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The North American Forest Database: going beyond national-level forest resource assessment statistics

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Abstract Forests cannot be managed sustainably without reliable data to inform decisions. National Forest Inventories (NFI) tend to report national statistics, with sub-national stratification based on domestic ecological classification systems. It is becoming increasingly important to be able to report statistics on ecosystems that span international borders, as global change and globalization expand stakeholders' spheres of concern. The state of a transnational ecosystem can only be properly assessed by examining the entire ecosystem. In global forest resource assessments, it may be useful to break national statistics down by ecosystem, especially for large countries. The Inventory and Monitoring Working Group (IMWG) of the North American Forest Commission (NAFC) has begun developing a harmonized North American Forest Database (NAFD) for managing forest inventory data, enabling consistent, continental-scale forest assessment supporting ecosystem-level reporting and relational queries. The first iteration of the database contains data describing 1.9 billion ha, including 677.5 million ha of forest. Data harmonization is made challenging by the existence of definitions and methodologies tailored to suit national circumstances, emerging from each country's professional forestry development. This paper reports the methods used to synchronize three national forest inventories, starting with a small suite of variables and attributes.

Keywords Forest inventory · Biometrics · Global forestry · Forest assessment · North America

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Introduction

North American forests total 723 million ha (FAO 2015a). Many of the continent's forest ecosystems cross international borders and many of the forest stewardship challenges faced by foresters in Canada, the USA, and Mexico are the same or very similar. Forestry agencies from all three countries have participated in the development and implementation of sustainability criteria and indicators (i.e., the Montreal Process) and, more recently, the formulation of Sustainable Development Goals (SDGs) used to track progress toward forest resilience and sustainable forest management (SFM; USFS 2018). The breadth of management objectives facing forest managers spans environmental, economic, and social dimensions. Historic emphasis on timber yields has been supplanted by the need to balance biodiversity, forest health, and the productive and protective functions of forests as a whole (www.montrealprocess.org). Forest managers must satisfy and balance the needs of diverse partners and stakeholders, including people far removed from the forests in question. Forest monitoring and reporting data keep partners and stakeholders informed about progress toward SDG objectives and point to areas where attention is needed.

Most forest inventory and monitoring are done to support decision-making at national or sub-national scales, but it is also important to be able to report statistics on ecosystems that span international borders. Forests and wildlife do not observe political boundaries; thus, ecosystems that span national political boundaries require an understanding of the state of the entire ecosystem. Monitoring cross-national ecosystems necessitates common reporting frameworks and consistent data. In instances where national inventory programs collect data using differing definitions and methodologies, harmonization of variables requires substantial cooperation between countries. Efforts have been made to partially harmonize forest inventories in Europe (Tomppo et al. 2010; Vidal et al. 2016), with participation from other countries. The small size of countries combined with the need for most European countries to report to multiple processes necessitates international data harmonization for those countries (e.g., Joint Forest Europe/UNECE/FAO questionnaire on pan-European indicators for sustainable forest management; FAO 2013).

Challenges to variable harmonization across North America differ from those of Europe because of the size of the three countries in question. Considerable efforts were needed to achieve domestic harmonization. Mexican states, Canadian provinces, and US states have all conducted forest inventories, but the establishment of harmonized national forest inventory programs within each of those countries to establish domestic consistency has occurred relatively recently (Bechtold and Patterson 2005; Gillis et al. 2005; CONAFOR 2012). Canada, Mexico, and the USA all provide national statistics for global forest resources assessments, but the coarse scale of national statistics limits the ability to assess progress toward SFM when a country contains many diverse forest ecosystems. Important forest sustainability crises could be taking place within a single ecosystem without impacting a large country's national statistics.

The Inventory and Monitoring Working Group (IMWG) of the North American Forest Commission (NAFC) has met regularly since 2000 to exchange knowledge, share information, and collaborate on forest inventory, monitoring, and assessment matters throughout North America. IMWG members have collaborated to develop a harmonized North American Forest Database (NAFD) for managing forest inventory data and enabling consistent, continental-scale forest assessment, supporting ecosystem-level reporting and relational queries. The NAFD complements the country-scale forest assessment data that are used by the Food and Agriculture Organization of the United Nations (FAO) for the Global Forest Resources Assessment (FRA) and establishes a platform for enhanced North American forest inventory and monitoring data integration. This paper describes the NAFD, discusses how data harmonization was approached, and discusses how new knowledge can be created from harmonized data such as these.

Methods

Ecological zones

Political or administrative boundaries frequently cut across natural ecosystems. Many North American forest ecosystems cannot be fully assessed by examining the data from only one country, but a common ecological classification system is needed before data from different countries can be integrated.

The IMWG collaborated with FAO and the Commission for Environmental Cooperation (CEC) to produce a North American ecological zone map that incorporates the major ecological classification systems currently

being used in North America. This map provides a meaningful set of zones at the continental scale that are consistent with the global ecological zones used for FAO forest reporting (FAO 2010). The new ecological zones were constructed by aggregating CEC level 3 ecoregions (CEC 1997) using Bailey's maps (Bailey 1998, 2009) as guides because of their strong basis in the classic macroclimate maps by Köppen (1931) and Trewartha (1968). The resulting, new ecological zones (Fig. 1) have been incorporated by FAO into the updated global ecological zones used for forest reporting (FAO 2012a) and so we now refer to these as the "FAO ecozones." The map also appears in the CEC's North American Environmental Atlas (Available online at www.cec.org).

Before using these new FAO ecozones in the NAFD, each country introduced an additional level of stratification where deemed necessary to reduce variance or provide additional reporting information. Stratification is commonly used to reduce variance—in this case for variables such as volume and biomass, where more precise estimates can be produced for smaller strata using the same sampling intensity by stratifying along ecological sub-zone boundaries. For example, the temperate mountain system in Canada was stratified into eastern and western subzones to distinguish the forests of the western cordillera from those of the eastern mountain systems, which are quite different in character. In Mexico, the CEC level 3 ecoregions have strong correspondence with the national vegetation type and soil use classifications as mapped by the National Institute of Statistics and Geography (INEGI), which are the basis for the stratification system used by Mexico's National Forest and Soils Inventory (INEGI-Conabio-INE 2008; Comisión Nacional Forestal 2012). These systems were used to stratify the CEC ecoregions for

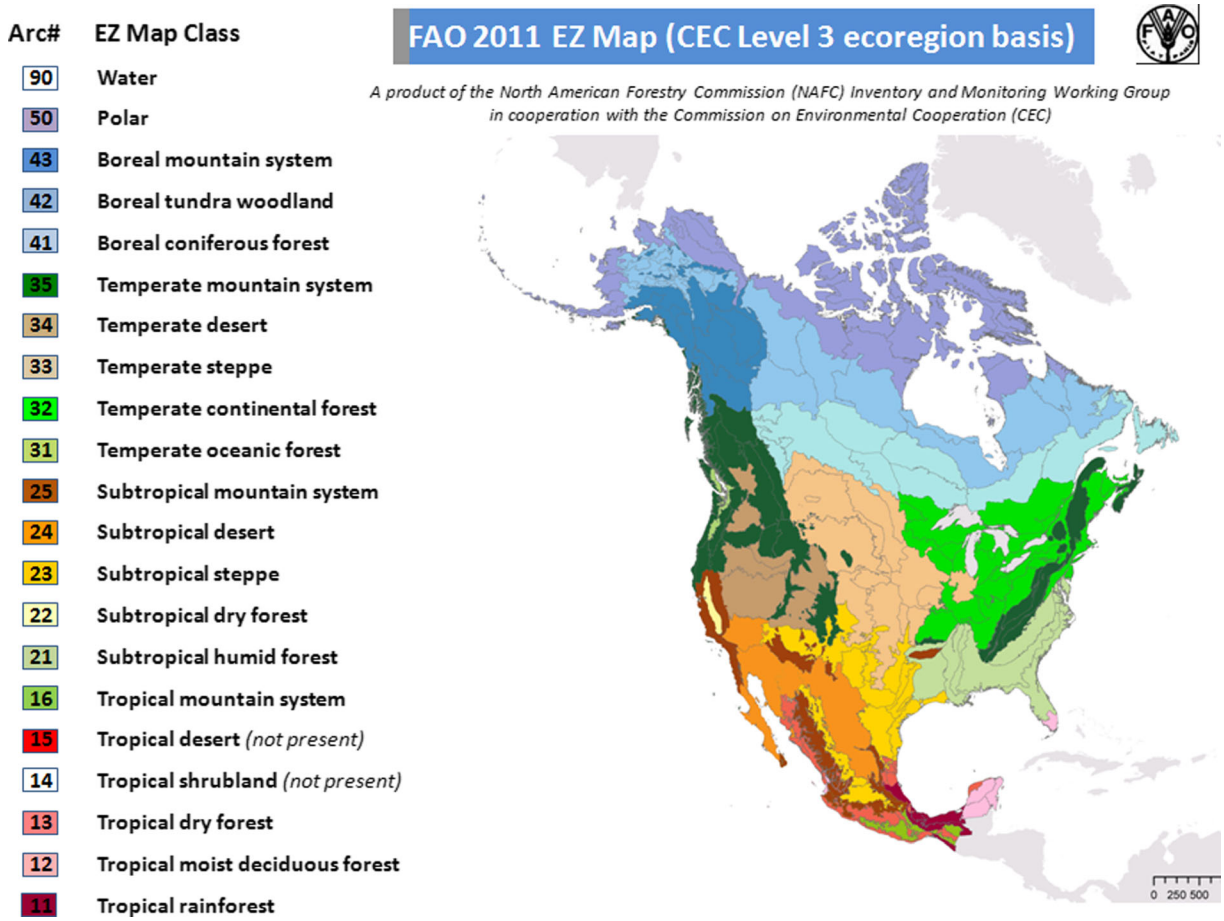

Fig. 1 The FAO 2011 Ecozone map for North America has its basis in the Commission for Environmental Cooperation's level 3 ecoregions (CEC 2011), which describes 21 ecoregions from the tropical rainforest through the polar north

NAFD so that statistical treatment of the data to generate summaries for NAFD can be consistent with statistical treatment of the data to generate national and sub-national summaries within Mexico. The CEC Tropical Rainforest ecozone falls entirely within Mexico's Selvas Cálido-Húmedas "Mexico's Tropical wet forest," as does the Tropical Moist Forest ecozone, so these ecozones were not stratified for NAFD (Fig. 2, Table 1). The Tropical Dry Forest ecozone corresponds well with Mexico's Selvas Cálido-Secas "México's Tropical dry forest," and the Tropical Mountain System falls entirely within Mexico's Sierras Templadas "México's Temperate mountains," so these ecozones did not need to be stratified into subzones for NAFD either. The Subtropical Steppe, however, was stratified into Elevaciones Semiaridas Meridionales "México Southern semi-arid highlands" and Grandes Planicies subzones "Great plains subzones," the Subtropical Desert was stratified into Elevaciones Semiáridas Meridionales and Desiertos de América del Norte subzones "North american deserts," and the Subtropical Mountain System was stratified into Sierras Templadas and California Mediterránea subzones "Mediterranean california subzones." All of the Mexican and Canadian subzones described above are retained in the NAFD but they are not used for reporting.

Data harmonization

The US Forest Inventory and Analysis (FIA) program, Canada's National Forest Inventory (NFI), and Mexico's National Forest and Soils Inventory ("Inventario Nacional Forestal y de Suelos"; INFyS) collect data on an ongoing basis to fulfill national forest monitoring requirements and meet domestic forestry information needs (Bechtold and Patterson 2005; Gillis et al. 2005; CONAFOR 2012). The three countries sponsored a special study (Lund 2003) that identified 175 data elements (attributes and variables) in their national forest inventories and found that 50 of these are common to all

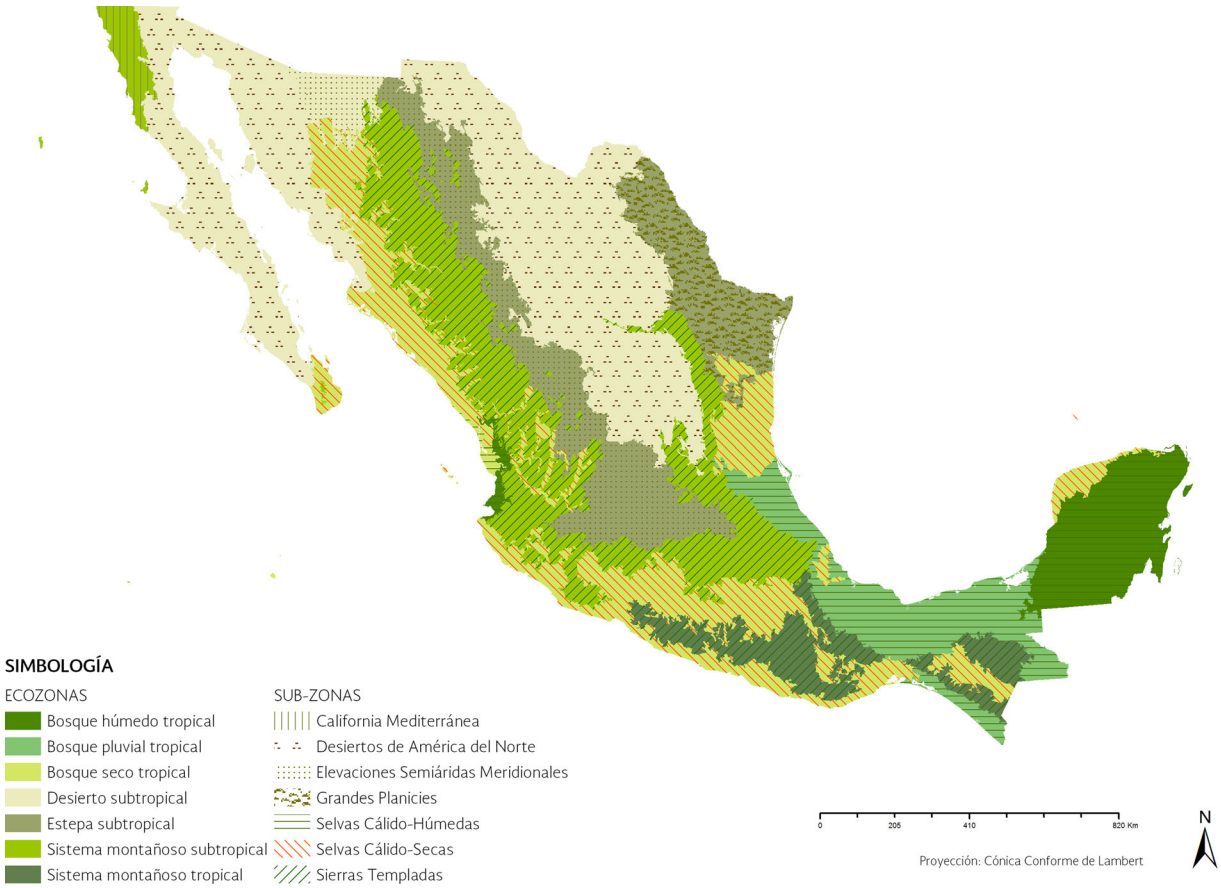

Fig. 2 Map of the ecological sub-zone classification in Mexico

Table 1 Relationship between CEC level 3 ecoregions (columns) and the Mexican ecological stratification system used by INFyS (rows). CEC ecoregions corresponding to more than one INFyS ecological stratum were sub-divided along the INFyS ecological boundaries. The resulting stratification has ten strata (filled cells in the matrix) and NAFD summaries can be produced consistent with either CEC or INFyS

	Tropical rainforest	Tropical moist forest	Tropical dry forest	Tropical mountain system	Subtropical steppe	Subtropical desert	Subtropical mountain system
Selvas Calido Humidas	X	X					
Selvas Calido Secas			X				
Sierras Templatas				X			X
Grandes Planicies					X		
Elavaciones Semiaridas Meridionales					X	X	
Desiertos de America del Norte						X	
California Mediterranea							X

three countries, 85 are common to two countries, and 40 are unique to only one country. A small subset of the 50 common data elements was selected for phase 1 of the NAFD project, including 3 variables (area, volume and above-ground biomass) and 3 attributes (forest type, ownership, and protection status). Others, such as tree height, crown closure, and stocking density, for example, are critical to the estimation of forest area, volume, and above-ground biomass. We used the three selected variables and three selected attributes to work through the entire process of data harmonization, rather than trying to harmonize definitions for all 50 before working through all the subsequent steps, which certainly would have taken far longer.

Three variables are included in the phase 1 NAFD: (i) forest area, (ii) volume, and (iii) above-ground biomass (Table 2). North American standard definitions were developed by starting with the FAO definitions (FAO 2012b) and tailoring these as needed to be practical and informative from a North American perspective. Each country measures these variables in its own way and developed its own approaches to convert national data to the North American standard. The FIA estimation routines, for example, were coded to produce estimates in metric units for the NAFD.

Three classifiers in addition to FAO ecozone are included in the Phase 1 NAFDB: (i) forest type (Table 3), (ii) ownership (Table 4), and (iii) protection status (Table 5). Each country has its own national classification system and developed its own approaches for summarizing data by the North American standard classes.

Canada's NFI is currently undertaking its second cycle, so data from the first and only completed cycle (2000–2006) were used for NAFD. Mexico's INFyS is undertaking its third cycle, so data from the most re-

Table 2 Phase 1 NAFD reporting variables

Variable	North American standard definition
Forest area	Land with trees higher than 5 m and a canopy cover of more than 10%, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use.[a]
Volume	Volume over bark of all living trees with a minimum diameter of 10 cm at breast height (or above buttress if these are higher). Includes the stem from ground level up to a top diameter of 0 cm, excluding branches.[b]
Above-ground biomass	All living biomass above the soil including stem, stump, branches, bark, seeds, and foliage.

[a] Forest is determined both by the presence of trees and the absence of other predominant land uses. The trees should be able to reach a minimum height of 5 m. The land should be more than 0.5 ha (CAN, MEX) or 0.4 ha (USA) and more than 20 m (CAN) or 37 m (USA) wide. Forest includes areas with young trees that have not yet reached but which are expected to reach a canopy cover of at least 10% and tree height of 5 m or more. It also includes areas that are temporarily non-stocked due to clear-cutting as part of a forest management practice or natural disasters, and which are expected to be regenerated within 5 years, or longer where local conditions justify that a longer time frame is used.

[b] Volume includes living trees that are lying on the ground but excludes smaller branches, twigs, foliage, flowers, seeds and roots

Table 3 North American standard forest type reporting classes

Class	North American standard definition
Coniferous	Forest with coniferous trees contributing 75% or more to the total basal area of the plot or stand
Broad-leaved	Forest with broad-leaved trees contributing 75% or more to the total basal area of the plot or stand
Mixed	Forest with neither coniferous nor broad-leaved trees contributing 75% or more to the total basal area of the plot or stand
Non-treed	Forest that is temporarily non-stocked

cently completed cycle (2009–2013) were used for NAFD. The US FIA program has been undertaking continuous annual measurements since 1998 and uses temporally indifferent moving average estimation (Bechtold and Patterson 2005). Western states combine data from 10 annual panels while most eastern states combine data from 5 or 7 annual panels to compile complete datasets for estimation, such that estimates nominally referenced to 2011 will be based upon data collected as far back as 2006 or 2004 in the east, and 2001 in the west (Fig. 3).

Table 4 North American standard ownership reporting classes

Class	North American standard definition
Public-national	Forest owned by the state at the national government scale; or by administrative units of the Public Administration; or by institutions or corporations owned by the Public Administration.
Public-subnational	Forest owned by the State at the sub-national government scale; or by administrative units of the Public Administration; or by institutions or corporations owned by the Public Administration.
Private	Forest owned by individuals, families, private co-operatives, corporations and other business entities, private religious and educational institutions, pension or investment funds, NGOs, nature conservation associations and other private institutions.
Community	Forest owned by a group of individuals belonging to the same community residing within or in the vicinity of a forest area or forest owned by communities of indigenous, tribal or Aboriginal Peoples. The community members are co-owners that share exclusive rights and duties, and benefits contribute to the community development.
Unknown	

Based on FAO (2012b)

Table 5 North American standard protection status reporting classes

Class	North American standard definition
Ia	Areas managed mainly for strict protection as a nature reserve
Ib	Areas managed mainly for strict protection as a wilderness area
II	Areas managed mainly for ecosystem conservation and protection
III	Areas managed mainly for conservation of natural features
IV	Areas managed mainly for conservation through active management
V	Areas managed mainly for landscape conservation and recreation
VI	Areas managed mainly for sustainable use of natural resources
Other	Areas managed mainly for other uses or purposes[a]

International Union for Conservation of Nature (IUCN) classes taken from Dudley (2008)

[a] It is important recognize that many of these areas have some degree of protection or restrictions on land and resource use.

Relational database

The North American Forest Database (NAFD) is a geographically referenced forest inventory database that draws existing national forest inventory reporting data of the three North American countries into a single common relational database management platform. NAFD houses reporting data. Plot data are compiled and estimates are produced for loading into the database, which then integrates these reporting data for the three North American countries. The database is stand-alone and will need to be updated periodically as the three national inventory programs produce new data. The phase 1 NAFD table structure and entity relationships were designed to provide flexibility and scalability so that the database can be expanded in later phases of development without requiring changes to its underlying structure.

The IMWG designed NAFD to benefit from recent FAO forest reporting data management advances. FAO

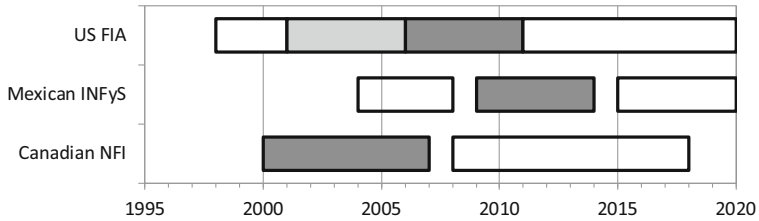

Fig. 3 Reference time periods for Canadian NFI, Mexican INFyS, and US FIA data in the phase 1 NAFD. Filled bars represent the inventory cycles or years during which measurements used for estimation were taken in the field. Canada's first NFI cycle data were used; the second cycle was completed in 2017 but data processing is still in progress. Data from Mexico's second cycle where used; the third cycle is scheduled for completion in 2019. The US FIA uses a continuous annual system with 10 rotation panels in the west and 5 rotating panels in the east (7 in some cases), so the US data in NAFD nominally referenced to 2011 are based upon 5 or 10 years of field data depending on which states are involved in the ecozone estimation

collaborated with Forest Europe, the International Tropical Timber Organization (ITTO), l'Observatoire des Forêts d'Afrique Centrale (OFAC), and Montréal Process countries to streamline data collection for FRA 2015 using a Collaborative Forest Resources Questionnaire (CFRQ) and created a Forest Resources Information System (FRIMS) for managing the data. These initiatives reduced the reporting burden on countries and will bring increased consistency to international forest assessment and reporting by making it possible to use the collected data many times (MacDicken 2015).

The NAFD builds upon the FRIMS approach by introducing a relational data structure that makes it possible to report on combinations of classifiers. The FRIMS was designed to streamline the process of assembling country data and producing FRA 2015. FAO could use FRIMS to generate reports on the protection status of forests or on forest ownership, but not the two in combination. Questions such as "What proportion of publicly owned forests is protected?" could not be answered using FRIMS. The NAFD has been structured and loaded with data that make this type of enquiry possible and anticipates the addition of more classifiers and classifier combinations at a future date. What's more, the use of ecological stratification instead of country-scale data makes it possible to answer questions that cannot be answered using country-scale data, such as "What is the area of the North American boreal forest and how is it changing?"

Statistical analysis and reporting

Each country compiled statistical estimates using its NFI data and employing its own statistical estimation procedures. The results were then formatted for loading into NAFD.

Canada

Canada's NFI uses a systematic sampling design, with 2×2 km square sample units located every 20 km in most ecozones, and every 40 km in some northern ecozones (Gillis et al. 2005; Stinson et al. 2016). Stereo photography flown at scales ranging from 1:10,000 to 1:20,000 are the preferred imagery data for these units ("photo plots") due to their high degree of spatial detail and the opportunity they present to interpret and measure land cover and forest attributes stereoscopically (Gillis and Leckie 1993). Imagery was interpreted by expert interpreters, typing and attributing forest cover polygons according to the NFI specifications (NFI 2008). First re-measurement data (T1 epoch: 2008–2017) were acquired by sensors mounted on orbiting satellites (Falkowski et al. 2009) where the preferred imagery data could not be acquired. This commonly occurred in the Boreal Tundra Woodland and Boreal Mountain System. During NFI establishment (T0 epoch: 2000–2006), portions of the survey in these ecozones were completed using a medium resolution remote sensing land cover product (Wulder et al. 2008). The NFI program also conducts ground sampling at a randomly selected subset of forested photo plot centroids, but there are currently only 1114 ground plots and so these are used primarily to support scientific research on topics such as forest carbon dynamics (Shaw et al. 2013), forest growth dynamics (Girardin et al. 2016) rather than for statistical estimation.

There are two basic types of estimators of NFI attributes: those that relate to areas with a certain classifier (e.g., coniferous forest type) and those that relate to per unit area values (e.g., volume per ha).

Areas relating to a certain classifier (or unique combination of classifiers) are estimated by first estimating

the mean area-proportion of the attribute in the NFI sample of remote sensing survey plots. The total area is then obtained by multiplying this proportion with a known total area obtained from an official statistic. The standard error of an area estimate is obtained as for stratified random sampling of a proportion and multiplied by the total known area.

Two different types of estimators for per unit area values are used. The first type has the entire landbase as the population of interest. Here, traditional design-based estimators of means and variances for simple random sampling within a stratum, region, or inventory unit are used (Cochran 1977, ch. 2). Weighted estimators are used whereby weights are proportional to the area of a plot that resides within the population of interest.

The second type of estimator is a ratio estimator for single stage sampling with clusters of unequal sizes. Here, the sample frame is the land in a specified condition class (e.g., treed and coniferous). For each 400-ha remote sensing survey plot, we obtain the total of an attribute value (e.g., total volume) and the total area in the specified condition class (coniferous). Means and approximate variances are computed as for ratio estimators (Cochran 1977, ch. 6). Volume is a derived attribute from photo-interpretation of one or more of the following: species composition, height of leading species, basal area or stocking or crown closure (by species), and age. To the extent possible, the photo-interpretation is by visible stand layers. Local and regional look-up tables, volume equations, and yield tables are also used where deemed appropriate by the provincial or territorial forest inventory agency supplying the volume data to the NFI. Above-ground biomass is modeled as function of volume and stand attributes (Boudewyn et al. 2007).

Mexico

The INFyS uses a systematic stratified cluster sampling design in two stages. First, the primary sampling units ("Unidades de Muestreo Primarias"; UMP) or clusters are distributed in a national 5 × 5 km quadrangular grid to provide regular and consistent spatial distribution of all sampling. The UMP sampling intensity is determined as a function of plant communities in the country, based on national Land Use and Vegetation (mapped at 1:250,000 scale). Sampling is done on a 5 × 5 km grid, with reduced sampling in semiarid communities (10 × 10 km) and in arid communities (20 × 20 km). This matching of highest sampling intensity to areas with greater variability in forest population is a cost effective way of increasing the statistical reliability of the inventory.

The UMP have an area of 1 ha. Within each UMP, four sites or secondary sampling units ("Unidades de Muestreo Secundarias"; UMS) are evaluated. These are geometrically arranged in a "Y" formation that is inverted with respect to North. Dasometric and dendrometric information is collected at the UMS, including variables characterizing tree, shrub, and herbaceous layers. Detailed information on the methodological design and information that is collected is provided in the INFyS field procedure manuals (CONAFOR 2009–2015).

Data collection is performed by INFyS providers who are contracted through international competitive bidding. The tender documents establish the various requirements that suppliers must satisfy with respect to quality control in order to ensure the reliability of the inventory. These are divided into three main components: internal supervision, external oversight, and cabinet review. Companies must provide their own internal supervision crews to perform field checks, ensure correct data entry in the field, and produce verification of the sampling work performed. The National Forestry Commission ("Comisión Nacional Forestal"; CONAFOR) may conduct external oversight by conducting field supervisions for 10% or more of plots measured by the companies responsible for the sampling (budget conditions permitting). Finally, data consistency is validated by a cabinet review process where mechanisms are employed to ensure that the results meet the established standards.

Variation in observations made at UMS can be high, so the estimation of forest parameters such as volume and biomass and others is done using a ratio estimator to increase the accuracy of calculated means and totals. The ratio estimator compensates for the presence of bias by ensuring that the value of the sample mean has a greater probability of being close to the true mean and a greater population inference accuracy (Velasco Bautista et al. 2005).

USA

The Forest Inventory and Analysis sampling design is based on a grid of hexagons superimposed on a map of the USA, with each hexagon approximately 6000 acres (2428 ha) in size and at least one permanent plot established in each hexagon. In phase 1 of FIA's multiphase inventory, the population of interest is stratified

and plots are assigned to each stratum to increase the precision of estimates. During phase 2 (P2), tree and site attributes are measured for forested plots established in each hexagon. P2 plots consist of four 24-ft (7.3 m) fixed-radius subplots on which standing trees are inventoried. Highly detailed explanations of current FIA sample design and estimation procedures are in Bechtold and Patterson (2005).

Data quality is carefully monitored through the use of checks on plots in the field, as well as post-collection error checks in both the field data recorder and the data processing system. Field personnel are expected to maintain a minimum quality score in order to retain data collection certification. If they do not meet the minimum quality, they are retrained in collection procedures. Detailed field methodology and sampling and estimation procedures can be found in the field manual (available online at http://srsfia2.fs.fed.us/data_acquisition/index.shtml) and in Bechtold and Patterson (2005).

Results

The NAFD contains data describing 1.9225 billion ha, including 677.5 million ha of forest. The Alaska interior is not included because data are not available for the referenced time period using compatible techniques. Future versions will contain the Interior of Alaska. Over half of North America's forests are coniferous. Broadleaved forests comprise 28% of the continent's forests, and mixed broadleaf/coniferous forests comprise 16% of forests (Fig. 4).

The largest proportion of North America's forests is located in the Temperate Mountain System and Boreal Coniferous Forest with approximately 38% of the continent's forests in each. The Temperate Mountain System (73% forested), Tropical Mountain System (74% forested), and Tropical Moist Forest (72% forested) are the most heavily forested relative to their total land base, but the Temperate Mountain, Boreal Coniferous, Temperate Continental, and Boreal Tundra Woodlands have the largest absolute forest area (Fig. 5).

North American forest ownership reflects the different political histories of the three countries, which is partly a reflection, in turn, of post-Columbian settlement patterns. Nearly 50% of North America's forests are owned by sub-national public entities (e.g., provinces, territories, states, municipalities) while 27% are in individual private ownerships. Only 12%, strikingly, are owned by National public entities (e.g., federal governments). Forest ownership varies widely between broad ecozones (Fig. 6). Ninety-six percent of forest area in the boreal coniferous forest is owned by sub-national public entities, while 94% of subtropical dry forest and 88% of subtropical humid forest are owned by private individuals. Ownership in much of the tropical forest ecozones and the subtropical desert and mountain forests remains unknown, illustrating an area where further data collection is necessary.

North America's forests support over 96 billion cubic meters of live-tree volume, or roughly 142 cubic meters per hectare. Temperate mountain system forests contribute the largest absolute volume, with 32.8 billion cubic meters, 75% of which is captured in coniferous forests (Fig. 7). Temperate forests, in total, comprise nearly 51 billion m^3 of volume, over half of North America's total. Relatively speaking, temperate oceanic forests are most productive, with 418 m^3 ha^{-1} volume (Fig. 8).

The forests of North America contain 59 billion tonnes of above-ground biomass. This is roughly equivalent to 29 billion tonnes of carbon (assuming that carbon accounts for 50% of the biomass). To put this into perspective, deforestation and other land use changes globally emitted 1.3 billion tons of carbon on average during 2007–2016, mostly in the tropics (Le Quere et al. 2017). Nearly 50% of biomass on the continent is owned by public sub-national entities, while 29% is owned by private individuals (Fig. 9).

Forest protection in North America varies by ecosystem (Fig. 10). The tropical rainforest ecozone has the highest proportion of forest area protected (20%) while subtropical dry forest and subtropical steppe ecozones have the lowest proportion of forest area protected (2%). Overall, 8% of North America's forests are protected (IUCN protection category Ia, Ib, II, III, or IV), with half of this area located in just two ecozones: temperate mountain system and boreal coniferous forest.

Discussion and conclusions

NAFD results are generally consistent at the continental scale with FRA 2015 (FAO 2015b), which is unsurprising because the same source data and methods were used with only a few exceptions. NAFD reports 96.1 billion m^3 of live-tree volume for the 677.5 million ha included in the database. FRA 2015 reports 723 million ha of forest for North America, including 347 million ha for Canada, 310 million ha for the USA, and 66 million

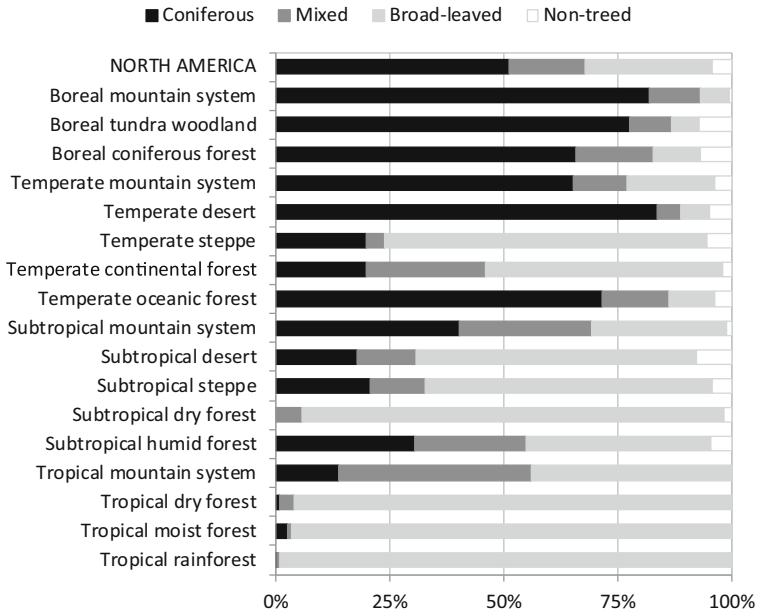

Fig. 4 Proportion of forest area in North America and each FAO ecozone by forest type. Refer to Table 2 for forest type definitions

ha for Mexico. The 46 million ha discrepancy for North America is accounted for by the inclusion of the Alaska interior when calculating area estimates in FRA. The 2012 update to the 2010 RPA Assessment reports 128.6 million acres (52 million ha assuming 0.404686 ha per acre) for the state of Alaska (Oswalt et al. 2014). NAFD does not include data for the interior Alaska because data are not available for the referenced time period using compatible techniques. Future versions will contain the Interior of Alaska as well as coastal Alaska.

FRA 2015 reported that the forest area within protected areas in the North and Central American region was 75 million ha in 2015, or 10% of the region's total forest area (FAO 2015a). National FRA 2015 statistics reported that 7, 10, and 13% of forest area was in protected areas in Canada, the USA, and Mexico, respectively (FAO 2015b). NAFD data can be used to reveal what national-scale statistics cannot: ecozones where there is relatively higher or lower proportion of forest in legally established protected areas. The degree

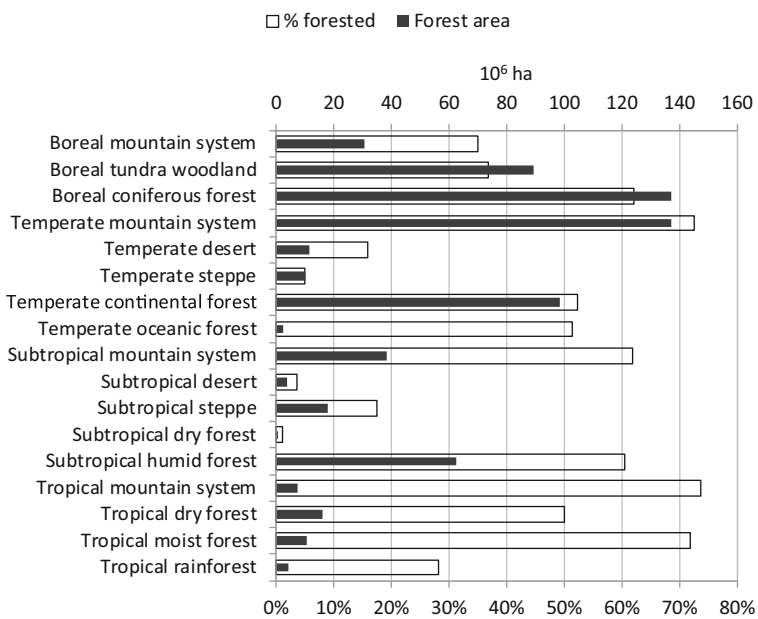

Fig. 5 Forest area (solid bars; top axis) and percentage of land area that is forested (hollow bars; lower axis) in each FAO ecozone

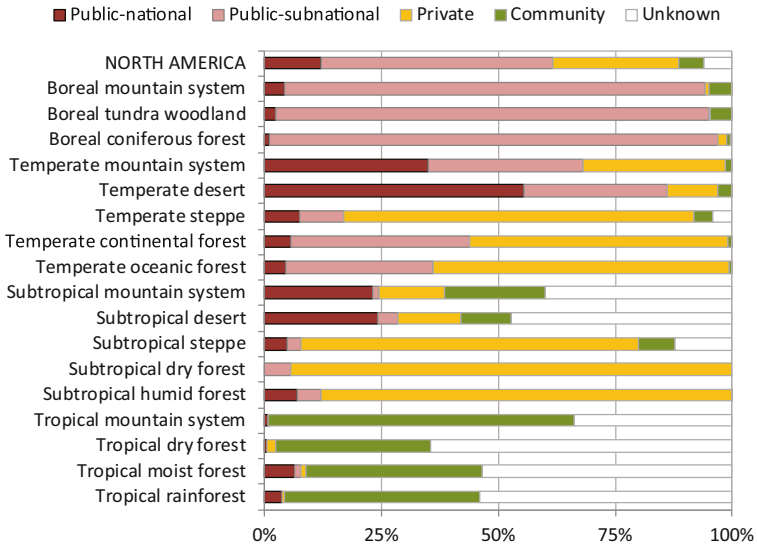

Fig. 6 Proportion of forest area in North America and each FAO ecozone by ownership class. Refer to Table 3 for ownership class definitions

of forest protection outside of IUCN category Ia, Ib, II, III, and IV areas may vary considerably, of course, so "protected forest area" is only one indicator of forest protection. Nevertheless, NAFD data confirm the expected finding that most forest protection coincides with public ownership. More than 90% of protected forests in North America are on publicly owned land. The establishment new protected areas have commonly involved lands already owned by the state, or (less commonly) acquisition of lands by the state. The NAFD data suggest that protection can and has been achieved in other ways as well. In subtropical ecozones, 11% of protected forests are on private land. In tropical ecozones, 23% of protected forests are on community lands. In fact, only 25% of protected forests in tropical ecozones are on public lands. The majority of protected forest in tropical ecozones (46%) is on lands with "unknown" ownership (i.e., not recorded in the forest inventory database).

FRA 2015 reports volumes of 40.7, 4.8, and 47.3 billion m^3 for the USA, Mexico, and Canada, respectively (FAO 2015b). These values are referenced to the nominal year 2015 except in the case of Canada, where

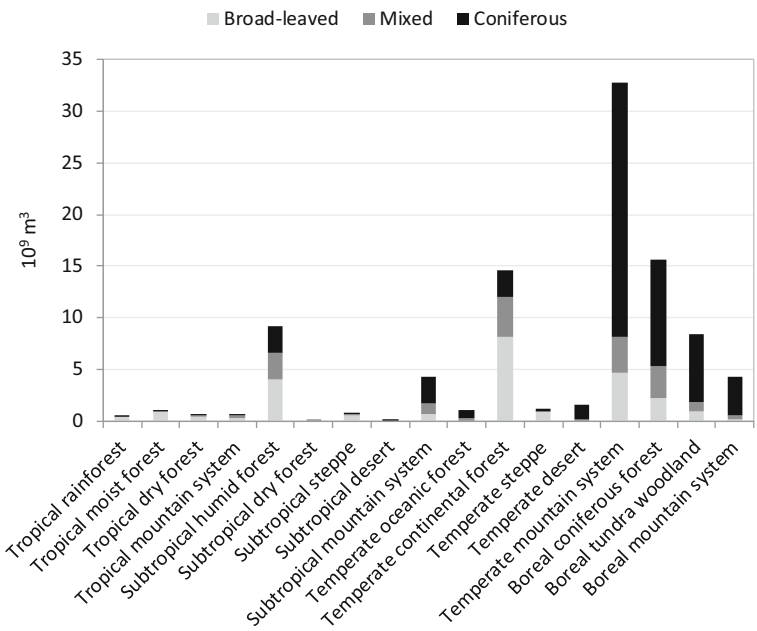

Fig. 7 Total forest volume by forest type in each FAO ecozone

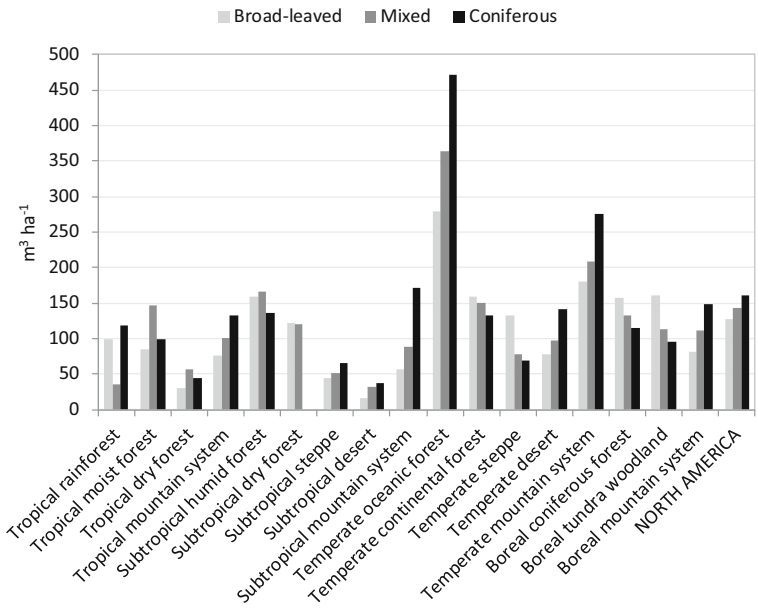

Fig. 8 Forest volume density by forest type in each FAO ecozone

the value is referenced to the year 2005. Canada did not report volume for 2015 in the most recent FRA because the NFI current measurement cycle was still incomplete at the time of reporting (2013) and the unpredictability of future natural disturbance impacts made the projection of 2015 volumes impossible (e.g., Kurz et al. 2008). The USA did not report volume for Interior Alaska because of accessibility limitations. The North American total volume reported in FRA 2015 of 92.8 billion m^3 is smaller than the volume reported in NAFD, 96.1 billion m^3.

Many databases and mapping products are available via online tools that allow users access to forestry statistics from North American countries. For example, FAO populates a multi-year database for participating countries worldwide. Countries, including Canada, the USA, and Mexico, voluntarily harmonize and supply data to FAO for the purpose of populating the database. Additionally, countries maintain their own internal or publicly accessible databases utilizing their own national definitions for forest related variables. The NAFD can be accessed at https://datosforestal.nfis.org. This web interface only provides access to statistical data; the database has not been designed to hold plot-level data yet. Instead, plot-level data are compiled and estimations are conducted in each country's system and the results of these estimations are loaded into the NAFD, where they can be queried using the web interface.

The NAFD is not intended to supersede or replace any of the currently available tools or databases to which each country contributes. Rather, it is intended as a compliment to the currently available tools and showcases how countries can work cooperatively to provide a harmonized relational database that is independent of country boundaries. By divorcing the data from their country affiliations, NAFD enables spatial summaries by ecological zone rather than by country boundaries. For many applications, summarizing national forest inventory data at the scale of FAO ecozones provides more useful information than

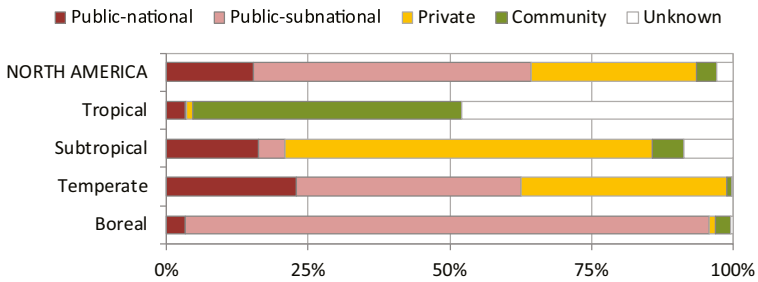

Fig. 9 Ownership of North American forest biomass by biome and continental total

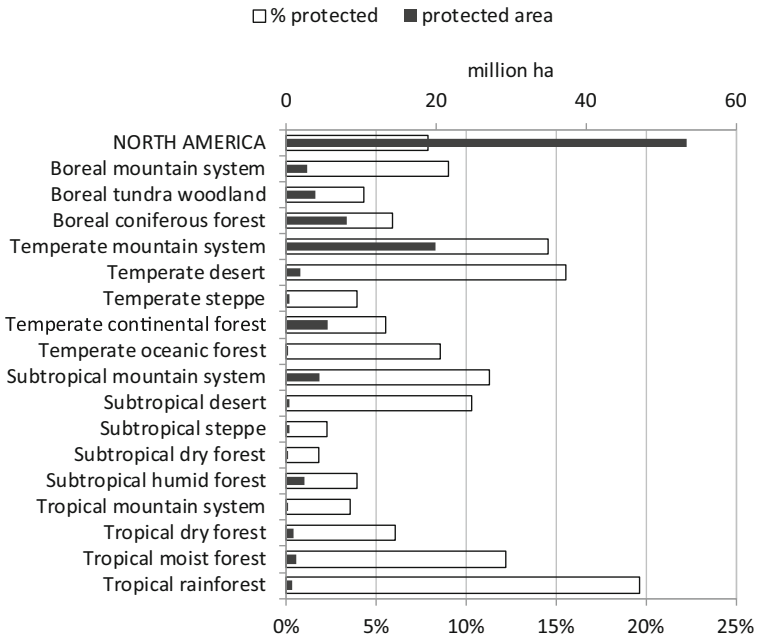

Fig. 10 Area of protected forest (solid bars; top axis) and percent of forest area protected in North American ecozones (hollow bars; bottom axis), including IUCN category I-IV protected areas

data summarized at the national scale, particularly for large countries such as Canada, the USA, and Mexico. In FRA 2015, for example, all forests in the USA are classified as temperate and all forests in Canada are classified as boreal when the results are summarized by biome (FAO 2015; Keenan et al. 2015; Köhl et al. 2015; Morales-Hidalgo et al. 2015). Such generalizations limit the utility of the FRA data and associated analyses for many applications.

Another advantage of the NAFD approach relative to national summary data currently used for FRA is its capacity to summarize data across multiple variables. The FAO database that is used to manage FRA 2015 data allows users to analyze, for example, forest area by country or forest area by country and ownership, but users cannot summarize data across multiple variables within a country's dataset, such as ownership and protection status. Users cannot summarize variables in relation to each other. Figure 7 provides an example of policy relevant information that can be obtained from NAFD but not from current FRA data management systems.

The NAFD's flexible approach to data management involves two innovations relative to the FRA 2015 approach. The first is the relational database management system. The second is a small but important change in how the statistical estimations are done. The same estimators are used, but the data must be summarized across combinations of classifiers. Reports for individual classifiers are not estimated individually; instead, they are rolled up from the base multiple-classifier report. There is a limit to how many classifiers can be included in a multiple-classifier statistical report because relative errors get bigger as the variable amounts involved get smaller. The area of private land in the temperate oceanic forest ecozone that has protection class III, for example, may be too small to estimate using NFI data, but this estimate can be used in sums to obtain a good estimate for a broader category, such as area of private land having protection status III in temperate North America, for example. The NAFD table structure anticipates these limitations by accommodating as many base multiple-classifier reports as the countries wish to produce in order to provide database users with flexibility to produce relational reports.

Most countries already use national ecological classification systems in their domestic forest monitoring and assessment activities. It is both desirable and possible to use this approach in international forest monitoring as well, as demonstrated here, but certain conditions must be met in order to do so. First, countries must agree on a common ecological classification system. Second, countries must be able to generate statistical reports for the zones in this system. This was possible in North America because

all three countries have systematic NFI sampling systems that make post-stratification possible.

Inconsistencies between NFI data persist in NAFD despite its standard variable and attribute definitions. In fact, the NAFD should become a useful tool for identifying inconsistencies between the NFI's of Canada, the USA, and Mexico and catalyzing exchange of knowledge between neighboring countries on how best to approach forest measurement and assessment challenges. In the Alaska interior, for example, the FIA approach is to classify treed lands as "forest" on the basis of tree species cover, such that lands stocked with *Picea mariana* individuals are classified as "forest" even where they do not meet the 5 m height threshold. In Yukon, these same forests would only be classified as "forest" by Canada's NFI if they are assessed as being able to reach the 5 m height threshold in situ. These assessments are highly uncertain because NFI ground plot data are lacking and assessments are based on photo-interpreted forest attributes and available records of natural disturbances and site quality indicators. The Canadian NFI approach may be more consistent with the North American standard definition of "forest," but it introduces more uncertainty than the FIA approach. The phase 1 NAFD is not impacted by inconsistency between FIA and Canadian NFI approaches to these forests, however, because the database does not yet included data for the Alaska interior. It should be noted that given the continental-scale issues, the USA will be taking a long look at the in situ issue of defining trees/forests in interior Alaska as we have already taken steps in the southwest to address this issue in national reporting. Canada is hoping to address the issue of uncertain forest productivity assessment in the NFI (for determining if stands shorter than 5 m have the potential to reach 5 m or not) by improving the availability of data to use in such assessments. This issue could affect estimates of forest area by causing more or fewer low-productivity treed areas to be classified as forest. NAFD only contains data for lands classified as forest; other wooded lands and trees outside of forests are not in the database.

In the case of Mexico, lands are classified as "forest" only where trees should be able to reach a minimum height of 5 m at maturity, including areas covered by saplings that have not yet reached the 5 m height or 10% canopy cover thresholds. "Forest" also includes dwarf mangroves that are less than 2.5 m in their adult stage, and palm vegetation. Xeric scrub and other herbaceous and secondary vegetation are considered forest vegetation in accordance with national legislation, but they not classified as "forest" for national forest inventory reporting purposes.

The phase 1 NAFD demonstrates that national forest reporting statistics can be harmonized and integrated for continental-scale forest reporting and assessment, but it holds data for only three attributes and three classifiers summarized at the scale of FAO ecozones. North American countries identified 50 common data elements in their national forest inventories, and so there is considerable room to expand the NAFD. The collaboration initiated by this project may also lead to NFI modifications that increase the number of common data elements in the future. Plans for future expansions to the NAFD and for increasing the degree of harmonization between Canada's NFI, Mexico's INFyS, and the US FIA programs will be explored by the NAFC IMWG.

Future NAFD development could also proceed toward the integration of plot data. Forest research is increasingly being conducted at a continental spatial scale. This scale of investigation requires datasets that span national borders. Harmonization of plot data from Canada, the USA, and Mexico and management of these data in an integrated, geographically referenced forest inventory database would accelerate forest science and make it easier for researchers to take a continental perspective. Having plot data integrated into the database would provide a lot more flexibility. We geographically stratified North America into ecozones before loading estimates into NAFD for phase 1. If plot data were loaded into the database before geographic stratification and the capability to run estimates was provided, then users could analyze the inventory data for any area of interest (provided it is sufficiently large to produce reliable estimates for given the available sampling intensity). For example, the ability to produce inventory-based estimates for dryland biomes as defined by Bastin et al. (2017) could add valuable information to the investigation of dryland forest area. Moving from a phase 1 NAFD that integrates forest assessment data to a phase that integrates plot data will be a significant undertaking. Fortunately, the challenges of such an undertaking are already being tackled by the forest inventory community (Tomppo et al. 2010) and there is experience to build upon. Efforts such as this may be a harbinger of future approaches to global assessment data that allows for more dynamic analysis of resource conditions.

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