hawaii [15]. The majority of the forests in the US are known as temperate forests, stretching from the northeastern region to the western US, as shown in Figure 1 [16]. Taiga or boreal forest, characterized by cold and snowfall, is found on the mountains in the north central to the pacific northwestern region [17]. The Northeastern US forest spans nine states, including Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont. This region contains temperate forest, which is dominated by deciduous and evergreen trees [18]. The northeastern temperate forests are composed of oaks, hickories, tulip poplar, American beech, hard maples, and basswood. Hardwood and coniferous tree species are prevalent in the northeastern forest.

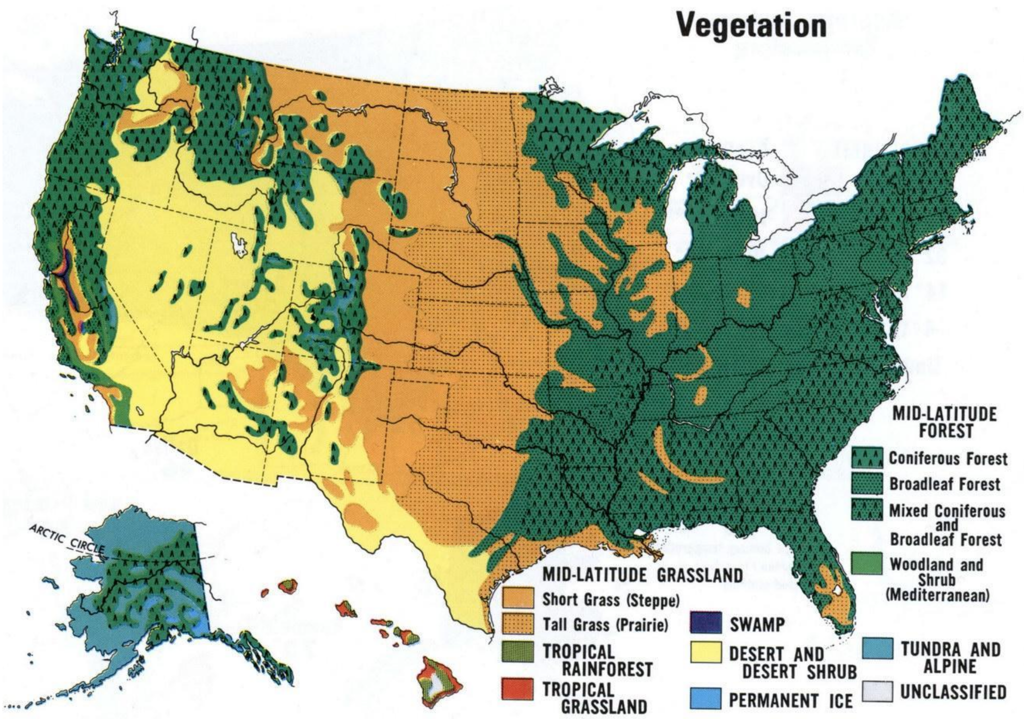

Figure 1. Map of the United States of America's forests [16].

2.1. Northeastern United States Forests

The Northeastern US lies in the northern hemisphere, approximately halfway between the north of the equator and the north, mid-latitudinal belts close to the polar regions. This location makes the temperature substantially different from other parts of the US The Northeastern US is distinguished by a humid continental climate with highly variable seasonal temperatures, which also has significant variations in temperature within the seasons as well. This region is known for having one of the most diverse climates in the world. This variation includes cold, snowy winters and warm, humid summers, droughts, heavy precipitation, and prevailing winds [19,20]. The Atlantic Ocean, the Great Lakes and mountains surrounding the northeast greatly influence its climate by influencing precipitation, increasing humidity levels, cooler air temperatures, and increased cloud immersion [20]. The average temperature in the region can have substantial intra-annual and inner-annual variations and there has been remarkable change in the climate of this region in the last several decades. In the twentieth century, an about 0.80 °C increase in average surface air temperature with about 2.1 °C increase during winter and 0.70 °C during summer was observed in the Northeastern US [21]. Figure 2 shows long-term average changes in monthly air temperature and precipitation in the region between 1991 and 2021 [22].

The forests in the Northeastern US are filled with broad-leafed, deciduous, coniferous evergreen trees and shrubs dominated by the temperate deciduous species [18,23,24]. The temperate deciduous forests are characteristic of the north hemisphere due to the location's proximity to the polar zone. This region is known for its remarkable temperature fluctuations, ranging from cold winters (i.e., −30 °C) to warm summers (i.e., 30 °C) and having a second highest annual precipitation of 750 to 1500 mm per year [22]. The region has deep, dark, and fertile soils and exposure to extreme events such as ice storms, hail storms, hurricanes, heat waves, coastal and river flooding, drought and heavy snowfall [25].

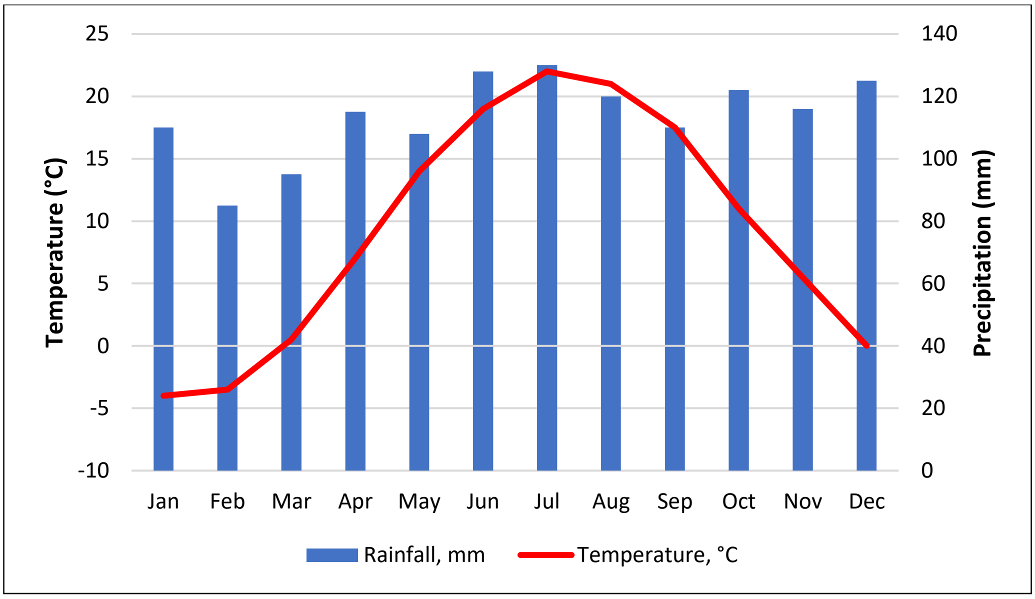

Figure 2. Long-term average changes in monthly air temperature and precipitation in the Northeastern United States between 1991 and 2021 [22]. The figure was adapted from "Climate Graph//Weather by month North East" in the following link https://en.climate-data.org/north-america/united-states-of-america/pennsylvania/north-east-138147/#climate-graph (accessed on 3 July 2023) by Copyright: CLIMATE-DATA.ORG under the license of "Attribution-NonCommercial 4.0 International (CC BY-NC 4.0)" that can be found in following link: https://creativecommons.org/licenses/by-nc/4.0/ The slight modifications were made on the figure (color change, showing each month by name rather than given by numbers, maximum scale in *y*-axis, etc.).

According to Braun representation of American forests, the Northeastern American forest corresponds approximately to seven forest zones: mixed mesophytic, western mesophytic, oak–hickory, oak–chestnut, northern hardwoods–hemlock, beech–maple, maple–basswood, and oak–pine [18,26]. The maps of land cover, all forest land use, forest groups and forest type of the Northeastern US based on the National Land Cover Database (NLCD) in 2021 are presented in Figure 3. The NLCD was used to visualize the spatial distribution of various land cover classes (Figure 3a), forest cover (Figure 3b), and forest type (Figure 3c) in 2021. The NLCD product is developed by the US Geological Survey (USGS), in collaboration with various federal agencies. These datasets offer detailed and dependable information about the land cover and its changes across the country. To uphold the NLCD's legacy and establish a long-term monitoring ability for the US land resources, the USGS introduced a new generation of NLCD products in 2016. This innovative effort has continued to evolve with enhancements in design and processing up to 2021, with the goal of consistently producing a multi-temporal land cover and land cover change database spanning from 2001 to 2021, with updates every 2–3 years. Some research has been undertaken, resulting in streamlined procedures that involve integrating specialized Multi-Resolution Land Characteristics data, incorporating various new datasets, compiling and preprocessing Landsat imagery and geospatial ancillary data, developing integrated training data using machine learning, implementing a comprehensive approach for analyzing land cover changes over time, employing a theme-based post-classification and integration protocol for generating land cover and change products, utilizing a continuous fields biophysical parameters modeling method, and deploying an automated operational system that incorporates AI/ML technologies for NLCD 2021 production. These processes have led to a notable five percent increase in accuracy as compared with the 2011 product, achieving overall accuracies of 86.4% and 90.6% in the NLCD 2016 dataset [27].

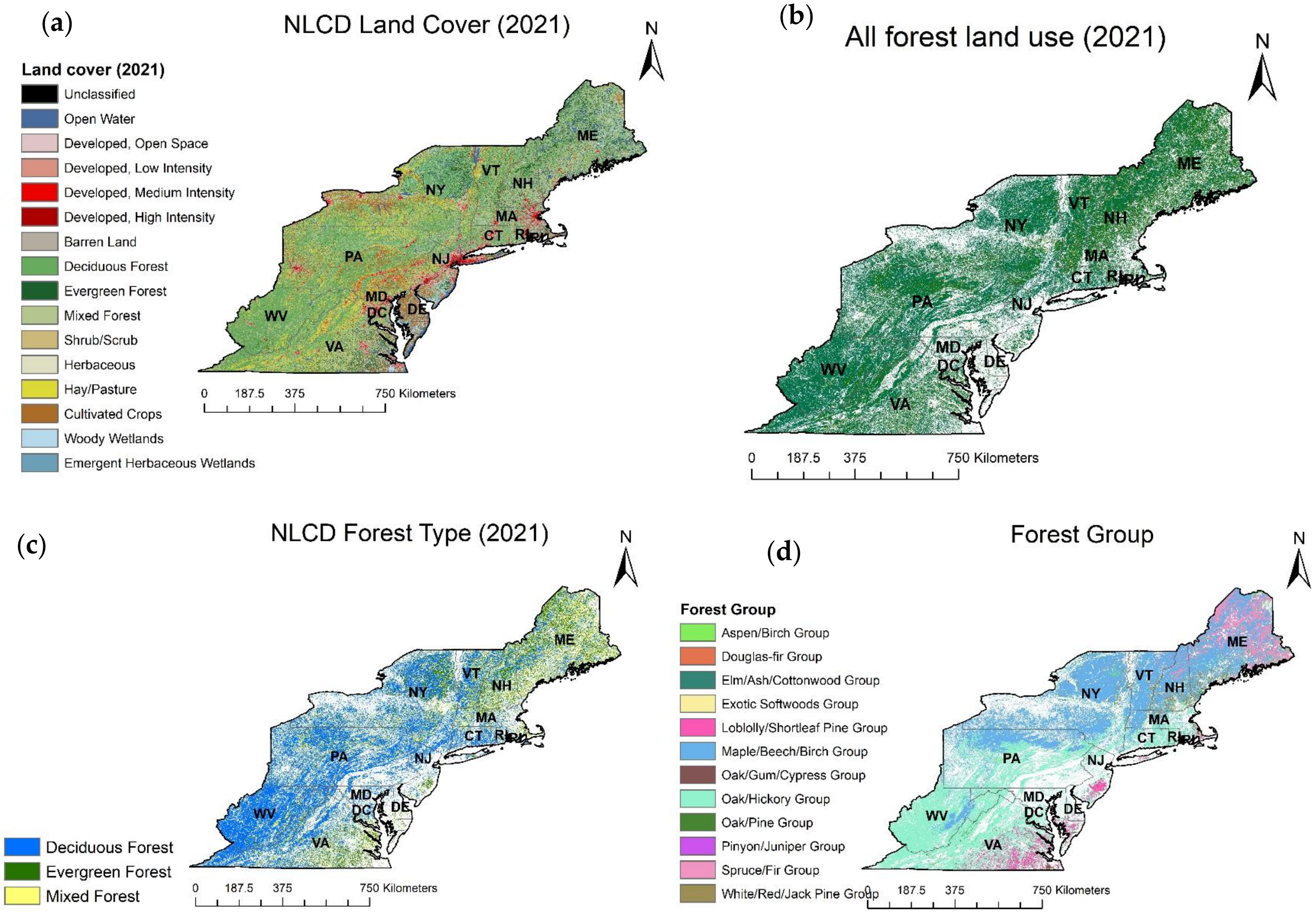

Figure 3. Spatial distribution of various land cover classes (**a**), forest cover (**b**), forest type (**c**) and forest group data (**d**) in the Northeastern United States region.

The Forest Group data (Figure 3d) was developed by a collaborative program of The USFS Forest Inventory and Analysis (FIA) program and the Geospatial Technology and Applications Center (GTAC) and was intended to depict the extent, distribution, and composition of the nation's forests. To construct this dataset, they employed a modeling approach that relied on more than a hundred geospatial predictor layers in conjunction with FIA plot data to predict forest types. As a result of this procedure, the dataset offers a finer-grained representation of forest type distribution than what can be gleaned solely from FIA plot data. This modeling effort drew upon nearly half a million FIA sample plots located across the country. Among the predictor layers used in this modeling process were digital elevation models (DEM) and DEM derivatives, multi-date composites, vegetation indices, and continuous vegetation fields from the Moderate Resolution Spectroradiometer (MODIS). Additionally, it incorporated class summaries from the 1992 National Land Cover Dataset (NLCD), various ecological zones, and summarized PRISM climate data. The modeling itself was conducted using a data mining package called Cubist/See5TM, which was loosely integrated with Leica Geosystems ImagineTM image processing software. For all maps (Figure 3a–d), we obtained national-level datasets and extracted them using a shapefile for Northeastern states. ESRI ArcMap was used to map these datasets for the Northeastern US The Northeastern states of Virginia (VA), West Virginia (WV), Washington, DC (DC), Maryland (MD), Delaware (DE), Pennsylvania (PA), New Jersey (NJ), Connecticut (CT), Rhode Island (RI), Massachusetts (MA), New York (NY), Vermont (VT), New Hampshire (NH), and Maine (ME) are considered to represent the Northeastern US In general, the region is dominantly covered by forests and the major type of forest is deciduous. While some of the major land covers (Figure 3a) include cultivated cropland, forestlands, hay-pastureland, woody wetlands, and shrublands, the region is dominated by different forest types (Figure 3b) extending from the south portion of the region from VA and WV all the way to the north-northeast portion of the region in ME. In terms of forest type (Figure 3c), the region's dominant forest type is deciduous from the southern edge of the region extending to the MA and VT area. The area beyond that (north-northeastern portion) is dominated by evergreen forest and mixed forestland. The southeastern portion of VA is also dominated by evergreen forest and mixed forestland. From the center (east–west direction) of PA and NJ to the north (up to ME), the major forest land cover includes the maple, beech, and birch group; and the southern portion is dominated by the oak–hickory group.

The temperate deciduous forest was termed "deciduous" because of the falling of tree leaves at certain life cycle stages and/or due to extreme changes in the external environmental conditions such as drought or low temperatures during winter. Deciduous trees are usually hardwood and have been traced to have originated from flowering plants in the Cretaceous (geological period from about 145 to 66 million years ago) as they thrive to adapt to the seasonal aridity, and this form of adaption spread to the trees at the higher latitudes, where the plants adapt to moderate winter, and at the lower latitudes, where the deciduous hardwoods thrive to adapt to cold and dry winters [28]. The reasons for deciduous leaf coloration and falling are due to extreme cold, heat, drought, lack of nutrients, or sometimes due to pathogen attacks [29,30]. In favorable conditions, deciduous trees have high rates of photosynthesis and leaf respiration due to the high nitrogen content of the leaves and large leaf area that contributes to leaf atmosphere gas and energy exchange, and this gas exchange is a function of surface (climate and microclimate) and below-surface (water availability) characteristics. Other factors such as tree age and health and the ability of the soil to keep pace (in terms of providing sufficient soil moisture and critical nutrients that are transported with soil water) with the rate of photosynthesis and transpiration also playing a critical role. However, the rate of photosynthesis (which is essentially conversion of taken-up CO_2 to oxygen that provides significant benefits for reducing atmospheric CO_2 concentration) greatly reduces with exposure to unfavorable conditions [31]. Before the eventual falling of deciduous leaves, they attempt to avoid drought by reducing the carbon/nitrogen (C/N) ratio in the leaves produced [32].

The United States' forests are composed of a wide range of deciduous and evergreen trees (Table 1). Even though deciduous trees and evergreen trees co-exist in the same forest, they exhibit different characteristics, including leaf patterns and defense mechanisms against various disturbances. They also respond differently to the same magnitude of changes in climate variables and other environmental conditions (flooding, drought, extreme heat, etc.). They are referred to as "evergreen" because they maintain their green leaves and have foliage all year long and their leaves are constantly renewed after falling off [33]. The Northeastern US evergreen forests are dominated by broad-leaved evergreen angiosperms, narrow conifers, broadleaved conifers, and scaled-leaved evergreen conifers. The broad-leaved evergreen trees are characterized by thick and smooth margins. Narrowed-leaved evergreen trees produce their seeds in compact structures and cones [34]. Evergreen leaves tolerate drought and other extreme weather through the production of high levels of structural carbon-based compounds and tough laminae [35]. Evergreen plant leaves' lifespan is usually longer with higher construction and maintenance [36]. The constant availability of green leaves on these trees makes them more prone to herbivory than deciduous trees [33].

Table 1. Lists of common deciduous and evergreen trees in the overall United States' forests.

Common Name	Scientific Name	Tree Type
American arborvitae	*Thuja occidentalis*	Evergreen
American beech	*Fagus grandifolia*	Deciduous
American elm	*Ulmus americana*	Deciduous
American holly	*Ilex opaca*	Evergreen
American hophornbeam	*Ostrya virginiana*	Deciduous
American hornbeam	*Carpinus caroliniana*	Deciduous
American sycamore	*Platanus occidentalis*	Deciduous
Anglojap yew	*Taxus media*	Evergreen
Apple	*Malus domestica*	Deciduous
Atlas cedar	*Cedrus atlantica*	Evergreen
Austrian pine	*Pinus nigra*	Evergreen
Balsam fir	*Abies balsamea*	Evergreen
Bigtooth aspen	*Populus grandidentata*	Deciduous
Bitternut hickory	*Carya cordiformis*	Deciduous
Black cherry	*Prunus serotina*	Deciduous
Black gum	*Nyssa sylvatica*	Evergreen
Black locust	*Robinia pseudoacacia*	Deciduous
Black maple	*Acer nigrum*	Deciduous
Black oak	*Quercus velutina*	Deciduous
Black tupelo	*Nyssa sylvatica*	Deciduous
Boxelder maple	*Acer negundo*	Deciduous
Butternut	*Juglans cinerea*	Deciduous
Canada hemlock	*Tsuga canadensis*	Evergreen
Carolina hemlock	*Tsuga caroliniana*	Evergreen
Carolina rhododendron	*Rhododendron carolinianum*	Evergreen
Catawba rhododendron	*Rhododendron catawbiense*	Evergreen
Chestnut oak	*Quercus prinus*	Deciduous
Chinese holly	*Ilex cornuta*	Evergreen
Chinese juniper	*Juniperus chinensis*	Evergreen
Christmas fern	*Polystichum acrostichoides*	Evergreen
Colorado spruce	*Picea pungens*	Evergreen
Common boxwood	*Buxus sempervirens*	Evergreen
Concolor-fir	*Abies concolor*	Evergreen
Creeping juniper	*Juniperus horizontalis*	Evergreen
Cucumber tree	*Magnolia acuminata*	Deciduous
Douglas-fir	*Pseudotsuga menziesii*	Evergreen
Downy serviceberry	*Amelanchier arborea*	Deciduous

Table 1. *Cont.*

Common Name	Scientific Name	Tree Type
Drooping leucothoe	*Leucothoe fontanesiana*	Evergreen
Eastern black walnut	*Juglans nigra*	Deciduous
Eastern hemlock	*Tsuga canadensis*	Evergreen
Eastern hop-hornbeam	*Ostrya virginiana*	Deciduous
Eastern juniper	*Juniperus virginiana*	Evergreen
Eastern red cedar	*Juniperus virginiana*	Evergreen
Eastern redbud	*Cercis canadensis*	Deciduous
Eastern white pine	*Pinus strobus*	Evergreen
Eastern white pine	*Pinus strobus*	Evergreen
English yew	*Taxus baccata repandens*	Evergreen
Flowering dogwood	*Cornus florida*	Deciduous
Fraser-fir	*Abies fraseri*	Evergreen
Garden phlox	*Phlox paniculata*	Evergreen
Gray birch	*Betula populifolia*	Deciduous
Great laurel	*Rhododendron maximum*	Evergreen
Hackberry	*Celis occidentalis*	Deciduous
Hinoki falsecypress,	*Chamaecyparis obtusa*	Evergreen
Horse-chestnut	*Aesculus hippocastanum*	Deciduous
Inkberry	*Ilex glabra*	Evergreen
Japanese black pine	*Pinus thunbergi*	Evergreen
Japanese cedar cryptomeria	*Cryptomeria japonica*	Evergreen
Japanese falsecypress	*Chamaecyparis pisifera*	Evergreen
Japanese holly	*Ilex crenata*	Evergreen
Japanese pieris	*Pieris japonica*	Evergreen
Japanese yew	*Taxus cuspidata*	Evergreen
Lacebark pine	*Pinus bungeana*	Evergreen
Leatherleaf mahonia	*Mohonia bealei*	Evergreen
Leatherleaf viburnum	*Viburnum rhytidophyllum*	Evergreen
Litterleaf boxwood	*Buxus microphylla*	Evergreen
Mountain pieris	*Pieris floribunda*	Evergreen
Mountain-laurel	*Kalmia latifolia*	Evergreen
Mugo pine	*Pinus mugo mughus*	Evergreen
Northern catalpa	*Catalpa speciosa*	Deciduous
Northern red oak	*Quercus rubra*	Deciduous
Northern white cedar	*Thuja occidentalis*	Evergreen
Norway maple	*Acer platanoides*	Deciduous
Norway pine	*Pinus resinosa*	Evergreen
Norway spruce	*Picea abies*	Evergreen
Ohio buckeye	*Aesculus glabra*	Deciduous
Oregon hollygrape	*Mahonia aquifolium*	Evergreen
Oriental spruce	*Picea orientalis*	Evergreen
Paper birch	*Betual papyrifera*	Deciduous
Paw paw	*Asimina triloba*	Deciduous
Pin oak	*Quercus palustris*	Deciduous
Pine tree	*Pinus strobus*	Evergreen
Pine umbrella	*Sciadopitys verticillata*	Evergreen
Pinyon pine	*Pinus cembroides*	Evergreen
Pitch pine	*Pinus rigida*	Evergreen
Red or swamp maple	*Acer rubrum*	Deciduous
Red pine	*Pinus resinosa*	Evergreen
River birch	*Betula nigra*	Deciduous
Scarlet firethorn	*Pyracantha coccinea*	Evergreen
Scots pine	*Pinus sylvestris*	Evergreen
Serbian spruce	*Picea omorika*	Evergreen
Serviceberry/shadblow/shadbush	*Amelanchier canadensis*	Deciduous

Table 1. *Cont.*

Common Name	Scientific Name	Tree Type
Shagbark hickory	*Carya ovata*	Deciduous
Sheep laurel	*Kalmaia angustifolia*	Evergreen
Shortleaf pine	*Pinus echinata*	Evergreen
Silver maple	*Acer saccharinum*	Deciduous
Striped maple/moosewood	*Acer pensylvanicum*	Deciduous
Sugar or rock maple	*Acer saccharum*	Deciduous
Sumac	*Rhus glabra*	Evergreen
Swamp birch	*Betula alleghaniensis*	Deciduous
Swamp Spanish oak	*Quercus palustris*	Deciduous
Sweet birch	*Betula lenta*	Deciduous
Sweetbay magnolia	*Magnolia virginiana*	Semi-evergreen
Tabletop pine	*Pinus densiflora umbraculifera*	Evergreen
Tamarack	*Larix laricina*	Deciduous
Trembling aspen	*Populus tremuloides*	Deciduous
Trident red maple	*Acer buergerianum*	Deciduous
Tulip poplar tree	*Liriodendron tulipifera*	Deciduous
Virginia bluebells	*Mertensia virginica*	Deciduous
Virginia pine	*Pinus virginiana*	Evergreen
Warty barberry	*Berberis verruculosa*	Evergreen
Weeping willow	*Salix babylonica*	Deciduous
White ash	*Fraxinus americana*	Deciduous
White fringetree	*Chionanthus virginicus*	Deciduous
White oak	*Quercus alba*	Deciduous
White spruce	*Picea glauca*	Evergreen
Wild black cherry	*Prumus serotina*	Deciduous
Winterberry	*Ilex verticillata*	Deciduous
Wintergreen barberry	*Berberis julianae*	Evergreen
Yellow birch	*Betula alleghaniensis*	Deciduous
Yellow or sweet buckeye	*Aesculus flava*	Deciduous

2.2. Disturbances in Northeastern Forests

Disturbance of the health of forest trees can alter the energy, mortality, structure, productivity, water quality dynamics and nutrient and biogeochemical cycling of both the tree and the plant [36,37]. Disturbance can also affect the soil water distribution in the trees' effective root zone, soil water uptake [38] and capillary transport to upper leaves and branches, leaf (stomatal) functions and gas exchange with the surrounding atmosphere [39]; in turn, all these variables/factors impact the magnitude and efficiency of photosynthesis, transpiration rates, net ecosystem productivity [40], etc.

One major natural disturbance in forest ecosystems is insect outbreaks [41–43]. Pests can lead to the defoliation of forest, which can result in decrease in transpiration, increase in tree mortality, enormous reduction in the growth of forest trees, high soil leaching losses of elements (i.e., nitrogen and potassium), reduction in nutrient uptake, decrease in above-ground biomass water uptake, increase in light penetration to forest grounds (understory), and increase in soil moisture and temperature, which likely increase the activity of microorganisms and decomposition rates [41]. The cadavers and excreta of these pests can also contribute to nitrogen leaching in deciduous forests. In past years, balsam fir and coniferous forests have experienced series of spruce budworm outbreaks, resulting in defoliation [42]. The elm span worm (*Ennomos subsignarius Hubner*) is another pest that defoliates the northeastern forest by feeding on the leaves, leading to a shot-hole effect [43]. It has been noted that the major defoliator of hardwood forests in the Northeastern US is the Gypsy moth (*Lymantria dispar*) [41]. The fall cankerworm (*Alsophila pometaria*), known to be native to North America, feeds on evergreen broadleaf trees and shrubs [44]. Oak, maples, elm, cherry, hickories, birch, dogwood, ash, and basswood are commonly defoliated by various pests including the Linden looper (*Erannis tiliaria*), spring cankerworn (*Paleacrita vernata*), oak leaf tier (*Croesia semipurpurana*), eastern oak looper (*Phigalia titea*), oak leaf caterpillar (*Lochmaeus manteo*), black locust (*Robinia pseudoacacia*), locust stem borer (*Megacyllene robiniae*), and forest tent caterpillar moth (*Malacosoma disstria*) [45]. Bark beetles feed on the bark of various trees [46].

Most recently, the spotted lanternfly (*Lycorma delicatula*), which is an invasive planthopper indigenous to Asia (primarily China, but including Japan, South Korea, India, Vietnam) that was first detected in north America in southeastern PA in Berks County in September 2014, has been causing significant damage and other challenges to forestry (primarily young trees and softwood-type trees) and other ecosystems (Figure 4) [47,48].

Figure 4. Image of spotted lanternflies feeding on forest trees. (Photo credit: Emelie Swackhamer, Penn State Horticulture Extension Educator).

These invasive insects present a significant threat to Pennsylvania's (and other states') agriculture and agro-forestry industry, including the grape, tree-fruit, hardwood and nursery industries, which collectively are worth nearly $18 billion to the state's economy [47]. The spotted lanternfly is a significant plant stressor and their feeding on trees and plants may contribute to the long-term weakening and health of established trees and plants. They are invasive and can be spread long distances by people who move infested material or items containing egg masses [49]. As presented by [50], This invasive insect's preferred host in North America, as it is in Asia, is the *Ailanthus altissima* (Mill.) Swingle (*Simaroubaceae*), which is also known as the tree of heaven [51] and locally known as paradise tree. It is considered invasive and readily escapes cultivation into disturbed woods, roadsides, vacant areas, and railroad banks. This planthopper utilizes this tree for feeding, mating, possible chemical sequestration, and egg depositing, where it overwinters in cryptic wax-colored masses of 30 to 50 eggs [52]. Nixon et al. (2022) stated that it continues to spread throughout the eastern US They evaluated the 2 wk survivorship of early nymphal instars, late nymphal instars, and adult *Lycorma delicatula* on single diets of ten wild and cultivated hosts: tree of heaven; apple, *Malus domestica*; peach, *Prunus persica*; black cherry, *P. serotina Ehrh*; black locust, *Robinia pseudoacacia* L.; black walnut, *Juglans nigra* L.; common hackberry *Celtis occidentalis* L.; mulberry *Morus alba* L.; sugar maple *Acer saccharum Marshall*; and white oak, *Quercus alba* L., and observed that, among them, early and late instars had significantly greater survivorship on tree of heaven and black walnut and adults had greatest survivorship on tree of heaven [53].

Another natural disturbance in the forest ecosystems is drought. The US Department of Agriculture noted that up until the present time, over 80% of the northeastern region of the US is experiencing varying degrees of drought with over 18% undergoing abnormal dry conditions, extending to severe or extreme drought [54]. Drought is a major environmental stress that negatively impacts tree health and decreases productivity and leaf death. It is the lack of required moisture for plant growth and development as a result of a continuous drop in precipitation and increase in evapotranspiration demand. Some trees (*Quercus macrocarpa*, *Juniperus virginiana*, *Cornus florida*, *Fraxinus americana*, *Fagus grandifolia*, *Quercus rotundifolia*, *Quercus alba*, *Quercus rubra*, *Prunus serotina*, Viburnum nudum, and *Viburnum rafinesquianum*) have been reported to be extremely drought-tolerant and remain evergreen during drought. Some others (*Oxydendrum arborerum*, *Fraxinus americana*, *Acer floridanum* and *Viburnum acerifolium*, *Acer rubrum*, *Liriodendron tulipifera* and *Nyssa sylvatica*) are sensitive to drought and lose about 50% of their nutrients and phosphorus due to desiccation, but adapt to drought by reabsorbing nutrients from their leaves, thereby they experience leaf senescence [55]. These trees tolerate drought by either morphological adaptations, which may include absorbing more water from the soil by extending their roots into the deeper soil profile, minimizing water loss through transpiration by partially or completely closing their stomata, and reducing leaf size and quantity, or physiological adaptations, which may include accumulating organic and inorganic solutes without decreasing water content, increasing leaf turgidity, regulations of plant growth responses through root-to-shoot signals by phytohormones and the increased production of antioxidant and photoprotective pigments to normalize metabolic activities [56,57]. Evergreen trees' most effective strategy of surviving during drought is the use of deeper sources of water [58]. *Liquidambar styraciflua*, *Acer saccharum*, and *Betula populifolia* have been reported to be poorly drought-tolerant tree species, therefore, water deficiency leads to a decline in vitality and, eventually, the death of these trees [55,59–61].

Extreme air temperature also causes considerable stress and damage to the forest environment [62]. There has been an expected continual increase of heat waves through the 21st century [63]. Extreme heat can reduce the rate of photosynthesis, increase photooxidative stress, lead to the abscission of leaves and reduction in plant growth, and can eventually cause plant mortality [64]. Heat waves are usually accompanied by drought conditions leading to exacerbated results [65]. Some trees have shown remarkable traits of strong tolerance to thermal stress. At high temperatures, they exhibit traits that include leaves cooling through stomatal conductance (inverse of stomatal resistance; 1/resistance) increase, inactivation of the Rubisco enzyme, and increased photorespiration and mitochondrial respiration and decreased photosystem II activity [64,66]. In addition to extreme temperatures, low air temperature is also one of the major factors in the distribution of trees. The main effects of low winter temperature on plants are freeze injury and flower hardiness, which have led to research on frost protection and flowering delay to reduce freeze injury [67]. However, this biological hazard is still responsible for the loss of flowers, buds, fruits, vegetables, and plant shoots [68]. Spring frost can also lead to cell damage, abnormal morphological development of fruits, abscission of fruits, and flower hardiness [68].

The growth and development of forest can be slowed because of browsing, fraying, and bark stripping that are caused by herbivores, deer, rabbits, hares, squirrels, and voles [69]. It was reported that a common form of predation in northeastern America is habitat-mediated predation. Herbivore activity can also lead to stem deformation, callousing or staining, reducing the quality of wood for timber production [69]. Browsing has been reported to have the most negative influence on trees, resulting in tree injury and the removal of tissues. Conifers, Douglas fir (*Pseudotsuga menziesii*), Norway spruce (*Picea abies*), and Sitka spruce (*Picea sitchensis*) are usually browsed by deer in various seasons [69].

The trees that have injuries or wounds caused by disturbances factors such as storms, extreme temperatures, hailstorms, fire, lightning, insects, animals, and incorrect pruning are vulnerable to wood decay. Although wood decay provides shelter for wildlife by creating cavities in the living trees, it can also cause complete loss of the trees (Figure 5). Wounds expose the tree components to organisms, primarily bacteria and fungi that cause decay of the wood. Wood decay can begin in the sapwood, the heartwood, or the roots. The process can go unnoticed for years, especially in remote locations of forest land. Wood decay fungi are classified as white-rot fungi, brown-rot fungi, and soft-rot fungi depending on the type of decay. They partially or completely degrade wood components (lignin, cellulose, or hemicellulose). For instance, white rot breaks down most of the wood components while brown rot fungi decompose the cellulose and hemicellulose in wood but cannot break down lignin.

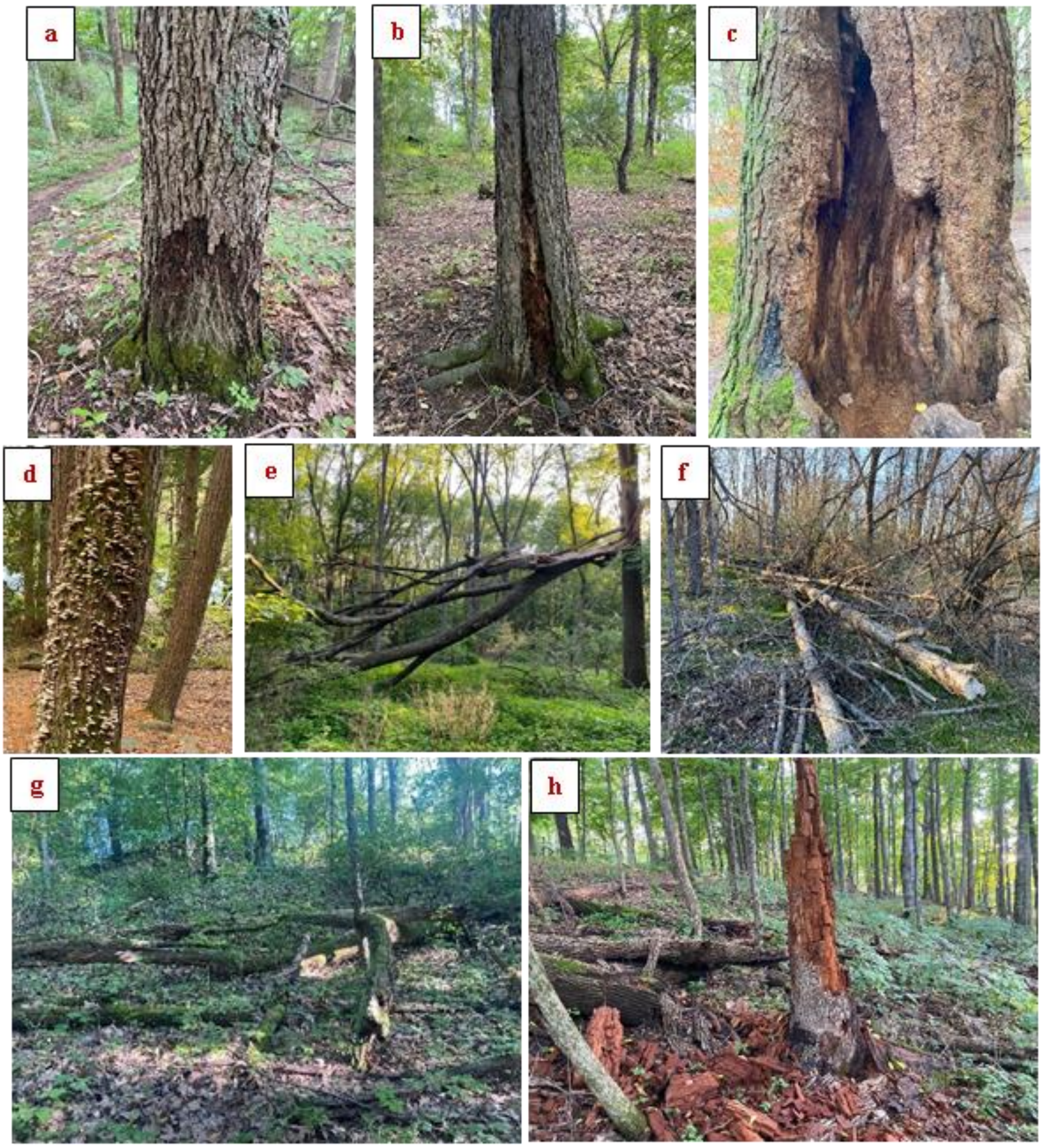

Figure 5. Damaged trees in the forests in the Northeast US: (**a**) wounded tree, (**b**,**c**) cavities, (**d**) wood decay fungi, (**e**) storm damage, (**f**) standing dead trees, (**g**) lying down dead trees, and (**h**) brown-rot fungi (Pictures collected from Port Matilda and Pocono, PA, forests by Professor Sibel Irmak).

The material left behind white rot is very light while brown rot leaves a reddish-brown colored material that is a result of lignin oxidation (Figure 5f). Most wood decay is caused by basidiomycetes, which are typically classified as either white- or brown-rot fungi [70]. Some ascomycetes can also decay wood by degrading cellulose or hemicellulose fractions, but they comprise a small quantity of wood decay fungi [71].

Increased forest fires due to climate change are another important threat to forests. Plant have developed diverse fire-adaptive traits as a result of biological and biophysical evolution. Such adaptation includes thick, protective bark and highly flammable litter in oaks (*Quercus* spp.) [72], the opening of serotinous cones in *Pinus contorta* and *Pinus banksiana* [73], insulating bark as in *Sequoiadendron giganteum* and *Quercus suber* [74], resprouting in *Gaylussacia baccata* [75], resprouting in *Quercus gambelii* and *Prunus virginiana* [76], and post-fire epicormic branching in white fir (*Abies concolor*) [77]. Natural or intentional fires can be used as a management tool for the determining the structure and composition of plant communities; however, large wildfires have been related to the infestation of insects and diseases that are agents of forest disturbance [78,79]. Increases in extreme environmental conditions that have been observed in the last decade and longer, such as drought and hot and windy conditions, as a result of climate change have contributed to significant increases in forest/wildlife fires, causing devastating damage to forestland and wildlife habitat.

Increase in forest fires can also cause the release of captured and stored carbon in deeper forest soil layers, causing increased CO_2 emission into the atmosphere. Increased CO_2 concentration in the atmosphere can cause increases in air temperature, which in turn can cause reduced soil moisture due to an increased vapor pressure deficit between the surface (i.e., forest canopy and atmosphere) and drier forest canopy, longer fire season, and increased number of fires. For example, based on the data reported by the US Forest Service and National Interagency Fire Center (NIFC) through the US Environmental Protection Agency, the number of wildlife/forest fires have been averaging an astonishing 70,000 fires/year. The extent of area burned by wildfires each year appears to have increased since the 1980s. Also, of the 10 years with the largest acreage burned, all have occurred since 2004, including the peak year in 2015. This period coincides with many of the warmest years on record nationwide [80]. Furthermore, wildfires burn more land in the western US than in the eastern US (due to drier and warmer conditions in the west), and parts of the western and southwestern region had the largest increase in burned land area between the first half of the period of record (1984–2001) and the second half (2002–2020). The burned land area in the western US has increased considerably in almost every month of the year. Also, importantly, the US wildfire season is occurring earlier. For example, during the period of 1984–2001, the national burned area peaked in August. However, more recently, the peak month was observed in July with an average of 1.7 million acres (~690,000 hectares) burned in July in each year from 2002 to 2020 [69]. Based on the data reported by the NOAA National Centers for Environmental Information, from 2001 through 2020, the average land area burned by wildfires was about 7 million acres (2.83 million hectares) per year [81]. Forests are disturbed by intensive human activities as well. Human activities such as overharvesting or large-scale destruction of trees/deforestation for the logging of wood for timber and charcoal production, converting forest to agricultural and urban uses, industrialization, etc., have greatly reduced the number of old-growth forests in north America [82].

3. Effects of Climate Change on Forests

Climate change influences several natural disturbances (insect outbreaks, invasive species, wildfires, storms, etc.) that threaten forest health. These disturbances can be direct or indirect impact(s) of climate change through increased drought [83], warmer air temperatures [84], extreme precipitation/storm events [85], increased incoming shortwave radiation, and increased duration, as well as the severity of some of these variables/factors [86]. Based on the level, frequency and duration of unusual weather events, the damage on forested ecosystems can be different. Climate change affects forest composition and productivity by influencing many factors such as tree growth and development, flowering times and seed quality and quantity, distribution, etc. Global climate models have been developed to predict changes in future climate based on greenhouse gas emissions. Forest health and productivity response to climate change can exhibit variations spatio-temporally as well as by tree type. For example, forests in the Northeastern US may not respond to climate change in the same way as forests respond in the western part of the country due to differences in interactions and productivity response of different tree species to the same climate variables (temperature, radiation, vapor pressure deficit, drought, precipitation, etc.). Even if the same tree species are considered, the same tree species grown in the Northeastern US and the western part, these same species can respond differently to the changes (both magnitude and duration) in the same climate variables due to differences and dynamics involved in genetic vs. environment and geolocation interactions. Different physiological, biophysical, evapotranspiration, photosynthesis, and productivity responses of forests to climate change have been studied. Mohan et al. (2009) stated that exceedances of United States and Canadian ozone air quality standards are apparent and offset CO_2-induced gains in biomass and predispose trees to other stresses [87]. The accumulation of nitrogen and sulfate in the Northeastern US changes forest nutrient availability and retention, negatively impacting the reproductivity of trees and frost hardiness, which can cause damage to the leaves and can also negatively influence the ability of trees to defend themselves against forest pests and diseases. These important stresses may cause declines in certain tree species and ecosystem health during the modulation to a warmer climate. For example, responses of tree species to climate change in New England and the northern New York region were examined by two forest impact models under two contrasting greenhouse gas emission (high and low) climate scenarios [88]. Based on this assessment, the researchers observed that tree species with ranges that extend to the south may increase. These include red maple, northern red oak, black cherry and American basswood. They also observed that the tree species associated with boreal forests may decrease, which include balsam fir, black spruce, white spruce, red spruce, quaking and bigtooth aspens, and white birch and gray birch. (Janowiak et al., 2018) also suggested that a loss of coastal forests may occur and tree species with low adaptive ability may decrease, which include black ash, white ash, balsam fir, butternut, and eastern hemlock [88]. Mohan et al. (2009) stated that climate change will restructure forests of the Northeastern US over the coming century, although the details of this restructuring remain uncertain. They further showed that climate change could bring some additional species into the Northeastern US, but more importantly, there is a potential for expansion of area and importance for species that are in the region but have relatively minor prominence [87]. Based on the interpretation of the modeling results, Mohan et al. (2009) suggested that "it is logical that many southern species, especially ones that are driven largely by climate (especially air temperature), would have suitable habitat appear or increase in the Northeastern US" [87]. The effects of non-climate variables, such as disturbance regimes, dispersal mechanisms, and fragmentation, add complexity and uncertainty to the final outcomes. Besides the possibility that there will be more habitat for less-common species, the habitat of some of the very common northern species, such as balsam fir, paper birch, red spruce, bigtooth and quaking aspen, and black cherry, will likely shrink. The models thus suggest a retreat of the spruce–fir zone back into Canada, as seen in the past [89]. Rusted et al. (2009) synthesized climate observations and modeling results and suggested that the Northeastern US and eastern Canada show that the climate of the region has become warmer and wetter over the past 100 years and that there are more extreme precipitation events and projections indicating significant declines in suitable habitat for spruce–fir forests and the expansion of suitable habitat for oak-dominated forests [90]. They further stated that climate change affects the distribution and abundance of many wildlife species in the region through changes in habitat, food availability, thermal tolerances, species interactions such as competition, and susceptibility to parasites and disease. They recommended that with the accumulating evidence of climate change and its potential effects, forest stewardship efforts would benefit from integrating climate mitigation and adaptation options in conservation and management plans. It is important to note that while climate change can regulate or influence forest species response to change in climate variables, the important role of the forest soil structure and soil's influence in the forest response to climate cannot be ignored. Lafleur et al. (2010) showed that the projected global warming and alteration of the precipitation regime will influence tree physiology and phenology and is likely to promote northward migration of tree species [91]. In addition to air temperature, solar radiation, vapor pressure deficit and precipitation, the coupled impact of hot climate as well as the increase in atmospheric CO_2 concentration, the impact(s) of climate change on forest health, productivity, and responses become more sophisticated. For example, through a complex and comprehensive modeling study, Ollinger et al. (2008) indicated a wide range of predicted future growth rates for Northeastern US forests [92].

Natural disturbances may increase the distribution and abundance of invasive plants and trees. Invasive species could reduce some plants and tree species that are vulnerable to climate change and cause decreases in forest biomass. Since invasive species are tolerant to changes, they are expected to spread more with climate change. This effect may vary depending on the region. Japanese honeysuckle (Lonicera japonica), kudzu (Pueraria montana var. lobata), autumn olive (*Elaeagnus umbellata*), garlic mustard (*Alliaria petiolata*), Japanese stiltgrass (*Microstegium vimineum*), mile-a-minute vine (*Polygonum perfoliatum*), tree of heaven (*Ailanthus altissima*), and wavyleaf basketgrass (*Oplismenus hirtellus* spp. *undulatifolius*) are some examples of the most commonly observed invasive plant/tree species in Northeastern US forests. The utilization of an excess amount of damaged or dead trees as well as invasive plant and tree species in forests play an important role in mitigating the negative impact of climate change by removing these carbon rich biomass materials from lands and transitioning to sustainable energy.

4. Utilization of Damaged Forest Trees and Forest Biomass for Biofuel Production

Utilization technologies for forest biomass for production of biofuels have not been fully developed for practical commercial production yet, but there are considerable efforts and undergoing research in this area. Bioenergy or biofuels production from biomass has been focused and studied more on other types of biomass resources (e.g., crops and agricultural biomass wastes) [93–97]. The main challenge for the utilization of forest biomass for biofuels includes harvesting and transportation difficulties and costs [98]. In addition, these biomass materials are in demand or preferable for other applications (e.g., construction and furniture industry, etc.) [99]. However, forest biomass utilization has received growing attention in recent years and the research efforts on this area have been encouraged by governmental programs. Grants and funding opportunities as well as assistances have been provided and regulations and public policies for the utilization of these resources have been improved. The forest woody biomass that has poor physical properties and low value becomes more important as dead and damaged trees generated by natural disturbances increase. The existing conversion of technologies for these abundant resources are expected to be improved in the near future.

Dead and damaged trees are also a very important part of the forest ecology and services as they play various critical roles in the maintenance of the forest biodiversity and the ecosystem. The degradation of dead wood is a critical process for nutrient cycling. Dead trees maintain biodiversity as they serve as food sources for wood-decaying fungi and bacteria, vertebrates, and invertebrates and as a home to parrots, woodpeckers, and owls. Decayed trees nourish the soil, thereby boosting the growth of other plants [100]. On the other hand, the woods from dead trees (coarse woody debris, CWD) are important sources of greenhouse gas emissions due to wood decomposition, containing carbon dioxide (CO_2) and methane (CH_4), the two main greenhouse gases of greatest concern causing climate change. Additionally, while forest soils emit large quantities of carbon dioxide (CO_2), they also serve as the most active CH_4 sinks in upland soils due to higher methanotrophic activity relative to other ecosystems, such as grasslands [101,102]. Therefore, it is important to develop and/or utilize existing beneficial uses for unhealthy forest biomass prior to conversion to CWD and reduce the environmental concern these waste materials cause. With about 304 million hectares of forestland in the US, there is a significant opportunity to utilize this abundant resource to generate high-value biofuel products. There is a significant amount of low-value woody biomass in the Northeastern US that is not being utilized for any high-value products in a practical and cost-effective manner.

In Pennsylvania alone, approximately 17 million acres (~7 million ha) of forestland, which is equivalent to an average of seven million tons of low-value woody biomass, are released per year due to not currently feasible or viable market demand [103]. As mentioned above, natural disturbances (windthrow, drought, extreme heat, fire, hurricane, insect and disease outbreaks, etc.) cause considerable damage to and destruction of forest trees that is exacerbated due to climate change and this process likely to increase in the future [104]. Therefore, utilization of this large but low-value forest-based biomass for high-value products is important. Climate change and natural disturbances continue to negatively impact forest health. For example, climate change and associated disturbances have contributed to beetle outbreaks in many states in the US. Winter cold is no longer limiting bark beetles, resulting in beetle infestations on a massive scale. On the national forests alone, the area affected has reached almost 13 million hectares. In the Northeastern US, during the past few decades, this region has experienced changes in climate that can cause its forests to shrink in size [105] due to damages caused to forestlands because of numerous factors, including root damage, root water logging (root rot), disease pressure, pathogenic disturbances, etc., which are mostly caused by increased air temperature, precipitation, and atmospheric evaporative demand. Kosiba et al. (2018) indicated that ~11.0 million ha of forestland (10% of the study region of northeast US) experienced at least one damage event (i.e., an Insect Disease Survey polygon) over the 17-year period, averaging 647,425 $\pm$ 215,482 ha (3.4 $\pm$ 1.1% of 30 the region's forestland) annually. Across the region, insects were the most extensive damage agent category (~8 million ha), with a relatively small number of invasive insects accounting for half of this damage [106]. These large damaged forestlands clearly indicate that there is a significant potential to convert damaged forest biomass into value-added products.

Recent research has proven the possibility of deriving renewable biofuel from trees destroyed by natural disasters. In addition to the environmental benefit, the utilization of dead forest can provide economic benefits to society as there is no viable market for these increasing biomass resources. Forest landowners and rural communities can benefit economically from the utilization of the large woody biomass sources for biofuel/bioenergy production. The development of such an industry would create new jobs and provide value to forest biomass residues in general including low-value trees.

Dead tree woody biomass can be converted through various pathways into biofuels, bioenergy, and biobased products [107]. After careful prescriptive treatment of these trees, using them to produce bioenergy could contribute to reduction in greenhouse gas emission [108]. The transition from energy dependent on fossil fuels to sustainable energy sources has been a significant practice and research area in the energy sector. This shift has gained considerable public attention due to the reproducibility and environmentally friendly nature of these sources. The utilization of biofuels for energy generation plays a pivotal role in mitigating atmospheric carbon emissions linked to fossil fuels [109]. Biofuels are generally solid, liquid, or gaseous fuel from biological materials, including plants, agricultural residues, algae, and biological wastes. They include biohydrogen, biogasoline, biodiesel, biomethane, bioethanol, biocrude, etc. Among them, bioethanol is the most produced biofuel in the US, followed by biogasoline [110].

Biofuels can be classified into various forms based on various factors including their physical state, feedstock used in their production and type of their production process. Table 2 shows classifications of biofuels according to these factors. Based on their sources or feedstock, biofuels are categorized into first, second, and third generations.

Table 2. Classification of biofuels.

Classification Type	Group Name	Examples Based on Current Production	References
Physical state	Solid	Wood, wood pellets, biochar.	[111–114]
	Liquid	Biodiesel, bio-oil, bioethanol, jet fuel.	[115]
	Gaseous	Biogas, biohydrogen, biomethane.	[116]
Feedstock	1st generation	Bioethanol, biodiesel, biogas, biohydrogen.	[115,116]
	2nd generation	Bioethanol, biodiesel, bio-oil, biogas, biochar, Fischer-Tropsch gasoline.	[113,115,116]
	3rd generation	Biodiesel, bio-oil.	[117]
Production process	Chemical	Biodiesel (by transesterification)	[118]
	Thermochemical	Heat (combustion) Biochar (torrefaction and pyrolysis) Bio-oil (hydrothermal liquefaction, gasification, pyrolysis) Pyrolysis Biogas, syngas or producer gas (gasification, hyrothermal gasification and pyrolysis).	[111,116,118–120]
	Biological	Bioethanol and other bioalcohols (fermentation). Biogas (anaerobic digestion) Biodiesel (biological transesterification)	[121,122]

The first generation encompasses the production of biofuels from edible food crops such as corn, sugar cane, sugar beet, vegetable oils, wheat, etc. They are produced through well-understood technologies and processes (fermentation, transesterification, etc.); however, they pose a problem as the feedstocks are used in the production of food products or animal feeds. The second generation pertains to the production of biofuels from non-edible biomaterials, including agricultural wastes, forest residues, organic wastes, food wastes, and various forms of biomass. They are produced from non-food biomass, but they may still compete with food production for the land use of feedstocks. Another drawback is that pretreatments (chemical, thermochemical, or biochemical) are required to release sugars from the plants. The third generation involves the production of biofuels from algae [123]. This group is the best possibility for alternative fuel as the feedstock does not compete with food; however, there are still some challenges in making the process economically feasible.

Currently, the primary source of biofuel in the Northeastern US is derived from food crops, falling within the category of first-generation biofuels. The production of biofuels has predominantly relied on crops like corn and soybean. However, as noted above, this practice poses a direct competition with food production, underscoring the necessity to explore alternative sources for biofuel production [112]. Lignocellulosic/woody biomass presents an appealing option for biofuel production due to its carbon-neutral nature. Biomass derived from coarse woody debris within forests is classified into primary feedstocks and secondary feedstocks. Primary feedstocks include tree residues, underutilized tree species, forest thinning residues, forest management byproducts, dead trees, and tree barks, while the secondary feedstocks are obtained from log companies, saw mills, and pulp mills and they include tree bark, wood scarp, wood chips, pallets, sawdust, cut offs, trimmings, edgings, hops, black liquor, tall oil, and paper mill residues [124].

It was reported that approximately 55 million tons of wood wastes were generated in the US during the year 2018 [125,126]. According to the United States Environmental Protection Agency (2017), around 17% of these wood wastes are pallets, which can be recycled into mulch and bedding materials; roughly 16% are subjected to combustion and a substantial 67% are landfill [127]. Therefore, these waste materials present a significant opportunity for conversion into biofuel rather than decomposing or combusting. As a substantial area of the Northeastern US is forest land, a large amount of forest wood wastes are generated continuously, and these abundant and low-grade biomass materials/sources are promising feedstocks for the production of various biofuels. Non-edible low-grade biomass such as dead or damaged trees is receiving increasing attention as renewable and economical natural resources that can contribute toward reducing the dependency on petroleum-based energy sources. However, the complicated and inflexible characteristics of woody biomass can impede their utilization for the aforementioned purposes. Several methods are employed to convert forest biomass into biofuels, including thermochemical conversion methods such as pyrolysis and gasification, as well as biological conversion methods such as fermentation and enzymatic processes. The direct combustion of woody biomass is a common thermochemical process that has been used for a long time for the production of heat and power for various industrial uses. The photosynthetically stored chemical energy in the biomass are converted into heat by combustion [128]. Forest biomass can be co-combusted with fossil fuels for enhanced power generation [129]. The main advantage of the co-combustion of woody biomass with fossil-based fuels (e.g., coal) is the reduction of carbon monoxide, nitrogen oxides, sulfide emissions and other harmful substances [130,131]. Fermentation is a biochemical process that is used to convert carbohydrate fraction of biomass to biofuel, ethanol. Woody biomass needs to be hydrolyzed with a pretreatment method to release sugars prior to fermentation. Because of this difficulty, woody biomass has not been preferred as feedstock for ethanol production and this conversion technology has been commercialized most commonly for corn and sugarcane rather than woody biomass [99].

Gasification is another thermochemical conversion process by which woody biomass can be converted to gaseous products (e.g., CO, H_2, CO_2, H_2O, CH_4, and C_2H_2) in a controlled concentration of oxygen and/or steam. This conversion method is one of the most efficient approaches to convert the chemical energy embedded in woody biomass to gaseous products that can be used as fuel or upgraded to be used as fuels. The gasification process is a mature technology for fossil-based feedstocks; however, it has some challenges for the commercial application of this process for woody biomass. The challenges include scaling up the processes, optimizing the yield, and process integration [99,132]. The pyrolysis process is a promising technology in which wood is subjected to rapid thermal degradation or decomposition in the absence of oxygen. This process results in the production of bio-oil, biochar, and non-condensable gases. The bio-oil from the pyrolysis of woody biomass is upgraded with various methods to bring its properties close to conventional fossil fuels. The pyrolysis process can be performed slow and fast to maximize biochar or bio-oil formation. Torrefaction, the mild pyrolysis of biomass, removes hemicellulose from biomass and upgrades it for enhancing the quality of the final products [133]. Torrefaction is performed to dehydrate biomass and increase the energy density and hydrophobicity of the final product. The biomass subjected to torrefaction can be easily ground to small-sized particles with narrow size distribution [134].

Biomass must be separated into constituents that have smaller molecular weights (e.g., oligo- and monosaccharides) or create access to these components in wood structure to be efficiently converted into a range of products by fermentation or hydrothermal gasification processes in which biomass components are converted to gaseous fractions in aqueous phase and mild conditions. The solubilized biomass components can be efficiently utilized for producing a wide range of value-added products, including biofuels (ethanol, hydrogen, etc.), industrially important chemicals (e.g., solvents), and food products (sugar and sugar alcohols, etc.). Developing cost-effective, efficient, and environmentally friendly technologies for the breakdown of biomass is one of the greatest concerns and potential impediments for these conversions. Most existing hydrolysis methods are not environmentally friendly and require either the use of toxic, corrosive, and hazardous chemicals (e.g., acid and alkali treatments) or longer retention times (e.g., enzymatic hydrolysis), which collectively make the process environmentally unsafe and/or expensive. In addition, second steps such as neutralization may require or release carbohydrates that may decompose during harsh treatment (e.g., high temperature) conditions. On the other hand, because of the rigid structure of woody biomass and resistance to decomposition, pretreatment is essential to break down the wood components and release the organic matter (lignin, cellulose, and hemicellulose) before the actual conversion process is applied for conversion to biofuels or other high-value chemicals and products. In addition to *physical treatments* (chipping, grinding, milling, microwave, ultrasonication), various *chemical* (ionic liquid, acid, alkali hydrolysis, organosolv, ozonolysis), *physico-chemical* (hydrothermal, liquid hot water, steam explosion, ammonia fiber explosion, CO_2 explosion) and *biological* (microbial and enzymatic) pretreatment methods are also applied to prepare organic-rich feedstocks for biofuel production via various conversion processes [135–137]. The application of a cost-effective pretreatment method for breakdown of rigid woody biomass structures provides success for the conversion of these feedstocks to various bioproducts including biofuels in an economically feasible way. Various pretreatment methods were evaluated and improved over the years for substantial reduction of the overall conversion cost [138].

The successful release of organic woody components from forest biomass and utilization of these feedstocks for various biofuels production (e.g., hydrogen, acetone, butanol, ethanol, char, etc.) have been studied via application of the pretreatments and conversion methods mentioned above [139–146]. The economic feasibility of these methods is important, as emphasized and evaluated in several studies [147]. As these research efforts continuously increase in the near future, the challenges for the utilization of forest woody biomass would be minimized; therefore, biofuel production industries that rely on these feedstocks would expand, enabling less reliance on fossil-based fuel and energy, which can result in substantial reductions in greenhouse gas emissions.

5. Conclusions

Forests are one of the most vital and precious resources on planet earth, providing a vast number of critical benefits and services to societies and environment. Forests support over 45 million direct and indirect jobs worldwide and their total contribution to the world economy exceeds $1.3 trillion. The Northeast US region is a heavily forested area that provides immense amounts of woody biomass that can be utilized for the production of a wide range of high-value products, including renewable energy.

Natural and climate-induced disturbances and human activities have greatly affected the health, productivity, and composition of forests, including Northeastern US forests. This study summarizes some of the impacts of climate change on forests, with the emphasis on Northeastern US forests and the utilization of damaged trees for bioenergy. These critical impacts imposed by climate drivers cause increases in the number of damaged trees in the forests. The damaged trees, dead trees, and other low-value forest-based biomass materials (invasive tree and plant species) are seen promising feedstocks for the production of various biofuels. Although the conversion of woody biomass to high-value products has currently not been fully adapted for large-scale production processes, there have been considerable efforts in this field, and the existing challenges are expected to be solved in the near future.

While global communities, policy and decision makers, and other federal and state governments are trying to better understand the scientifically based data and information about climate change and its negative (or positive) impacts on forestlands, technological advances and their utilization, finances, and social acceptance of potential solutions and mitigation to climate change need to take place simultaneously to develop more comprehensive mitigation strategies and best management practices (effective and adaptive practices for reduction in greenhouse gas emission, managing climate threats, community-driven and applied strategies, government incentives for adopting best forest management practices, developing new/newer climate-resilient forest species, developing new research- and science-based forest management actions, etc.) to encounter the negative impacts of climate change and natural disturbances on forestlands' health and productivity. In this process, it is also important for all entities (public, private, university, federal and state government, and other professionals) to work together toward a solution to mitigate the climate change and natural disturbance impacts on forests and their crucial services. Thus, it is also important to realize some of these critical services and potential responses of forests to climate change and some of the negative implications so that effective mitigation strategies utilizing good-quality modeling efforts, technological advances, research and scientifically based approaches can be developed in partnership among these entities to protect these critical resources for current and future generations of humankind, plants, and animals for the sustainability of the planet Earth.

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