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Assessing the effect of snow/water obstructions on the measurement of tree seedlings in a large-scale temperate forest inventory

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National-scale forest inventories have endeavoured to include holistic measurements of forest health inclusive of attributes such as downed dead wood and tree regeneration that occur in the forest understory. Inventories may require year-round measurement of inventory plots with some of these measurements being affected by seasonal obstructions (e.g. snowpacks and seasonal flooding). In order to assess the potential effects that snow/water obstructions may have on the measurement/analysis of forest seedlings across large scales, the differences in seedling abundance between two inventory measurements (~5-year remeasurement period) and as affected by snow/water depth was ascertained using a repeated forest inventory across the eastern US. Results indicate that there is a general trend of decreasing seedling density over time (−33.16 seedlings ha^{-1} year^{-1}) in the eastern US, with snow/water depths in excess of 15 cm significantly affecting resulting estimates of seedling abundance. Although snow/water obstruction to seedling measurement occurred on ~9 per cent of inventory plots across the eastern US, snow was a much more common situation occurring on nearly 50 per cent of plots (at time 1, 2 or both) at high latitudes (>45°). Given the statistically significant effect of snow/water on seedling abundance estimates, tree regeneration assessments should not include observations obstructed by snow/water depths that exceed minimum seedling heights. Furthermore, seedling abundance inventories may mitigate the influence of measurement obstructions by sampling only during the summer or incorporating climate information into their sampling logistics.

Introduction

Over the past few decades, nations have endeavoured to monitor numerous aspects of their forest health and biomass/carbon attributes through processes such as the Montreal Process Criteria and Indicators (MPWG, 2006) and United Nations Framework Convention on Climate Change (Heath *et al.*, 2011). A diversity of criteria and indicators, ranging from maintenance of forest productivity to societal/legal frameworks, have been developed that require the input of empirically derived assessments of forest attributes (MPCI, 2009). In the US, a national-scale inventory of forests has been used to inform much of the US's forest sustainability assessments (Woodall *et al.*, 2011, Robertson *et al.*, 2011) and carbon stocks (Heath *et al.*, 2011). Quantifying the area and condition of planted forests (Smith and Oswalt, 2011), in particular status of tree regeneration, is central to large-scale sustainability assessments, as it is an indicator of future forest occurrence and species composition. In addition to monitoring contemporary forest sustainability, large-scale inventories of tree seedlings have been used to assess tree ranges and potential shifts (Woodall *et al.*, 2009; Zhu *et al.*, 2012). Given the central role of tree seedling measurements in large-scale forest sustainability assessments and climate change research (e.g. tree range assessments), ensuring the accuracy of seedling assessments based on field inventories is paramount.

As a component of the US's national inventory of forests (Smith, 2002; Smith *et al.*, 2009), tree seedlings are measured as a standard component of the standing tree inventory (USDA Forest Service, 2008). In addition to seedlings, there are a variety of other forest ecosystem attributes that are measured along the ground line (e.g. down woody materials, Woodall *et al.*, 2013; forest floor, Woodall *et al.*, 2012) on a sub-set of inventory plots during summer months. The forest inventory of the entire eastern US is conducted year-round, regardless of weather conditions (USDA Forest Service, 2012; Majewsky, 2013). As such, field crews can encounter deep snowpacks in winter or seasonally flooded areas during Spring/Summer. The frequency of such conditions is sufficient to warrant the measurement of their depth as standard field inventory protocols as Forest Inventory and Analysis (FIA) defines 'seedlings' as having minimum heights (e.g. 15.2 cm for conifers) that can easily fall below winter snowpacks in areas of the eastern US (USDA Forest Service, 2008; NOAA, 2013). The

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effect of snow/water depth on the measurement of forest inventory attributes in the understory has never been assessed. Furthermore, snowpacks have been shown to be one of the strongest controls of forest composition and distribution in areas such as the Lake States where deep snow can occur (Henne *et al*., 2007). Snowpacks often serve as regulators of hydrologic cycles and associated nutrient dynamics (Kobe, 2006), thus controlling regeneration success and sapling growth (Brooks and Williams, 1999). Given the role of tree seedling abundance measurements in forest resource assessments and ecological research, exploration of potential interactions between snow/water depth and estimates of seedling abundance in a large-scale forest inventory is warranted.

The goal of this study is to assess the effects of snow/water obstructions on the forest seedling abundance assessments using a forest inventory across the eastern US with specific objectives to: (1) estimate the frequency of potential seedling measurement obstructions (snow and water) by classes of latitude and month, (2) to examine changes in seedling abundance estimates in relation to snow/water depths on forest inventory plots and (3) to suggest general guidelines for tree regeneration analysis using the US's national forest inventory and potential field inventory improvements to mitigate snow/water obstructions to seedling measurements.

Methods

Data

The USDA Forest Service's FIA program is the primary source of information about the extent, condition, status and trends of forest resources across all ownerships in the US (Bechtold and Patterson, 2005). FIA applies a nationally consistent sampling protocol using a quasi-systematic design covering all ownerships in the entire nation (Bechtold and Patterson, 2005). FIA operates a multi-phase inventory based on an array of hexagons assigned to separate interpenetrating, non-overlapping annual sampling panels. In Phase 1, land area is stratified using aerial photography or classified satellite imagery to increase the precision of estimates using stratified estimation. Remotely sensed data may also be used to determine whether plot locations have forest land cover; forest land is defined as areas at least 10 per cent stocked with tree species, at least 0.4 ha in size and at least 36.6 m wide. In Phase 2, permanent fixed-area plots are installed in each hexagon when field crews visit plot locations that have accessible forest land. Field crews collect data on $>$300 variables, including land ownership, forest type, tree species, tree size, tree condition and other site attributes (e.g. slope, aspect, disturbance, land use) (USDA Forest Service, 2008). Plot intensity for Phase 2 measurements is $\sim$1 plot for every 2,428 ha of land (roughly 125 000 plots nationally). In the eastern US, inventory plots are re-measured every five years. Briefly, the plot design for FIA inventory plots consists of four 7.2-m fixed-radius subplots spaced 36.6 m apart in a triangular arrangement with one subplot in the centre. All trees, with a diameter at breast height (d.b.h.) of at least 12.7 cm, are inventoried on forested subplots. Within each sub-plot, a 2.07 m microplot offset 3.66 m from sub-plot centre is established. Within each microplot, all live tree seedlings are tallied according to species. Conifer and hardwood seedlings must be at least 15.2 and 30.5 cm in height; respectively, with both having a d.b.h. of $<$2.5 cm. Additionally, within each microplot all sapling-sized trees, d.b.h. between 2.5 and 12.7 cm, are measured.

All inventory data are managed in an FIA database (FIADB; Woudenburg *et al*., 2010; http://apps.fs.fed.us/fiadb-downloads/datamart.html) and are publicly available. Data for this study were taken entirely from the FIADB using the most recent annual inventory in 28 eastern states on a total of 21 099 plots spanning nearly 24° of latitude (25–49°N latitude) (Figure 1). Individual plots (i.e. all subplots combined) with no anthropocentric disturbances (e.g. harvest) and fully occupied by a forest condition (i.e. no other land uses such as agricultural) at both measurement times were considered individual study observations. Annual inventories and associated plots for each state were first established between 1998 and 2003 (Time 1, T_1) with subsequent re-measurement roughly 5-years later (Time 2, T_2), so sample intensities may vary by state.

Analysis

Given that the purpose of FIA's inventory is to assess the forest resources (e.g. forest land area and volume growth/mortality/removals) of the US, the inventory was not explicitly designed to directly examine the effect of snow/water on seedlings. Rather, the hypothesis of this study is that snowpacks affect the measurement of seedlings conducted during large-scale inventories where gauging the frequency and magnitude of such effects can improve the monitoring of the said forest resources. There are a few constraints to this study inherent with a national forest inventory. First, the remeasurement of forest inventory plots occurred over a 5-year time span across the eastern US. Although remeasuring an inventory plot pre- and post-snowpack for seedling abundance would be optimal for gauging the effect of snow/water obstructions, it is currently cost-prohibitive with FIA's mission to re-visit a sufficient number of plots during the same growing season. Second, because stand development continues over the 5-year period between measurements seedling change

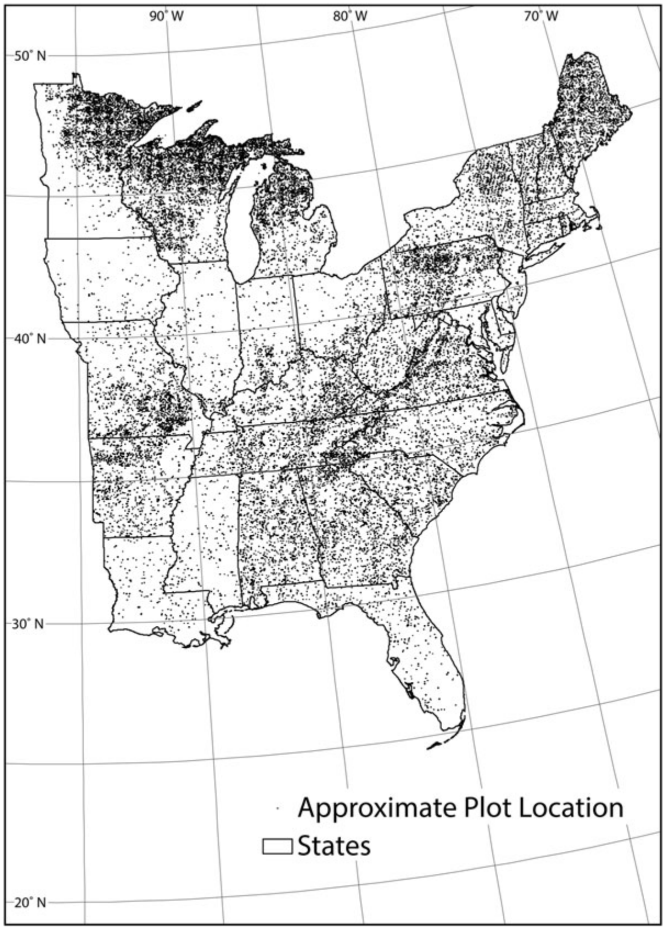

Figure 1 Approximate plot locations, eastern US forests, 1998–2010.

cannot be solely attributed to the presence/absence of measurement obstructions. However, trends in tree regeneration on plots that incurred no obstruction at T_1 or T_2 can substantially inform this study's objectives. Finally, field crews measure two variables related to snow/water on the plot (variables *watercd* and *waterdepth*; Woudenberg *et al.*, 2010). The *watercd* variable indicates the type of water body present on the plot (e.g. permanent water feature or seasonal flood) and is measured at the plot level (i.e. one value for all subplots). The *waterdepth* variable measures the depth of water or snow on each subplot (averaged for one mean depth across all the 4 subplots in this study). For the purposes of this study, a plot was considered to have water present when $watercd = 4$, 5 or 9 and $waterdepth > 0$ (i.e. there is an ephemeral water body on the plot). Permanent water features were not included in this study, assuming that they were present at both T_1 and T_2 (i.e. imparts no effect to seedling change estimates). A plot was considered to have snow present when $watercd \neq 4$, 5 and 9 and $waterdepth > 0$ (i.e. no permanent or ephemeral water features).

In order to assess the frequency of snow/water obstructions to seedling measurements, the proportion of observations by nine classes of various combinations of measurement status (bare ground, snow, or water) and time period (T_1 or T_2) was determined by latitude class (class width = 4°). Next, annual seedling change [(T_2 seedling count per ha$-T_1$ seedling count per ha)/measurement interval] was determined by T_1 and T_2 measurement month (snow/water depth T_2-snow/water depth T_1) in addition to estimates of mean snow/water depths at T_1 and T_2. To test for a significant effect of snow/water obstruction on estimates of seedling change, the baseline mean change was estimated using only plots that were unobstructed at both T_1 and T_2. To evaluate the effect of measurement obstructions, depth differences for each plot were used to sequentially incorporate obstructed plots into the sample. In 1-cm depth threshold increments, plots having an absolute difference, |(snow/water depth T_2- snow/water depth T_1)|, less than the depth threshold were added into the sample and the mean change was recalculated. Using the standard errors for these recalculated means, 95% confidence intervals were constructed and evaluated to determine whether the baseline mean value was contained within the interval. Failure of the baseline mean to be encompassed by the interval indicated the inclusion of obstructed plots resulted in a statistically different estimate than would be obtained from unobstructed plots alone. As initial results from this analysis suggested that only obstructions in excess of 15 cm resulted in statistically significant differences in seedling population estimates, the proportion of observations with snow/water obstructions in excess of 15 cm was determined by measurement month for both T_1 and T_2 as a means of inferring potential field/analytical impacts.

Results

The relative occurrence (percentage of all observations) of the various permutations of snow, water or bare ground at T_1 and T_2 by classes of latitude in eastern US forests suggests a potentially strong influence of latitude (Figure 2). As latitude is a reasonable surrogate for climate in the eastern US, nearly 50 per cent of inventory plots above 45° latitude had snow at T_1, T_2 or both. This percentage drops to ~35 and 10 per cent for plots located within the 41–45° and 37–41° latitude, respectively. Except for plots located below 33° latitude, there appeared to be a 'baseline' occurrence of water at either T_1 or T_2 in combination with snow or bare ground at the opposing time that accounted for ~10 per cent of observations. Plots located below 33° latitude were an exception with various combinations of water and bare ground (along with measurement errors creating snow misclassifications) accounting for nearly 20 per cent of observations. Across the eastern US, ~32 per cent of study plots had a snow/water obstruction at T_1, T_2 or both.

The mean depth of either snow or water (for study plots with non-zero snow/water depth) varied in accordance with the seasons in the eastern US, which appeared to influence resulting estimates of changes in seedling abundance (Figure 3). The largest mean snow depths of ~30 cm occurred at both T_1 and T_2 during the months of February and March. The largest mean water depths of ~17.5 cm occurred during the month of February. As estimates of seedling change can be attributed to either the T_1 or the T_2 measurement month, there are two trend lines of seedling change that are roughly converse of each other. For example, for seedlings that were measured during February at T_1 but remeasured at a random month for T_2, the resulting estimate of annual

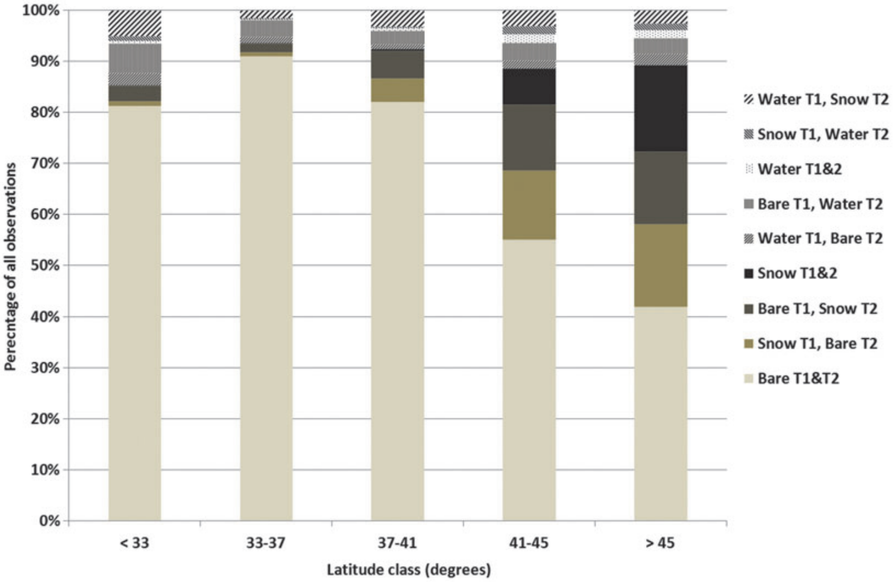

Figure 2 Percentage of tree seedling observations by snow/water measurement obstruction class by latitude class, eastern US forests, 1998–2010.

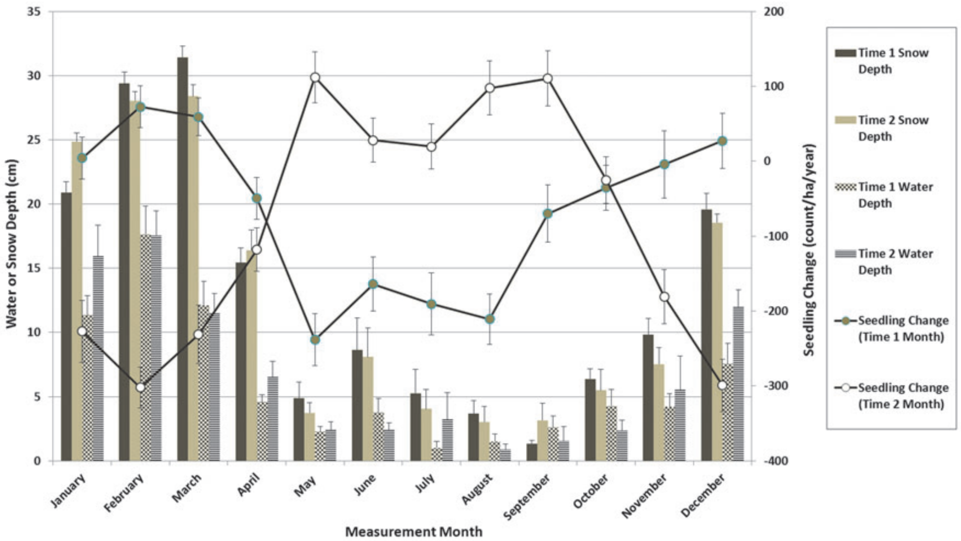

Figure 3 Mean snow/water depth and associated standard errors at time 1 and time 2 and annual change in seedling density (time 2 − time 1; count ha^{-1} $year^{-1}$) based on both time 1 or 2 measurement month for study plots where snow/water obstructions were present, eastern US forests, 1998–2010.

seedling change was ~50 counts ha^{-1} $year^{-1}$. In contrast, if T_1 is a random month with T_2 being February, the resulting estimate of seedling change was nearly -300 counts ha^{-1} $year^{-1}$.

The effect of snow/water obstructions on estimates of seedling population abundance was evaluated as observations were sequentially added with increasing snow/water depth differences (1 cm intervals) (Figure 4). The estimate of mean seedling change using unobstructed plots was −33.16 seedlings ha^{-1} $year^{-1}$. This estimate declined steadily as plots having increasingly larger obstructions were added to the sample. At a mean seedling change of −42.00 count ha^{-1} $year^{-1}$, the 95% confidence interval no longer included the baseline value of −33.16, indicating that a statistically different estimate was attained with an approximate depth of 15 cm. The seedling abundance estimate of −33.16 seedlings ha^{-1} $year^{-1}$ from the unobstructed plots was statistically different from zero ($P < 0.0001$), indicating a decline in seedling abundance over the study period. The same conclusion is reached when all plots are used with a resulting estimate of −46.00 seedlings ha^{-1}, which is also different from zero ($P < 0.0001$). However, the use of plots where measurements were obstructed by snow/water may be problematic, as the difference between the two values (−12.84 seedlings ha^{-1} $year^{-1}$) was statistically different from zero ($P < 0.0001$).

We evaluated the frequency of snow/water obstructions >15 cm by measurement month as this is the depth at which obstructions appeared to produce seedling abundance estimates that were significantly different from estimates obtained using unobstructed plots exclusively (Figure 5). Snow obstructions in excess of 15 cm depth on a plot occurred at proportions that ranged from 0.2 to 0.4 for plots measured at either T_1 or T_2 during the months of January, February, March and December. A water obstruction of >15 cm was an infrequent occurrence throughout the year with ~9 per cent of all study plots having such depth at T_1, T_2, or both.

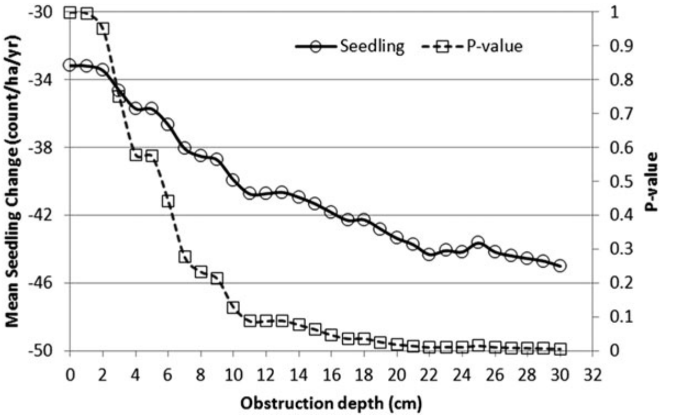

Figure 4 Estimates of mean seedling change (count ha^{-1} $year^{-1}$) and associated P-values for testing differences with the baseline value (−33.16) at 1-cm depth difference intervals.

Discussion

There is little doubt that snow/water obstructs the measurement of tree regeneration. As tree regeneration is an important component of forest resource and sustainability assessments (Smith *et al.*, 2009; Smith and Oswalt, 2011), failing to account for the influence of tree seedling measurement obstructions on estimates of seedling abundance could lead to erroneous conclusions. Given the diversity of forest regeneration dynamics, seasonal variability in snow/water depths, effect of wildlife browse (White, 2012; Fisichelli *et al.*, 2013) and logistics of conducting annual forest inventories, determining the specific influence of snow/water on forest regeneration attributes is necessary for improving the veracity of forest resource evaluations and guiding management directions.

First, given that eastern US forests as a whole are well-stocked (Woodall *et al.*, 2006), one might expect a general trend of less regeneration over time due to self-thinning and shading (Oliver and Larson, 1996). Indeed, in forests where there was no snow/water obstruction at either measurement time, there was a slight but significant decrease (−33.16 seedlings ha^{-1} $year^{-1}$) in estimates of

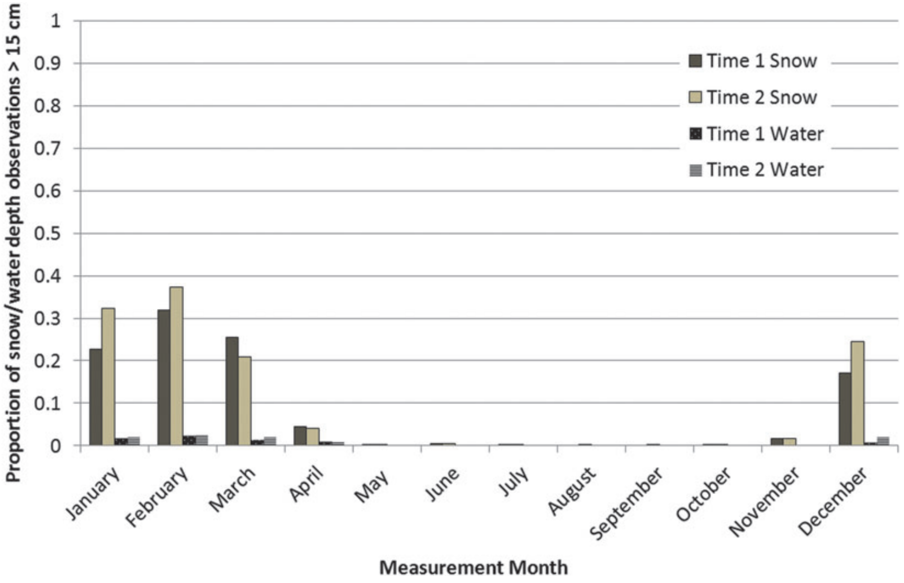

Figure 5 Proportion of snow/water depth observations exceeding 15 cm by month and measurement time period, eastern US forests, 1998–2010.

tree seedling abundance over time. Hence, the results of this study need to be viewed against a 'background' reduction in seedling abundance over time. Regardless of whether there were seedling measurement obstructions, one should expect less tree regeneration over time as the forests of the eastern US gradually mature (Smith *et al*., 2009) at a landscape scale. However, the inclusion of snow/water obstructed observations in the same analysis resulted in an estimate of -46.00 seedlings ha^{-1} year^{-1}. Given the scale of the seedling inventory across the eastern US, the effect of including snow/water obstructed plots in seedling analyses was not large but was significant, which could influence management decisions and/or inventories at smaller scales.

Second, water did not appear to be a substantial obstruction to seedling measurement except for the lowest latitude forests in southern Florida, where wetland systems abound. There was a consistent occurrence of field crews classifying water bodies as potentially permanent water features at T_1 and as ephemeral at T_2 and vice versa on <10 per cent of inventory plots. Despite annual field crew training, certification and quality analysis and control procedures, there is the logistical reality that varying field crews will visit the same plot during different seasons and weather. The varying classification of water bodies affected our study's interpretation of snow versus water obstruction on a minority of plots. When viewed broadly across all study observations, water obstruction in excess of 15 cm was a very infrequent occurrence and did not reach the same depths as snow obstructions when there was any water on a plot. The climate endemic to a region's forests should be considered when designing a forest inventory such that snow depths should be incorporated into inventories spanning much of the eastern US except for the southern limits where water obstructions may be a consideration.

Third, this study found that snow/water depths in excess of 15 cm significantly affected resulting population estimates of seedling abundance. It is perhaps beyond serendipity that this depth aligns with FIA's population definition of seedlings which require a minimum height (>15.2 cm for conifers). Based on this, a hypothesis can be forwarded that snow/water depths even slightly above the minimum seedling height can affect abundance estimates. Assessment of tree regeneration below FIA's minimum height thresholds could be affected by snow/water depths to an even greater extent than those examined in this study while their status is only just now being explored on regional scales (McWilliams *et al*., 2012). The design of forest inventories should explicitly account for the influence of snow/water depths in their assessment of tree regeneration whether through field logistics, analytical procedures or both.

Fourth, obstructions were mainly limited to high-latitude forests (>41° latitude) with deeper snowpacks. For forests over 45° latitude, nearly half of all the observed plots had snow/water obstructions at one or both measurement times. Given that there were roughly equal proportions of plots that had T_1 and T_2, T_1 only and T_2 only snow/water obstructions at high latitudes (latitude > 45°), there should not be a strong bias of snow/water obstructions on assessments of seedling change across large scales. However, obstructions to measurement of seedlings should increase the uncertainty associated with these estimates and potentially result in erroneous conclusions when the uncertainty is not acknowledged. Given the legislative mandate to conduct an annual inventory across the US (USDA Forest Service, 2012), sampling forests to avoid the effect of snow/water is problematic. Western US field crews conduct only summer sampling of inventory plots which is facilitated by early field season sampling in valley bottoms where high elevation sampling occurs towards the end of the field season when snowpacks have melted (Majewsky, 2013). As the eastern US has less elevational gradient compared with western forests, summer sampling presents a logistic hurdle. Field crews often depend on winter sampling to access wetland areas that are frozen allowing efficient access (Majewsky, 2013). In contrast, in 'snow belt' regions of the Upper Peninsula (Scott and Huff, 1996), plots are often scheduled for summer sampling for years in which deep snowpacks occur (Majewsky, 2013). Regardless of the field logistics needed to complete efficient plot measurement, regeneration assessments conducted in temperate forest ecosystems must respond to snow/water obstructions to measurement to reduce seedling estimate uncertainty.

Snow/water obstructions may never be completely avoided in annual forest inventories that are conducted in high-latitude/elevation environments, so it is relevant to ask: how can the potential effect of obstructions on resource inventories be mitigated? Field crews should be encouraged to schedule sampling during similar seasons for plots in 'snow belts.' This practice would help avoid the confounding effect of tremendous changes in snow/water depth over time that obviously affects seedling counts as seen in this study. Another possibility is to not sample tree regeneration during winter months, opting to 'subsample' tree regeneration during leaf-on months (McWilliams *et al*., 2012). This approach could potentially increase the sampling error (i.e. less sample intensity) associated with tree regeneration surveys, but reduce the effect of snow/water obstructions (e.g. measurement error). The effects of snow/water depth on seedling abundance analyses could be simply mitigated by removing obstructed observations from analyses as long as bias was not introduced (e.g. plots only dropped from high quality sites). Furthermore, given the difference in minimum height required for tallying seedlings (i.e. 15.2 cm for conifers and 30.5 cm for hardwoods), there could be a differential effect of snow/water depth on estimates of seedling abundance by conifer/hardwoods. For forest inventory analyses, perhaps incorporation of meteorological records of snow depth in 'snow belt' regions (Scott and Huff, 1996; NOAA, 2013) and/or direct calculation of changes in plot-measured snow depths could inform resources assessments and field logistics. Beyond identifying potential confounding factors to forest resource assessments, careful consideration of snow/water obstructions on the measurement and analysis of seedling dynamics should improve the understanding of tree regeneration in forest ecosystems.

Conclusions

Against a background trend of a general decrease of seedling abundance in eastern US forests (-33.16 seedlings ha^{-1} year^{-1}), this study found that the presence of snow/water in excess of a 15-cm depth on annual forest inventory plots significantly affected population estimates of seedling abundance across the eastern US. Approximately nine per cent of forest inventory plots had obstruction (>15 cm snow/water depth) of seedling measurement by snow/water with higher proportions in high latitude forests ($>45°$ latitude). Snow obstructions were a much more frequent occurrence at greater depths than water obstructions. Given the obvious effect that snow/water can have on seedling measurements, obstructed observations should not be included in tree regeneration analyses while forest inventories should be designed/conducted in a manner that mitigates the influence of snow/water obstructions (e.g. conducting only summer sampling of tree regeneration).

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