Assessing Sustainability Using Data from the Forest Inventory and Analysis Program of the United States Forest Service

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ABSTRACT. Forest sustainability has emerged as a crucial component of all current issues related to forest management. The seven Montreal Process Criteria are well accepted as categories of processes for evaluating forest management with respect to sustainability, and data collected

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by the Forest and Inventory Analysis (FIA) program of the United States Forest Service are well suited for such evaluations. The FIA program focuses on the collection, analysis, and distribution of data for a core set of variables obtained using a plot configuration, a sampling design, and measurement protocols that all feature national consistency. Plot, subplot, and tree-level observations include traditional mensurational measurements such as forest area, tree species, diameter, and survival and a suite of non-tree measurements related to the health of the forest. FIA data are recognized for their completeness, geographic coverage, and accessibility to users via a user-friendly interface to a national database. Three examples for three different regions of the United States illustrate the relevance and utility of FIA data for environmental and ecological assessments in the context of the Montreal Process. Several conclusions may be drawn from the examples: (1) for the Southern region, the forest land base is stable, and growing stock volume is increasing; (2) for the Mid-Atlantic region, contributions to carbon accumulation are slightly greater than for storage, and storage increases from north to south; and (3) for the Central Hardwoods region, tree species richness increases from north to south and from west to east and is stable or slightly increasing.

KEYWORDS. Forest land area, biomass, net primary productivity, tree species diversity

FOREST SUSTAINABILITY

The concept of forest sustainability or sustained forest yield is generally attributed to 18th and 19th century European foresters who were concerned that much of Europe was being deforested due to the role of wood in driving the European economy in those centuries. Today, a complex web of environmental, social, and economic interactions surrounds the concept of forest sustainability. Definitions of forest sustainability generally incorporate three components: (1) a process based on the integration of environmental, economic, and social principles; (2) satisfaction of present environmental, economic, and social needs; and (3) maintenance of forest resources to assure that the needs of future generations are not compromised. Devising, implementing, and reporting measures of forest sustainability have been at the forefront of sustainability issues in the late 20th and early 21st centuries.

Following the 1992 Rio Earth Summit, national and international programs involving more than 100 countries were initiated with the objectives of reaching common understanding on sustainable forest management, how to achieve it, and how to measure progress toward it. Following this Summit, the Conference on Security and Cooperation in Europe sponsored and the Government of Canada convened an international seminar on sustainability for boreal and temperate forests in Montreal in 1993. The focus of the seminar was development of a scientifically rigorous set of criteria and indicators for assessing forest management (Montreal Process 1998). A criterion is a category of conditions or processes by which sustainable forest management may be evaluated and is further characterized by a set of indicators that are monitored periodically to assess change. An indicator is a measurable quantitative or qualitative variable which, when observed over time, demonstrates trends. Following the seminar, European countries initiated a regional effort, while non-European countries launched a separate initiative that ultimately led to what is known as the Montreal Process. After several months of informal international meetings in 1994, the latter initiative was formalized and renamed the Working Group on Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests. However, the term, Montreal Process, is frequently used to refer to the Working Group. Of all the forest sustainability initiatives, the Montreal Process is geographically the largest, involving 12 countries on five continents and accounting for 90 percent of the world's temperate and boreal forests (Forests of the Future, 1999).

Participants in the final meeting of the Working Group in Santiago, Chile, in 1995, documented the following seven Montreal Process Criteria (Montreal Process, 2003):

1. *Conservation of biological diversity:* Ensure that ecosystem, species, and genetic diversity are maintained.
2. *Maintenance of the productive capacity of forest ecosystems:* Ensure that timber and other forest resources are not being harvested unsustainably from a given forest area, and ensure that one forest area is not providing so few products that forests elsewhere must be overharvested to compensate.
3. *Maintenance of forest ecosystem health and vitality:* Ensure that forests do not lose their ability to provide goods and services as a consequence of being exposed to processes (e.g., fire, wind, floods)

or agents (insects, disease) outside the range of historical variation.

4. *Conservation and maintenance of soil and water resources:* Ensure the protective and productive capabilities of forests with respect to soil and water erosion.
5. *Maintenance of forest contribution to global carbon cycles:* Forests can temporarily sequester carbon as they grow and return carbon to the atmosphere as they rot or burn.
6. *Maintenance and enhancement of long-term multiple socio-economic benefits to meet the needs of society:* Ensure that forests provide social benefits such as employment, recreation opportunities, cultural and spiritual values and at the same time provide such economic benefits as timber/non-timber resources and investment in the forest sector.
7. *Legal, institutional, and economic framework for forest conservation and sustainable management:* Sustainable forest management is contingent upon the existence of rational social agreements that promote and protect responsible management, public awareness, property rights, and other socio-cultural functions.

Although there is general consensus regarding the Montreal Process Criteria, development of a robust set of indicators has been more difficult due to variations among forests and variations among approaches to ecosystem management.

Montreal Process assessments rely on the premise that Indicators are based on metrics that can be monitored for trend and that statistical estimates of trends and tests of hypotheses regarding the trends may be used to make scientific statements regarding Criteria. Thus, Montreal Process assessments focus on monitoring forest resources via measurements of Indicators so that trends may be detected and estimated and their potential or probable causes may be explained. Data collected by the Forest Inventory and Analysis (FIA) program of the United States Forest Service are well suited for environmental and ecological assessments such as those arising from the Montreal Process. The completeness, consistency, and geographical coverage of this data and its forest-, plot-, and tree-level scales provide the basic information for assessments of many Montreal Process Criteria (Report of the United States, 1997). To illustrate the utility of FIA data for these assessments, an overview of the FIA program and several of its relevant features is provided and is followed by three illustrative examples of how the data may be used for Montreal Process assessments.

THE FOREST INVENTORY AND ANALYSIS PROGRAM

The FIA program conducts inventories of the nation's forest land to determine its extent, condition, and the volume of standing timber, timber growth, and timber depletions. Although the primary purpose of FIA data is to estimate and report the current status of forest resources, the data is increasingly viewed as useful and appropriate for a variety of other analyses. However, the utility of FIA data and the confidence with which researchers, land managers, and decision-makers are willing to use it depend on their familiarity with and acceptance of the underlying objectives of the program and the methods by which those objectives are achieved. Thus, for purposes of creating greater awareness of the utility of FIA data for forest sustainability analyses, several salient features of the program are discussed further.

Ends and Ways

Recent revisions of the national FIA program have emphasized national consistency via a set of five objectives or Ends:

End 1: to conduct field inventories of all forested lands;

End 2: to consistently measure a core set of variables that have nationally consistent meanings;

End 3: to produce nationally consistent estimates which satisfy national precision standards;

End 4: to consistently report and distribute data and estimates annually;

End 5: to foster and enhance credibility with users and stakeholders.

To assure that the five Ends are achieved, the FIA program has prescribed eight methods or Ways:

Way 1: a national field manual that prescribes measurement procedures and protocols for a core set of variables;

Way 2: a nationally consistent plot configuration and sampling design;

Way 3: nationally standardized formulae for sample-based estimators;

Way 4: data released at prescribed intervals;

Way 5: a national database of FIA data with core standards and user-friendly public access;

Way 6: a national information management system (NIMS);

Way 7: publication of estimates of core variables at 5-year intervals;

Way 8: documentation and peer review of the technical aspects of the program.

Thus, the FIA program collects, processes, reports, stores, and distributes data for all forested lands in the nation at regular intervals. The data satisfy national standards for consistency, measurement errors, and precision. As a means of further describing the utility of the data for user-defined analyses, three features of the national program are discussed: (1) the national plot configuration and sampling design, (2) the three phases of the program, and (3) the means of accessing the data.

The National Plot Configuration and Sampling Design

The national FIA plot consists of four 7.31-m radius circular subplots. The subplots are configured as a central subplot and three peripheral subplots with centers located at 36.58 m and azimuths of 0°, 120°, and 240° from the center of the central subplot. The plot configuration includes smaller components for sampling other forest attributes such as small trees, non-woody vegetation, down woody debris, soils, and vegetation diversity and structure.

The national sampling design was derived from the worldwide sampling array developed by the U.S. Environmental Protection Agency as part of the Environmental Monitoring and Assessment Program (EMAP) (US-EPA, 1997; White et al. 1992). Initially, the nation was divided into an array of approximately 65, 000-ha hexagons which formed the basis for the Forest Health and Monitoring (FHM) program sampling design (Overton et al., 1990). This array was used as a framework for generating smaller FIA hexagons, each of which contains approximately 2, 400 ha. The FIA sampling design was established by selecting a permanent plot in each FIA hexagon (Brand et al., 2000). This latter array of plots is designated the federal base sample and is considered to be an equal probability sample. Thus, the FIA sampling design is nationally consistent, provides systematic coverage of all lands, and is fully integrated with the FHM sampling design. The federal base sample was systematically divided into five interpenetrating, non-overlapping panels. Panels are selected for measurement on a rotating basis with targets of one panel per year in the eastern U.S. and one 50-percent sub-panel per year in the western U.S.

The Three-Phase Program

The FIA program accomplishes its objectives in three phases. Phase 1 entails the use of remotely sensed data to obtain initial classifications of land cover and to stratify land area in the population of interest with the objective of increasing the precision of estimates. Phase 2 entails field crew visits to the physical locations of permanent field plots determined in Phase 1 to include accessible forest land. For each tree, field crews record a variety of observations and measurements including species, live/dead status, lean, diameter, height, crown ratio (percent of tree height represented by crown), crown class (e.g., dominant, co-dominant, suppressed), damage, and decay status. Subplot-level observations include ownership, land cover, forest type, stand origin, stand age, stand size, site productivity, forest disturbance history, slope, aspect, physiographic class, and land use. Inventory specialists use field crew measurements to calculate values for additional variables including individual tree volume and per unit area estimates of number of trees, volume, and biomass by subplot, by species groups, and by live/dead status.

The third phase of the FIA program focuses on forest health. Phase 3 is administered cooperatively by the FIA program, other Forest Service programs, other federal agencies, state natural resource agencies, and universities and is partially integrated with the FHM program. The FHM program consists of four interrelated and complementary activities: Detection Monitoring, Evaluation Monitoring, Intensive Site Ecosystem Monitoring, and Research on Monitoring Techniques. Detection Monitoring consists of systematic aerial and ground surveys designed to collect baseline information on the current condition of forest ecosystems and to detect changes from those baselines over time. Evaluation Monitoring studies examine the extent, severity, and probable causes of changes in forest health identified through the Detection Monitoring surveys. The Intensive Site Ecosystem Monitoring program conducts research into regionally specific ecological processes at a network of sites located in representative forested ecosystems. Finally, Research on Monitoring Techniques focuses on developing and refining indicator measurements to improve the efficiency and reliability of data collection and analysis at all levels of the program.

The ground survey portion of the FHM Detection Monitoring program was integrated with the FIA program as Phase 3 in 1999. The Phase 3 sample consists of a 1:16 subset of the Phase 2 plots with one Phase 3 plot for approximately every 38,450 ha. Phase 3 measurements are obtained by field crews during the growing season and include an extended suite of ecological data: lichen diversity and abundance, soil quality (erosion, compaction, and chemistry), vegetation diversity and structure, and down woody material. The incidence and severity of ozone injury for selected indicator species are also monitored as part of an associated sampling scheme. Because each Phase 3 plot is also a Phase 2 plot, the entire suite of Phase 2 measurements is also collected on each Phase 3.

The Phase 3 suite of variables was selected to monitor long-term trends in forest health using variables closely related to indicator variables proposed by the Montreal . Observations of an indicator variable represent an index of ecosystem functions that can be monitored over time to assess trends. Indicator variables are used in conjunction with each other, Phase 2 data, data from FHM Evaluation Monitoring studies, and ancillary data to address ecological issues such as vegetation diversity, fuel loading, regional air quality gradients, and carbon storage. The Phase 2 and Phase 3 data of the FIA program serve as the nation's environmental report card and are a primary source of reporting data for the Montreal Process Criteria.

The National Information Management System

The National Information Management System (NIMS) is crucial to the success of the FIA Program and has two primary functions, data storage and data processing (USDA-FS, 2000; 2002). NIMS has been designed to accommodate in a nationally consistent manner Phase 1, Phase 2, Phase 3, and quality assurance data and to provide user-friendly access to FIA data. Custom tables and maps based on FIA data may be obtained using the Forest Inventory Mapmaker Web application (Miles, 2001) available online at http://www.ncrs.fs.fed.us/4801/fiadb/index.htm. Mapmaker requires simply that users select a geographic or political area of interest, an attribute of interest (e.g., forest land area, number of trees), and table classification variables for page, column, and row headings.

MONTREAL PROCESS ASSESSMENTS

The relevance and utility of FIA data for Montreal Process assessments is illustrated via three examples, each for a different region of the United States. The first analysis uses FIA core program forest area and volume estimates to assess sustainability with respect to trends in forest area, distribution of forest area by forest type, land use, and growing stock volume for the Southern region of the United States. The second and third analyses illustrate how FIA plot- and tree-level data may be used to address Montreal Process Criteria that are not part of the core FIA reporting program. The second analysis addresses trends in biomass, carbon, and net primary productivity for the Mid-Atlantic region, while the third addresses the effects of forest disturbance on tree species diversity using FIA data for the Central Hardwoods region.

Forest Area, Species Composition, and Volume in the Southern Region

Introduction–Trends in forest area serve as an indicator for assessing Montreal Process Criterion 1, Conservation of biodiversity, while changes in volume over time may be used to assess Criterion 2, Maintenance of productive capacity. The FIA program routinely reports estimates of both forest area and volume as part of its core program. As previously discussed, the FIA program uses a panel-based sampling design in which each plot is remeasured at regular intervals to track changes at the plot and tree levels. From consecutive plot- and tree-level measurements, changes in ground land use, forest type, growth, mortality and removals are estimated.

Methods–Forest management type, diversions and additions of forest land, and growing-stock volume of forests were estimated for 13 southern states (Figure 1) using FIA plot data collected since 1953. Estimates for forest land diversions and additions do not include the State of Kentucky due to the lack of consistency in specific non-forest land use codes. Specific definitions are used for the forest management type classes:

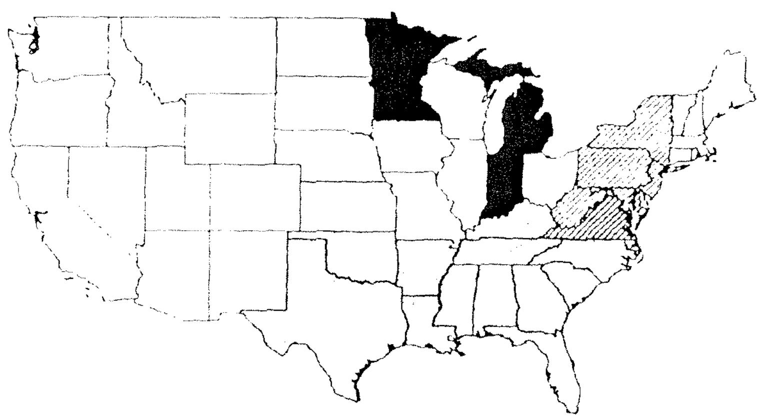
- Pine plantation: Stands that have been artificially regenerated by planting or direct seeding, are classed as a pine or other softwood type, and have at least 10 percent stocking.

- Natural pine: Stands that have not been artificially regenerated, are classed as a pine or other softwood type, and have at least 10 percent stocking.
- Oak-pine: Stands that have at least 10 percent stocking of which hardwoods (usually upland oaks) constitute a plurality of the stocking but in which pines account for 25 to 50 percent of the stocking.
- Upland hardwood: Stands that have at least 10 percent stocking and are classed as an oak-hickory or maple-beech-birch forest type.
- Lowland hardwood: Stands that have at least 10 percent stocking with a forest type of oak-gum-cypress, elm-ash-cottonwood, or other tropical species.

Estimates of diversions of forest land to agriculture and urban land uses, and additions to forest land from agriculture and urban land uses were obtained using the land use change information collected at each FIA plot since 1968.

Growing-stock volume is defined as the volume (m^3) of sound wood in growing-stock trees at least 12.7 cm diameter at breast height (1.37 m

FIGURE 1. Montreal Process assessment study areas



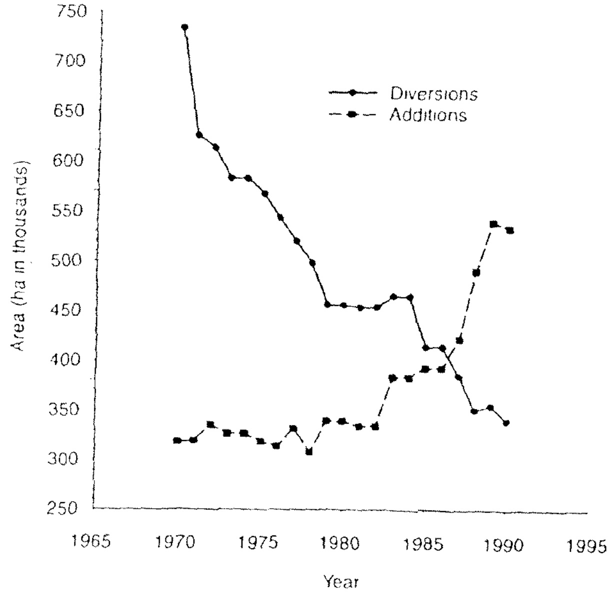
Southern forest sustainability study
Mid-Atlantic forest biomass study
North Central forest biodiversity study

above ground) from a 0.30-m stump to a minimum 10.2 cm diameter outside bark top of the central stem. Species specific volume models were used to estimate individual tree growing-stock volume. The volume models are based on estimated relationships between volume and diameter at breast height and total height. Total volume per plot was estimated by adding volumes for all sampled plot trees, and population volume totals for volume were obtained from plot volumes using stratified estimation procedures.

Results–Change in forest area has been estimated in the Southern region since the 1930s using FIA data. For this region, forest area has been relatively stable with estimates of 88 million ha in 1982, 85 million ha in 1992, and 83 million ha currently (Conner and Hartsell, 2002). As a subset of the broad category of forest land, FIA defines timberland as land capable of producing volume of 1.4 m^3/ha annually but excludes lands such as wilderness areas that are not eligible for timber harvesting. Approximately 93 percent of the Southern region's forest land is classified as timberland, and area estimates have been relatively stable with 80 million ha in 1982 and 81 million ha currently.

Although forest land and timberland areas have been relatively stable, there has been considerable change in the relative proportions of forest land by the five broad Southern forest management types (Figure 2). Estimates of the area of natural pine have declined from 29 million ha in 1953 to 14 million ha in 1999, while estimates of the area of plantation pine have increased from 0.8 million to 13 million ha over the same period. These changes are attributed to a combination of forest succession and forest management. FIA estimates from the 1980s and 1990s indicate 28 percent (1.3 million ha) of new pine plantations were formerly natural pine stands; 47 percent (2.3 million ha) were formerly hardwood and oak-pine stands; and 25 percent (1.2 million ha) were formerly agricultural lands. During this same period, 3.7 million acres of natural pine were converted to hardwood and natural oak-pine as the result of natural succession to more shade tolerant species such as oaks and hickories or as the result of pine harvest. FIA estimates indicate that while plantation pine accounts for only 12 percent of the Southern region's total growing stock volume, it contributes 43 percent of the softwood net annual growth and 35 percent of annual softwood removals. The area of pine plantations is forecast to rise by 67 percent from 13 million ha in 1999 to approximately 22 million ha by 2040 (Wear and Greis 2002). Model-based forecasts (Murray, 2001) predict that non-planted forest types will decline 17 percent or 10 million ha between 1995 and 2050.

FIGURE 4. Southern forest land additions and diversions.

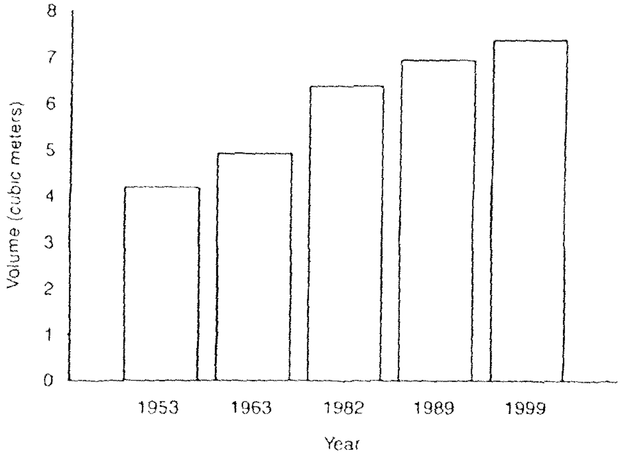


western part of the region. Although timber production is forecast to expand, overall forest resources are not predicted to fall below current levels, a continuation of recent historical trends. Over the last 50 years, growing-stock volume for the Southern region increased by 72 percent (Figure 5). The primary ecological change in Southern forests is expected to occur as a result of expanding pine plantations and diversion of significant portions of natural forests to urban land use.

In addressing Montreal Process Criterion 1, Conservation of biological diversity, none of the five major forest management types are at risk of being lost from the current mix found throughout the Southern region. However, if declines in area of certain forest types (e.g. natural pine) continue, then not only will tree and associated plant species be at risk, but so will animal species dependent on the associated habitats.

The potential loss of natural pine points to the need for improved measurement of biological diversity. Current monitoring emphasizes trees, because advocates of wise forest management have had a long-

FIGURE 5. Volume of Southern forest lands.



standing land use perspective. Monitoring programs should be enhanced to survey important plants and animals that are not currently monitored, rare species, and specialized habitats. Such enhancements will facilitate monitoring of crucial components of forest ecosystems and provide early warning of problems. For example, questions pertaining to the sufficiency of plantation pine habitats for maintaining viable populations of plants and animals currently utilizing natural pine forest habitats could be addressed.

Growing stock volume addresses Montreal Process Criterion 2, Maintenance of productive capacity. Even though the Southern region now supplies 63 percent of all removals for the United States, growing stock volume continues to increase in the region. One method of increasing productivity with increased harvesting pressure and potential reductions in the available forest land base is through plantations. As illustrated for Criterion 1, such a trend toward plantations has occurred in the Southern region.

Biomass, Carbon, and Net Primary Productivity in the Mid-Atlantic Region

Introduction–Montreal Process Criterion 2, Maintenance of productive capacity of forest ecosystems, and Criterion 5, Maintenance of forest contribution to global carbon cycles, may be readily assessed using FIA data. Productive capacity may be assessed via net primary productivity (NPP), defined as production of organic matter by vegetation per unit area per year. Expressing growth in biomass units yields an estimate of net primary productivity (NPP) for the arboreal component of the forest (Table 1). Current biomass above and below ground per unit area provides a more complete evaluation of forest stocks and fluxes than merchantable volume and provides estimates of carbon contributions. Converting biomass to carbon allows carbon pools to be estimated by forest type, age, and other attributes.

Evaluation of Criterion 2 requires a measure of forest ecosystem production. Existing indicators for this Criterion address area of forest land, merchantable inventory volume, and removals for timber and non-timber products. Considerable effort has been expended on developing measures that quantify productive capacity and permit statistical hypothesis testing of comparisons between existing productivity and a reference level. Schmidt (1999) compared realized productivity using FIA site productivity data to potential productivity obtained using models of production at the culmination of mean annual increment. This approach, which assessed production of the commercial volume of wood, was extended for this study by comparing FIA plot-based estimates of total forest production as described by the NPP of the arboreal compo-

TABLE 1. Biomass and annual net primary productivity estimates developed from FIA data for the seven-state mid-Atlantic region *

Forest type group	No. plots	Total tree biomass (mg/ha)		Net primary productivity (g/m²/yr)	
		Mean	SD	Mean	SD
Aspen-Birch	38	203 8	59 8 bc	868 9	103.0 d
Elm-Ash-Cottonwood	59	223 6	67 2 bcd	886 9	140.3 d
Loblolly-Shortleaf Pine	94	156 9	37 2 a	777 6	145 6 ab
Maple-Beech-Birch	964	253.9	64.7 e	847 8	104.7 c
Oak-Gum-Cypress	16	291 1	77 6 e	942 4	154 6 d
Oak-Hickory	1,132	244 2	63 8 d	868.3	111 1 d
Oak-Pine	106	199 8	52 8 b	803 8	99 8 b
Spruce-Fir	43	185.3	48 9 ab	719 6	87 2 a
White-Red-Jack Pine	187	225.4	66.7 cd	805 0	104.2 b

* Means in the same column followed by the same letter are not statistically significantly different (α = 0 05) with ANOVA and Tukey pairwise comparison test

nent to estimates obtained from ecological process models and estimates found in the literature.

Evaluation of Criterion 5 is straightforward using biomass and carbon estimates (Birdsey et al., 1993; Smith et al., 2003). Estimates for some components may be derived from inventory measurements of trees on FIA plots, while estimates for soil biomass and carbon and other non-inventoried components are typically derived from models based on data from other forest ecosystem studies (Birdsey 1992). Results may be evaluated by type and age to gauge the contribution of forests to the overall carbon budget.

Methods–Biomass and NPP were estimated for seven Mid-Atlantic states (Figure 1) using data for FIA plots satisfying four criteria: first, the plots had been measured at least twice; second, there was little or no evidence of fire, insect or disease damage, or harvest between the two most recent plot measurements; third, the stands in which the plots were located did not originate from planting or seeding; and fourth, forest canopies on the plots were designated as closed on the basis of plot basal areas being at least 20 m^2/ha. The analyses were restricted to naturally regenerated stands because planted stands are rare in the region and were restricted to closed canopy stands because the estimates will represent the productivity of naturally regenerated stands with no major recent disturbance and will provide a baseline for evaluating stands with varying levels of management, harvest, and other disturbance. Individual tree wood biomass estimates were obtained from allometric models (Wharton and Griffith, 1993) describing the relationship between above-ground tree biomass and tree diameter at breast height (1.37 m above ground). Estimates of foliage and root biomass were obtained using ratios based on allometric models (Jenkins et al. 2001). Total tree biomass was estimated by adding estimates for all tree components, and plot-level biomass in trees was estimated by adding estimates for all trees with diameters at breast height of at least 5 cm.

For the arboreal component of forests, NPP includes total wood production, fine litterfall, and fine root production. Total wood production was estimated as the difference between biomass estimates for each tree from the two most recent diameter measurements. Annual litterfall per unit area was estimated by forest type using data from a continental-scale litterfall database (E.A. Holland, University of Colorado, personal communication). Finally, fine root production was estimated under the assumption that below-ground litter equals above-ground litter (Raich and Nadelhoffer, 1989; Davidson et al., 2002).

Ecological model-based estimates of biomass and NPP were obtained from the VEMAP project (Schimel et al., 2000) using Century (Parton et al., 1993), Biome-BGC (Hunt and Running, 1992), and TEM (Raich et al., 1991; McGuire et al., 1997). Because ecological models are typically parameterized spatially, process model predictions are often represented using spatial grid cells of uniform size. For this study, FIA-based estimates of NPP and biomass per unit area were calculated for each 0.5 x 0.5 degree grid cell (approximately 240, 000 ha) by averaging data for FIA plots with centers in the cell. The precision of the biomass and NPP estimates were calculated for each cell and were found to exhibit considerable spatial variation because the numbers of FIA plots per cell ranged from one to 46 plots.

The FIA-based biomass and NPP estimates were compared by forest-type group and were compared to model-based and published estimates. The FIA-based estimates provide a means of examining sensitivity to modeled parameters and for estimating upper and lower bounds for model-based estimates.

Results–Maximum current forest biomass estimates, including above- and below-ground components, ranged from 157 Mg/ha for the loblolly-shortleaf pine forest-type group to 291 Mg/ha for the oak-gum-cypress forest-type group. Average current biomass estimates were 248 Mg/ha for deciduous forest-type groups and 200 Mg/ha for coniferous forest-type groups (Table 1). Biomass estimates by grid cell ranged more widely from 101 to 326 Mg/ha, primarily due to variability in sample sizes. Mean NPP estimates ranged from 720 g/ha/yr for the spruce-fir forest-type group to 942 g/ha/yr for the oak-gum-cypress forest-type group. Grid cell estimates of mean NPP ranged from 1, 062 to 1, 858 g/m^2/yr. No clear spatial patterns were evident, aside from higher estimates for areas with denser human populations and relatively small sample sizes.

FIA-based biomass and NPP estimates were consistent with published values for plot-level studies conducted in this region, despite the small-scale variability inherent in natural systems. Comparisons of estimates developed from FIA data and from process models suggest that the latter represent forest production in closed canopy stands fairly accurately, but that they may be over-estimating forest biomass stocks. Century NPP estimates were 7 percent lower than FIA-based estimates, while Biome-BGC NPP estimates were 14 percent higher and TEM estimates were 17 percent higher than FIA-based NPP estimates. Finally, total biomass carbon estimates obtained from Century, Biome-BGC, and TEM averaged 1 percent, 392 percent, and 63 percent higher, respectively, than FIA-based estimates. Over-estimates are particularly acute for models that do not account for the effects of human management.

Conclusions–Montreal Process Criteria 2 and 5, Maintenance of productive capacity of forest ecosystems and Maintenance of forest contribution to global carbon cycles, respectively, may be assessed using trends in FIA-based estimates of current biomass per unit area and NPP. In addition to their value for developing large-scale carbon budgets, these estimates may be compared to biomass and NPP estimates obtained from ecological process models and to estimates reported in the literature. Finally, the focus of Criteria 2 and 5 is on maintenance and require baseline estimates for comparative purposes; the results of these analyses provide those baseline estimates. For NPP, collection of new data from continued monitoring is needed as are new models for completed application to all forest cover types and management regimes. Global carbon research continues to expand and improve with respect to accounting for all forest carbon components, while global carbon flux is increasingly used to measure and evaluate the potential impacts of climate change (Joyce and Birdsey, 2000).

Tree Species Diversity in the Central Hardwoods Region

Introduction–Montreal Process Criterion 1, Conservation of biological diversity, expresses species diversity in terms of numbers of forest dependent species. Species richness, defined as the number of species per unit area, is a commonly used metric for analyzing species diversity. This criterion was assessed with respect to forest disturbance on the basis of tree species richness which was estimated using counts of tree species observed on FIA plots for deciduous forests in Southern Indiana, Southern Michigan, and Southern Minnesota (Figure 1). These three areas represent the central, northern, and northwestern ranges of the Central Hardwoods region of the United States.

Methods–FIA field crews observe and record stand disturbance history for all plots using classes that include no disturbance, natural disturbance due to events such as fire or windthrow, and human-caused disturbance such as harvesting. When assessing disturbance, field crews consider only the time period since the previous plot measurement; that time period averaged 13 years for the three study areas. Stands determined to have been disturbed prior to the second previous measurement but undisturbed between measurements are classified as undisturbed. Two species richness analyses were conducted using tree species counts for FIA plots. First, the means of numbers of species for disturbed and undisturbed plots in the previous inventory were compared to the mean number of species for undisturbed plots in the second previous inventory using a standard t-test. Second, for plots measured in both inventories, linear regression models of the relationships between change in numbers of species per plot between inventories versus number of species at the second previous inventory were separately constructed for plots undisturbed and disturbed at the second previous inventory.

Results–Three results of these analyses are noted. First, statistically significant increases in mean numbers of tree species per plot were observed for plots undisturbed at the second previous inventory, regardless of whether they were undisturbed or disturbed at the previous inventory (Table 2). Second, larger mean numbers of tree species per plot were observed in the central portions (Indiana) of the Central Hardwoods region with tree species richness generally increasing from north to south and from west to east. Third, for plots dominated by sugar maple in Michigan and Minnesota, the fewer the numbers of species at the second previous inventory, the greater the predicted change in the number of species between inventories (Figure 6). For disturbed plots and for undisturbed plots with small numbers of species at the last inventory, the predicted change was positive; i.e., there were more species at the previous inventory than at the second previous inventory.

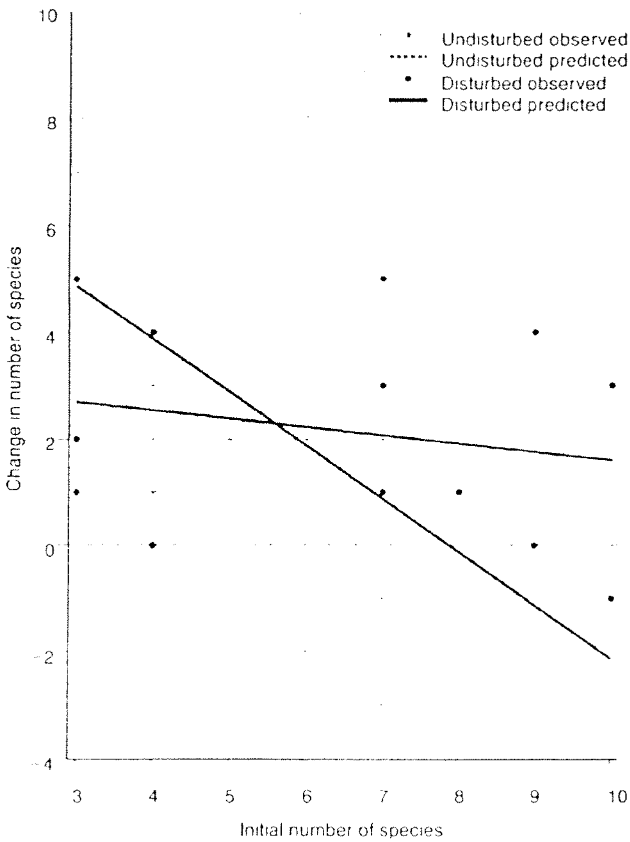
Conclusions–From an ecological perspective, these results suggest that disturbance contributes to an increase in the number of species, regardless of the pre-disturbance number of species. Further, for sugar

TABLE 2. Mean number of tree species per plot

State	Inventory period	Stand history	Number of plots	Mean number of species
Indiana	1986	Undisturbed	200	9.41
	1998	Undisturbed	132	11.24*
	1998	Disturbed	68	11.10*
Michigan	1980	Undisturbed	346	4.88
	1993	Undisturbed	285	7.12*
	1993	Disturbed	61	7.08*
Minnesota	1977	Undisturbed	622	4.54
	1990	Undisturbed	302	6.01*
	1990	Disturbed	320	5.44*

*Statistically significantly different ($\alpha = 0.01$) than mean number of species in undisturbed stands at previous inventory

FIGURE 6. Change in number of species for Minnesota and Michigan sugar maple plots.



maple dominated plots in Michigan and Minnesota, a substantial portion of the resource in these states, both undisturbed and disturbed plots with few species tended to gain species between inventories, while undisturbed plots with large numbers of species tended to lose species. Ecologically, the latter result may be due to sugar maple's shade tolerance which permits it to reproduce under a variety of forest conditions. With respect to Montreal Process Criterion 1, these results indicate that in all three study areas there has been a net increase in tree species diversity and that disturbance tends to contribute to an increase rather than a decrease in tree species diversity on a per unit forested area basis. However, for undisturbed areas dominated by shade tolerant species such as sugar maple, tree species diversity may decrease.

SUMMARY

Data collected by the FIA program of the United States Forest Service is well suited for large scale environmental and ecological analyses such as those based on the Montreal Process Criteria. The FIA program features national consistency in crucial areas such as plot configuration, sampling design, core variables, measurement protocols, and user access to data. The utility and relevance of FIA data for Montreal Process assessments were illustrated through three analyses: (1) assessments of Criteria 1 and 5 using FIA core program estimates of forest area and growing stock volume in the Southern region, (2) assessments of Criteria 2 and 5 using biomass and net primary productivity for the Mid-Atlantic region, and (3) an assessment of Criterion 1 for the Central Hardwoods region using tree species counts on FIA plots as a measure of tree species richness. For the Southern region, the conclusions are that the forest land base is stable, growing stock volume is increasing, but natural pine as a forest management type is being replaced by plantation pine. In the Mid-Atlantic region, baseline NPP and biomass have been estimated so that with new data from continued monitoring, trend estimates may also be obtained. In the Central Hardwoods region, the conclusions are that tree species richness increases from north to south and from west to east, that species richness is generally stable or increasing, but that in undisturbed sites dominated by shade tolerant species such as sugar maple, tree species richness may be decreasing. The FIA program is the only source of data with the consistency, coverage, and completeness for these kinds of assessments.

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