Chapter 4

Forest Ecosystem Services: Carbon and Air Quality

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INTRODUCTION

Forests provide various ecosystem services related to air quality that can provide substantial value to society. Through tree growth and alteration of their local environment, trees and forests both directly and indirectly affect air quality. Though forests affect air quality in numerous ways, this chapter will focus on five main ecosystem services or disservices related to air quality that have the potential to be estimated for forest stands:

(1) Air pollution removal and its effect on air pollution concentrations,

(2) Volatile organic compound emissions,

(3) Pollen emissions,

(4) Carbon sequestration, and

(5) Air temperature reduction.

The objectives of this chapter are to:

(1) Provide a background on how forests influence each of the above ecosystem services,

(2) Recommend methods on how to quantify the magnitude of these ecosystem services, and

(3) Review new approaches in assessing the value associated with these ecosystem services.

BACKGROUND

For each of the five air quality ecosystem services, this section will provide a brief description of: a) how forests impact the service, b) past forest ecosystem service assessments and approaches to value the ecosystem service, and c) challenges associated with estimating the service and values. However, before assessing ecosystem services and values derived from a forest, it is critical to assess the forest structure, as structure strongly influences the ecosystem services.

Assessing Forest Structure and Cover

There are four main steps needed to quantify ecosystem services and values from forests:

1. Quantify the forest structural attributes (e.g., number of trees, tree cover) that provide the service for the area of interest.
2. Quantify how the structure influences the ecosystem service (e.g., tree density, tree sizes, and forest species composition are significant drivers of carbon storage).
3. Quantify the impact of the ecosystem service, because it is typically the impact of the service on human health or other attributes of the environment that provide value to society.
4. Quantify the economic value of the impact of the ecosystem service.

In quantifying the forest structure (step 1), there are various sub-steps that could be followed:

a) Delimit the boundaries of the forest area of interest (study area) and determine the area of forest land.

b) Determine the percentage or amount of tree cover within the study area. This information can be derived from the National Land Cover Database (NLCD) (USGS 2015), but the 2001 NLCD data tended to underestimate tree cover (Nowak and Greenfield 2010). Cover data can also be photo-interpreted (e.g., Nowak and Greenfield 2012) using i-Tree Canopy (www.itreetools.org), which allows users to easily interpret Google images. However, depending on image resolution, all forest areas may not be interpretable. Tree cover maps have an inherent error that may or may not be known (often photo-interpretation is used to determine the map error). NLCD 2001 tree cover layers, on average, underestimate tree cover by 9.7 percent nationally, but the differences vary by region and land cover class (Nowak and Greenfield 2010). These data layers can be adjusted to meet photo-interpreted estimates, but there will be errors in the locations of adjusted tree cover. High resolution tree cover layers or data often produce more accurate maps, particularly when LIDAR is used, but also have errors that are often hand corrected. These hand-corrected data sets can have error rates < 5 percent. With photo-interpretation, the cover attributes are assumed to be classified without error and standard error of the estimates are reduced with increased sample size.

c) Determine the structural characteristics of the forest area (e.g., number of trees by species, diameter and condition class) by sampling the area of interest. This information can often be obtained from USDA Forest Service Forest Inventory and Analysis (FIA) data, particularly for rural forests. The most important forest structural attributes used in assessing forests effects on air quality include total tree biomass, tree condition, crown competition, and leaf area and leaf biomass by species.

d) If field data are not available, structural characteristics can be estimated by extrapolating a regional average of characteristics per unit tree cover (e.g., number of trees per hectare of tree cover) to tree cover in the area of interest.

Estimates based on measurements in the field assume that plot/tree data are measured without error and sampled properly (e.g., random samples). Estimates from these data have an associated estimate of sampling error. When extrapolating regional standardized values per unit tree cover to the study area, additional uncertainty is added by assuming that the regional average applies to the condition of the study area, and there is also an additional sampling error in estimating tree cover in the study area (which is often quite small and can be calculated).

From these basic forest structural data, estimates of ecosystem service flows and values can be derived through process models and economic valuation procedures.

Air Pollution Removal and Its Effect on Air Pollution Concentrations

Biophysical service—Trees affect air quality through the direct removal of air pollutants, by altering local microclimates and building energy use, and through the emission of volatile organic compounds (VOCs) that can contribute to ozone (O_3), carbon monoxide (CO), and particulate matter formation (e.g., Chameides and others 1988). However, integrative studies have revealed that trees, particularly low VOC-emitting species, can be a viable strategy to help reduce urban O_3 levels (e.g., Taha 1996). While all plants can impact air quality, trees tend to have greater impacts due to their larger leaf surface area. In general, the best tree species for improving air quality are species with a large healthy leaf surface area, relatively low VOC emissions, low maintenance needs, and a long lifespan (are adapted to the site conditions). Species that transpire more water will have a greater capacity to reduce air temperatures and remove gaseous pollutants. Species with more textured or waxy surfaces and smaller leaves are generally better at capturing particulate matter. In addition, evergreen species offer the ability to capture particles year-round.

Trees remove gaseous air pollution primarily by uptake through leaf stomata, though some gases are removed by the plant surface area. For O_3, sulfur dioxide (SO_2), and nitrogen dioxide (NO_2), most of the pollution is removed via leaf stomata. Once inside the leaf, gases diffuse into intercellular spaces and react with inner-leaf surfaces or may be absorbed by water films to form acids (Smith 1989). Trees directly affect particulate matter in the atmosphere by emitting particles (e.g., pollen), intercepting particles, and resuspending particles captured on the plant surface. Some particles can be absorbed into the tree, though most intercepted particles are retained on the plant surface. The intercepted particles are often resuspended to the atmosphere, washed off by rain, or dropped to the ground with leaf and twig fall. During dry periods, particles are constantly intercepted and resuspended, in part, dependent upon wind speed. The accumulation of particles on the leaves can negatively affect photosynthesis (e.g., Darley 1971) and therefore potentially negatively affect gaseous pollution removal by trees. During precipitation, particles can be washed off and either dissolved or transferred to the soil. Consequently, vegetation is only a temporary retention site for many atmospheric particles, which are eventually moved back to the atmosphere or moved to the soil. Once in the soil, some chemical elements can be retained for substantial periods in slowly decomposable woody debris (Aber and Melillo 1982, Bieby and others 2011).

In addition to pollution removal via dry deposition, forests also affect local meteorology. Trees influence air temperature, radiation absorption and heat storage, wind speed, relative humidity, turbulence, surface albedo, surface roughness, and the atmospheric mixing-layer height. These effects consequently impact emission of pollutants from various sources and the concentration of pollutants in the atmosphere. For example, lower temperatures will reduce the emission of numerous biogenic and anthropogenic VOCs and other temperature-dependent pollutant emission sources (Cardelino and Chameides 1990). In addition, altering the local environment (e.g., air temperature reduction, shade, altered wind speeds) will affect building energy use and consequently emissions from power plants. Reductions in wind speed can reduce the dispersion of pollutants, which will tend to increase local pollutant concentrations as the pollutants are not dispersed as much with lower wind speeds. Subsequently, with slower winds the volume of the atmosphere where the pollutants mix can be reduced. This reduction in the "mixing height" will also tend to increase pollutant concentrations as the same amount of pollution is now mixed within a smaller volume of air (e.g., Nowak and others 2000).

Pollution removal by urban trees in the United States has been estimated at 711,000 tonnes (t) per year with average percentage air quality improvement in cities during the daytime of the season that vegetation is in-leaf typically < 1 percent (Nowak and others 2006). A more recent assessment of pollution removal by trees across the conterminous United States estimated pollution removal at 17.4 million t in 2010 (range: 9.0-23.2 million t) with

96 percent of the pollution removal occurring in rural areas. This pollution removal also equated to an average air quality improvement of < 1 percent (Nowak and others 2014).

There are many factors that determine the ultimate effect of trees on air pollution. Integrative studies of tree effects on ozone pollution have illustrated how these various factors affect air quality. One model simulation illustrated that a 20-percent loss in forest cover in the Atlanta area due to urbanization led to a 14-percent increase in ozone concentrations for a typical summer day (Cardelino and Chameides 1990). Although there were fewer trees to emit VOCs (chemicals that can contribute to ozone formation), an increase in Atlanta's air temperatures due to the increased urban heat island, which occurred concomitantly with tree loss, increased VOC emissions from the remaining trees and other sources (e.g., automobiles) and altered the chemistry of ozone formation (e.g., reaction rates) such that concentrations of ozone increased.

Another model simulation of California's South Coast Air Basin suggests that the air quality impacts of increased urban tree cover can be either positive or negative with respect to local ozone concentrations. However, the net basin-wide effect of increased urban vegetation is a decrease in ozone concentrations if the additional trees are low VOC emitters (Taha 1996).

Modeling the effects of increased urban tree cover on ozone concentrations in several cities from Washington, DC, to central Massachusetts revealed that urban trees generally reduce ozone concentrations in cities but tend to slightly increase average ozone concentrations regionally (Nowak and others 2000). As previously explained, the effects of trees on the physical and chemical environment demonstrate that trees can cause changes in pollution removal rates and meteorology, particularly air temperatures, wind fields, and mixing-layer heights, which, in turn, affect ozone concentrations. Changes in urban tree species composition had no detectable effect on ozone concentrations (Nowak and others 2000). Modeling of the New York City metropolitan area also reveals that increasing tree cover 10 percent within urban areas reduced maximum ozone levels by about 4 parts per billion (ppb), which was about 37 percent of the amount needed for air quality standards attainment (Luley and Bond 2002).

Though reduction in wind speeds can increase local pollution concentrations due to reduced dispersion of pollutants and mixing height of the atmosphere, altering wind patterns can also have a positive effect. Tree canopies can potentially prevent pollution in the upper atmosphere from reaching ground-level air space. For example, measured differences in ozone concentration between above- and below-forest canopies in California's San Bernardino Mountains have exceeded 50 ppb (equivalent to a 40-percent improvement below the canopy) (Bytnerowicz and others 1996). Under normal daytime conditions, atmospheric turbulence mixes the atmosphere such that pollutant concentrations are relatively invariant with height. Forest canopies can limit the mixing of upper air with ground-level air, leading to significant below-canopy air quality improvements. Standing in the interior of forest stands can offer cleaner air if there are no local ground sources of emissions (e.g., from automobiles). Various studies have illustrated reduced pollutant concentrations in the interior of forest stands compared to outside of the forest stand (e.g., Cavanagh and others 2009, Dasch 1987). However, where there are numerous pollutant sources below the canopy (e.g., automobiles), the forest canopy could increase concentrations by minimizing the dispersion of the pollutants away from ground level (Gromke and Ruck 2009, Salmond and others 2013, Vos and others 2013, Wania and others 2012). This effect could be particularly important in areas with heavy tree canopy and vehicle traffic.

Economic valuation—The values associated with reduced air pollution concentrations are generally related to improved human health, improved visibility, and reduced damage to materials, plants, and ecosystems. Some studies have used "externality" values to estimate the value of pollution removal. For example, the value of the 711,000 t removed per year by U.S. urban forests was estimated at $3.8 billion using externality values (Nowak and others 2006). In this context, "externality" values are the estimated cost of pollution to society that is not accounted for in the market price of the goods or services that produced the pollution. There are a few studies that have linked pollution removal and improved health, including one in London where a 10 × 10 km grid with 25-percent tree cover was estimated to remove 90.4 t of PM_{10} annually, which equated to the avoidance of two deaths and two hospital admissions per year (Tiwary and others 2009). In addition, Nowak and others (2013) reported that the total amount of $PM_{2.5}$ removed annually by trees in 10 U.S. cities in 2010 varied from 4.7 t in Syracuse to 64.5 t in Atlanta. Estimates of the annual monetary value of human health effects associated with $PM_{2.5}$ removal in these same cities (e.g., changes in mortality, hospital admissions, respiratory symptoms) ranged from $1.1 million in Syracuse to $60.1 million in New York City. Mortality avoided was typically around one person per year per city, but was as high as 7.6 people per year in New York City. Most of the health values came from reduced mortality, which was estimated based on the value of a statistical life (e.g., Viscusi and Aldy 2003). The human health value of the 17.4 million t of air pollution removed by conterminous U.S. forests in 2010 was $6.8 billion (Nowak and others 2014). Sixty-seven percent of the pollution removal value occurred in urban areas. Health impacts included the avoidance of more than 850 deaths and 670,000 incidences of acute respiratory symptoms. Health valuation is based on the U.S. Environmental Protection Agency (EPA) BenMAP model procedures that estimate the health impacts and monetary value when populations experience changes in air quality (Abt Associates 2010, Davidson and others 2007, U.S. EPA 2012). The health value varies spatially based on changes in pollution concentration and the number and age of people receiving that change in concentration.

Challenges in estimating air pollution impacts—Computer modeling has overcome some of the challenges related to quantifying the impacts of trees on air pollution concentrations. Though the models can always be improved, the greatest challenges are related to quantifying the secondary effects (i.e., tree effects on energy use, pollution emission and formation, and effects of tree VOC emissions on secondary pollutant formation [see below]). Tree effects on ozone concentrations are particularly challenging to quantify due the numerous influences that trees have on this secondary pollutant. In addition, modeling could be refined to explore marginal returns of pollution removal to determine potential diminishing returns per unit tree cover with additional tree cover.

Volatile Organic Compound Emissions

Biophysical service—Trees can reduce air pollution by changing the local microclimate and directly removing pollution, but trees can also emit various chemicals that can contribute to air pollution, such as volatile organic compounds (e.g., isoprene, monoterpenes). These compounds are natural chemicals that make up essential oils, resins, and other plant products, and may be useful in attracting pollinators or repelling predators (Kramer and Kozlowski 1979). Complete oxidation of VOCs ultimately produces carbon dioxide, but carbon monoxide is an intermediate compound in this process. Oxidation of VOCs is an important component of the global carbon monoxide budget (Brasseur and Chatfield 1991).

Emissions of VOCs by trees and other sources can also contribute to the formation of ozone and secondary aerosols (e.g., Poschl 2005). Because VOC emissions are temperature dependent and trees generally lower air temperatures and remove ozone, increased tree cover can lower overall VOC emissions and, consequently, ozone levels in urban areas (e.g., Cardelino and Chameides 1990, Nowak and others 2000, Taha 1996). VOC emissions from urban trees generally are < 10 percent of total VOC emissions in urban areas (Nowak 1992).

VOC emission rates vary by species (e.g., Guenther and others 1994). Seven tree genera that have the highest standardized isoprene emission rate, and therefore the greatest relative effect on increasing ozone, are: sweetgum (*Liquidambar* spp.), black gum (*Nyssa* spp.), sycamore (*Platanus* spp.), poplar (*Populus* spp.), oak (*Quercus* spp.), black locust (*Robinia* spp.), and willow (*Salix* spp.). However, due to the high degree of uncertainty in atmospheric modeling, results are currently inconclusive as to whether these genera will contribute to an overall net formation of ozone in cities (i.e., whether ozone formation from VOC emissions are greater than ozone removal or whether increasing tree cover reduces VOC emissions through temperature reduction).

Globally, average emission factors for isoprene are 12.6 mg per m^2 per hour for broadleaf trees and 2.0 mg per m^2 per hour for non-broadleaf evergreen trees (Guenther and others 2006). In the United States, emission factors for monoterpenes are 449.2 μg per m^2 per hour for broadleaf trees and 872.6 μg per m^2 per hour for needle leaf trees (Sakulyanontvittaya and others 2008).

Economic valuation—The negative impacts of biogenic VOC emissions are often not directly associated with the emissions themselves, but rather the formation of secondary chemicals due to the VOCs emission (e.g., ozone, carbon monoxide, particulate matter). Thus, the valuation of VOC emissions is more dependent upon the impacts of the secondary chemicals that the VOCs help form (e.g., human health effects). The valuation of VOCs would likely best be done by valuing the impacts of the secondary pollutants as detailed in the air pollution removal section, but instead of the positive effect from pollution removal, the valuation would be a negative effect due to pollution formation.

Challenges in estimating the negative impacts of VOC—Due to the complexity of the atmosphere and chemical reactions, it is challenging to quantify the amount of secondary pollutants formed due to VOC emissions. To a lesser extent, quantifying total VOC emissions from a forest area is also challenging due to the number of VOC chemical species emitted. Methods for quantification of isoprene, monoterpenes, and some other VOC emissions by trees have been extensively addressed (e.g., U.S. EPA 2015, Washington State University 2015).

Pollen Emission

Biophysical service—Pollen emission is another air quality issue related to forests. While pollen plays an important ecological role, it does have the potential to negatively affect humans by causing allergic reactions (Puc 2003). While the proximity of trees to people is an important factor related to pollen allergies, various attributes of the forest influence allergic responses to pollen production. These attributes include: a) plant species composition, size, and abundance; b) allergenic potential of species (i.e., the relative potential of the pollen to cause an allergic reaction based on its shape and composition) (e.g., Ogren 2002); and c) length of pollination period (Carinanos and others 2014). Various studies have analyzed allergic responses to common tree species (e.g., Strandhede and others 1984).

Economic valuation—Valuation of the negative impacts of forest pollen production is difficult. Several factors need to be considered including pollen exposure to humans by species with varying levels of allergenicity, quantifying the impact of that exposure to human health, and then determining the economic cost of the health impacts.

Challenges in estimating the negative impacts of pollen—The first challenge in quantifying the forest's role in pollen formation is quantifying the pollen allergenicity of forest trees (e.g., Ogren 2002), then estimating the exposure of people to the pollen from the forest. Further challenges relate to quantifying the health and economic impact on the human population that is affected by the forest pollen.

Carbon Sequestration

Biophysical service—Trees, through their growth process, remove carbon dioxide from the atmosphere and sequester the carbon within their biomass. When a tree dies and the wood is allowed to decompose or is burned, most of the stored carbon goes back to the atmosphere, though some of the carbon can be retained in soils (or wood products). Thus, the net carbon storage in a given area with a given tree composition will cycle through time as the population of trees grows and declines (e.g., through aging and harvest). When forest growth (carbon accumulation) is greater than decomposition, net ecosystem carbon storage increases.

Human influences on forests (e.g., management) can further affect CO_2 source/sink dynamics of forests through such factors as fossil fuel emissions from machinery used for management and harvesting/utilization of biomass (Nowak and others 2002). Management choices such as fertilization and rotation length also affect carbon dynamics (Johnson 1992, Noormets and others 2015). For example, soils are often lacking in nitrogen or phosphorus, so the addition of these fertilizers can significantly increase tree growth and carbon sequestration (Oren and others 2001). However, fertilization during a drought period can worsen the drought impacts and significantly reduce carbon sequestration due to reduced transpiration and canopy conductance per unit leaf area, possibly due to structural and physiological changes in fine root area or hydrologic conductivity (Ward and others 2015). Prescribed burning immediately releases some carbon to the atmosphere but can also release nutrients tied up in understory vegetation that in turn make the nutrients more available to the trees and increase forest growth and carbon sequestration (Johnson and others 2014). Both air quality and climate change affect tree growth and consequently carbon sequestration by forests (Aber and others 1995, Sitch and others 2006). Longer growing seasons and increased precipitation are predicted to increase southern U.S. pine forest productivity (McNulty and others 1996). Through their influence on air temperature, trees also affect building energy use and consequently alter carbon emissions from sources such as power plants.

Above- and below-ground biomass in all forest land across the United States, which includes forest stands within urban areas, stored approximately 20.2 billion tonnes of carbon in 2008 (Heath and others 2011). Factors that influence carbon storage and sequestration include tree size, species, tree density, tree health, and tree growth rates.

Economic valuation—Current carbon valuation is typically based on the social cost of carbon as reported by the Interagency Working Group on Social Cost of Carbon or SCC (2013). Social cost associated with a pollutant (e.g., CO_2) refers to an estimate of total (global) economic damage attributable to incremental increase in the level of that particular pollutant in a given year. The current value (in 2015) is $38 per metric ton of CO_2 based on a 3-percent discount rate. The cost of carbon emissions varies through time. The market price of carbon offset credits on commercial and regional trading platforms has also been used to represent the value of avoided carbon emissions to landowners (Hein 2011). Using the SCC, the total value of avoided damage attributable to potential destruction of all forests could be obtained by multiplying $38 by the CO_2 equivalent of all of the carbon stored in forests. On the other hand, if the objective is to estimate value of avoided damage attributable to a flow (of carbon to atmosphere) rather than stock, the cost could be multiplied by the annual rate of carbon sequestration.

Challenges in estimating carbon sequestration—Given the amount of forest data related to tree size, density, species composition, etc., collected by the Forest Service FIA program (USDA Forest Service 2016), the various forest carbon calculators (e.g., USDA Forest Service 2015) and carbon calculation procedures (Eve and others 2014), this service is relatively easy to calculate and value using either the SCC or the current price from an offset market.

Air Temperature Reduction

Biophysical service—Air temperature affects human health and well-being both directly and indirectly through its influences on the environment. These influences include effects on building energy use, human comfort and health, evaporative cooling, ozone production, and pollutant emissions. Urban areas tend to create heat islands that, on average, tend to be warmer than surrounding rural areas (e.g., Howard 1818, Oke 1973). Reducing air temperatures by a few degrees can have a significant economic impact through reduced energy use and improved human health.

Heat waves in cities can cause hundreds and sometimes thousands of human deaths. More than 700 deaths in Chicago were attributed to a heat wave in July 1995 (U.S. EPA 2006). Over 30,000 excess deaths were related to the heat waves in Western Europe during the summer of 2003 (Golden and others 2008). Forests reduce air temperatures mainly through transpirational cooling, shading of surfaces, and altering wind speeds. While forests can increase air temperature in winter relative to open spaces, they tend to reduce average and extreme high temperatures during the summer (Boggs and McNulty 2010, Karlsson 2000, Spurr and Barnes 1980).

Air temperature affects numerous attributes of the environment. It affects other ecosystem services such as evapotranspiration, and it also impacts biogenic emissions, anthropogenic emissions, and pollution formation. Air temperature also directly affects human comfort and human health (e.g., Harlan and others 2014, Martens 1997).

Economic valuation—Valuation of the effects of air temperature could be done by quantifying the impact of air temperatures on energy use and resulting emissions and human morbidity and mortality. Once these relationships are determined, the impacts could be valued based on energy costs, externality costs of emissions, and the statistical value of human life. Recent studies have used multivariate regression techniques to directly link forest coverage with mortality, while controlling for other factors that impact human health (e.g., Walton and others 2016).

Challenges in estimating forest impacts on air temperature—The relationship between forests and air temperature are well understood (Huang and others 1987, Kurn and others 1994). However, challenges still remain in modeling air temperatures and their impacts on other ecosystem services and human health and comfort.

BIOPHYSICAL QUANTIFICATION OF ECOSYSTEM SERVICES

Three of the five air quality ecosystem services can currently be assessed (air pollution removal, VOC emissions, and carbon sequestration), while others need more research and development (i.e., pollen, air temperature reduction). The following text details how these services can or could be assessed.

Air Pollution Removal and Impacts on Air Pollution Concentrations

Pollution removal by trees and forests, along with its health effects and values, has been estimated for the conterminous United States using models that incorporate U.S. hourly weather and pollution monitor data, national tree cover maps, and U.S. Census data (Nowak and others 2014). These data are incorporated within i-Tree Canopy, Design and Landscape to allow managers to roughly estimate the quantity and health value of air pollution removal by trees and forests.

In addition to pollution removal by trees, various model calculations in i-Tree are used to estimate the consequent effects on pollution concentrations and human health (e.g., Nowak and others 2013). The U.S. EPA BenMAP program was used to estimate the incidence of adverse health effects (i.e., mortality and morbidity) and associated monetary value that result from changes in NO_2, O_3, $PM_{2.5}$, and SO_2 concentrations due to pollution removal by trees. The model estimates assume that: a) the measured inputs (meteorology and pollution concentrations) represent the conditions in the region around the monitors; b) the boundary layer is well mixed; c) input variables are correctly measured; d) the dry deposition model in i-Tree accurately portrays pollution removal (Hirabayashi and others 2011, Morani and others 2014); and e) BenMAP accurately estimates and values health effects due to changes in pollution concentrations.

Under most situations, atmospheric acid deposition of NO_x and SO_x are below levels that cause reductions in forest health. However, a combination of high acidic deposition and/or low soil acid buffering capacity can result in forest soils exceeding the critical acid load level in places. At this point, the forest soil is termed to be "in exceedance" of the critical acid load. The trees growing on soils that are in exceedance are much more likely to experience reductions in growth and increased risk of early mortality. Additionally, excess acids can leach into streams and thereby reduce water pH and aquatic biodiversity. Simple mass balance equations are typically used to estimate critical acid loading and to identify forest areas that are in exceedance of their critical acid load. For example, McNulty and others (2007) applied this approach to the conterminous United States at a 1-km resolution and found that the region with the largest proportion of forest area in exceedance of the soils critical acid load was the Northeast. Forest harvesting and base cation fertilization (e.g., the use of calcium carbonate lime) are two methods used to either remove acids from the ecosystem or neutralize acidic soil. Through a combination of forest growth and harvest, trees can be used to remove excess acid from forest soil, which will improve both terrestrial and aquatic ecosystem health.

Volatile Organic Compound Emissions

VOC emissions from forests can be quantified using either a) the Biogenic Emissions Inventory System (BEIS) model methodology (U.S. EPA 2015), which is also incorporated into the i-Tree model (www.itreetools.org), or b) the MEGAN Model - Model of Emissions of Gases and Aerosols from Nature (Washington State University 2015). Both models estimate VOC emissions from trees and forests, making various assumptions and using various structural and meteorological inputs. While assumptions can always be questioned, these models are likely the best available options for estimating plant VOC emissions. Neither model estimates the secondary impacts (e.g., ozone formation) or the value of changing VOC concentrations. More research is needed on these topics.

Pollen Emissions

There are databases on pollen allergenicity of numerous tree species and methods to estimate pollen allergenicity index for areas with tree cover. For example, the i-Tree model has a prototype allergenicity index that could be used to rate allergenicity of forests. This module has not been released yet and is similar to the index used in Carinanos and others (2014). However, these index values have not yet been linked to impacts on human health (e.g., allergies). More research is also needed on this topic.

The main assumptions of the pollen index approach are that the allergenicity ratings of tree species are correct and that pollen emissions are related to plant crown/leaf volume or biomass.

Carbon Sequestration

Carbon storage and sequestration by forests can be estimated using Forest Service forest carbon calculators (e.g., USDA Forest Service 2015), urban forest calculators (e.g., i-Tree), or carbon calculation procedures detailed in Eve and others (2014).

There are various carbon equations used to estimate carbon storage by trees, and it is assumed that these equations accurately estimate carbon based on the measured structural data (e.g., species, diameter, height). Sequestration rates are based on estimates of annual tree growth. Although there are limitations, the procedures used to estimate carbon stocks and flows are pretty well established and accepted.

Air Temperature Reduction

Satellites can be used to measure surface temperatures (e.g., NASA 2015, Sobrino and others 2004). For example, land surface temperature maps can be downloaded at neo.sci.gsfc.nasa.gov/view.php?datasetId=MOD11C1_M_LSTDA&date=2015-01-01. Various models can also be used to estimate air temperatures (e.g., Chen and others 1993, Yang and others 2013). However, there are limited procedures or models showing how forests and others surfaces affect air temperatures.

Use of land surface temperatures is based on a reasonable assumption that these temperatures are related to air temperatures. However, while surface temperatures influence local air temperatures, they can be quite different from air temperatures. Models used to estimate air temperatures make various assumptions about the atmosphere and earth surfaces to produce reasonable estimates of hourly air temperatures and temperature variations, but more research is needed on this topic.

ECONOMIC VALUATION OF ECOSYSTEM SERVICES

Once the flow or provision of the good or service (e.g., carbon, air pollution removal) is quantified, various methods of market as well as non-market valuation can be applied to characterize their value. Since none of these services (perhaps except for carbon sequestration) are currently traded in the market, non-market valuation methods are used to estimate their values. Methods of non-market valuation can be pecuniary or non-pecuniary. We focus on pecuniary methods that obtain the money equivalent value of a service. There are also non-pecuniary methods for characterizing value in other than monetary terms, such as number of human lives saved, number of clear days observed etc.

This section introduces market and non-market valuation methods that are potentially applicable in valuing one or more air quality services (table 4.1), provides guidance on choosing the most appropriate method, and discusses important considerations in benefit aggregation.

Market Price Method

This method relies on the prevailing price for the service as traded in the local market. Since many of the air quality services are not currently traded in the market, this method is not applicable except in the case of carbon sequestration. Carbon offset credits are currently traded in national and international cap-and-trade institutions and other "over-the-counter" voluntary transactions. Market prices are typically less than the SCC, because the transactions are motivated by the expected benefits and costs to individual sellers and buyers, reflecting both their preferences and the regulatory framework, and hence do not necessarily take account of all of the social benefits associated with sequestration or reduced emissions. Price of emission permits for other kinds of air pollutants (e.g., SO_2) represent the value of abatement service that forests provide, provided we can attribute such service to forests and assuming that the current policy regime will continue. However, the market prices of such services could be distorted by lack of information and failure to capture external benefits of production. Moreover, the price of such a permit or offset credit is strongly influenced by the regulatory environment (i.e., whether the emitters are subject to mandatory regulation to offset their emission).

Contingent Valuation Survey Method

This method relies on asking people to state their willingness to pay (WTP) to consume or enjoy the benefit of a given air quality service by forests. Once the service provided by forests to improve the air quality is defined and quantified, a randomly selected sample of potential beneficiaries is asked to express their WTP to maintain a specified area of forest for the purpose of providing the service. The most common approach is to split the sample and ask different groups whether they would be willing to pay a specified amount that varies across groups. Typically, the WTP estimated at household level is extrapolated to an entire population to get the total value of the service attributable to a forest area. Dividing the total estimate by total hectares of the specified forest could yield value on a per-hectare basis, which provides an approximate measure to evaluate the marginal impact of forest area change. A similar approach can be taken by surveying how much forest landowners are willing to accept (WTA) in compensation for delaying or forgoing their harvest in favor of air pollution removal or carbon storage. Such an agreement would require landowners to forgo all other economic interests for a specific period of time, and their stated WTA to commit to this agreement is considered a proxy of the production cost of air quality. A few studies have applied the contingent valuation method to estimate landowners' WTA and buyers' WTP for carbon services (Poudyal and others 2012, Tsang and Burge 2011).

This method assumes that people will do what they say, and it is sensitive to how the WTP question is designed and how non-responses (or refusals) are factored into benefit estimation. The questionnaire needs to be very specific in attributing the benefit to the forest of interest. It is worth noting that Zhang and Li (2005) have argued that the value of a good or service can be more accurately approximated by deriving a shadow price from the opportunity costs of the resources involved, rather than eliciting producers' WTA. However, caution is required here because the full value, as captured by WTA, may be greater than the costs of acquisition. Despite the limitations, when there are no prior

Table 4.1—Summary of applicable valuation methods and example application by forest ecosystem service types

Method	Ecosystem service	Applicability[a]	Example application (where available)
Market price[b]	Air pollution removal		
	VOC removal		
	Pollen emission	✔	
	Carbon sequestration	✔	Jerath and others (2012), Hein (2011)
	Air temperature	✔	Pandit and Laband (2010)
Value of statistical life saved	Air pollution removal	✔	Levinson (2012)
	VOC removal	✔	
	Pollen emission	✔	
	Carbon sequestration	✔	
	Air temperature	✔	
Contingent valuation	Air pollution removal	✔	
	VOC removal	✔	
	Pollen emission		
	Carbon sequestration	✔	Carlsson and others (2010), Jerath and others (2012)
	Air temperature	✔	Carlsson and others (2010)
Replacement or substitute cost method	Air pollution removal	✔	
	VOC removal		
	Pollen emission		
	Carbon sequestration	✔	Platinga and Miller (1999), Richards and others (1993)
	Air temperature		
Hedonic method	Air pollution removal	✔	Luechinger (2009)
	VOC removal		
	Pollen emission		
	Carbon sequestration		
	Air temperature	✔	Pandit and Laband (2010)
Damage cost avoided[b]	Air pollution removal	✔	Hein (2011)
	VOC removal	✔	
	Pollen emission	✔	
	Carbon sequestration	✔	Interagency Working Group on Social Cost of Carbon (2013), Jerath and others (2012)
	Air temperature		
Life satisfaction or happiness method	Air pollution removal	✔	Levinson (2012), Welsch (2009), Luechinger (2009)
	VOC removal		
	Pollen emission	✔	
	Carbon sequestration	✔	
	Air temperature	✔	Rehdanz and Maddison (2005), Levinson (2012)
Benefit transfer	Air pollution removal	✔	
	VOC removal	✔	
	Pollen emission	✔	
	Carbon sequestration	✔	Moore and others (2013)
	Air temperature	✔	

[a] Applicable to ecosystem service if checked.

[b] Interrelated, when the damage involves market goods/services.

studies of the value of a good and no related market behaviors that indirectly reveal the value, contingent valuation may be the only way to obtain an estimate of the value of the service.

Replacement or Substitute Cost Method

This cost-based method relies on the assumption that the value of a given ecosystem service provided by forests is equivalent to the cost of providing such a service by some alternative or artificial means. For example, the value of forest carbon sequestration, as typically measured in per metric ton of CO_2 sequestered, would be estimated as the cost of offsetting equivalent CO_2 from forest projects such as afforestation (Platinga and Miller 1999) or non-forest projects such as methane capture, agriculture soil carbon, or renewable energy. Similarly, various kinds of indoor ventilation and air purifying or conditioning systems have been designed to regulate VOCs in air, and the cost of acquisition and operation of such devices could offer a surrogate "price" for estimating the value of services like VOC removal by forests.

This method is reliable only if: (1) the service provided by forest is the same (in nature and quality) as that provided by an alternative project; (2) the alternative is the next least-cost means for providing the service; and (3) the benefits of the service provided by the alternative project exceed the cost of the alternative project (Brown 2017). While air quality and carbon-related services provided by forests and alternative means are likely to be similar in nature and quality, their level of provision and therefore their costs are likely to be determined by the regulatory framework, meaning that the benefits do not necessarily exceed the costs. While these are significant limitations on use of this method to estimate values, it can be used to quantify the cost-effectiveness of forests as a way to meet externally set standards such as national ambient air quality standards.

Hedonic Method

Even though no markets exist to observe financial transactions involving forest ecosystem services related to air quality, their benefit can be revealed by examining whether and how the change in supply of such a service is compounded in a related good for which market prices are available. The hedonic method is particularly applicable to valuing air pollution removal, due to the local nature of the benefits. In the case of air quality or volatile organic compounds, the price (or rent) of a residential house is a market value that relates directly to the air quality in the neighborhood. By regressing prices of properties against their structural features and some measure of air quality (e.g., air pollutant concentration), one could estimate the implicit value of a marginal unit reduction in a pollutant. The implicit marginal willingness to pay (WTP) for air quality improvement can be obtained from the regression. The value of this service can be obtained on a per-hectare basis by multiplying the resulting WTP by the rate of pollution removal (amount removed by a hectare of forest).

Damage Cost Avoided Method

When a damage can be avoided with a given ecosystem service in place, then the avoided cost of the damage is one value of that ecosystem service. One measure of the damage cost is the amount that society is willing to pay to avoid the damage, and thus insurance premiums are sometimes used to estimate the cost. In other words, if society incurs a cost to avoid a damage, then the worth of an ecosystem service that prevents that damage is at least as much as the cost incurred.

The SCC is a type of damage cost avoided, as it involves projecting the physical damage (including change in agricultural productivity, human health, property damage, etc.) from CO_2, and then estimating the monetary value of that damage (Pizer and others 2014). Avoided damage due to the sequestration (capture and long-term storage) of carbon by a forest can be interpreted as the value of carbon service for a given forest stand. The global SCC is estimated at $38 per metric ton of CO_2 based on a 3-percent discount rate (Interagency Working Group on Social Cost of Carbon 2013).

This method could also be applied to estimate the value of the pollen emission disservice. If one knows how the amount of pollen emitted per forest area relates to the number of allergy-related illnesses, then the total public expenditure on allergy medications (i.e., cost of illness) could be used to obtain a lower bound on the value of the disservice (assuming that the total cost, or utility lost, due to allergies is greater than the expenditures).

Value of Statistical Life Saved Method

This method can be considered similar to the method of damage cost avoided with particular relevance in human health. It has been widely applied in risk and health economics studies (Viscusi and Aldy 2003). Forest ecosystem services like reduction in air pollution can be linked with positive health outcomes among the human population. The assumption here is that people are WTP for the marginal reduction in mortality attributable to a change in forest cover or condition. The benefit of a marginal reduction in mortality is the monetary equivalent of the reduction of mortality risk from one to none. For example, if the removal of x metric tons of air pollution as a result of expansion of y hectares of forest reduces the morality risk by 1 in 1 million for 2 million people, the air pollution control service provided by y hectares of forest is 2 avoided deaths. Multiplying this value by the statistical value of a life saved yields the total value of the service attributable to y hectares of forest.The statistical value of life has been estimated by contingent valuation and by hedonic wage models, in which a regression analysis quantifies the tradeoffs people are willing to make between fatality risks and wage rates. Federal agencies like the U.S. EPA and U.S. Department of Transportation use $7.4 million (mean estimate based on several wage-risk studies and contingent valuation survey) (U.S. EPA 2010) and $9.1 million (based on wage-risk study), respectively, (Revez 2014) as the monetary value of avoiding the death of a single person.

Life Satisfaction or Happiness Method

The marginal effect of air quality on self-reported life satisfaction or happiness can be analyzed to reveal the marginal value of air quality, if the income equivalent of changes in life satisfaction or happiness can also be estimated. If one could quantify the change (better or worse) in carbon storage or air quality attributable to change in forest area or condition, this change could be linked with some measure of life satisfaction as reported by the beneficiaries. The basic assumption of this method is that measures of life satisfaction are reliable proxies of people's underlying utility, and the value of an ecosystem service such as air pollution removal can be estimated by evaluating how people tradeoff between the service and income. For example, if a 25-percent increase in carbon sequestration or air pollution removal (as a result of expansion of forest area or a similar increase in growing stock of an existing forest) increases the life satisfaction measure by 1 unit, and it takes a $10,000 increase in annual household income to achieve a comparable increase in people's life satisfaction, then this method would conclude that the total value of the service provided by the increased forest area or improved forest condition to beneficiaries would be $10,000 multiplied by the number of beneficiaries. By estimating a production function for the service, its value can easily be estimated on a per-hectare basis. Luechinger (2009) and Levinson (2012) have already applied this method to value reduction in air pollution and for changes in air temperature.

Benefit Transfer Method

When there is a budget or time constraint on collecting new data, benefit transfer is typically used to quantify the value of an ecosystem service. In a unit value benefit transfer, the value of a specific service (e.g., carbon sequestration per hectare of given forest type) in a given "policy site" is derived from an average of such values reported in one or more study areas of similar characteristics elsewhere (study sites) (Loomis 1992; also discussed in chapters 2 and 3 of this publication). Values reported in study sites would be estimated by one of the methods described above. These would be per-hectare value of a given ecosystem service provided by a given type of forest. The analyst would then 'transfer' them to the policy site by multiplying the average per-hectare value by the total area occupied by that type of forest. Many of the recent studies that characterized the value of forest ecosystem services in Southern States have used this approach (e.g., Moore and others 2013, Simpson and others 2013). A key consideration is that the ecological and socioeconomic characteristics of the "study site" and "policy site" should be as similar as possible because species composition (hardwood, softwood), location of forest relative to source of pollution, and beneficiaries can make a substantial difference in the level of supply and public value of the service. Several reports including Troy and others (2006), Liu and others (2010), and Costanza and others (2014) provide per-area values of air quality related to ecosystem services that may be applicable to regions of similar characteristics.

Aggregation

Aggregation involves extrapolating the value of each ecosystem service across the entire geographic region of interest (e.g., State) or the beneficiary population (e.g., State population). If the value is estimated per hectare, simply multiplying the per-hectare value by the total area of forest would yield a statewide total value of that particular service. Services such as air temperature reduction in urban areas are often estimated on a per-household basis rather than per hectare of forest. In this case, the per-household value of a service could be extrapolated to the total number of households that benefit from the service to get a statewide estimate. While this approach to aggregation is easy to implement, it is subject to a number of caveats.

First, the marginal value of a forest ecosystem service benefit can vary (impact of the loss of first hectare vs. the last hectare of forest). Unfortunately, there is no general guidance on how to incorporate nonlinearity of marginal benefits in valuation. Second, since neither the supply (nature of forest) nor the demand (preference of beneficiaries) of ecosystem services are homogenous across entire States, it is important to stratify the State into relatively homogenous regions and to use the most appropriate or adjusted value for each region (e.g., Moore and others 2013) before summing up regional estimates to get the statewide total value. Again, it is difficult to provide guidance on exactly how to stratify the State, i.e., how far it must be disaggregated.

Finally, the statewide total value of all services can be obtained by a sum of the statewide value of each type of service. Considering the interrelatedness of production process and consumption, it is important to avoid double counting and hence overestimating the total benefits. Only services that are mutually exclusive should be added. Likewise, it is important to account for tradeoffs between services, and at the extreme, to avoid summing services that are mutually exclusive (e.g., wilderness values and timber production).

IMPROVING FUTURE VALUATION

There is interdependence between forest structure and ecosystem services and values. Valuation is dependent upon accurate estimates of the magnitude of the service provided; service estimates are dependent upon accurate estimates of forest structure and how structure affects services. The key starting point to valuing services provided by forests is quality data on forest structure. Services and values cannot be adequately valued without accurate forest data. Combining accurate forest data with valid procedures for quantifying ecosystem services will lead to reliable estimates of the magnitude of ecosystem services provided by the forest. Finally, with accurate estimates of forest ecosystem services, values of the services can be estimated using valid economic estimates and procedures. Thus, three critical elements in sequence are needed to value forest ecosystem services: structure – services – values. Errors with precursor elements will lead to errors in subsequent estimates (e.g., errors in characterization of forest structure will lead to errors in estimating services and valuation). All estimates and means of estimation can be improved to varying degrees.

Quantifying Forest Structure

Mapping of tree cover from NLCD 30-m resolution data can be improved by creating or utilizing high resolution tree cover data. These tree cover data are being created in some areas at the city or county scale (e.g., www.nrs.fs.fed.us/urban/utc/status/). Another option for calculating tree cover is to use photo-interpretation. With photo-interpretation, one can often get tree cover estimates with a standard error of around 1.4 percent with 1,000 interpreted points (about one day's worth of work). This accuracy is often better than that produced by cover maps, but photo-interpretation does not map specific locations of tree cover. There is a free photo-interpretation tool (i-Tree Canopy) that provides users an easy means to interpret and analyze tree and other cover types using Google maps (www.itreetools.org/canopy/index.php).

For estimates of local forest structure (e.g., number of trees, species composition), FIA collects plot data for forest areas at a density of one plot every 2,428 hectares. For small study areas (e.g., where sample size does not meet a minimum threshold), there are likely not enough plots to make a reasonable estimate of forest structure. In this case there are two options:

1) Collect more local data. This can be done using FIA procedures with plot intensification or by collecting your own data (e.g., using i-Tree Eco),

2) Use FIA plot data from the region to determine the forest structural attributes (e.g., number of trees) per unit of tree cover within the FIA sampled area, and then apply these standard values to the amount of tree cover in the study area. Plot data from FIA have been imputed to non-plot areas (e.g., Wilson and others 2013). This approach is less accurate, but it applies regional average values to local tree cover and could illustrate regional differences in forest structure and functions.

Air Pollution Removal and Its Effect on Air Pollution Concentrations

Forest effects on air pollution concentration have been estimated using i-Tree Landscape for urban and rural areas in counties of the conterminous United States, with valuation of those effects based on health impacts and values from BenMAP. However, health values only occur when people live in close enough proximity to forests to receive the improved air quality. As there are fewer people in rural areas, the health value of the air quality improvement decreases substantially from urban to rural areas.

As air quality affects more than human health (e.g., visibility, plant health, damage to materials), another approach to valuation has been to use "externality values" calculated for each air pollutant (e.g., Van Essen and others 2011). An externality value is a constant value per ton of pollution removed ($ per t) derived from the literature. Externality values should be higher than health values as they should include health and other values. For example, pollution removal by trees in the conterminous United States in 2010 had a health value of $6.8 billion but had an externality value estimate of $86 billion (Nowak and others 2014).

While methods for modeling pollution removal by trees and forests are well developed, further research is needed on secondary pollutants that are formed through chemical reactions (e.g., ozone), including understanding the role of VOC emissions. For all pollutants, secondary effects of trees on pollutant emissions (e.g., via altering air temperatures and energy use) need to be quantified to provide a more comprehensive analysis of forest impacts on air quality.

Volatile Organic Compound Emissions

Though improvement can always be made, the BEIS and MEGAN procedures are likely the best available procedures to estimate plant VOC emissions. If VOC emissions can be converted to tons or concentrations of particulate matter, ozone, and carbon monoxide, then valuations can be done similar to pollution removal.

Pollen Emissions

Compared to other air quality (dis)services, there is relatively less certainty about pollen emissions. Current methods only produce a relative index value of pollen for forests but do not estimate actual pollen emission by species. Developing emission rates for each species by time of year would be helpful in improving pollen estimates. To model human health impacts, better understanding is needed of how species emissions affect pollen concentrations and their specific impact on allergic responses in humans. Given current knowledge, relating the relative index values to health impacts (e.g., increased allergies) and then health values associated with these effects could be used to value the impact of pollen emissions.

Carbon Sequestration

Improvement can always be made by developing more and/or better carbon estimation equations and developing better estimates of tree growth. However, the procedures used are pretty much the standard in estimating carbon storage and sequestration from trees and forests. The current (2015) value of forest carbon sequestration is $38 per metric ton of CO_2 based on a 3-percent discount rate (Interagency Working Group on Social Cost of Carbon 2013).

Air Temperature Reduction

As air temperatures affect many attributes within forest ecosystems (e.g., transpiration, growth, photosynthesis, VOC emissions) and have secondary effects that impact air quality (e.g., photochemical rates, pollutant emissions), this service requires more research to improve model estimates of forest effects on air temperatures and associated secondary effects on other ecosystem services and air quality.

Changes in air temperature affect human health directly (e.g., heat stress) and also affect chemical emissions from numerous sources, which can influence human mortality. If these impacts can be quantified, then they can be valued either using the valuation procedures related to air pollution removal or using the statistical value of a life.

Economic Valuation

Most of the valuation methods presented in this chapter are established methods and have been widely used by resource economists. A bigger challenge in ecosystem service valuation lies in accurately quantifying the benefits. However, a number of issues still exist in modeling (users' preference, demand) and benefit aggregation that lead to potential over- or underestimation of benefits. Nonetheless, more rigorous methods are evolving with advancement in the field of econometrics. On the other hand, valuation studies so far have relied on cross-sectional data (market or household survey data of one particular point in time), but parameters estimated from such models may not be stable enough to be useful in forecasting and benefit transfer purposes. When the benefit transfer method becomes the only choice in valuation, researchers should attempt to get a mean estimate of benefits ($/hectare) from as many studies as possible.

Improvements in the valuation approach could also be made by integrating economic methods presented here with other disciplines such as regional science and public health. For example, there currently is no single method accepted as standard practice in estimating the value of heat reduction services provided by forests. However, the per-person value of human life has been estimated by several studies worldwide (Viscusi and Aldy 2003), whereas the marginal benefit of increasing forest area in reducing heat-related deaths is estimated in regional science studies (e.g., Walton and others 2016). Taken together, these two estimates (value per life and number of lives saved) can be combined to characterize the total value attributable to heat reduction services. Considering the dynamics of ecosystem service production functions and the complexity of data collection and modeling, efficient approaches in ecosystem service valuation in the future may have to utilize existing information that are valid, reliable, and reasonably accurate for the study area.

SUMMARY AND CONCLUSIONS

Forest management and land use decisions in the past have rarely acknowledged the value of ecosystem services. This omission is largely because our society has taken those services for granted. These services could be undersupplied, especially in the Southeast, due to a lack of proper incentives to private landowners. This chapter reviews published and theoretically defensible methods and techniques to quantify and value several air quality services of forest ecosystems.

With the market for ecosystem services slowly emerging, it is becoming increasingly possible to estimate the value of some services (e.g., carbon) based on market price of offset credits. On the other hand, most other air quality services are currently not traded in the marketplace and require non-market valuation methods. Part of the difficulty in monetizing some services is quantifying the magnitude or impact of forests on the services. Hence, more research is needed to better understand the production function of those services, as well as the flow of benefits to natural and human systems. There are some user-friendly, computer-based tools (e.g., i-Tree) that are at the disposal of practitioners to explore and understand the production and value of some of the services discussed in this chapter.

Despite the available methods and tools, quantification and valuation of many specific services are still challenging because of the secondary effects (both in cost and benefit) of some of the services. In other words, the interrelation in production process of multiple ecosystem services complicates the process of characterizing value and aggregating benefits at the forest landscape level. For example, management practices that increase carbon sequestration will likely impact water flow and quality. Thus, when aggregating the values of these services, the analyst needs to avoid double counting and hence overestimating the total economic value.

While the valuation methods discussed here are standard, the procedure to be followed in the quantification of services and aggregation of benefits could be specific to the context or objective of valuation. For example, if the objective is to estimate the value of change in a provision of services as a result of proposed policy (e.g., increasing forest area or improving forest health), then appropriate caution should be exercised to estimate the level of service between two States (say, State A and B) and to multiply that by the value of benefit-per-unit evaluated for the respective State where possible. The difference of products can be interpreted as the public value of the policy.

The methods presented in this chapter do not constitute an exclusive list of prescribed methods for quantification and valuation of services but are intended to serve as guidelines to aid in quantifying forest and environmental resource values. Reliability and validity of many of these valuation methods are still being debated. Moreover, as the methodological research in ecosystem service continues to grow, several other approaches and tools are likely to be tested and proposed in the future.

Each method has its own strengths and limitations and relies on a unique set of assumptions regarding the ecological processes that produce a service, as well as economic principles of utility and welfare. While "benefit transfer" from the existing literature is a lower cost option, it is only reliable across areas with identical characteristics. In other words, a benefit function developed in a study area should only be applied to new areas that fall within the range of characteristics of the study area. Hence, the need for a new valuation study depends on the uniqueness of the ecological and socio-cultural context of the area of interest. Valuation methods for these unique cases can be improved through further integrated and site-specific research that involves both ecologists and economists.

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