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The Effect of Harvest on Forest Soil Carbon: A Meta-Analysis

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Abstract: Forest soils represent a substantial portion of the terrestrial carbon (C) pool, and changes to soil C cycling are globally significant not only for C sequestration but also for sustaining forest productivity and ecosystem services. To quantify the effect of harvesting on soil C, we used meta-analysis to examine a database of 945 responses to harvesting collected from 112 publications from around the world. Harvesting reduced soil C, on average, by 11.2% with 95% CI [14.1%, 8.5%]. There was substantial variation between responses in different soil depths, with greatest losses occurring in the O horizon (−30.2%). Much smaller but still significant losses (−3.3%) occurred in top soil C pools (0–15 cm depth). In very deep soil (60–100+ cm), a significant loss of 17.7% of soil C in was observed after harvest. However, only 21 of the 945 total responses examined this depth, indicating a substantial need for more research in this area. The response of soil C to harvesting varies substantially between soil orders, with greater losses in Spodosol and Ultisol orders and less substantial losses in Alfisols and Andisols. Soil C takes several decades to recover following harvest, with Spodosol and Ultisol C recovering only after at least 75 years. The publications in this analysis were highly skewed toward surface sampling, with a maximum sampling depth of 36 cm, on average. Sampling deep soil represents one of the best opportunities to reduce uncertainty in the understanding of the response of soil C to forest harvest.

Keywords: forest management; harvest; soil carbon; soil order; deep soil; meta-analysis

1. Introduction

Forest ecosystems contain 1240 Pg C [1,2], which represents as much as 80% of aboveground terrestrial C and 70% of all soil organic C [3–5]. The relative proportion of forest C found in soils varies among biomes, ranging from roughly 85% of the terrestrial C pool in boreal forests, to 60% in temperate forests, to 50% in tropical rainforests [1,6]. The net balance of soil C in forests relies upon large rates of detrital inputs (61.4 Pg C year^{-1}) and respiratory losses (60 Pg C year^{-1}), which together represent substantial yearly turnover in the soil C pool [7]. By altering the rates of detrital inputs and respiratory outputs in soils, the extent and intensity of forest harvest can have substantial impacts not only on ecosystem function but also on atmospheric chemistry and global climate [6,8,9].

C is one of the principal components of soil organic matter (SOM), a key component of soil that plays an important role in many biological, chemical, and physical properties [10–12]. SOM provides a crucial source of energy and nutrients for soil microbes, buffers soil pH, and helps to stabilize soil structure [12,13]. Along with nitrogen and phosphorus, SOM is considered a critical indicator for soil health and quality.

Thus, soil C is an essential component of forest C accounting, yet many models assume that only surface soil responds to forest management and that soil C returns to equilibrium within 20 years after harvest [14]. Recent national or global assessments of forest C lack any mention of mineral soil

C [15–17], implicitly assuming that soil C remains constant after forest harvest. Furthermore, carbon monitoring programs include soil C inconsistently. For example, the American Carbon Registry [18] and the Verified Carbon Standard [19] do not require or specify protocols for soil C measurements. The Intergovernmental Panel on Climate Change (IPCC) inventory standards [20] assume constant mineral soil C in Tier 1, with an option for inclusion of national soil C inventories only if preferred by a particular agency, and the U.S. Forest Service Inventory and Analysis Program [21] specifically limits soil sampling to 20 cm depth. The inclusion of soil in models of ecosystem C following harvest can have significant effects. For example, in a model of the forest C pool change following intensive bioenergy harvest, Zanchi et al. [22] show that the inclusion of soil increases the C payback period by approximately 25 years when substituting forest bioenergy for coal. Thus, the inclusion or exclusion of soil in ecosystem C models and ecological monitoring programs can have a major impact on forest policy when attempting to mitigate climate change through forest management [14].

Ambiguity about the effect of forest harvesting on soil C has persisted in the literature, likely exacerbated by the inherent spatial and temporal variability in soil measurements that can obscure the results of even the most well-designed studies [23]. By gathering the results from many studies that apply similar treatments, meta-analysis can overcome the high levels of spatial and temporal variability to provide cumulative answers that may not have been evident within individual sites [23,24]. Previous meta-analyses on the effect of harvesting on soil C have found either minimal effects on soil C pools [25] or substantial (30%) loss to O horizon pools with little change to mineral soil C [9]. Variation in soil C response has been shown to significantly differ among soil types and different harvesting strategies [9].

Studies of soil C change due to harvest have historically been strongly biased toward surface sampling [26]. Nave et al. [9] reported a mixed response to harvest in deeper soil (20–100 cm depth), ranging from a slight average decrease (−5%) in studies that reported C pools to a large average increase (+20%) in studies that reported only C concentration. Several recent reviews have highlighted the need for greater sampling of deep soil [26–28], especially as the shifting paradigm of SOM research has come to reject the assumption that deep soil C cannot not change on timescales relevant to anthropogenic C emissions [29–31]. Resolving the response of deep soil horizons to harvesting is important because these horizons occupy a much greater volume than surface O and A horizons. Even small changes in subsurface C can exacerbate or compensate for changes in surface soil C, and neither the magnitude nor direction of subsoil C change is clear from previous research.

The process of meta-analysis is necessarily cumulative, with each iteration updating previous analyses to further constrain the error in effect size estimates and to extend the scope of analysis. Thus, the objective of our meta-analysis is to update and extend the findings of Nave et al. [9] with respect to five major research questions:

(1) What is the overall effect of forest harvesting on soil C pools?
(2) How does the effect of forest harvest on soil C change with soil depth?
(3) To what extent does the effect of harvesting differ among soil orders?
(4) Do site pretreatment strategies or increasing harvesting intensity (i.e., whole tree harvest) moderate or accentuate harvesting impacts on soil C?
(5) How long does soil C take to recover from harvest across different soil types?

2. Materials and Methods

Meta-analysis is a cumulative activity which builds upon previous research and meta-analyses on similar research questions. Our meta-analysis builds upon the work of Nave et al. [9] and Johnson and Curtis [25] by updating their results with studies published between 2008 and 2016. The database published by Nave et al. [9] was independently recreated from each of 75 references. Metadata for each study was verified, and additional metadata such as the sampling depth of each response ratio was gathered. A total of 8 effect sizes differed in our dataset from the Nave et al. [9] database, all of which were either additional data for mineral soils or a split of one effect size into two based upon sampling depth.

To add to this database with studies published between 2008 and 2016, we searched the peer-reviewed literature for relevant studies using the online database Web of Science with combinations of the terms: forest, timber, harvest, logging, soil C, soil organic matter, and management. No climate criteria was used to screen studies. To be included in the meta-analysis, publications had to report both a control as well as harvested treatments. Both pretreatment soil C and unharvested reference stands were considered acceptable controls, and measurements of reference stands were considered the superior control. For forest chronosequence studies, soil C data from the oldest stand was used as the control. A minimum stand age of 30 years was considered acceptable for control stands, although most studies used controls of considerably greater age. Nave et al. [9] found that studies reporting only soil C concentration data yielded different conclusions about the direction of harvest effects than those studies reporting soil C pool data. Consequently, soil C pool data was used in our meta-analysis when both concentration and pool data were available.

We collected potentially useful predictor variables of soil C response from each publication, including soil order, geographic region, and time since harvest (Table 1). Binning of continuous predictor variables (such as precipitation) was carried out in the same intervals as Nave et al. [9] for ease of comparison. Each study was categorized by harvest, residue management, and site preparation strategies. Harvesting technique was categorized as sawlog when only the merchantable bole (stem) was removed from the site or whole tree harvest (WTH) when the tops, limbs, and foliage were removed in addition to the bole. To test the response of soil C at different depths, data from each study was separated into one of five groups: O horizon, top soil (0–15 cm), mid soil (15–30 cm), deep soil (30–60 cm), and very deep soil (60–100+ cm). A sixth group called whole soil was assigned to studies that aggregated mineral soil samples instead of reporting results at separate depths. Several studies aggregated soil data from 0–100 cm, which reduced the number of unique deep and very deep soil observations even though these depths were separately sampled.

Table 1. Factors gathered as potential predictor variables in this meta-analysis.

Factor	Levels	
Reporting units	Pool (Mg·ha^{-1}), concentration (% or mg·g^{-1})	
Soil Depth	O horizon	Forest Floor
	Top Soil	0–15 cm
	Mid Soil	15–30 cm
	Deep Soil	30–60 cm
	Very Deep	60–100+ cm
Overstory species	Hardwood, conifer/mixed	
Soil order	Alfisol, Andisol, Entisol, Inceptisol, Mollisol, Spodosol, Oxisol, Ultisol	
Geographic group	NE North America, NW North America, SE North America, SW North America, Europe, Asia, Pacific (Australia, New Zealand)	
Harvest type	Clearcut, thin	
Harvest intensity	Stem only, whole tree	
Residue management	Removed, spread	
Site preparation	Broadcast burn, tillage/scarification	
Soil texture	Fine (mostly silt or clay), coarse (mostly sand), organic	
Time since harvest	Continuous	
Mean Annual Temperature	0–5, 5–7.5, 7.6–10, 10.1–15, 15.1–20, >20 (°C)	
Mean Annual Precipitation	<500, 500−750, 751−1000, 1001−1400, 1401−1800, >1800 (mm)	

Our meta-analysis estimates the magnitude of change in soil C using the ln-transformed response ratio R, which is defined as

$$\ln(R) = \ln\left(\frac{\overline{X_T}}{\overline{X_C}}\right) \quad (1)$$

where $\overline{X_T}$ is the mean soil C value of treatment (harvested) observations, and $\overline{X_C}$ is the mean soil C value of control observations for a given set of experimental conditions at a specific site and depth. Multiple response ratios were recorded for each publication, with the number of response ratios (k) depending upon the number of experimental conditions imposed and the number of samples taken by depth. For example, a publication that reports the results of two thinning treatments and two clear-cut treatments at three depth increments (forest floor, top soil, and mid soil) versus a control would yield 12 response ratios. R is a unit-less measure of effect size, which allows comparison among studies that report data in different units [24]. By back transforming ln(R), $[(e^{(\ln(R))} - 1) \times 100]$, mean response ratios can be interpreted as the percentage change in soil C relative to the control. Estimates of the standard deviation and sample size for each $\overline{X^T}$ and $\overline{X^C}$ were not available in several publications. Consequently, an accurate estimate of total heterogeneity (Q_T) for the dataset was not possible. Subsequent partitioning of Q_T into within- and among-group heterogeneity (Q_W and Q_A, respectively) for random and mixed effect models (as is customary for meta-analyses) was not possible [24]. Instead, we used nonparametric resampling techniques (bootstrapping) to estimate confidence intervals around mean effect sizes in an unweighted meta-analysis [9]. Adams et al. [32] recommend bootstrapping confidence intervals for ecological meta-analyses, and show that confidence bounds based on this method are more conservative than standard meta-analyses. Bootstrapping was implemented using the bootES package [33] in *R* [34]. For all statistical tests in our analysis, $\alpha = 0.05$.

Although not exhaustive, the database we compiled from the literature search contained 945 soil C response ratios from 112 publications published between 1979 and 2016. Roughly half the dataset was comprised of response ratios analyzed by Nave et al. [9]. The full dataset is available as Supplementary Material, including maximum sampling depth and the number of response ratios from each paper (Appendix A).

3. Results

3.1. Overall Effect and Change with Depth

Across all studies, harvesting led to a significant average decrease in soil C of 11.2% relative to control (Figure 1). Whether the response to harvest was reported as pools or concentrations had a large impact on the estimated effect of harvest on soil C, with mean response for studies reporting C concentration units (%, mg·g^{-1}, etc.) 16.2% higher (with a 95% CI [20.9%, 11.8%]) than studies reporting C pool units (Mg·ha^{-1}, tons·ha^{-1}, etc.). Concentration responses are higher than pool responses at all soil depths, except for very deep and whole mineral soil, which did not have enough concentration response ratios to construct separate confidence intervals (Figure 1). Consequently, all subsequent analyses focused on the subset of data reporting soil C pools.

Several different soil layers show significant losses of C due to harvesting. Overall, O horizons lost 30.2% of their carbon as a result of harvesting. Losses from top soil were much smaller, although the estimated loss when reported in pool units was significant (−3.3%). In mid (15–30 cm) and deep soil (30–60 cm), the average loss of soil C was greater than topsoil, although the smaller number of response ratios for these depths resulted in more poorly constrained estimates. Studies only reporting C concentration observed a 14.5% increase in deep soil (30–60 cm), although the sample size was relatively small. The overall effect in very deep soil (60–100+ cm) was significant, with an average loss of 17.7%. Unfortunately, this region of the profile was not frequently sampled (21 response ratios out of 945 total), and consequently the 95% confidence interval is quite wide.

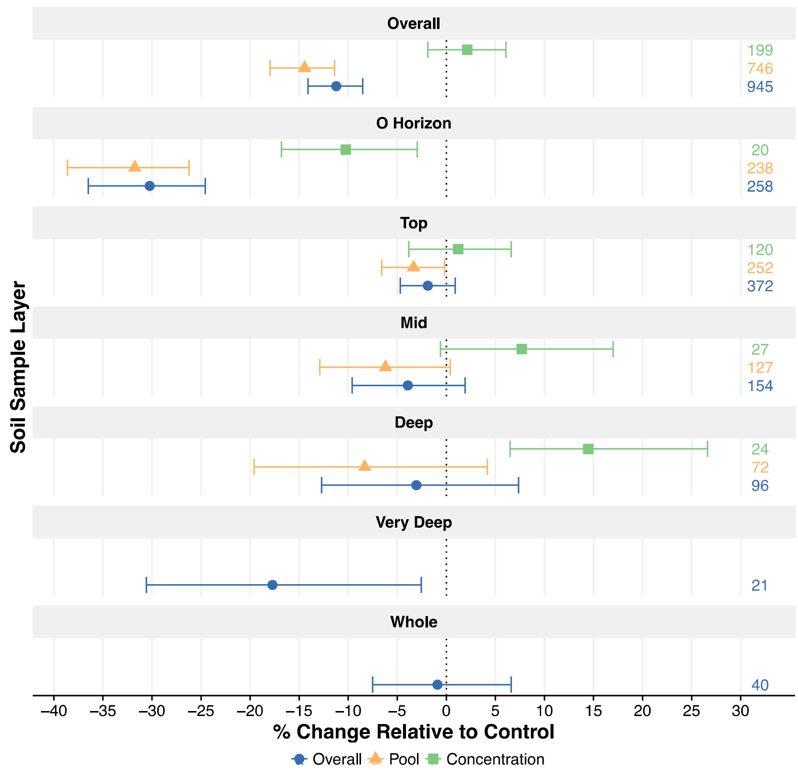

Figure 1. Response of soil C to forest harvesting, overall and faceted by soil depth. All points are back-transformed mean effect sizes ± 95% confidence intervals calculated by nonparametric bootstrap. The number of response ratios (k) that make up each mean effect is listed on the right. Mean effects with confidence intervals overlapping the dashed line (0%) show no significant change in soil C due to harvesting. Within each facet, mean effect sizes are shown for the overall effect as well as separately for studies reporting C pool units or concentration units.

3.2. Effect of Harvesting across Soil Orders

The effect of harvesting on soil C differs between soil orders (Figure 2). For the Alfisols and Inceptisols, there are significant losses in O horizon C pools (−12.0% and −45.4%, respectively), but no significant loss in the mineral soil. Mollisols lost an average of 17.7%, although neither O horizon nor mineral soil responses were significantly different from 0. In several cases, small samples sizes made separate testing of organic and mineral soil impossible within a single order (Andisols, Entisols, Oxisols). However, in each of these cases the overall effect was significant. Soil C increased by 24.5% on average in Andisols, but decreased by 18.8% in Entisols and 30.9% in Oxisols. The number of response ratios was more concentrated in the Alfisol, Inceptisol, Spodosol, and Ultisol orders, although a large number of publications did not report information on soil classification. The response to harvesting in Spodosols is substantial (−19.0% overall), with significant losses in both the O horizon (−36.4%) and moderately less in the mineral soil (−9.1%). Likewise, Ultisols lost significant soil C in response to harvesting (−24.7% overall), with the most substantial losses occurring in the O horizon (−66.0%) rather than in the mineral soil (−11.9%).

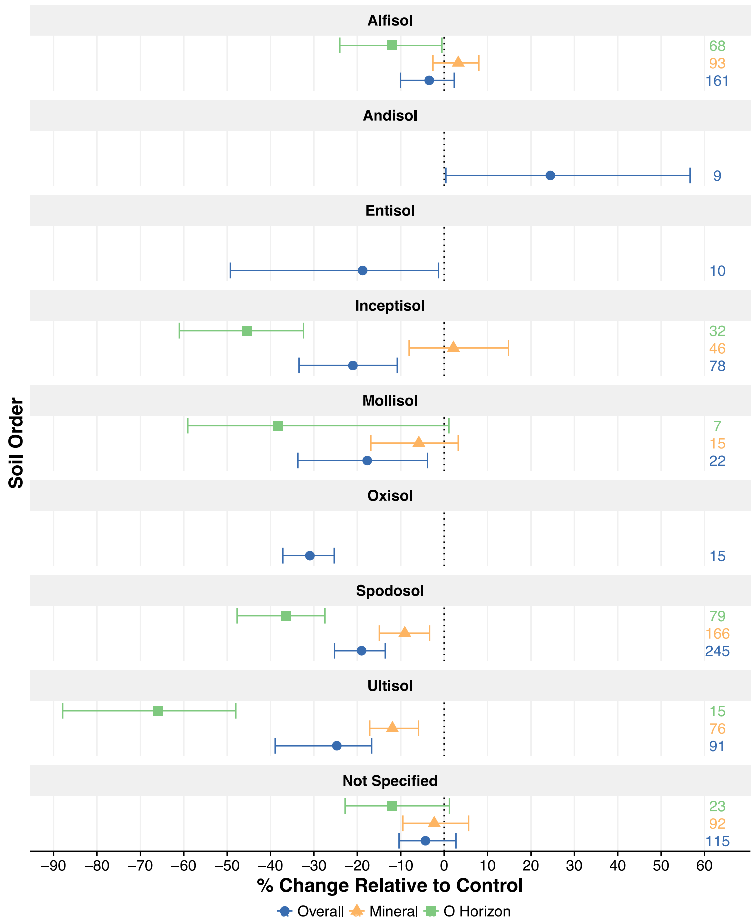

Figure 2. Response of soil C to harvesting in different soil orders. Mean effect sizes ± 95% confidence intervals calculated by nonparametric bootstrap are shown for all response ratios in each soil order (Overall) and broken out into mineral soil or O horizon. The number of response ratios (k) comprising each mean effect are listed on the right. Effect sizes were calculated only on response ratios reported in pool units (k = 746).

3.3. Differences in Response to Harvest between Forest Types

The response of soil C to harvest differs between hardwood and coniferous/mixed forest types (Figure 3). The decline in O horizon C pools is significantly greater in conifer/mixed forests (−38.1%) compared to hardwood forests (−25.4%). Differences between forest types were not significant for any mineral soil layer. However, the decline in soil C after harvest was significant for hardwood forests but not conifer/mixed forests in deep soil (30–60 cm) and in studies reporting whole mineral soil C pools. Also in these studies, the difference between hardwood and conifer/mixed forest response to harvest is marginally significant ($p < 0.1$). The number of observations are highly concentrated in O horizon and top soil, consequently limiting the precision of mean effect size estimates in deeper layers. No observations for hardwood forest were made in very deep soil (60–100+ cm).

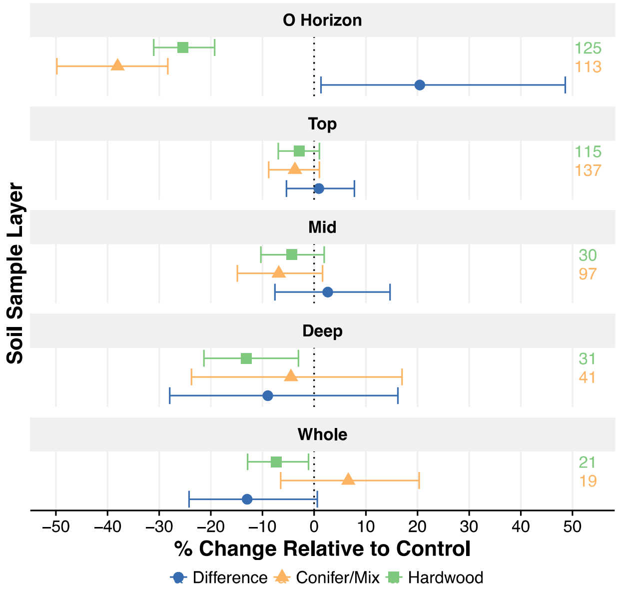

Figure 3. Response of soil C harvesting at different depths in soil, broken down by hardwood or conifer/mixed forest types. Mean effect sizes ± 95% confidence intervals calculated by nonparametric bootstrap are shown for hardwood and conifer/mixed forests. Blue circles show the mean difference between these forest types (Hardwood–Conifer/Mix) ± 95% confidence interval for the difference. Differences are calculated on the logarithmic effect size scale, and then back-transformed to % change, and thus do not necessarily add up on the % change scale. The number of response ratios (k) in each forest type at each depth is listed on the right. Data for very deep soil is not shown because there were no observations for this soil layer in hardwood forests.

3.4. Harvest Intensity, Residue Management and Site Pretreatment

Differences in forest management strategies can significantly impact the response of soil C to harvesting (Figure 4). While there was no significant overall difference observed between thinning and clear-cut harvesting, less C was lost from mineral soils under clear-cut harvesting compared to thinning (+9.3%). Likewise, harvest intensity significantly changed the response of mineral soil C, with soils undergoing whole tree harvesting losing 13.3% less C than bole-only harvesting. Possible mechanisms for these counter-intuitive results are considered in Discussion Section 4.5.

The practice of broadcast burning sites in preparation for planting after a harvest leads to significant additional losses of soil C, with burned soils losing 15.2% more C than soils with no pretreatment. This effect is especially severe in the O horizon (40.9% additional loss than if sites were not burned), and somewhat curtailed in the mineral soil (8.3% additional loss). The wide 95% CI for the estimate of differences in O horizon responses due to burning reflects disparities in burn severity and treatment implementation among different studies.

Spreading of residual materials across harvested sites (by chipping tops and limbs or other methods) resulted in significant additional loss of soil C (−10.9%), with these extra losses occurring mostly in the mineral soil (−17.5%). On the other hand, residue removal resulted in no significant additional losses to soil C.

Tillage is sometimes used to prepare soils for planting after harvest, either to create raised planting beds or to prepare the soil seed bed. This intensive style of site preparation did not result in significant losses in soil C, especially in the mineral soil. However, very large losses were reported in the O horizon (mean effect = −37.1%) with a very wide confidence interval due to a small number of observations. Additional study of the effect of tillage would help to reduce this error.

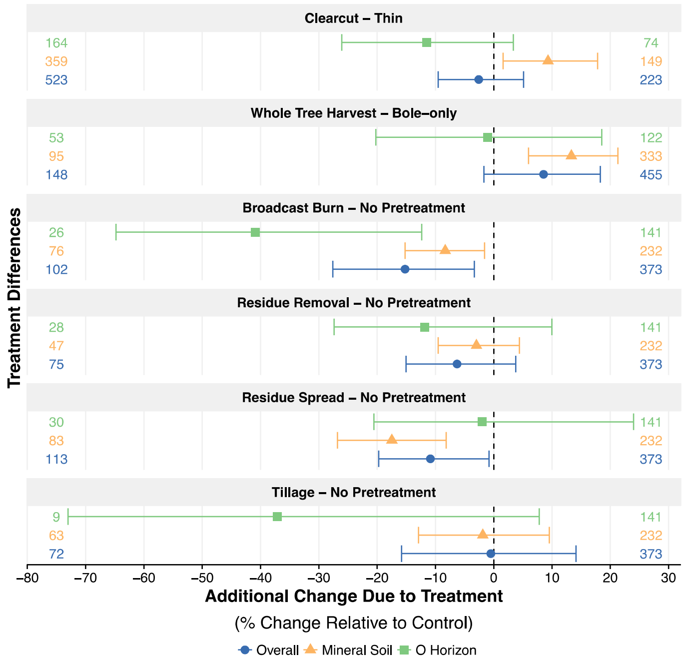

Figure 4. Differences in response of soil C to harvesting between treatment strategies. Differences are calculated by subtracting [more intensive treatment] − [less intensive treatment], such that positive differences represent reduced loss of C due to more intensive treatment, and negative differences represent increased losses of C due to more intensive treatment. Point estimates are back-transformed differences between mean effect sizes ± 95% confidence intervals calculated by nonparametric bootstrap. Mean effect differences with confidence intervals overlapping the dashed line (0%) show no significant difference between the harvesting, residual management, or pretreatment strategies. The number of response ratios (k) for the intensive treatment in each comparison appear on the left and for the less intensive treatment on the right.

3.5. Recovery of Soil C after Harvest

The recovery time for soil C following harvest differs among soil orders (Figure 5). Only 4 soil orders contained enough observations over time to model recovery times: Alfisols, Inceptisols, Spodosols, and Ultisols. We modeled time as a second degree polynomial (Time + Time^2) separately for O horizons and mineral soils for each soil order (Table 2).

Table 2. Linear regression coefficients and significance for second degree polynomial model of response of soil C to harvesting over time.

Coefficient	Estimate	SE	*t*-Value	*p*-Value
Intercept (Alfisol, mineral soil)	12.702	3.587	3.541	0.0004
O horizon	−21.475	3.766	−5.703	<0.0001
Inceptisol	−10.876	5.717	−1.902	0.0577
Spodosol	−14.717	4.320	−3.407	0.0007
Ultisol	−24.776	5.391	−4.596	<0.0001
Time	−67.834	41.56	−1.632	0.10325
Time^2	120.412	40.361	2.983	0.0030
Residual SE: 40.24 on 533 *DF*				
F-Statistic: 10.74 on 6 and 533 *df*, $p < 0.0001$			$R^2 = 0.108$	Adj. $R^2 = 0.098$

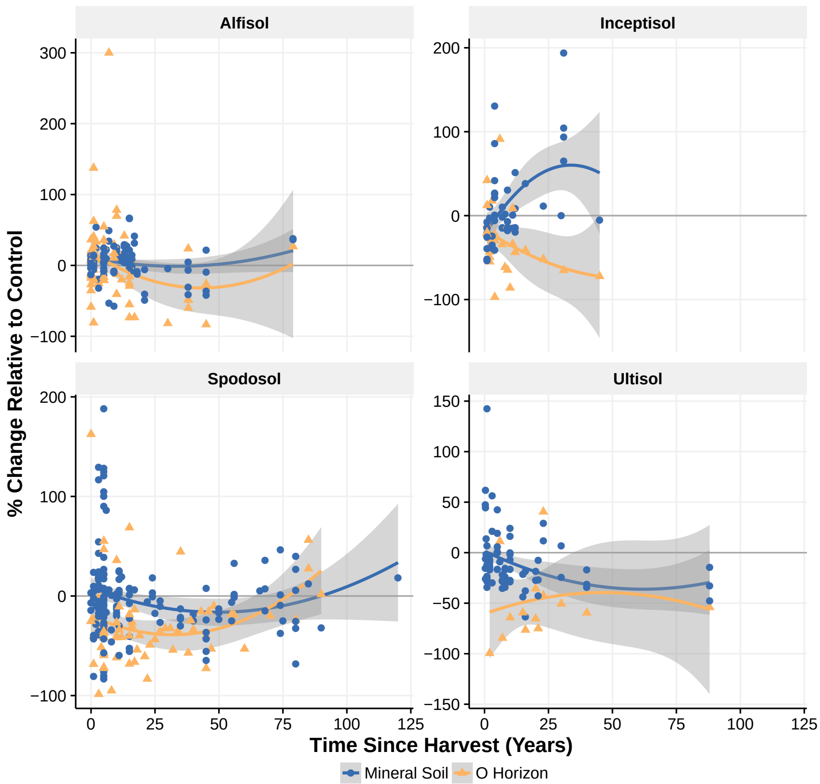

Figure 5. Temporal patterns in both O horizon (yellow triangle) and mineral soil (blue circle) C pools for Alfisol, Inceptisol, Spodosol, and Ultisol orders. Other soil orders are not shown due to an inadequate number of response ratios over time. Regression lines show trends with time using a second order polynomial. For the overall model, F = 9.205 on 7 and 532 degrees of freedom, Adj. R^2 = 0.096, and p < 0.0001 (Table 2).

4. Discussion

4.1. Overall Effect of Harvesting on Soil C

Our results reveal that across many publications in the literature there is a significant loss of soil C in response to harvest (−11.2% overall, −14.4% for studies reporting C pools). This estimate is slightly greater than that found by Nave et al. [9], who reported −8% change relative to control. The difference between these estimates derives from additional losses reported in mineral soil, since the effect of harvesting on O horizon C is identical between this study and Nave et al. [9] (−30%). Indeed, while no significant loss of soil C due to harvesting was reported in previous meta-analyses on the subject [9,25], this analysis reveals significant if small losses in various mineral soil layers. Our meta-analysis has roughly double the number of responses than previous meta-analyses on the subject, and consequently has greater statistical power. In particular, this has allowed us to break down the response of mineral soil C to harvest into more depth increments to better characterize how response is moderated or accentuated by depth.

4.2. Depth Distribution of Soil C Response to Harvest

The response of soil C to harvest differs among depths in the soil. O horizons show the most substantial declines (by percentage), although the O horizon is typically a smaller pool of C than mineral soil horizons. Consequently, smaller absolute declines in O horizon C pools can lead to larger response ratios. Forest type significantly alters the response of O horizons to harvesting, with hardwood forests undergoing less drastic losses than conifer and mixed forests (Figure 3). This result is in contrast with Nave et al. [9], who found that conifer O horizon soil C declines significantly less than hardwood forest floors. Coniferous forest litter is thought to be more chemically recalcitrant to decomposition because of higher C/N and lignin/N, as well as slower N mineralization rates [35,36]. The trend for more soil C loss from coniferous forest floors could be due to differences in the harvesting techniques utilized for each forest type. On the other hand, less change in soil C in coniferous forests in deeper mineral soils could suggest that some of the additional loss in O horizon C pools is the result of translocation of C into mineral soil rather than mineralization to CO_2. Whatever the case, the mechanism for this difference is not clear and warrants additional study.

In mineral soils, the relative response to harvest is typically less than the O horizon, but this small relative loss might correspond to a larger absolute loss of C in the mineral soil in many forests. The major exception to this pattern are Spodosols, which can contain larger proportions of total soil C in deep, acidic O horizons. Declines in top soil C pools were modest (−3.3%) but still significant (Figure 1). Mean effect size estimates become more negative with soil depth, although these estimates are not significant. The overall estimate of change in very deep soil (60–100+ cm) shows substantial and significant loss of C (−17.7%). This estimate, however, only covers a small number of observations (21) from Spodosol, Ultisol, Alfisol, and Inceptisol soil orders and completely excludes hardwood forests. The lack of observations in deeper soil horizons leads to very wide confidence intervals.

On average, the maximum depth of soil sampled by the publications in this meta-analysis was 35.9 cm (Figure 6). The average depth of sampling for each response ratio in the database is even more surface-skewed at 21.3 cm. Many of the observations down to 100 cm in the literature only report treatment differences for the whole mineral soil profile (0–100 cm), which eliminates any possibility of understanding the relative response of different horizons or depths. The scarcity of observations in deep soil is incongruous with the increasing loss of soil C with depth relative to control observed in this analysis. More important than the magnitude or significance of the harvest response in very deep soil is the conclusion that much greater attention should be paid to deep soil C pools in both individual forest manipulation experiments and broad-scale C inventory.

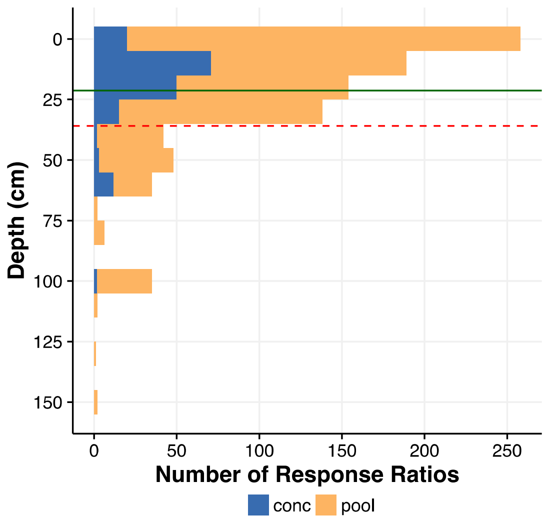

Figure 6. Number of response ratios plotted by the maximum depth of sampling for each observation. Response ratios calculated from concentration are in blue, and from pools in orange. The average depth of all response ratios is denoted by the solid green line (21.3 cm, n = 945). The average maximum sampling depth for all 112 publications in the meta-analysis is denoted by the dashed red line (35.9 cm).

While soil C in deep soil is much less concentrated than in O and A horizons, subsurface soil represents a much greater volume of soil than surface soil, especially in older/more well developed soil orders like Alfisols, Ultisols, and Oxisols. Some major regions for forestry contain substantial portions of total soil C in deep horizons. For example, 38% of total soil C was below 50 cm and 24.1% below 1 m in production forest soils in the Pacific Northwest [37]. The imprint of biological activity extends many meters into soil, even into the C horizon [38]. Globally, the average maximum rooting depth for trees is ~7 m [39], far outreaching even the deepest observations in this database. Harvesting disrupts the continued growth and turnover of roots extended deep into soil by mature trees, which in turn disturbs the steady state of C cycling in deep soil by changing environmental conditions (temperature, moisture) as well as the type and rate of C inputs. Furthermore, the flush of nitrate and dissolved organic matter that frequently follows harvest [40,41] could prime the breakdown of older, subsurface C by providing a spike in nutrient availability and labile energy sources [31,42,43]. Alteration of aboveground ecosystems can cause changes in subsurface soils. For example, Mobley et al. [44] observed that, over a period of several decades following afforestation of agricultural land, modest C gains in surface soil were more than offset by large losses in soil C below 30 cm. Neither the response of deep soil C to harvest nor the mechanisms for that change have been sufficiently resolved in the literature, and future work to address these questions are necessary.

4.3. Differences in Soil C Response to Harvest among Soil Orders

Substantial variation in response to harvest was observed among soil orders. Several soil orders had very few response ratios (Andisols, Entisols, Mollisols, and Oxisols), which greatly widens confidence intervals. Nonetheless, significant changes in soil C in response to harvest were observed for all four of these orders. Andisols were the only order to show a significant average increase in soil C in response to harvest. This likely stems from Andisols particular mineralogy, which is often characterized by short-range-order minerals like allophane and imogolite [45–47]. The capacity for these types of minerals to adsorb organic matter makes Andisol soil C especially resistant to loss after harvesting. Alfisols also appear to be resistant to loss of soil C after harvesting, with relatively small loss in O horizons (−12.0%) being the only significant effect. All other soil orders have significant overall losses in soil C, roughly −20% for Entisols, Inceptisols, Mollisols, Spodosols, and Ultisols. The uneven distribution of observations among soil orders (most response ratios in the database are from Alfisols, Inceptisols, Spodosols, and Ultisols) results in substantial differences in the size of confidence intervals among different orders. Unfortunately, many studies did not report soil taxonomic information, and thus 115 response ratios could not be assigned to a soil order. The lack of studies on Andisols is curious given the importance of these soils to forestry in several regions such as the Pacific Northwest, USA and New Zealand. Several studies on Andisol and other under-represented soil orders were excluded from this analysis because of a lack of appropriate controls.

4.4. Recovery of Soil C after Harvest

Recovery of soil C after harvesting can take several decades [9]. O horizon pools decline more severely than mineral soil pools, especially in the first several decades (Figure 5). In Spodosols, O horizons recovered from harvesting after 60–85 years, while mineral soil recovered over a longer period of 75–100+ years. While the response to harvest was less severe in mineral soils, the longer recovery period implies either lagged response time between forest floor and mineral soils or differences in the decay rate constants leading to longer-term changes in mineral soil C compared to the forest floor. In the case of Alfisols and Inceptisols, soil C in mineral pools increased or stayed the same after harvest, while O horizons declined. However, the observations of harvest effects on Alfisols, Inceptisols, and Ultisols were largely confined to within the first 50 years post-harvest. Consequently, an estimate for the recovery period of soil C pools in these soil orders cannot be assessed with much confidence. Continued observation of existing harvesting experiments in other soil orders must be made to better characterize changes in soil C over time. For Andisols, Entisols, Mollisols, and Oxisols, only a few time points have been documented, and much further study will be necessary to understand recovery of soil C after harvest.

The modeled recovery time has a fairly low adjusted R^2 (0.1) and thus a low predictive capacity. Substantial variation in the response to harvest exists within each soil order, reflecting differences in tree species, harvest intensity, and pretreatment strategies, among other factors. Moreover, soil orders are hardly homogeneous, and differences in the response of soil C among lower levels of classification within each order could be as important as order-level differences. Nonetheless, the substantial and significant differences between orders considered in the model suggest that both the resistance of soil C to change and the recovery period of soil C following harvest (resilience) consistently varies among soil types. Compared with 20-year recovery periods assumed by many models [14], our results indicate that soil C recovery takes place over at least triple that time frame for both O horizons and mineral soil in many cases.

While forests >30 years of age were considered acceptable controls for this analysis, the preponderance of data in this meta-analysis show decreases in soil C relative to control at time = 30 years. Consequently, studies that use mature second growth stands barely over this threshold for experimental controls likely underestimate the response of soil C due to harvesting treatments. Depending upon the site conditions and soil order, control stands of at least 50–75+ years since harvest would be recommended, with older stands being more accurate controls.

4.5. The Effect of Harvest Strategies on Soil C

Differences in harvesting and soil pretreatment strategies significantly impact the loss of soil C after harvest. Curiously, despite the greater relative losses of soil C in O horizons, significant differences between harvest intensities and pretreatment strategies were only found in the mineral soil with the exception of broadcast burning (Figure 4). The reduced loss of soil C from mineral soil observed in treatments with greater harvest intensity (+9.3% for clearcut, +13.3% for whole tree harvest) runs counter to the intended effect of these experimental treatments on soil C. One possibility is that increased harvest intensity reduces the quantity of dissolved organic matter and inorganic nutrients leached into the mineral soil, thus reducing the priming [42,48,49] of mineral soil C mineralization through less addition of energy-rich substrates and nutrients. Another possibility is that response of soil C to increased harvest intensity is soil-type specific, and thus an aggregate analysis such as this is subject to bias by unequal sampling of different soil orders. Whatever the case, this dataset cannot identify the specific mechanism(s) driving this difference, and further study is warranted.

Tilling of forest soils prior to planting should intuitively disrupt O horizons to a greater extent than less intensive practices. However, due to the very small number of observations of this practice in the dataset, the large mean treatment effect on soil C was could not be differentiated from 0. By mixing organic material into the surface mineral soil, tilling could increase top soil C in the short term and possibly prime additional breakdown of C over time. In regions where this practice is used, additional research could help to reveal the mechanisms driving change in the soil C of O horizons and mineral following tillage.

Broadcast burning led consistently to additional loss of soil C in both O horizons and mineral soil. The large additional reduction in O horizon C (−40.9%) is expected given that such a treatment is intended to reduce slash on site to facilitate planting. The loss of carbon after harvest extends into deep soil, especially following slash burning (Figure 7). Although there are few observations in very deep soil (60–100+ cm), burning appears to especially exacerbate C losses in this layer. This result is despite the direct effects of fire (such as soil heating and nutrient volatilization) being highly attenuated with depth [50,51]. Levels of mineralized nitrogen (NH_4^+ and NO_3^-) and soluble sugars spike within the first year following fire, leading to increased microbial biomass N and N leaching loss [52]. Thus, the flush of nutrients and organic matter into deeper mineral soil following post-harvest broadcast burning has the potential to impact soil C dynamics throughout the soil profile. The number of observations in deep and very deep layers is small, and consequently additional research is necessary to better differentiate between harvesting and fire effects in deep soil horizons.

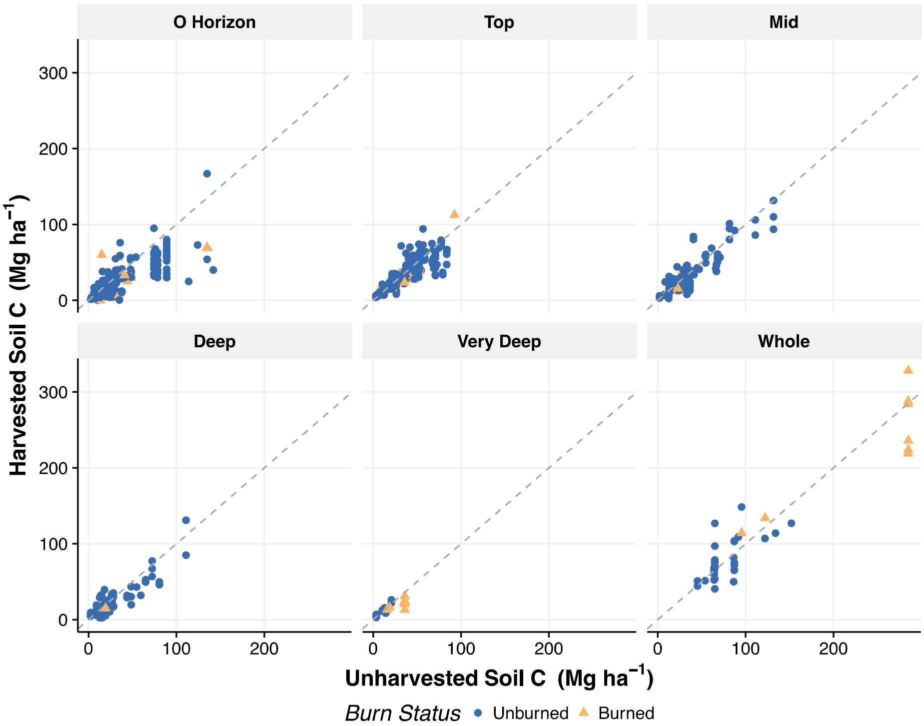

Figure 7. Absolute change in soil C due to harvest for each soil depth in this analysis (O horizon, top, mid, deep, very deep, and whole mineral soil). Different points show burned (yellow triangle) and unburned (blue circle) pretreatment strategies. Dashed 1:1 lines in each facet represent no response due to harvest. The total number of responses shown is $k = 746$.

5. Conclusions

We analyzed 945 studies from 112 publications to examine the effect of harvest on forest soil C around the globe. There is a significant overall reduction in forest soil C following harvest that occurs in both the O horizon and mineral soil. Significant variation in the response to harvesting was observed among different soil depths, among soil orders, between overstory forest types, and between different harvest intensities and pretreatment strategies. Broadcast burning, in particular, appears to exacerbate loss of soil C in both organic and mineral horizons following harvest. The recovery period of soil C following harvest depends upon soil type and takes at least 60 years in many production forests. One of the most important findings of this analysis is a significant loss (−17.7%) of soil C following harvest in very deep soil (60–100+ cm). Deep layers of the soil are greatly under-represented in the literature, and consequently, there is great uncertainty around this estimate. Examination of deep soil horizons in existing manipulative forest studies, in new studies, and in C inventory should be a clear objective for future research.

Supplementary Materials: The following are available online at www.mdpi.com/1999-4907/7/12/308/S1, Table S1: Harvest meta-analysis database (Excel file).

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Appendix A. Publications Providing Response Ratios for This Analysis

Reference	Year	k	Max Depth (cm)	Time Since Harvest [a] (years)	Location
Alban and Perala [53]	1992	7	50	35	MN, USA
Bauhus et al. [54]	2004	6	40	9	Germany
Bisbing et al. [55]	2010	6	100	40	MT, USA
Black and Harden [56]	1995	15	20	23	CA, USA
Boerner et al. [57]	2006	4	10	2	SC, USA
Borchers and Perry [58]	1992	4	15	14	OR, USA
Bravo-Oviedo et al. [59]	2015	8	30	15	Spain
Cade-Menun et al. [60]	2000	12	26	5	BC, Canada
Carter et al. [61]	2002	8	15	2	LA, TX, USA
Chatterjee et al. [62]	2009	19	54	21	WY, USA
Chen et al. [63]	2013	24	100	29	China
Chiti et al. [64]	2016	24	100	24	Ghana, Cameroon, Gabon
Christophel et al. [65]	2013	6	30	15	Germany
Christophel et al. [66]	2015	18	30	33	Germany
Cromack et al. [67]	1999	1	100	10	OR, USA
Dai et al. [68]	2001	3	70	14	NH, USA
DeByle et al. [69]	1980	10	5	3	WY, USA
Deluca and Zouhar [52]	2000	6	8	5	MT, USA
Diochon et al. [70]	2009	28	50	35	NS, Canada
Edmonds and McColl [71]	1989	4	20	3	Australia
Edwards and Ross-Todd [72]	1983	6	45	1	TN, USA
Elliott and Knoepp [73]	2005	3	15	3	NC, USA
Ellis et al. [73]	1982	4	10	2	Tasmania
Ellis and Graley [74]	1983	2	10	1	Tasmania
Esquilin et al. [75]	2008	1	10	14	CO, USA
Falsone et al. [76]	2012	3	130	5	Russia
Fraterrigo et al. [77]	2005	1	15	30	NC, USA
Frazer et al. [78]	1990	4	14	12	CA, USA
Gartzia-Bengoetxea et al. [79]	2009	2	5	10	Spain
Gillon et al. [80]	1999	2	0	1	France
Goh and Phillips [81]	1991	4	60	2	New Zealand
Goodale and Aber [82]	2001	2	10	85	NH, USA
Gough et al. [83]	2007	15	80	41	MI, USA
Grady and Hart [84]	2006	2	15	12	AZ, USA
Grand and Lavkulich [85]	2012	6	80		BC, Canada
Gresham [86]	2002	6	30	10	SC, USA
Griffiths and Swanson [87]	2001	3	10	20	OR, USA
Gundale et al. [88]	2005	4	10	3	MT, USA
Gupta and DeLuca [89]	2012	12	50	5	Wales
Hart et al. [90]	2006	2	15	1	AZ, USA
Hendrickson and Chattarpaul [91]	1989	6	20	3	ON, Canada
Herman et al. [92]	2003	2	9	8	CA, USA
Holscher et al. [93]	2001	2	20	22	Germany
Hwang and Son [94]	2006	2	30	2	Korea
Jang and Page-Dumroese [95]	2015	8	30	38	MT, USA
Johnson [96]	1991	3	20	3	NH, USA
Johnson and Todd [97]	1998	6	45	15	TN, USA
Johnson [98]	1995	12		7	NH, USA
Johnson et al. [99]	1997	14	53	6	NH, USA
Johnson et al. [100]	2014	4	60	1	CA, USA
Jones et al. [101]	2011	12	30	15	New Zealand
Kaye and Hart [102]	1998	2	15	1	AZ, USA
Keenan et al. [103]	1994	1	20	4	BC, Canada
Kelliher et al. [104]	2004	4	50	22	OR, USA

Reference	Year	k	Max Depth (cm)	Time Since Harvest [a] (years)	Location
Kishchuk et al. [105]	2014	4	7	6	AB, Canada
Klockow et al. [106]	2013	9	20	1	MN, USA
Klopatek [107]	2002	6	20	30	WA, USA
Knoepp and Swank [108]	1997	4	30	33	NC, USA
Korb et al. [109]	2004	1	10	1	AZ, USA
Kraemer and Hermann [110]	1979	2	10	26	WA, USA
Kurth et al. [111]	2014	72	30	8	MI, MN, USA
Laiho et al. [112]	2003	5	22	5	NC, LA, USA
Latty et al. [113]	2004	2	15	90	NY, USA
Law et al. [114]	2001	3	100	21	OR, USA
Law et al. [115]	2003	9	100	62	OR, USA
Leduc and Rothstein [116]	2007	1	10	5	MI, USA
Maassen and Wirth [117]	2004	2	5		Germany
Mattson and Smith [118]	1993	30	10	11	WV, USA
Mattson and Swank [119]	1989	8	60	5	NC, USA
May and Attiwill [120]	2003	2	10	5	Australia
McLaughlin and Phillips [121]	2006	2	50	17	ME, USA
McKee et al. [122]	2013	8	60	24	AL, USA
McLaughlin [123]	1996	10	50	5	MI, USA
Merino and Edeso [124]	1999	6	15	1	Spain
Moreno-Fernandez et al. [125]	2015	54	50	60	Spain
Mu et al. [126]	2013	18	50	5	China
Murphy et al. [127]	2006	20	60	1	CA, USA
Neher et al. [128]	2003	3	20	2	NC, USA
Norris et al. [129]	2009	15	100	16	SK, Canada
O'Brien et al. [130]	2003	6	50	18	Australia
Powers et al. [131]	2011	20	30	13	MN, WI, USA
Prest et al. [132]	2014	5	50	35	NS, Canada
Prietzel et al. [133]	2004	4	0	1	WA, USA
Puhlick et al. [134]	2016	10	100		ME, USA
Rab [135]	1996	8	10	1	Australia
Riley and Jones [136]	2003	3	10	1	SC, USA
Roaldson et al. [137]	2014	16	20	5	CA, USA
Rothstein and Spaulding [138]	2010	6	30		MI, USA
Sanchez et al. [139]	2007	6	105	2	SC, USA
Sanscrainte et al. [140]	2003	4	70		WA, USA
Saynes et al. [141]	2012	8	5	11	Mexico
Selig et al. [142]	2008	3	30	14	VA, USA
Shelburne et al. [143]	2004	4	10	1	SC, USA
Sheng et al. [144]	2015	5	100	8	China
Skovsgaard et al. [145]	2006	12	30	0	Denmark
Slesak et al. [146]	2012	12	60	5	OR, WA, USA
Small and McCarthy [147]	2005	3	10	7	OH, USA
Stone et al. [148]	1999	1	15	1	AZ, USA
Stone and Elioff [149]	1998	4	30	5	MN, USA
Strong [150]	1997	8	40	18	MN, USA
Strukelj et al. [151]	2015	12	10	5	QC, Canada
Tang et al. [152]	2009	12	60	29	MI, WI, USA
Trettin et al. [153]	2011	6	150	11	MI, USA
Ussiri and Johnson [154]	2007	15	60	8	NH, USA
Vario et al. [155]	2014	6	60	49	NH, USA
Vesterdal et al. [156]	1995	9	0		Denmark
Waldrop et al. [157]	2003	3	0	1	CA, USA
Wu et al. [158]	2010	1	20	10	China
Xiang et al. [159]	2009	8	30	0	China
Yanai et al. [160]	2000	35	0	29	NH, USA
Zabowski et al. [161]	2008	2	20	25	OR, WA, USA
Zhong and Makeshin [162]	2003	2	10	16	Germany
Zummo and Friedland [163]	2011	15	60	3	NH, USA

[a] For chronosequence studies, time since harvest in this table is averaged across all response ratios for that study.

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