CHAPTER 6.

Changes in Coarse Woody Material Attributes, U.S. Forests, 2002–2011 to 2012–2019

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INTRODUCTION

Coarse woody materials (CWM) are often defined as dead wood of a certain minimum size in forest ecosystems (Harmon and others 1986). For the purposes of the U.S. national inventory, CWM has a minimum diameter of 3.0 inches at the point of intersection with a sampling transect (i.e., transect diameter) in addition to having a lean angle <45 degrees from vertical to delineate it from standing dead trees (Woodall and others 2019). For decades now, CWM has been recognized as an important component of forest ecosystems (Harmon and others 1986) serving as a substrate for tree regeneration (Bolton and D'Amato 2011), habitat for wildlife (Nordén and others 2004), and store of carbon (Bradford and others 2008), among a host of other functions (e.g., Stokland and others 2012). In recognition of these critical functions, the Forest Inventory and Analysis (FIA) program of the U.S. Department of Agriculture Forest Service has been conducting a nationwide inventory of CWM since ca. 2000 as a component of its strategic-scale forest inventory (Woodall and Monleon 2008, Woodall and others 2019). Concomitant with this resource inventory, there has been documentation and concern regarding tree mortality and associated forest health issues at various scales around the world (e.g., McDowell and Allen 2015). Along present trajectories of global change (e.g., tree mortality from climate change and/or insects/disease), it can be hypothesized that increasing rates of tree mortality will have impacts to related forest resources such as CWM. Because one of the largest hurdles to monitoring CWM change is its inherent nature at small scales (e.g., spatially and temporally heterogeneous tree mortality combined with various decay pathways), quantifying how CWM attributes are changing across large spatial domains is an important first step towards future conservation efforts.

As a means to objectively evaluate CWM change across U.S. forests within the context of expected global change impacts, fundamental parameters (e.g., changes in size distribution) of CWM resources (e.g., biomass) were examined across spatial scales of inference ranging from inventory survey units to the conterminous United States using FIA's multidecadal inventory (2002–2011 to 2012–2019). Specific objectives of this study were to: (1) evaluate changes in CWM biomass, in terms of stocks and spatial trends; (2) evaluate changes in CWM transect diameter and decay class distributions; (3) evaluate changes in CWM species composition; and (4) within the context of identified CWM changes, suggest novel indicators of CWM change and associated monitoring refinements.

METHODS

Data

Downed dead wood are sampled by the FIA program using line-intersect sampling (LIS) on a subset of inventory plots that are classified as forested. Forest land is defined as having at least 10-percent canopy cover of live tree species or the potential to support such cover if recently cut/disturbed along with a spatial size requirement of 1 acre and at least 120 feet

in width (USDA Forest Service 2016). The FIA design is based on a spatially balanced sample of approximately one plot per 6,000 acres (Reams and others 2005). Each inventory plot consists of four points arranged in a cluster with one point at the center and three points oriented from the central subplot at 0, 120, and 240 degrees. Each of these four points is referred to as a subplot. The distance from the central point to the center of the surrounding points is 120 feet. These four points form the center of fixed-area plots (24-foot fixed radius) used to tally live and standing dead trees in addition to serving as the origin of transects used to measure CWM pieces.

For most regions of the United States, CWM is sampled using LIS on a subset of forest inventory plots whose sample intensity has changed over time (ranging from every inventory plot to 1/16th of inventory plots) (Woodall and others 2019). Line-intersect sampling itself consists of arraying one-dimensional sampling transects across forest domains of interest with any piece of CWM intersecting a transect being considered part of the sample (Woodall and Monleon 2008, USDA Forest Service 2016). Population estimators are constructed based on the length of transect, CWM piece transect diameter, and the attributes of interest derived from measurements of each sampled piece (e.g., CWM piece volume). Population estimates are calculated from combined plots using the standard, FIA post-stratification estimators (Scott and others 2005). A major delineation in the execution of the national inventory of CWM was a major national change in the plot sampling protocols between the 2002–2011 and 2012–present inventories. As these changes can be considered independent inventories valid for evaluation of changes in the U.S. CWM population over 2 decades, they form the basis of this assessment. In terms of the quality analysis and quality control of the CWM inventory program, despite the often decayed and fractured state of much of the CWM population, the measurement repeatability of various CWM attributes such as diameter and species identification (Campbell and others 2019) is on par with various live tree attributes such as tree grade. The model error associated with estimating carbon stocks of highly decayed CWM pieces and sampling error associated with the 2002–2011 inventories are examples of sources of uncertainty that may outweigh the error from a number of CWM field measurement errors. (For details regarding the evolution of the CWM inventory along with all relevant field protocols, inference procedures, and database documentation, see Woodall and others [2019].) Finally, it is strongly noted that the downed dead wood inventory conducted by the FIA program contains more dead wood components than CWM, including residue piles, fine woody debris, duff, and litter. We chose to focus solely on CWM in this study as a precursor to examining all aforementioned components as the CWM inventory measures numerous attributes (e.g., size, decay, and species) of interest by themselves and in concert with the standing tree inventory. We hypothesize that a firmer foundation for understanding changes

in fine woody debris or residue piles should be built upon robust understanding of changes in the CWM population.

Analyses

The FIA CWM inventory, sampled from 2002–2011 to 2012–2019, is the basis for the analysis presented in this assessment. Valid CWM samples for each State were pulled from the FIA Database (Burrill and others 2017) for each decade to enable change estimation for all States where possible, except for Nevada, New Mexico, Wyoming, Hawaii, and Alaska, where annual inventories were implemented at later dates. Although there are contemporary CWM inventories for those excluded States (and territories such as Puerto Rico and the U.S. Virgin Islands), we decided to focus on CWM change estimation in the conterminous United States where there were valid CWM inventories for change estimation across nearly 2 decades. Unlike resource-change analysis for live trees, where individuals are tracked over time for estimation of live tree resource changes, the tracking of individual CWM pieces does not form the basis of FIA CWM monitoring, although it can be brought to bear when modeling CWM dynamics (Russell and others 2014). Instead, a "stock-change" approach is used where valid estimates of CWM populations are compared across time. Therefore, in this study, CWM changes are evaluated at relatively large scales such as the survey unit or State level. The procedures for developing CWM population estimates across these varying domains are described in Woodall and Monleon (2008).

RESULTS AND DISCUSSION

As FIA's CWM inventory has varied in its plot protocols and sample intensity across space and time since its inception in ~2000 (Woodall and others 2019), there are various approaches to data analysis and associated interpretations of CWM resource attributes. If remeasured individual CWM inventory plots are used as a mode of inference, the result is a greatly reduced number of plots across time (fig. 6.1A). In addition, extreme care must be given when comparing such results at the individual plot level due to changes in plot sampling protocols and sample intensity across time (e.g., fig. 6.1A, western Texas and the West Coast). In contrast to only using remeasured plots, entire collections (i.e., panels) of CWM inventory plots can be considered independent samples of the CWM population at discrete points in time. All contemporary (~2012–2019) CWM inventory plots number in the tens of thousands (fig. 6.1B), forming the basis of rigorous examination of CWM at strategic scales. Using all available within-State CWM inventory plots at two points in time for States that had such inventories, the amount of CWM biomass is seen as mostly increasing across FIA survey units with an average increase of a few tons per acre (fig. 6.2). For the area considered in this study (i.e., remeasured State CWM inventories), an estimate of 2.3 billion tons of CWM from 2002–2011 has increased by 17 percent to 2.7 billion tons in 2012–2019. In a general sense, the balance of CWM biomass across large scales is driven by changes in tree mortality, harvest, decay/combustion, and salvage utilization. It

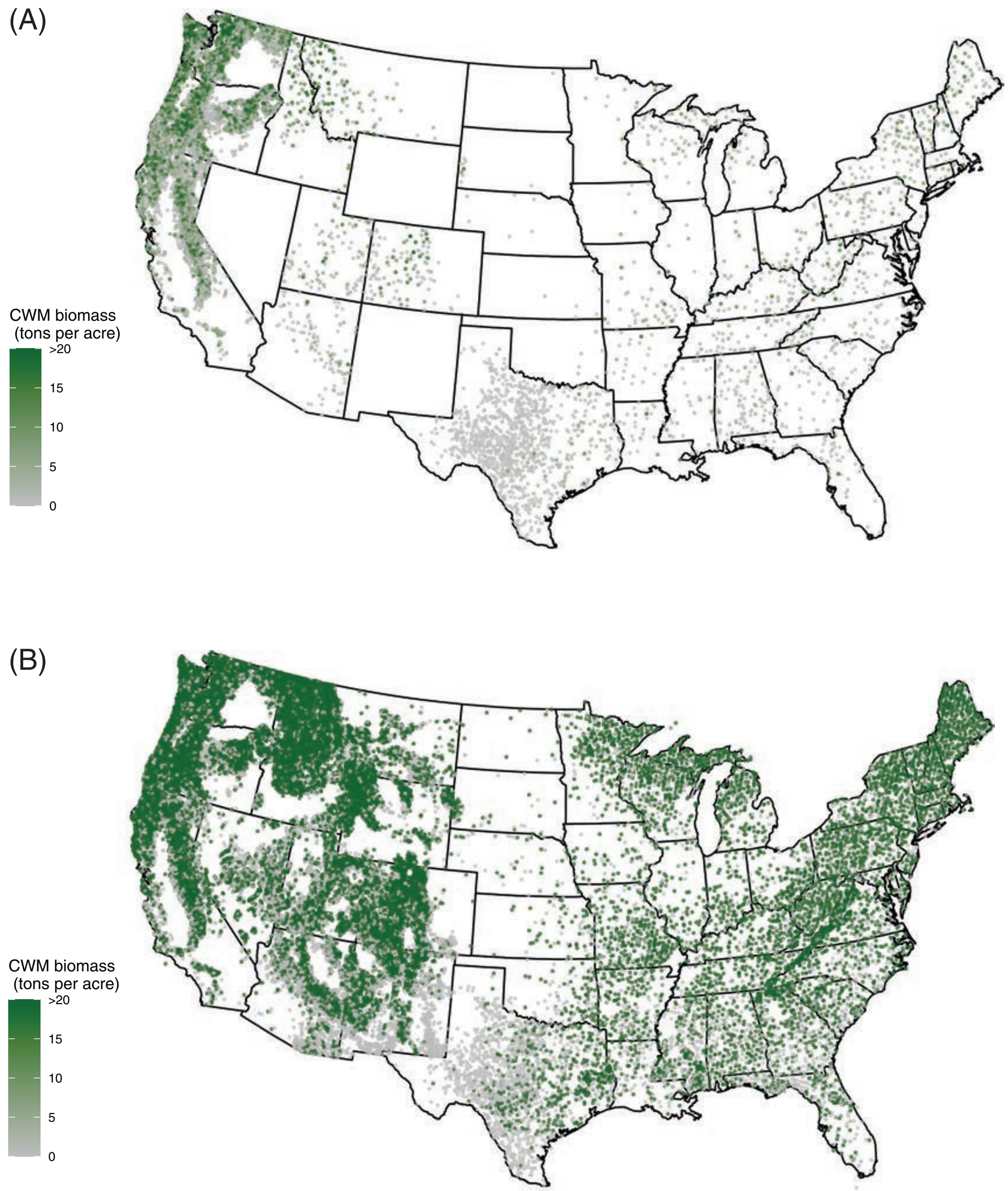

Figure 6.1—(A) Total coarse woody material (CWM) biomass (2012–2019) for only remeasured, forested down woody material (DWM) plots (2002–2011 to 2012–2019). (B) Total CWM biomass for all plots with at least one forested condition measured between 2012 and 2019.

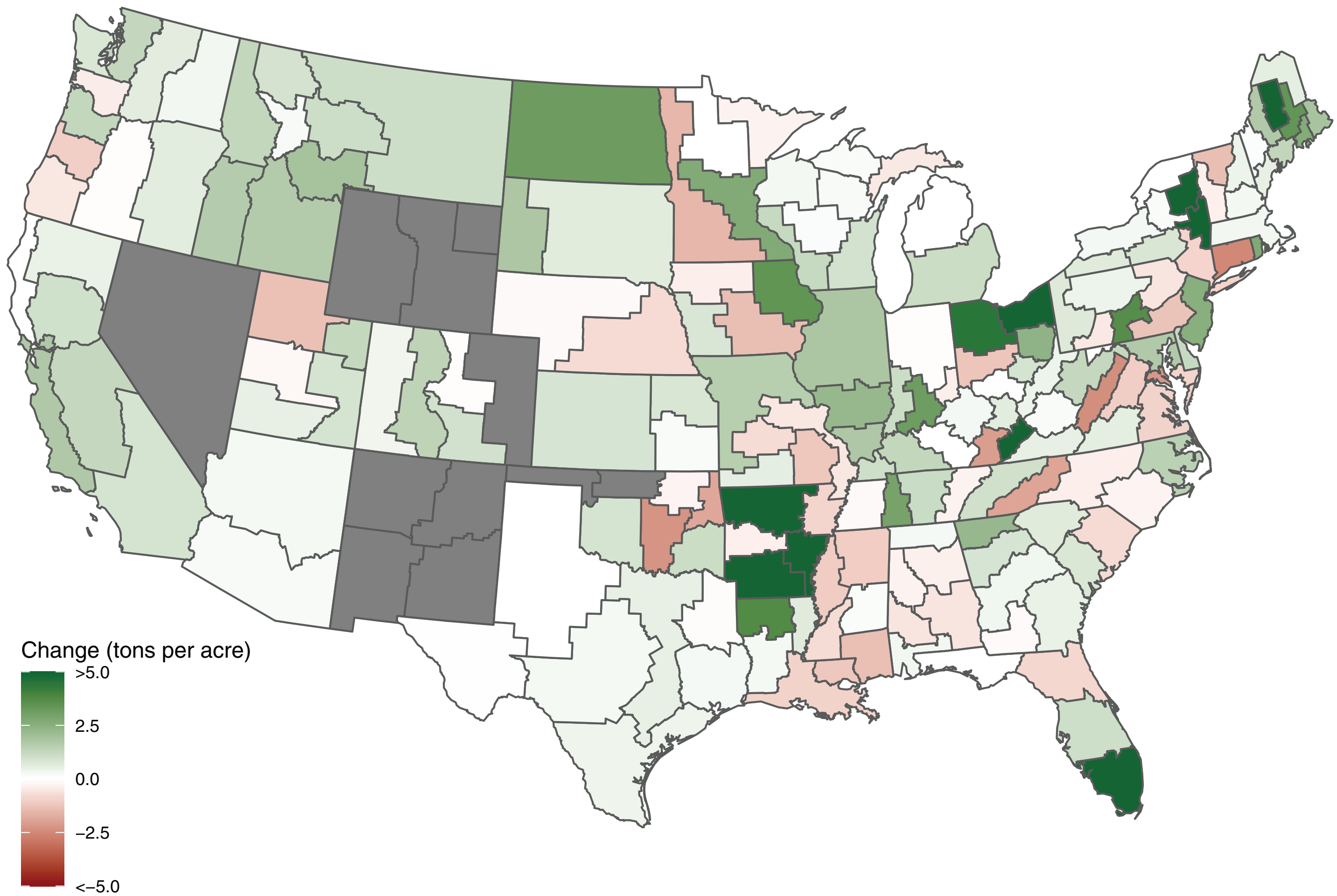

Figure 6.2—Change in coarse woody material (CWM) biomass (tons per acre) in U.S. forests by survey unit, 2002–2011 to 2012–2019. Gray States/survey units indicate no remeasured plots.

can be hypothesized that increases in CWM observed for most areas of the country resulted from mortality/harvest inputs exceeding decay/combustion and/or salvage utilization. Despite this overall increase in CWM biomass, some areas of the United States saw some minor reductions, including the Midwest, Louisiana and Mississippi, and along the Appalachian Mountains. These reductions may be attributed to declining mortality/harvest in combination with continuing decay processes. However, if decay is assumed to be relatively stable over decadal time scales, these CWM reductions suggest lower mortality rates and/or harvest utilization in these regions, which might be attributed to recovery from acid rain deposition along the Appalachian Mountains (Kosiba and others 2018) and vigorous post-hurricane recovery in the Gulf of Mexico.

To further unravel the dynamics of CWM change, the general attributes of decay, size, and species can be examined. The distribution of decay status for CWM is normally distributed and centered on moderately decayed pieces (decay class 3; fig. 6.3). Since the 2000s, the CWM population has slightly shifted towards a more advanced decay status with a notable increase in the total biomass of moderately decayed pieces. Changes in CWM stage of decay has varied across States, with the greatest increase in freshly fallen CWM pieces (decay class 1) occurring in Midwestern States (fig. 6.4). In a similar manner, there was disparity in slightly decayed CWM pieces (decay class 2) across States with some States showing large increases (e.g., Maine, Arkansas, Montana, North Dakota, and South Dakota) and others showing decreases (e.g.,Washington, Oregon, Idaho, Vermont, and Michigan). For the more advanced stages of decay (decay classes 3–5; Woodall and Monleon 2008), there was a more consistent increase across all States, especially for decay classes 3 and 4. The percentage of change of moderately to advanced decayed CWM biomass compared to freshly fallen or slightly decayed biomass across States indicates that most States are experiencing overall increases in the amount of advanced decayed

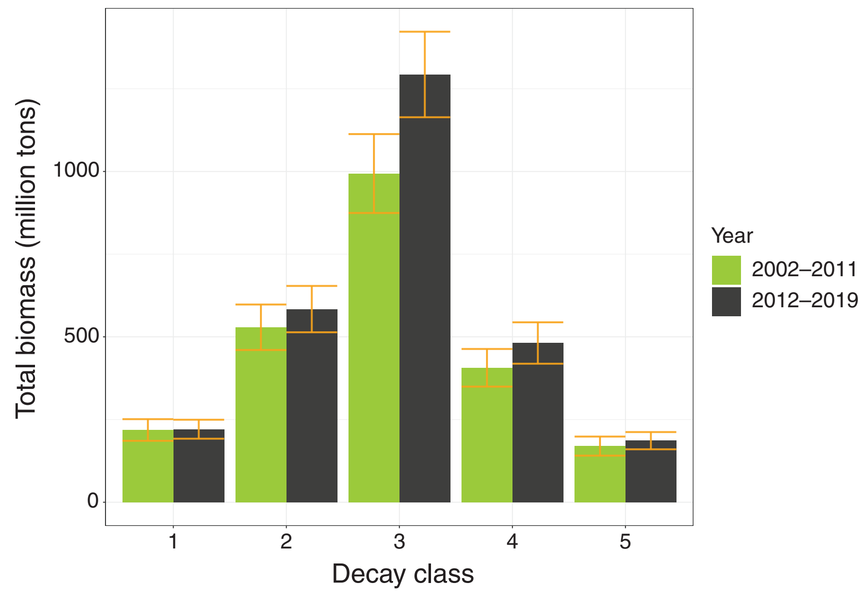

Figure 6.3—U.S. coarse woody material (CWM) decay class distribution, 2002–2011 to 2012–2019.

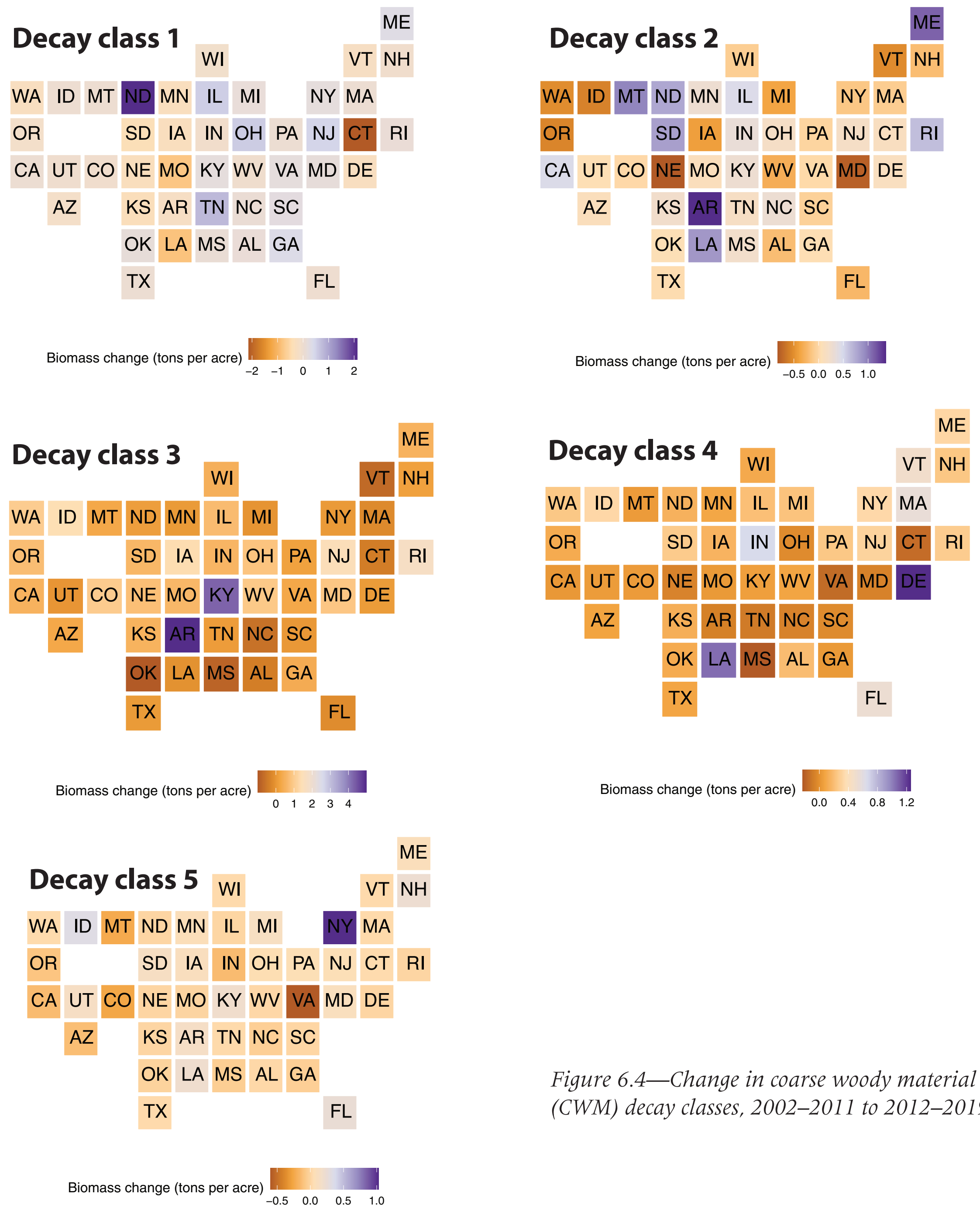

Figure 6.4—Change in coarse woody material (CWM) decay classes, 2002–2011 to 2012–2019.

CWM biomass (fig. 6.5). The States that have had an increase in the amount of fresh CWM compared to advanced decayed CWM were North Dakota, Mississippi, Maine, Tennessee, North Carolina, and Oklahoma.

The biomass of CWM is largely represented by smaller sized CWM pieces if transect diameter is considered an indicator of CWM size (fig. 6.6). Over the course of nearly 2 decades, the plurality of CWM biomass has been in pieces with a transect diameter between 4.1 and 16.0 inches. In terms of change, the largest-sized CWM pieces (transect diameter >24.0 inches) approximately doubled in biomass from ~300 million tons to ~600 million tons. Most States had increases in the amount of CWM biomass residing in smaller sized pieces (3.0 to 8.0 inches), while higher latitude States appeared to experience greater increase in moderately sized CWM (8.1 to 16.0 inches) over 2 decades (fig. 6.7). Increases in the largest sized CWM (>16.0 inches) appeared to be equally distributed among States. When viewing the change of large-sized versus smaller sized CWM pieces over time, it is evident that

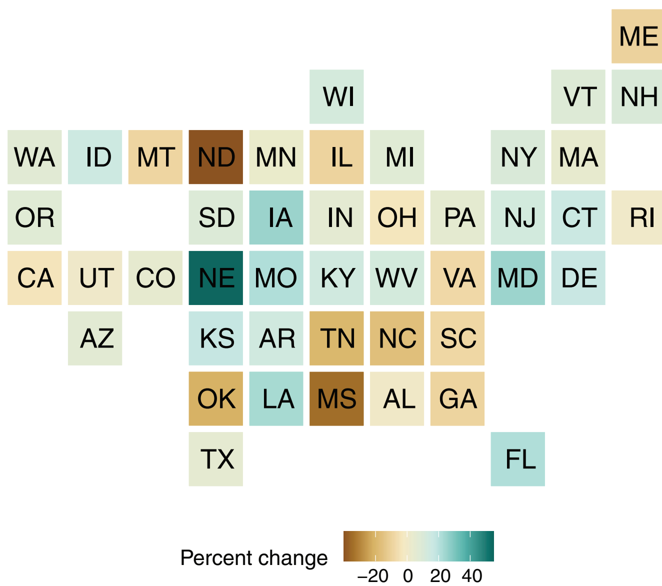

Figure 6.5—Change in percentage of moderately to advanced decayed coarse woody material (CWM) biomass, 2002–2011 to 2012–2019. (Note: a positive value indicates that the State's population of CWM biomass is becoming more advanced in decay over nearly 20 years.)

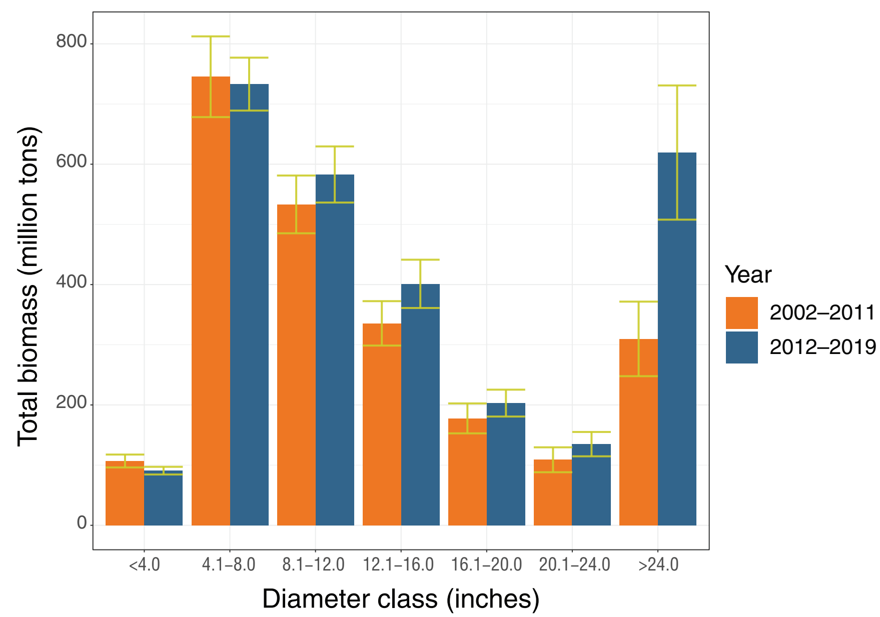

Figure 6.6—U.S. coarse woody material (CWM) transect diameter class distribution, 2002–2011 to 2012–2019.

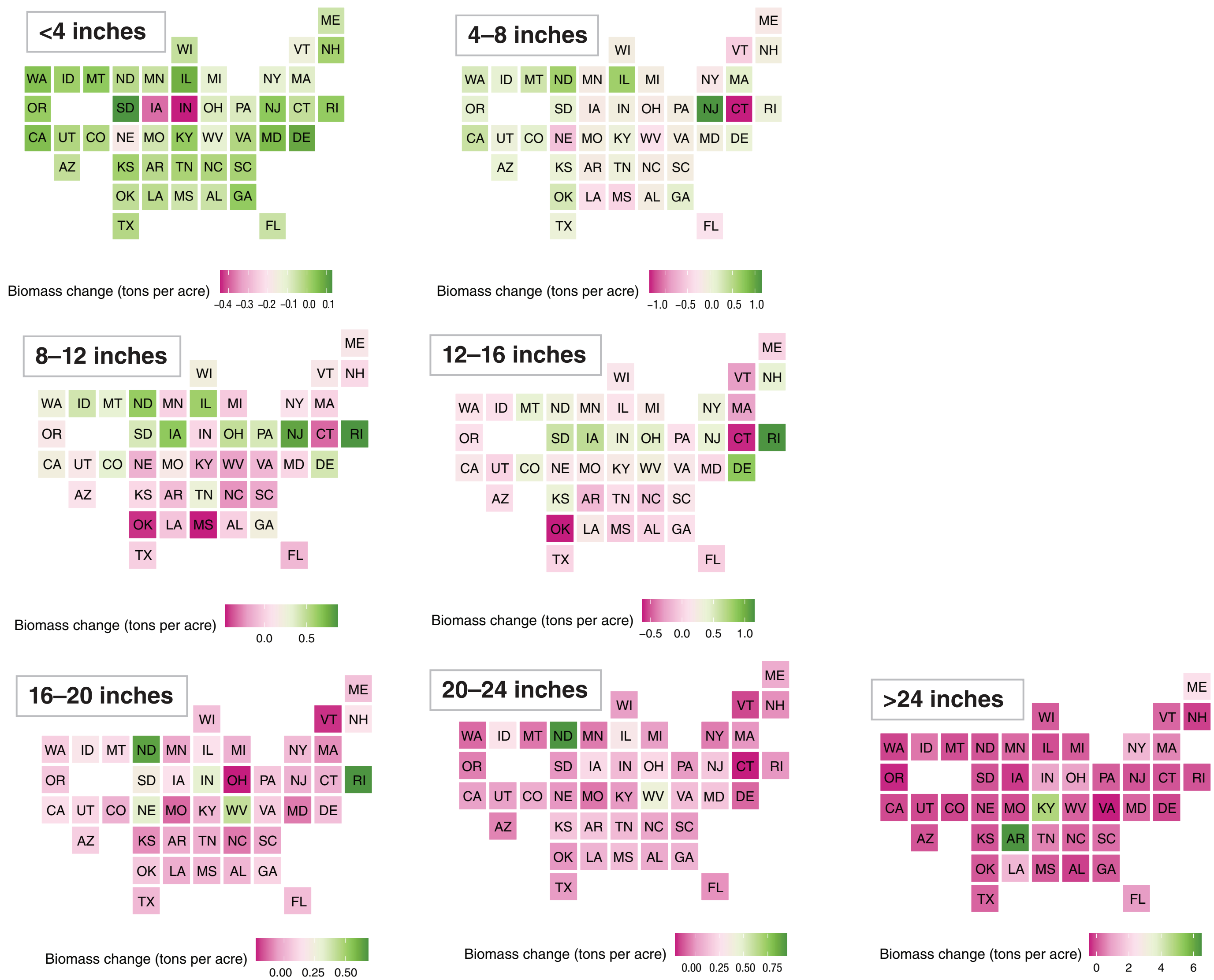

Figure 6.7—Changes in coarse woody material (CWM) transect diameter class distribution, 2002–2011 to 2012–2019.

most States are at least experiencing a minor increase in the relative prevalence of larger sized CWM pieces (fig. 6.8). In particular, the States of Maine, Florida, Arkansas, Kentucky, Louisiana, Texas, Mississippi, West Virginia, Indiana, North Dakota, Nebraska, and New York had higher levels of large-sized CWM increases relative to smaller sized pieces over 2 decades.

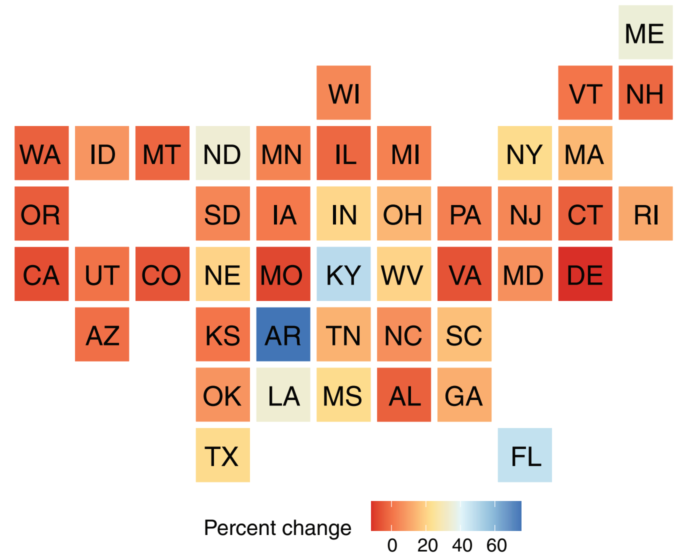

Figure 6.8—Change in percentage of large-sized coarse woody material (CWM) biomass (transect diameter >16.0 inches), 2002–2011 to 2012–2019. (Note: a negative value indicates that the State's population of CWM biomass is becoming increasingly represented by large-sized CWM pieces.)

Very few studies have evaluated changes in CWM species composition, although such analyses might help evaluate the influence of large-scale forest mortality events (e.g., Woodall and Nagel 2006) on subsequent CWM accumulation and depletion (Russell and others 2015, Woodall and others 2015; i.e., decay and/or combustion). As no CWM species types and/or documented CWM species assemblages exist for monitoring purposes (i.e., forest types for dead trees as opposed to just live trees), the top three CWM species in terms of biomass prevalence can be examined (fig. 6.9). For a plurality of States, the top three CWM species are of such advanced decay they are recorded as an unknown species or unknown hardwood. However, in many cases, the prevalence of any particular CWM species can be attributed to past forest health issues, disturbance events, or long-term stand development/successional pathways. Certainly for the West Coast, the prevalence of Douglas-fir (*Pseudotsuga menziesii*) CWM can be attributed to Douglas-fir being a dominant tree species that has been a focus of dead wood studies for decades (e.g., Spies and others 1988). In Rocky Mountain States, ponderosa pine (*Pinus ponderosa*) is often a top CWM species owing to both its prevalence and widespread mortality events stemming from droughts, wildfire, and insects/disease (Bottero and others 2017). In the East, the prevalence of beech (*Fagus* spp.), eastern white pine (*P. strobus*), and red maple (*Acer rubrum*) may be an indicator of past diseases (e.g., beech bark disease; Morin and others 2007), trajectories of old-field succession, and/or natural progression of stand development. Akin to relative changes in decay and transect-diameter distributions of CWM biomass (e.g., figs. 6.5 and 6.8), the change in the relative percentage of the top five

CWM species relative to all other species over time can be examined by State (fig. 6.10). For a few States, CWM biomass is becoming more dominated by fewer species such as found in Arkansas, Massachusetts, Tennessee, Indiana, Florida, Texas, and Idaho; in contrast, Vermont, Connecticut, Kansas, and Oklahoma exhibited less dominance of the top five CWM species. The dominance of one species accounting for a plurality of CWM biomass across a State may be an indicator of past mortality events that primarily affected one major tree species in the context of perhaps a less diverse live tree diversity (e.g., ponderosa pine and mountain pine beetle [*Dendroctonus ponderosae*] mortality in Idaho) compared to the mortality of a less dominant tree species in a highly diverse system (e.g., flowering dogwood [*Cornus florida*] mortality in the Great Smoky Mountains).

The results of this national CWM change evaluation can be used to indicate trends in forest health dynamics with implications for CWM resource trajectories. Additionally, such an analysis may help identify CWM resource metrics of utility for conserving forest resources inclusive of dead wood (e.g., forest carbon stocks or habitat). Overall, CWM biomass has increased across forests of the United States, which is not surprising given concomitant increases in live tree volume and biomass during the same time period (Oswalt and others 2019). However, CWM biomass is increasingly represented by larger sized pieces of more advanced decay with a species composition that is less dominated by a few species (i.e., perhaps greater species diversity and/or species evenness). It can only be speculated as to what this CWM resource trend indicates as much more research into uncertainty analyses and relationships between CWM and standing live/dead trees needs to occur. However, the following hypotheses can be suggested. First, the increasing amounts of CWM biomass of larger sized pieces are probably indicative of the maturing forest resource across the United States. Second, as CWM pieces are increasingly of advanced decay, it suggests that there are fewer episodic disturbances (e.g., blowdown events) relative to mortality from stand development (i.e., tree suppression, senescence) and/or insects/disease (e.g., spruce budworm [*Choristoneura freeman*] or beech bark disease). Third, the somewhat steady or slightly reduced dominance of CWM species composition by a few species by State suggests that widespread species-specific mortality events are not imparting substantial additions to the CWM population beyond that of natural mortality dynamics (e.g., stand development). However, the relatively sparse sample intensity of the CWM inventory (especially during the 2002–2011 period) prevents further conclusions regarding mortality events that operate at the stand level (e.g., root rots). Overall, examinations of CWM resource dynamics provide an insight into past trajectories of forest development across large scales with implications for carbon and nutrient cycles, as well as an amenity of ecosystem services.

Beyond strategic-scale resource assessments, additional research is needed to enable further refinement of the initial analyses provided in

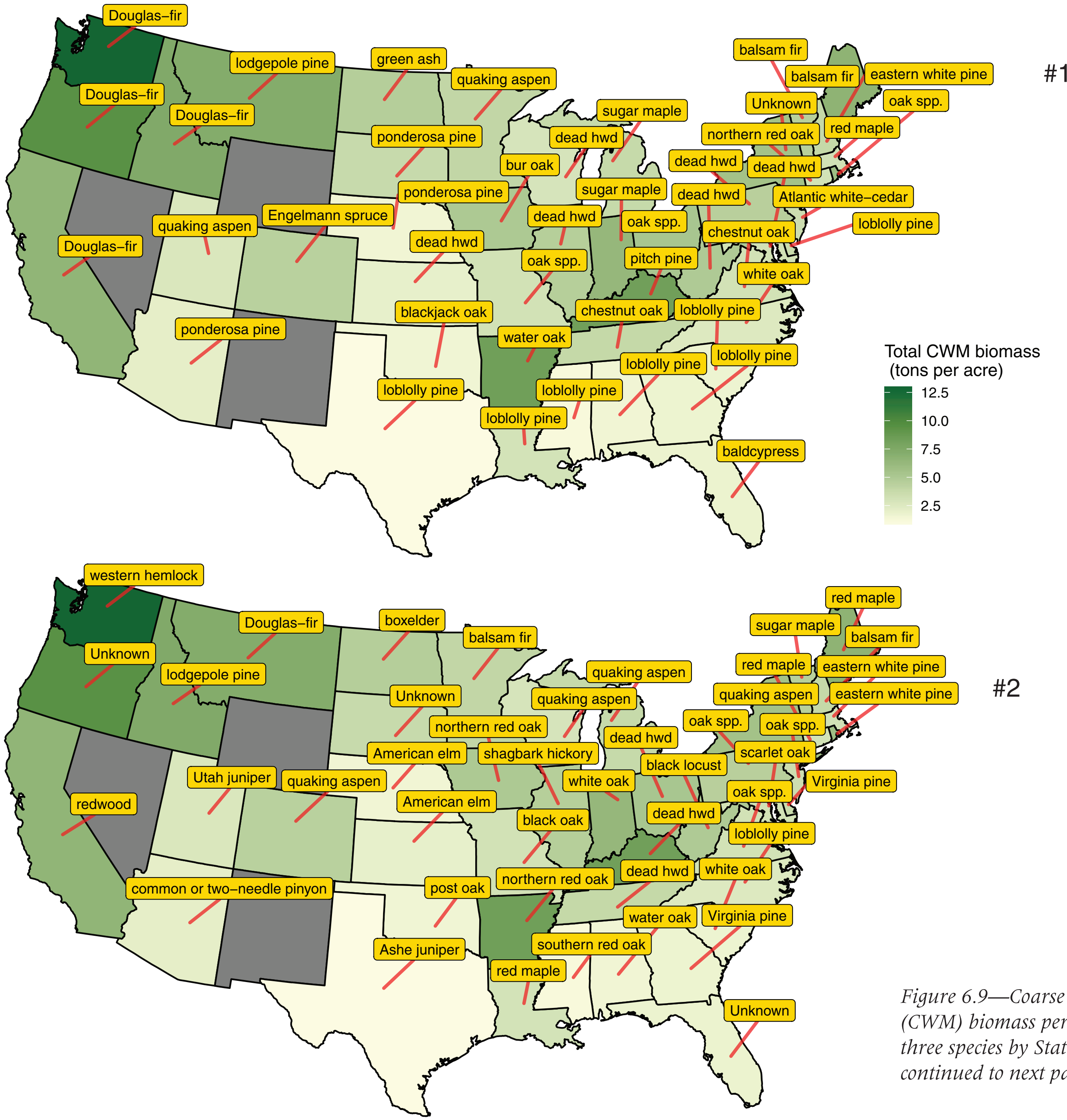

Figure 6.9—Coarse woody material (CWM) biomass per forested acre and top three species by State, 2012–2019.

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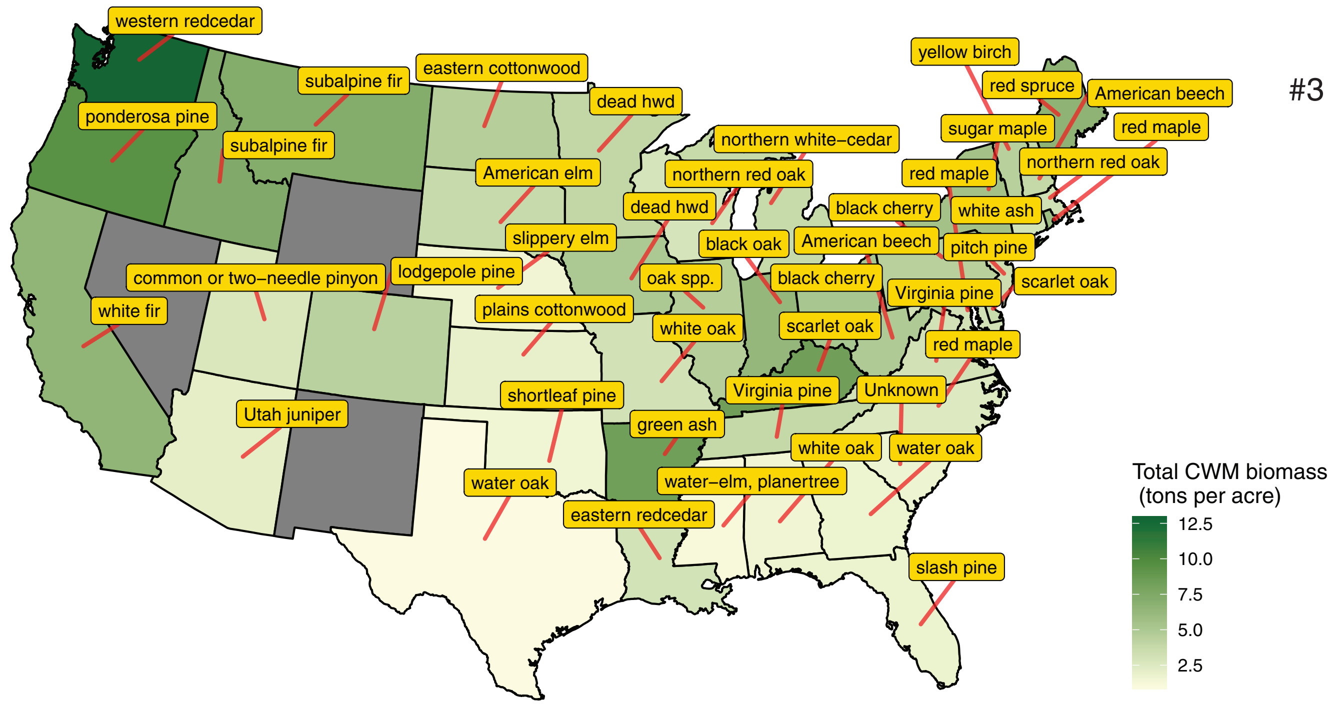

Figure 6.9 (continued)—Coarse woody material (CWM) biomass per forested acre and top three species by State, 2012–2019.

this study. Explicit linkages to standing live/dead trees provides a more comprehensive assessment of tree life cycles, stand development processes, and successional changes. Such a linkage is beyond the objectives of this study but would greatly aid efforts to manage carbon stocks and adapt forest management for future global change (e.g., climate change events or insects/disease). Furthermore, although individual CWM pieces are not explicitly tracked in FIA's strategic inventory, refinement of change estimation procedures beyond coarse large-scale stock change estimation paradigms would assist with unraveling CWM dynamics. It can be suggested that numerous resource monitoring paradigms for live trees do not necessarily apply to CWM given that CWM populations decline (volume and biomass loss) over time with a dependence on tree mortality for accretion, quite the opposite of live trees. Another topic of critical importance is the assessment of total uncertainty in CWM resource assessments. The FIA program enables the determination of sampling error associated with CWM data through online tools and documented procedures (Woodall and others 2019). However, there are numerous other sources of error that should be acknowledged in CWM resource analyses such as model

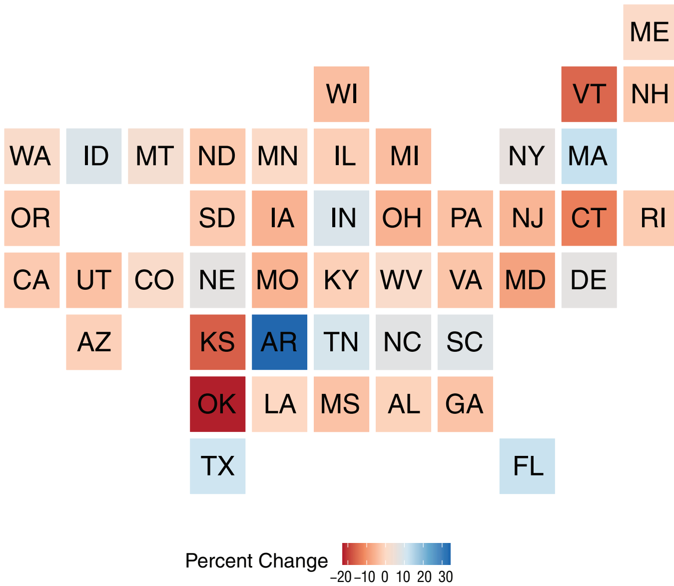

Figure 6.10—Change in percentage of biomass of top five coarse woody material (CWM) species accounting for total CWM by State, 2002–2011 to 2012–2019. (Note: a positive value indicates that the State's population of CWM biomass is becoming more dominated by fewer species over nearly 20 years.)

error (e.g., log volume) and uncertainties in decay reduction factors (Campbell and others 2019). Finally, more robust approaches to quantifying CWM diversity (e.g., species, size, decay state) are needed that are reflective of the unique aspects of this resource. Can functional traits indicative of tree decay pathways be incorporated to assist with interpretation of future resource trajectories? Relative to the lengthy history of forest management and associated sciences, the science of CWM resource monitoring and management has many opportunities for substantial advancement.

In conclusion, nearly 20 years of effort invested in a consistent, national inventory of CWM has established a baseline of data regarding the attributes of the CWM population at the outset of the 21st century as U.S. forests face increasing stressors (e.g., episodic precipitation, invasive species, and/or development). Although comparisons between the 2002–2011 and 2012–present CWM inventories should be at the population scale (e.g., survey units or States) due to revisions to plot measurement protocols, there remains an abundance of analytical possibilities that will only be expanded upon once the 2012–present inventory is fully remeasured. Not only will remeasured plots enable more sophisticated CWM dynamics modeling and longitudinal analysis (e.g., Russell and others 2014), the initial results of this study suggest that refining paradigms of CWM resource analysis in the context of live and standing dead tree attributes would greatly advance our understanding of forest structure, carbon pools, and nutrient cycles, among a host of vital forest ecosystem processes that all tier to dead wood.

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