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An assessment of the selection criteria, roles, and representativeness of indicator trees in the nationwide forest inventory of the United States

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ABSTRACT

In forest inventories, trees are often singled out to represent forest attributes and other environmental conditions. These "indicator" trees may be selected to estimate site level attributes, including site productivity, stand age, climate history, and growth rates. Here, we use data from the nationwide forest inventory (NFI) in the United States (US) to assess how indicator tree attributes compare to tally tree attributes across space and through time. First, we use contemporary field guides and NFI data to describe indicator tree selection criteria across regions of the US. Second, we compare indicator tree diameter, height, and species to two subsets of associated tally trees: a) all live tally trees and b) tally trees conforming to indicator tree selection criteria. Finally, we use annual ring width information from indicator trees to compare growth rates, as well as diameter and species to compare site trees and tally trees from historic inventories in the northeastern US. Contemporary and historic indicator tree attributes are rarely equivalent to either subset of tally tree attributes, but the differences are smaller when comparing to tally trees with consistent selection criteria. Across regions of the US, the differences between indicator tree and tally tree attributes are often close to or centered around zero, suggesting they may represent population-level tree attributes. With the increasing use of NFI data, it is important to understand the original intent for data collection, how the data were collected, and potential limits that might impact the efficacy of the data in new contexts.

1. Introduction

In statistics, sampling units or individuals are often selected to represent population parameters of interest (Levy and Lemeshow, 2008; Acharya et al., 2013). That is, samples can be used to make inferences about the entire population or some subset of the population when it is not practical to measure key attributes from the entire population. In the field of forestry, inventories are often designed to sample a population of interest by systematically establishing data collection plots for a given area. These data are used for various purposes in many national forest inventories around the world (Tomppo et al., 2010). In the United States (US), the Nationwide Forest Inventory (NFI) is collected and maintained by the US Department of Agriculture Forest Service Forest Inventory and Analysis (FIA) Program. Like many national forest inventories, the US NFI is a valuable source for informing forest management and planning activities, timber availability and harvest utilization, and carbon estimation from local to national scales (Westfall et al., 2022; Domke et al., 2024).

Nations have been designing, collecting, and maintaining NFIs for various purposes since the 1920's (Breidenbach et al., 2021). The intent of early NFIs were often to monitor forest resources and estimate sustainable timber yields, but since their inception the applications of NFI data has expanded based on country-specific circumstances and needs, e.g., to monitoring and managing multiple dimensions of forest health and ecosystem services, in particular, carbon storage and sequestration (Tinkham et al., 2018). The original aim of early US inventories was to quantify productive timberland (Bechtold and Patterson, 2005), defined as "nonreserved forest land capable of producing at least 20 cubic feet of wood volume per acre per year" (Burrill et al., 2024). Forest lands were inventoried based on a threshold of productivity and on a periodic basis.

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Around the turn of the 21st Century, a nationally consistent, annualized sampling design was established following the 1998 Farm Bill, initiating a comprehensive NFI, designed to characterize conditions across all forest land (Bechtold and Patterson, 2005).

All current and historic NFIs involve (re)measurements of individual trees, documenting species, diameter, height information, and tree status, among many other attributes within a specified plot design (Fig. 1A). Trees within the plot boundary, which are subject to standard data collection procedures (e.g., diameter and height measurement), are hereafter referred to as tally trees. In addition to field measurements of tally trees, tree core samples from a small number of trees on or associated nearby with the inventory plots may be taken for a variety of purposes: characterization of site productivity (site trees), estimation of stand age (age trees), and estimation of growth in new plots or for special studies on environmental change impacts (growth trees). Here, we have grouped these latter three types of trees together and refer to them as "indicator trees" as all are chosen based on a specific set of selection criteria, such that the trees can be used as an indicator of plot-, condition-, or stand-level information. Mapped domains (i.e., conditions) on annual plots were an important addition in the transition to a nationally consistent NFI design, such that tally trees on subplots may be associated with different forest conditions (forest types, ownerships, stand ages, etc.), and an indicator tree is typically sampled for each condition (U.S. Department of Agriculture, Forest Service, 2022d, Fig. 1A). As such, information obtained from indicator trees such as site productivity or stand age class may be used as a domain classifier when aggregating tally-tree and plot-level attributes to population estimates (Bechtold and Patterson, 2005; Westfall et al., 2002).

Of the indicator trees, site trees may be the most commonly used for classifying purposes in a forestry context. A site tree is intended to characterize the maximum growth potential of trees on a site and is often a dominant or codominant tree (i.e., the tallest tree present that is not overtopped or the uppermost vegetation layer) (U.S. Department of Agriculture, Forest Service, 2022b) selected from within the plot boundary or outside the plot boundary but within a given distance. While in some regions a site tree may also be a tally tree, they are unique from tally trees in that they are also cored with an increment borer to determine individual tree age by counting tree rings in the field or in the lab. Site tree attributes are primarily used to estimate site index, which is a measure of potential site productivity and is defined as the "average total length in feet that dominant and co-dominant trees are expected to attain in well-stocked, even-aged stands at the specified base age" (Burrill et al., 2024) for a given species (Skovsgaard and Vanclay, 2008). To determine site index, age (from the tree core) and height are related to site-tree curves for a particular species that were developed, sometimes decades earlier, with the purpose of assessing site quality (Carmean et al., 1989). From a forest management perspective, understanding the potential of a site to produce biomass allows managers to forecast timber yields and plan management activities to meet landowner objectives (e.g., maximize wood production) (Carmean, 1975). In this way, site tree attributes inform the expected or potential growth rate of a forest stand on a given site, integrating the effects of climate, soil, and other site attributes on tree growth. In the NFI context, information from site trees (e.g., site productivity class or site index) may be used as a domain classifier for population estimation in reporting and management contexts (Fig. 1A) (e.g., reporting the stocking density of all forests in a particular jurisdiction with a potential growth >120 cubic feet/acre/year [~ 840 cubic meters/sq.km/year]).

Cores can also be collected from other indicator trees ("age" or "growth" trees) to estimate stand age or periodic growth increment, respectively. Like site trees, age trees are often selected to be dominant or codominant trees, but unlike site trees, they are selected from the stand size class, which characterizes the predominant size class of all live trees, seedlings, and saplings (U.S. Department of Agriculture, Forest Service, 2022b). To avoid coring additional trees, a core from a site tree may be used to estimate stand age (U.S. Department of Agriculture, Forest Service, 2022b). Like site trees, attributes from age indicator trees in the US NFI may be used to aggregate tree or plot information by domains of interest, such as stand age classes. Regionally, for specified tally trees or timber species, cores may also be collected to determine radial growth (especially in initial sampling of a plot when trees do not have previous measurements (Burrill et al., 2024; U.S. Department of Agriculture, Forest Service, 2022e) or for particular forest health monitoring efforts (Hornbeck et al., 1988; Smith, 1990). In the western US, NFI remeasurement periods are approximately 10 years, and increment information from growth indicator trees has been used to estimate previous growth rates in newly established plots prior to remeasurement (DeRose et al., 2017; Witt et al., 2012). In the Northeastern US in the 1980s, a special collection of > 20,000 indicator trees were selected as "stand age" trees and cored to estimate growth trends and quantify species productivity in response to acid rain deposition (Smith, 1990). While indicator trees in NFIs have been sampled for different reasons, (e.g., site, age, growth) they are typically measured with similar criteria (a focus on dominant and codominant trees), may be used to classify tally trees into a particular domain of interest, and are often used opportunistically for other purposes.

While attributes from cored indicator trees, including tree diameter, tree height, and species and growth information, are primarily measured to estimate forest stand conditions (e.g., site index, stand age), data from these trees may be used in new contexts. Retention of increment cores from the US NFI has allowed for the measurement and maintenance of annual ring width information (Hornbeck et al., 1988; Smith, 1990; DeRose et al., 2017; U.S. Department of Agriculture, Forest Service, 2023). These indicator tree data have since been used in novel ways, despite different motivations for measurement. For example, tree-ring data collected from NFI plots have been used to parameterize climate-sensitive tree growth models and predict growth responses under future climate (Klesse et al., 2020; Giebink et al., 2022a; Heilman et al., 2022), quantify local differentiation and adaptation of tree species to climate (Canham et al., 2018; Evans et al., 2024) and even reconstruct past climate (DeRose et al., 2012, 2013).

Although NFI-based indicator tree data have been used to estimate climate sensitivity and interannual responses, there is little information about indicator tree applicability for prediction and management (e.g., to parameterize forest growth and yield models and inform management decisions). Selection criteria may place constraints on which tally trees in the inventory plot are represented by the measured indicator trees. While the indicator tree selection criteria are available in the USDA Forest Service field guides (U.S. Department of Agriculture, Forest Service, 2022a, 2022b, 2022c, 2022d, 2022e, 2023), a comparison of cored indicator trees to tally trees is needed to characterize the population of trees that indicator trees represent within the US NFI. Here we use US NFI data across space and through time to address three main questions: 1) Based on the selection criteria in the field guides, what subset of tally tree attributes are indicator tree attributes intended to represent?, 2) How do indicator tree attributes compare to tally tree attributes on the same NFI plots, specifically with regards to tree diameter at breast height (DBH), tree height, and species composition?, and 3) Do these criteria affect representativeness of growth information from cored indicator trees? We focus on indicator trees, using recent NFI field guides (U.S. Department of Agriculture, Forest Service, 2022a, 2022b, 2022c, 2022d, 2022e, 2023) and contemporary (i.e., 1995–2022) indicator tree data (n = 529,698) across the conterminous US and Alaska from the FIA database (Burrill et al., 2024) to address the first and second questions, respectively. Then, as a novel use case, we further address the second question and the third question using cored indicator trees (n = 22,936 total; 5139 in fixed area plots) with ring width information from cored indicator trees from early inventories (i.e., completed prior to the current annualized design 1982–1991) (Hornbeck et al., 1988; Smith, 1990; Hansen et al., 1992).

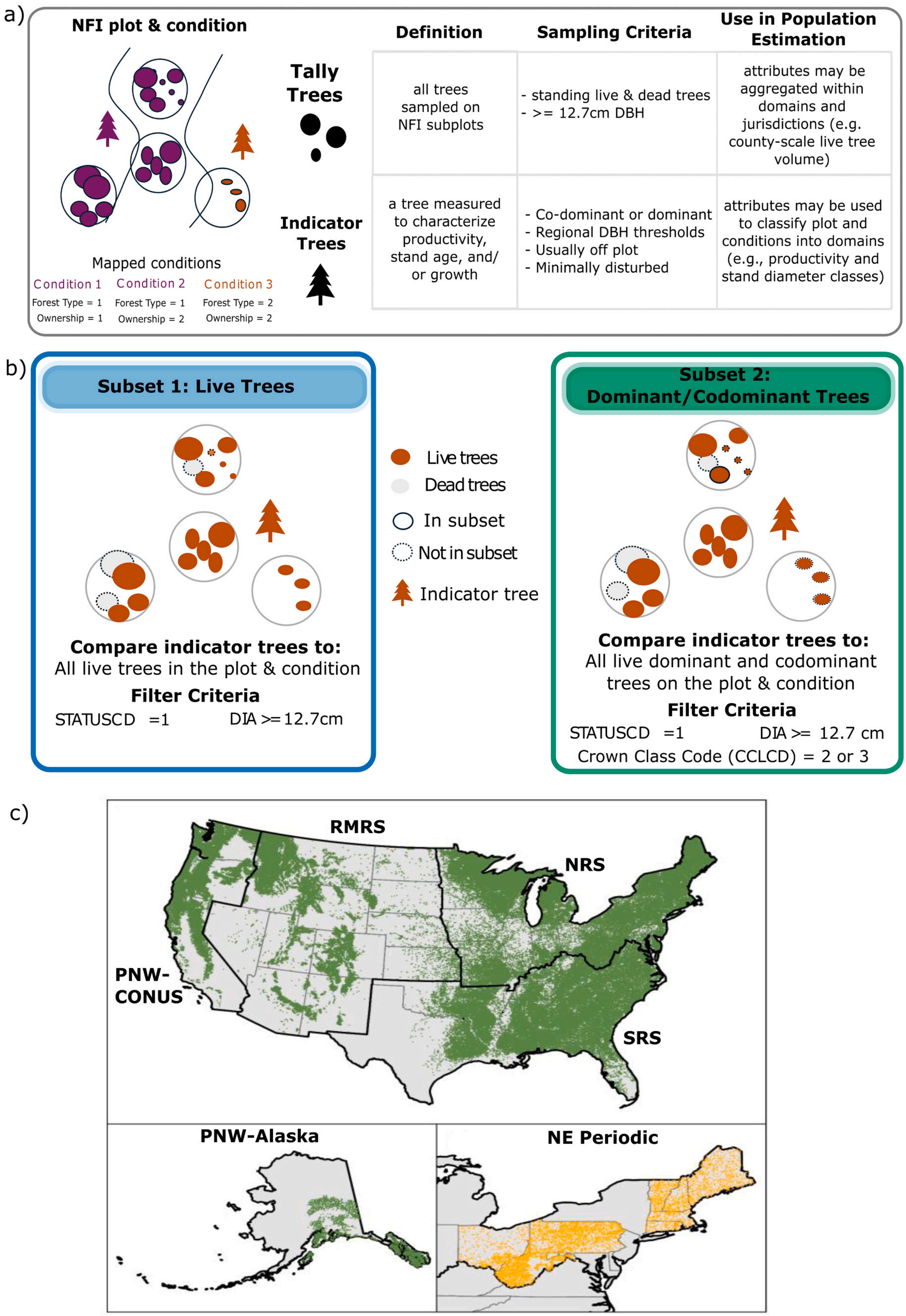

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Fig. 1. a) Conceptual overview of US NFI plot design and the definitions of tally trees and indicator trees, their sampling criteria and example uses in population estimation. The US NFI conducts measurements of all standing live and dead tally trees on individual plots that consist of four subplots (microplots and macro plots not shown) and have mapped conditions which may delineate different forest types, stocking densities, ownerships, etc., if present. Indicator trees (≥ 1 per condition) are typically sampled off plot and used to characterize features of a plot and/or condition. While attributes of tally trees are aggregated in population-level estimates (e.g., county-level forest volume), indicator trees may be used to classify plots and conditions into domains for estimation (e.g. tree volume by productivity classes). b) Example plot diagrams showing the trees included in the two tally tree subsets (Live and Dominant/Codominant) considered in comparisons of tally and indicator tree attributes. c) Perturbed forest inventory plot data across the United States (US). Green dots designate locations where site trees were cored as part of the annual inventory design, whereas yellow dots represent locations where trees were cored in the northeastern US with a periodic inventory design.

2. Methods

2.1. Field guide examination

Field crews can reference selection criteria for indicator trees (i.e., site, age, and/or growth trees) in the appropriate USDA Forest Service field guide. For the field guide examination, we focus on the criteria for indicator tree selection, as our analysis primarily uses site tree data, which is easily accessible from the FIA database (Burrill et al., 2024). Further, the criteria for site tree selection vary more across regional field guides than the criteria for age tree selection and growth tree selection are specific to one region (U.S. Department of Agriculture, Forest Service, 2022e). To determine which tally tree attributes these indicator tree attributes are intended to represent, we compiled site tree selection criteria from the national (U.S. Department of Agriculture, Forest Service, 2022b) and regionally-specific FIA field guides (U.S. Department of Agriculture, Forest Service, 2022a, 2022c, 2022d, 2022e, 2023). The national field guide provides a nationally consistent framework for collection procedures, from which regional research stations base their regional field guides. The Northern Research Station (NRS) oversees data collection and maintenance across 20 northeastern states, the Southern Research Station (SRS) across 13 southern states, the Rocky Mountain Research Station (RMRS) across 12 states encompassing the Great Basin, Southwest, Rocky Mountains, and parts of the Great Plains, the Pacific Northwest Research Station (PNWRS) for Alaska, Washington and Oregon, as well as California, Hawaii, and the US-affiliated Pacific Islands. Here we perform regional analyses, based on field guide delineations, consistent with research station boundaries except in the case of PNWRS, which has separate field guides for Alaska (U.S. Department of Agriculture, Forest Service, 2023) and the Washington, Oregon, and California region (U.S. Department of Agriculture, Forest Service, 2022a), which we refer to as PNW – Alaska and PNW – CONUS, respectively (Fig. 1). Notably, a full inventory of interior Alaska's boreal forest is yet to be completed. Hence, we limited our analyses to data available publicly. We exclude Puerto Rico, US Virgin Islands, Hawaii, and US-affiliated Pacific Islands from our analysis.

2.2. Data

2.2.1. CONUS Site trees from the annual inventory design

In addition to a qualitative analysis of indicator tree selection criteria across the 5 study areas, we performed a quantitative analysis comparing indicator tree attributes to attributes from tally trees (i.e., trees greater than or equal to 12.7 cm) they are intended to represent. We obtained indicator tree and tally tree attributes for each of the 5 study areas (i.e., NRS, SRS, RMRS, PNW – Alaska, and PNW – CONUS) from the site tree table (i.e., SITETREE) in the FIA database (Burrill et al., 2024). Indicator trees collected from a plot design consisting of four 7.3152 m fixed-radius subplots (approximately 0.0169 ha) as well as indicator trees collected on the southeast Coastal Alaska periodic grid plot design with 7.3 m fixed-radius subplots were analyzed. We did not filter for consistent sampling designs across microplots because we did not compare indicator trees to saplings (2.54–12.7 cm DBH) collected on microplots. Subplot tally trees were matched to their representative indicator tree by plot identifier (i.e., PLT_CN) and condition number(s) (i.e., CONDID). All trees present on the microplot and macroplot were excluded from the study, avoiding complications with tree expansion factors due to varying plot sizes. were excluded from the study, avoiding complications with tree expansion factors due to varying plot sizes.

2.2.2. Northeastern US site trees from the periodic inventory design

Tree cores were collected in the northeastern US state-level periodic inventory plots by the USDA Forest Service FIA program in the 1980s and early 1990s as stand age trees and previously used to quantify impacts of acid rain on tree growth (Hornbeck et al., 1988; Smith, 1990). Documentation describing the tree selection and sampling indicates this collection was similar to contemporary site tree selection and sampling, being "healthy dominant or codominant trees representing major species" (Smith, 1990). See Hornbeck et al. (1988) and Smith (1990) for a description of traditional dendrochronological methods to prepare cores, measure ring widths, and cross-date (Speer, 2010). The dataset includes growth increments from almost 23,000 cores from 75 different species distributed across 9 states in the northeastern US (Fig. 1c) and associated measured or estimated DBH information (Canham et al., 2018). We matched the northeastern indicator tree cores to tally trees in periodic forest inventory plots in the Eastwide forest inventory database (Hansen et al., 1992), which was developed to unify differences in forest inventories across eastern US. These periodic inventories prior to the establishment of the annualized sampling design were conducted at the state-level, where all plots sampled were visited in the same inventory year in most states. States had varying remeasurement periods (9–17 years), and varying plot designs, including both fixed radius and 10-point variable radius sampling schemes. To keep the analysis consistent with the annual inventory design analysis and data, variable-radius plots were removed from the data set in the main analysis presented here (n = 5139). See Supplementary methods for additional information and analysis with variable radius plots, and different plot designs. Cored indicator trees were matched to all Live tally trees greater than or equal to 12.7 cm by plot identifier, based on the state, county, and plot number, as well as closest plot measurement year to core collection year (See Supplementary methods).

2.3. Comparisons

To evaluate the efficacy of using indicator tree attributes from the US NFI for future applications (e.g., the development of tree growth models), we first compared each indicator tree attributes to live tally tree attributes on the matching plot and mapped condition (where applicable). Then, we applied the selection criteria of "dominance or codominance" and compared each indicator tree to dominant or codominant tally trees (i.e., crown class code [CCLCD] is 2 or 3). In other words, our first comparison is to test how representative indicator tree attributes (e.g., species, DBH, height, growth) are of the subset of live tally trees (Fig. 1B) and our second comparison is to test how representative indicator tree attributes are of the subset of live dominant and codominant tally trees on their respective plot (and conditions). Subsets are referred to as "Live" and "Dominant/Codominant" or "Dominant and Codominant" hereafter. We also compared cored indicator trees from the periodic northeastern US to both all Live tally trees and live Dominant/Codominant tally trees on the associated plots to evaluate their representativeness for future applications.

2.3.1. DBH and height equivalence tests

To test for similarity in DBH and height between the indicator trees and tally trees and quantify the difference, we used an equivalence test, where the null hypothesis is dissimilarity (Robinson and Froese, 2004). We performed the two one-sided test (TOST) for equivalence (Kirkwood and Westlake, 1981; Schuirmann, 1981) with each attribute (i.e., DBH and height), using a robust *t*-test (Yuen and Dixon, 1973; Yuen, 1974), which makes no assumption of normality. We paired each indicator tree attribute to tally trees on their respective plots (and conditions) and tested for dissimilarity in the paired difference between the indicator tree attributes and associated tally tree attributes for two subsets: 1) all Live trees > = 12.7 cm DBH and 2) all live Dominant/Codominant trees > = 12.7 cm DBH (Fig. 1B). With both equivalence tests, we set the region of similarity (i.e., epsilon) to 25 % of the standard deviation of the difference between the indicator tree and associated live tally tree attribute of interest (i.e., DBH or height). We summarize the results of all equivalence tests by region (PNW-Alaska, PNW-CONUS, RMRS, SRS, and NRS, and for the attributes available, NE periodic). For the set of cored indicator trees in the northeastern US periodic design, an equivalence test for height was not performed because the data lacked height information. The equivalence test results in either “rejecting the null hypothesis” (equivalent), “not rejecting the null hypothesis” (not equivalent), or “not enough data” for an equivalence test.

2.3.2. Species importance value

To assess how representative the indicator tree species is to its associated tally trees (that is, at the plot and condition-level for indicator trees collected from annual inventories and at the plot-level for cored indicator trees collected from periodic inventories), we calculated the importance value (percent) of the indicator tree species. Importance value here is an average of the relative dominance (percent), which is based on basal area, and relative density (percent), which is based on number of stems, for the two subsets of tally trees (i.e., Live and Dominant/Codominant). An importance value of zero percent would mean the indicator tree species is not present at the condition or plot level, whereas an importance value of 100 percent would mean the indicator tree species is the only species present at the condition or plot level. We removed indicator trees with not enough live tally tree DBH information to make a statistical comparison (Supplementary Table 2), which could overinflate the extreme (i.e., zero or 100 %) values.

2.3.3. Growth equivalence test

For the set of cored indicator trees in the northeastern US periodic inventories with tree-ring growth data, we performed a robust TOST for equivalence between mean annual diameter increment (MAI) for each indicator tree core and the matched Live tally trees and Codominant/ Dominant tally trees from the plot to test for similarity based on 25 percent of the standard deviation of the difference in MAI of all Live tally trees. For periodic inventory plots that have been measured twice, the Eastwide database provides the previous tree measurement and the remeasurement period, from which we can calculate MAI (i.e., an average annual growth rate), as DBH at the current measurement minus DBH at the previous measurement divided by the remeasurement period. Ingrowth tally trees with no previous DBH measurement were removed from the analysis, while Live tally trees with the same or smaller DBH at remeasurement were retained for the analysis. MAI for indicator tree cores was calculated with the same number of years as the tally tree calculation (i.e., n = remeasurement period length, See Supplementary materials). The Eastwide database also includes some variable radius plots, and fixed radius plots with different size thresholds. We report and discuss the equivalence tests on all fixed radius plots, but document differences in growth and diameter attributes that arise under different sampling designs (See Supplemental materials and Methods).

3. Results

3.1. Field guide exploration

National field guide criteria for indicator tree selection, particularly site trees, are to select a dominant or codominant tree with no visible suppression or damage from a species that is ideally representative of the stand and on a defined list for the region, which is often comprised of species with valid models to estimate site index (Supplementary Table 1; U.S. Department of Agriculture, Forest Service, 2022b). The PNW field guides (i.e., for Alaska, California, Washington, and Oregon) state that a species that is “representative of a stand” is a defining member of the forest type (U.S. Department of Agriculture, Forest Service, 2022a, 2023). The national field guide mandates that one indicator tree be selected for each forest condition unless differences in condition status are not due to differences in site productivity (e.g., ownership) (U.S. Department of Agriculture, Forest Service, 2022b), whereas regional field guides mandate one to ten indicator trees per accessible forest condition be selected (Supplementary Table 1). Other regionally specific criteria include diameter and age requirements (Supplementary Figs. 1–5). In some regions, indicator trees may be selected on the subplot, whereas other regions require indicator trees off the subplot but within a given range (Supplementary Table 1).

3.2. Comparisons

The results of the equivalence tests for DBH, height, and MAI are split into 3 categories: not equivalent (where the null hypothesis of dissimilarity is not rejected), equivalent (where the null hypothesis of dissimilarity is rejected), and not enough data to make a statistical comparison. There are several reasons why there might not be enough tally trees associated with a cored indicator tree for a particular plot and/or condition, for example, a recent clearcut event, or regenerating stands with many saplings only on the microplot. For all tests, filtering from all Live to only Dominant and Codominant tally trees resulted in a greater number of cored indicator trees that did not have enough tally tree data to perform a statistical test of equivalence.

3.2.1. DBH and height equivalence tests

Across space (i.e., regions) and time (i.e., periodic to annualized inventory design), a small percentage of indicator trees (approximately 4–12 %) are equivalent in DBH to both Live tally trees and Dominant/ Codominant tally trees (Supplementary Table 2). Most indicator trees (approximately 61–91 %) are not equivalent (i.e., outside a threshold of difference) in DBH for Live tally trees and Dominant/Codominant tally trees. Across space, the number of indicator trees that are equivalent increased after filtering for only dominant and codominant tally trees, which was driven by relatively greater changes with filtering in the SRS and PNW-CONUS regions (Supplementary Table 2). A majority of indicator trees from the annual NFI design have a positive mean difference in DBH, meaning indicator trees often have a larger DBH than both Live tally trees and Dominant/Codominant tally trees (Fig. 2a–e, Supplemental Table 5). A slight majority of cored indicator trees from the fixed area periodic design have a negative mean difference in DBH (meaning cored indicator trees are often smaller than both Live tally trees and Dominant/Codominant tally trees), but the mean differences for non-equivalent comparisons are relatively small (− 1.5 cm and − 3.3 cm for all Live and Dominant/Codominant subsets respectively) (Fig. 2f, Supplemental Table 5). Additional analysis of the NE periodic dataset shows this is likely driven by larger, sawtimber-sized trees on fixed area plots (Supplemental Fig. 10). NE periodic variable radius plots also show indicator trees having substantially smaller diameter than tally trees (Supplemental Fig. 11). While most of the individual indicator trees are not equivalent to, and slightly larger than tally trees on the plot, the median of the difference in DBH is < 5 cm within most regions (PNW – CONUS is the exception, with median differences of 14.7 and 10.0 for

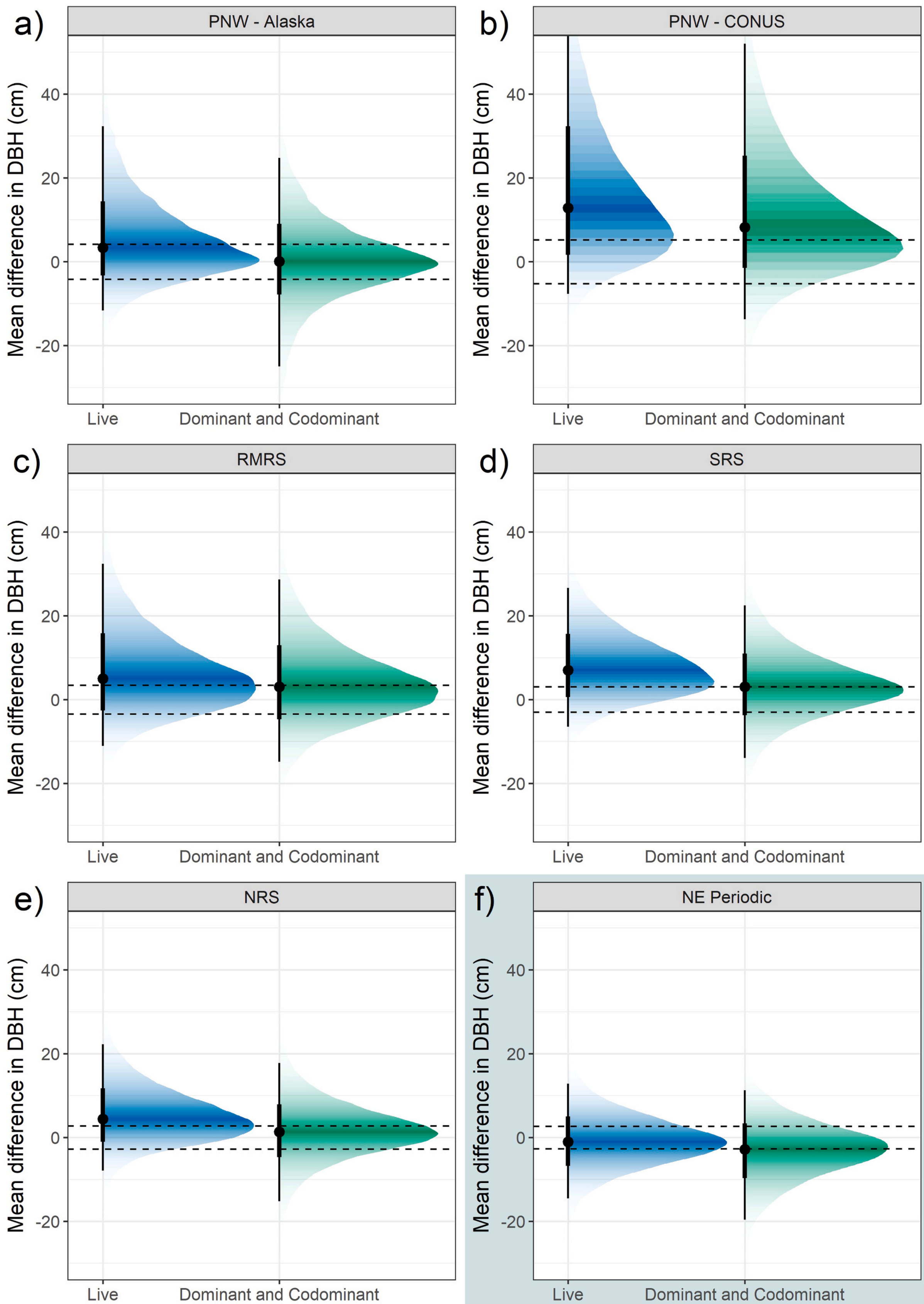

Fig. 2. Difference in diameter at breast height (DBH). Mean difference in DBH (cm) between a site tree and its associated live tally trees and dominant and codominant tally trees and the region of similarity (i.e., epsilon, dashed lines) for a) PNW-Alaska, b) NRS, c) PNW-CONUS, d) SRS and e) RMRS annual inventories, as well as f) fixed radius northeastern (NE) US periodic inventories. Points and error bars represent the median and 95 % Confidence Intervals of the difference distributions.

the Live and codominant and dominant subsets respectively), especially for Dominant/Codominant tally trees (Fig. 2, Supplemental Table 5), suggesting that indicator trees may represent tree attributes at the population level across space and time.

Like DBH, a small percentage of indicator trees from the annual design (approximately 5–14 %) are equivalent in height to both Live tally trees and Dominant/Codominant tally trees (Supplementary Table 3). Most indicator trees (approximately 60–90 %) are not equivalent to both Live tally trees and Dominant/Codominant tally trees. Across regions, the number of indicator trees that are equivalent in height increased after filtering for only Dominant/Codominant tally trees. Most indicator trees showed a positive mean difference in height (Regional medians are < 7 m for Live trees and < 5 m for Dominant/Codominant subsets), meaning indicator trees often have a greater height than both Live tally trees and Dominant/Codominant tally trees (Fig. 3, Supplemental Table 5). The 50 % quantile mean difference in height is reduced, often crossing the threshold of similarity (i.e., epsilon), for Dominant/Codominant tally trees compared to Live tally trees.

3.2.2. Species importance value

The importance value (i.e., the average of a species relative dominance and relative density; percent) of the indicator tree species has a higher proportion greater than 50 % in the Western US and less than 50 % in the Eastern US (Fig. 4). That is, in the NRS and SRS annual inventories and the northeastern US periodic inventories, species of the cored indicator tree was often not the prominent species on the condition(s) or plot, respectively, whereas in the PNW-Alaska, PNW-CONUS, and RMRS annual inventories, species of the cored indicator tree was more often the prominent species on the condition(s). The top three species selected as an indicator tree and summaries of the indicator tree importance values are reported in Supplemental Table 5.

3.2.3. Growth equivalence test

In terms of MAI, a small percentage of cored indicator trees from the periodic fixed radius plot design are statistically equivalent (approximately 10 %) to both Live tally trees and Dominant/Codominant tally trees (Supplementary Table 4). Most cored indicator tree MAI values (approximately 70–80 %) are not equivalent to both Live and Dominant/Codominant tally tree MAI, and the rest do not have enough data to make a statistical comparison. The number of cored indicator trees that are equivalent decreased after filtering for only Dominant/Codominant tally trees (Fig. 5, Supplemental Table 5). While most of the indicator trees are not equivalent, for all the fixed radius plots, the 50 % quantile of mean difference in MAI is close to zero and within the threshold of similarity (i.e., 25 % the standard deviation of the difference in MAI) for both Live tally trees (median difference = (Median Difference = 0.07 cm) and the Dominant/Codominant tally trees (median difference (Median Difference = 0.04 cm) (Fig. 5, Supplemental Table 5). While the fixed radius plot mean differences are close to zero, an analysis of the variable radius plot differences in growth indicates a slight negative difference (Supplementary Fig. 23).

4. Discussion

Indicator trees are widely used in forest inventory applications to characterize site quality, stand age, and tree growth, among other forest stand and site-level characteristics. As selecting, coring, and measuring indicator trees involves substantial investments, we evaluated how well those indicator trees represent associated tally trees at the plot and population (i.e., regional means) level. Here, we find that selection criteria has implications for the tally trees within the domains (i.e., plot and mapped conditions) that indictor trees represent—we find that indicator trees often are larger in DBH and height than their associated tally trees, vary in terms of the importance of site tree species varies on the plot/subplot, and MAI of site trees is more often than not +/- 1 cm of the tally tree MAI. With most attributes and regions, the differences are smaller between indicator trees and Dominant/Codominant tally trees (compared to the Live tree subset). However, average differences between indicator and tally trees at the plot and subplot scale (for most attributes and regions) are often close(r) to zero, suggesting in most cases that indicator trees may represent certain tree attributes at the population level (i.e., county, state, region), especially for dominant and co-dominant trees.

4.1. Selection criteria for indicator trees

Based on the selection criteria in the field guides, indicator trees are not intended to be representative of all of the trees in a stand, but are selected to be above a given diameter threshold and from a population of Dominant/Codominant trees (U.S. Department of Agriculture, Forest Service, 2022b) (See Table S1). Indeed, indicator trees in the annual design are often larger in DBH and height than associated tally trees, with indicator tree DBH and heights often outside a threshold of similarity (i.e., 25 % the standard deviation of the difference) for all Live tally trees and the dominant and co-dominant tally tree subset. However, when averaged across a region, these individual indicator tree attributes are more similar (i.e., the 50 % quantile mean difference in DBH was closer to zero) to associated Dominant/Codominant tally tree attributes than all Live tally tree attributes. Therefore, analyses using indicator tree attributes from the annual design as a means to classify tally trees into a domain of interest (e.g., stand diameter or site productivity classes) for population estimation may misrepresent small diameter or understory trees. However, when averaging across a population (i.e. a region) these differences are often small (less than 3 cm for most regions), but scale with average tree sizes across regions (PNW-CONUS region has larger diameter differences due to large diameter indicator trees) (Fig. 2, Supplemental Table 4).

While indicator trees from the annual design were often larger than associated tally trees, we found indicator trees from the northeastern US periodic design were often slightly smaller, in terms of DBH, than the tally trees on the plot (by 1.5 and 3.3 cm for Live and Dominant/Codominant subsets respectively). Exploration of diameter distributions and diameter differences by plot design suggests that sampling of sawtimber sized trees (which tend to be larger than the indicator trees) in some fixed area plot designs explains these differences (Fig. S10). Further, for a majority (almost 80 %) of indicator trees from the periodic design, DBH was not measured, instead it was estimated by summing radial increments (Canham et al., 2018), which may under-estimate DBH by inaccurately accounting for bark thickness. Additionally, indicator trees are generally smaller compared to plot tally trees in variable radius plot designs (Supplementary Fig. 10), which is expected based on variable radius plot designs, where tree size and distance from plot center are related to determine whether a tree is within or outside the plot boundary. Thus, differences in the plot designs and size thresholds used in periodic inventories in the Eastwide database (Hansen et al., 1992), in addition to the tree size classes should be evaluated when applying indicator tree information to tally trees.

Selection criteria also instruct field crews to select a species that is ideally representative of the stand, i.e., a defining member of the forest type (U.S. Department of Agriculture, Forest Service, 2022a, 2023), and on a list for the region (U.S. Department of Agriculture, Forest Service, 2022b), which might exclude species that may not have a model for estimating site index, for example. In assessing the relative importance of the site tree species, we found that in the eastern US, the species of the indicator tree was often not fully representative of the associated tally tree species (Fig. 4b, d, and f), which may be due to more mixed or multispecies forest stands in the eastern US compared to other regions. Further, a high proportion of species may not have site index models because they may either be economically unimportant or relatively rare across the region (Westfall et al., 2017; Zobel et al., 2022). On the other hand, in the western US, we found the indicator tree species to be fairly

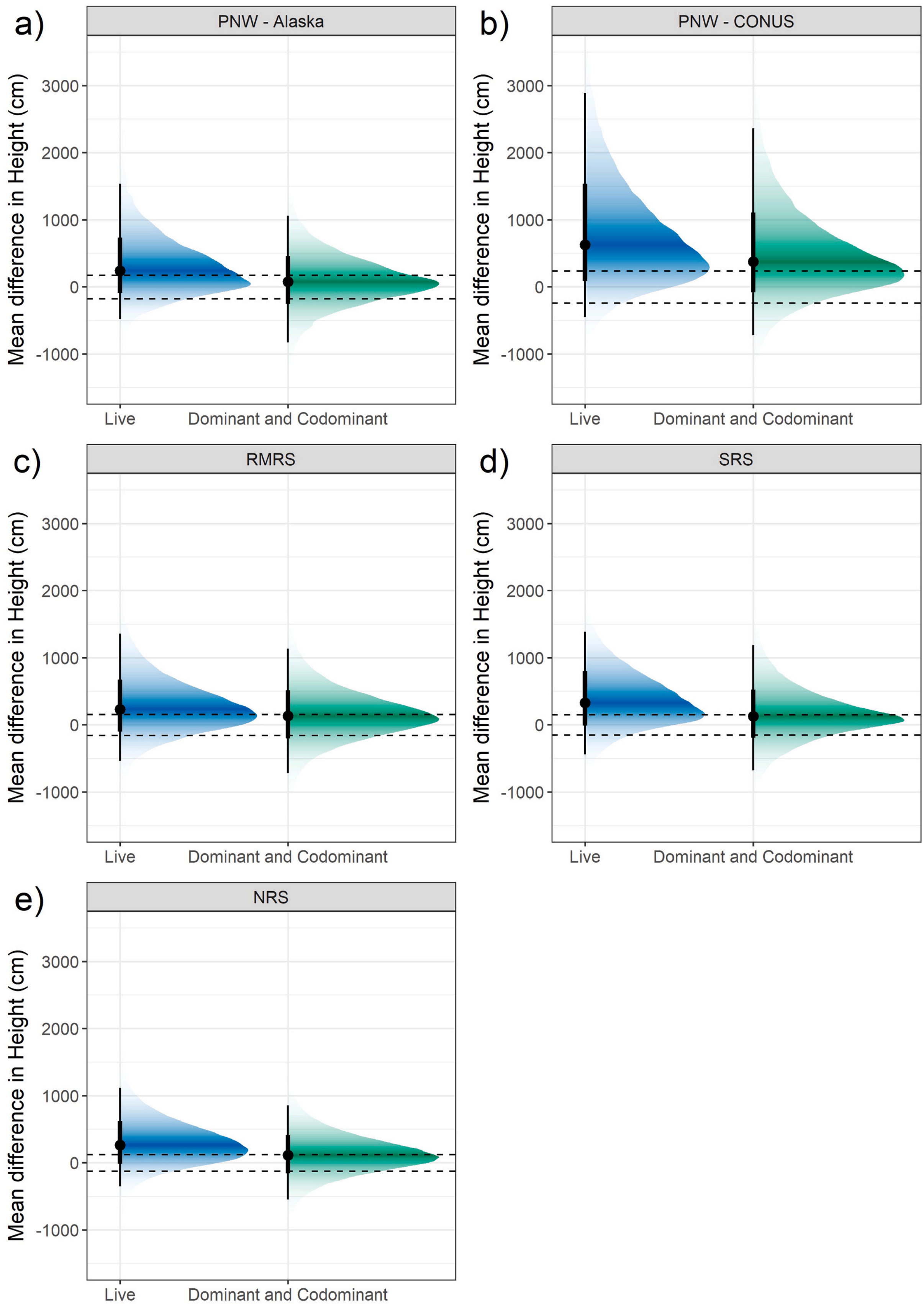

Fig. 3. Difference in height. Mean difference in height (cm) between a site tree and its associated live tally trees and dominant and codominant tally trees and the region of similarity (i.e., epsilon, dashed lines) for a) PNW-Alaska, b) NRS, c) PNW-CONUS, d) SRS, and e) RMRS annual inventories. Points and error bars represent the median and 95 % CI of the difference distributions.

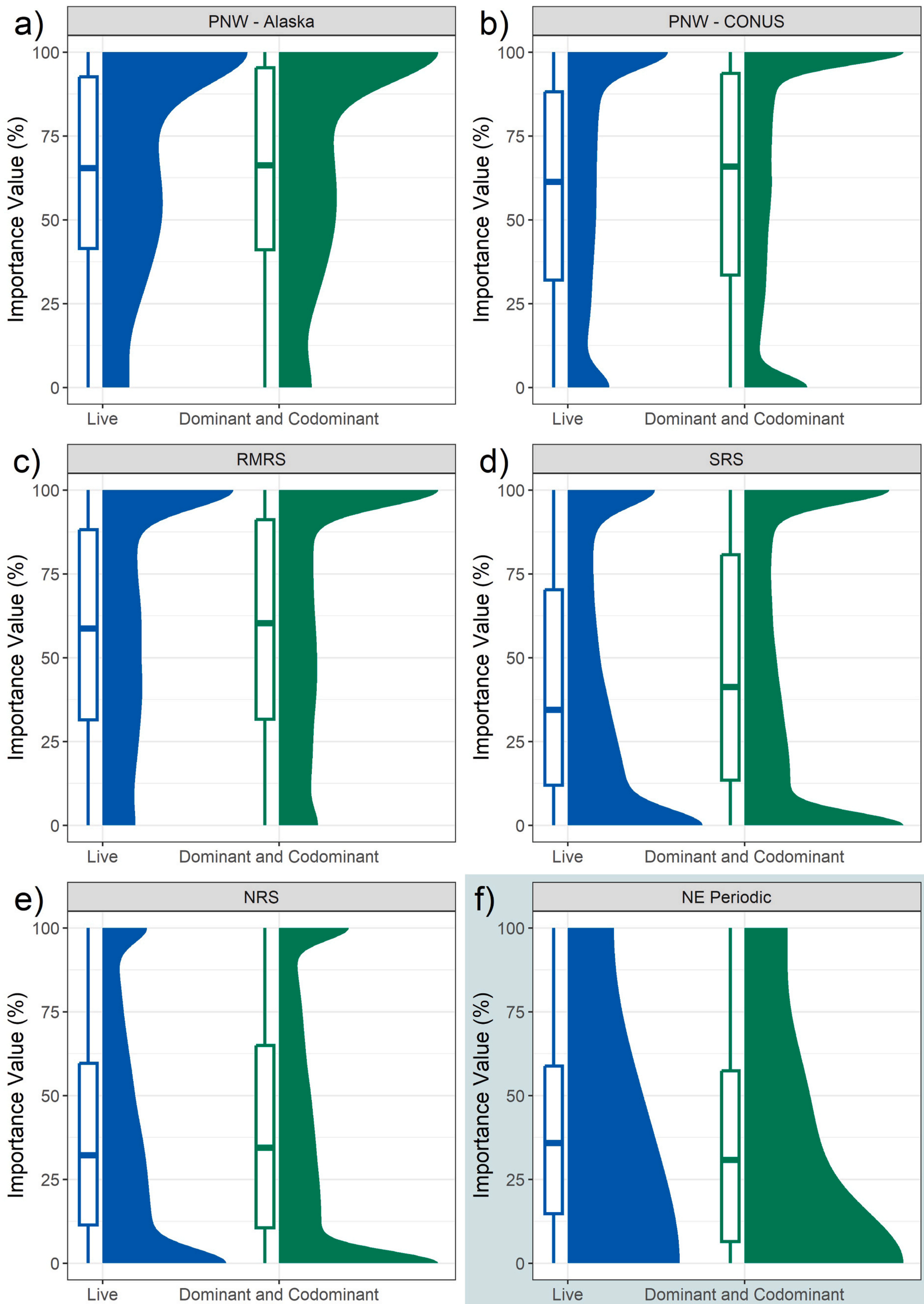

Fig. 4. Site tree species importance value. Importance value (percent), calculated as the average of relative dominance and relative density, based on both associated live tally trees and dominant and codominant tally trees for a) PNW-Alaska, b) NRS, c) PNW-CONUS, d) SRS and e) RMRS annual inventories, as well as f) fixed radius northeastern (NE) US periodic inventories.

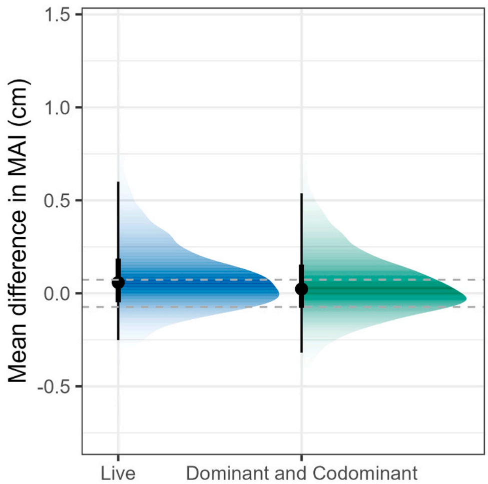

Fig. 5. Mean difference in mean annual diameter increment (MAI, cm) between a cored site tree and its associated live tally trees and dominant and codominant tally trees and the region of similarity (i.e., epsilon, dashed lines) for fixed radius northeastern (NE) US periodic inventories. Points and error bars represent the median and 95 % CI of the difference distributions.

representative of the associated tally tree species (Fig. 4a, c, and e), which may be due to a less mixed forest stands that do not require as much of an investment in site index model development.

Another criterion is to select indicator trees with no visible suppression or damage due to, for example, disturbance, which can be common at the tree-level (Nigh and Love, 1999; Fitts et al., 2022). Despite these criteria, indicator trees may have experienced these conditions in the recent past—dendrochronological analysis of cores from the northeastern US periodic inventory design had evidence of growth suppression due to spruce budworm defoliation in several counties in Maine (Smith, 1990). The field selection criterion that indicator trees have no visible suppression could lead to misrepresenting the growth of understory trees and the known presence of disturbances in the dendrochronological samples likely contribute to the observed MAI differences. There are differences in MAI between indicator trees and their tally trees at the plot-level, but averaged across the region, MAI was comparable with Live tally trees and Dominant/Codominant tally trees (i.e. median of the differences is centered very close to zero; 0.07 and 0.04 cm respectively). Averaging increments may smooth out interannual variation, which may differ or be more variable among trees of different sizes or species on the plot. For example, average growth and growth sensitivity to climate are often both size dependent, with smaller trees generally growing faster and larger trees being generally more sensitive to climate (Bowman et al., 2013; Canham et al., 2018; Anderson-Teixeira and Belair, 2022; Heilman et al., 2022). While our analysis suggests that indicator tree selection criteria may not over or underestimate average growth rates (on average), further research is necessary to determine how indicator trees can be used to accurately predict interannual growth and growth-climate sensitivity of tally trees.

In general, site trees are intended to represent a maximum growth potential for any tree on the plot (U.S. Department of Agriculture, Forest Service, 2022a). In this way, site trees should be representative of the location or site characteristics (e.g., climate and soil) that impact the height-growth observation. That is, the productivity of a site is treated as an attribute of the land base, not necessarily the trees themselves. Therefore, by collecting information at the tree level, the indicator tree is representative of the cumulative conditions it has experienced since establishment (e.g., species-specific susceptibility to insects or disease, competition), which may be different than conditions experienced by nearby tally trees or the broader population they represent. Indeed, selecting indicator trees that meet all the criteria for site index calculations can be challenging. For example, classifying crown position (dominant, codominant, intermediate, or suppressed) can be subjective and vary between remeasurements and among observers (Nicholas et al., 1991). With indicator trees being permitted to be used both as site trees and age trees and to estimate stand age (U.S. Department of Agriculture, Forest Service, 2022b), it is important to understand the selection criteria and how they influence the data collected (Supplementary Table 1).

4.2. *Indicator trees and site productivity estimation*

There is considerable variation in indicator tree attributes across space and their equivalence to tally tree attributes both within a plot and across regions, which may influence large scale analyses that use indicator tree information directly, or through derived estimates (i.e., site index/site productivity class and/or stand age). Within a stand, variation in stand density, structure, and composition can complicate collection and estimation (Toraño Caicoya and Pretzsch, 2020). Further, selecting a tree in a younger stand tends to result in higher estimates of site index (Nigh and Love, 1997). Regionally, indicator trees may be selected on the plot or within a given distance off plot (Supplementary Table 1). Sometimes an indicator tree is not available on plot or off plot within a given distance (McRoberts, 1996) due to selection criteria or a recent clearcut. Under such scenarios, an indicator tree may be selected from an adjacent stand, as permitted by the SRS field guide (U.S. Department of Agriculture, Forest Service, 2022d), or an unsuitable indicator tree may be selected, as permitted by the RMRS field guide (U.S. Department of Agriculture, Forest Service, 2022e) (see Supp. Table 1), leading to variation in selected trees. Variation in estimated site index calculated from these trees can then influence other attributes in the NFI, which may be used in domain-level estimation (i.e., summaries by stand productivity class) and the output of forest simulation models (Gertner and Dzialowy, 1984; McRoberts et al., 1994), which can be useful for decision support systems. To reduce variation and dependance on selecting for an idealized tree, an index of site productivity that leverages tally tree information may be considered (Berrill and O'Hara, 2013).

Site and indicator tree selection have implications for estimates of the site index and productivity over time (Mailly et al., 2004). For example, selecting a new site tree during a plot remeasurement can lead to a change in site productivity class (e.g., from unproductive to productive timberland, or the reverse) which would impact population estimates of growth and removals (Pugh, 2012) and influence management decisions. To avoid drastic and unprompted changes in site index and subsequently site productivity, indicator trees from one measurement can be carried over, which is often common practice. The field guide for data collection in Alaska mandates the collection of a new site tree if a treatment has occurred affecting the site's productivity (e.g., clearcut harvest, heavy thinning, irrigation, or fertilization) (U.S. Department of Agriculture, Forest Service, 2023). However, non-treatment events, whether abrupt (e.g., saltwater intrusion; Tully et al., 2019) or gradual (e.g., global warming; McDowell et al., 2020; Combaud et al., 2024), can contribute to variation in growing conditions on a site and thereby present as a change in site productivity. In light of changing climate, clear guidance for indicator tree selection in rapidly changing places may be necessary. Alternatively, a hybrid approach may be used, where estimates of site index can be adjusted with a process model based on changing conditions (Baldwin et al., 2001; Nothdurft et al., 2012; Bontemps and Bouriaud, 2014).

4.3. *Applications of indicator trees in forest health and management*

As NFI data, including indicator tree information, are increasingly being harmonized with auxiliary datasets to characterize multidimensional aspects of forest health, it is important to understand whether the original intention for data collection could introduce misleading outputs in these novel contexts. Site index and stand age have long been used in projecting forest growth and dynamics (Weiskittel et al., 2011), from early whole-stand yield tables (Meyer, 1929) used to inform timber production to landscape-level models used to account for carbon stocks and stock changes (Kurz et al., 2009). Tree-ring data from indicator trees have the potential to enhance inference from NFIs and improve models of forest dynamics to better understand demographic drivers and correlate changes (Evans et al., 2022). While FIA plots provide average annual growth estimates between plot remeasurements (every 5–10 years), models of tree growth that include climate sensitivity estimated from cored indicator trees could be used to infer or predict annual growth patterns in tally trees and generate annual estimates of tree growth for use in reporting and management (Giebink et al., 2022b). Our comparison of indicator tree attributes to associated tally tree attributes adds to recent work aimed at understanding potential limits in the application of NFI tree ring collection to growth models. In the context of climate change, predictions from growth models fit to tree-ring data from FIA indicator trees are likely more representative of growth for all trees in the population compared to typical dendroclimatology samples (Klesse et al., 2018). We show that indicator tree and tally tree selection differ and lead to regionally varying, but systematic size differences that generally scale with indicator tree size distributions. Additionally, while most plots have differences in growth between indicator trees and tally trees, average growth may not be systematically over or underestimated by indicator tree selection in the northeastern US periodic dataset. But, because annual growth typically varies by tree size and tree size often mediates climate sensitivity, the tree-ring data sampled from indicator trees have potential limits that are important to acknowledge when applying climate-growth relationships from indicator trees to predict tally tree growth. Plans to scale quantitative information from indicator trees (e.g., climate sensitivity and annual growth rates estimated from tree-ring data) to inform associated tally tree estimates require a clear understanding of indicator tree collection criteria, field practices, and the site conditions that indicator trees represent.

5. Conclusion

In this study we highlight the importance of understanding sampling protocols and intent of data collection in the US NFI, as these data are increasingly paired with auxiliary information at various scales to address myriad research and management objectives. Three conclusions can be drawn from this assessment. First, based on selection criteria in national and regional field guides, indicator trees may be selected for a range of intents, but all should be Dominant/Codominant trees, above a regionally specific size threshold, from a pre-established site tree species list, and have no visible damage or suppression. Second, indicator tree attributes are largely consistent with regional field guides; DBH and height are rarely equivalent with their associated tally trees on plots and/or conditions, but the indicator tree attributes may represent attributes of dominant and co-dominant trees at the population level (i.e., county, state, region), as average differences are often small (close to zero). Likewise, there is large variation in the relative importance of indicator tree species on the plot, which may reflect species diversity and differences between selection criteria and tally tree response to growing conditions. Third, selection criteria may contribute to growth differences observed in the historic northeastern US NFI – average growth rates (MAI) of indicator trees are rarely equivalent to tally trees on the same inventory plot, but these differences may cancel each other out at the population level (average MAI differences are < 0.1 cm). Further investigation with contemporary data from other regions would determine if this finding is consistent across sites and forest conditions. Variation in the differences between indicator tree and tally tree diameter, height, and species importance may reflect contrasting collection protocols and ecology over space (from Alaska to the Southern region of the US), and differences in inventory intent and changing conditions over time (from periodic to annual inventories). With the increasing use of NFI data across disciplines, our findings reinforce the importance of understanding the original intent of data collection, how that purpose influenced what or how the data were collected, and potential limits of the data in new contexts.

CRediT authorship contribution statement

Courtney L. Giebink: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Kelly A. Heilman:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Sean M.P. Cahoon:** Writing – review & editing, Writing – original draft, Methodology. **Grant M. Domke:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

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Data availability

All publicly available data from the US Nationwide Forest Inventory maintained by the USDA Forest Inventory and Analysis program is available at: https://research.fs.usda.gov/products/dataandtools/fia-datamart. Code for this analysis is available upon request.

Declaration of Competing Interest

I have nothing to declare.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.123200.

Data availability

All data from the US Nationwide Forest Inventory maintained by the USDA Forest Inventory and Analysis program is publicly available online at the FIA DataMart 2.0. Code is available upon request.

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