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Land use and management effects on soil carbon in U.S. Lake States, with emphasis on forestry, fire, and reforestation

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Abstract- There is growing need to quantify and communicate how land use and management activities influence soil organic carbon (SOC) at scales relevant to, and in the tangible control of landowners and forest managers. The continued proliferation of publications and growth of datasets, data synthesis and meta-analysis approaches allows the application of powerful tools to such questions at ever finer scales. In this analysis, we combined a literature review and effect-size meta-analysis with two large, independent, observational databases to assess how land use and management impact SOC stocks, primarily with regards to forest land uses. We performed this work for the (Great Lakes) U.S. Lake States, which comprise 6% of the land area, but 7% of the forest and 9% of the forest SOC in the U.S., as the second in a series of ecoregional SOC assessments. Most importantly, our analysis indicates that natural factors, such as soil texture and parent material, exert more control over SOC stocks than land use or management. With that for context, our analysis also indicates which natural factors most influence management impacts on SOC storage. We report an overall trend of significantly diminished topsoil SOC stocks with harvesting, consistent across all three datasets, while also demonstrating how certain sites and soils diverge from this pattern, including some that show opposite trends. Impacts of fire grossly mirror those of harvesting, with declines near the top of the profile, but potential gains at depth and no net change when considering the whole profile. Land use changes showing significant SOC impacts are limited to reforestation on barren mining substrates (large and variable gains) and conversion of native forest to cultivation (losses). We describe patterns within the observational data that reveal the physical basis for preferential land use, e.g., cultivation of soils with the most favorable physical properties, and forest plantation establishment on the most marginal soils, and use these patterns to identify management opportunities and considerations. We also qualify our results with ratings of confidence, based on their degree of support across

approaches, and offer concise, defensible tactics for adapting management operations to site-specific criteria and SOC vulnerability.

Key words: forest harvest, carbon management, meta-analysis, best management practices

1. Introduction

Soil organic matter (SOM) is critical to agricultural and forest productivity (Vance 2000). In soils, SOM and the organic carbon (SOC) that is its principal constituent are vital to many biogeochemical, hydrologic, and other ecosystem services that are foundational to ecosystems themselves, and the fiber, fuel, and food resources that they provide humanity (Nave et al. 2019a). Recognizing the roles that SOC and SOM play on the site (i.e., within the ecosystem), and in larger-scale issues such as greenhouse gas accounting, mitigation of atmospheric CO_2 pollution and climate change, policy and management professionals are justifiably concerned with the potential for land use and forest management to impact SOC and SOM (Harden et al. 2018).

Many broad reviews have reported that land use and forest management impact SOC (e.g., Certini 2005; Jandl et al. 2007; Post and Kwon 2000; Smith et al. 2016). Indeed, research synthesizing information on SOC management impacts has reached a point that it is now possible to review reviews (Dignac et al. 2017; Mayer et al. 2020). This maturation of SOC management syntheses provides some strong foundations for general understanding, and has been sufficient in some cases to quantify SOC impacts and their uncertainties in response to forestry, fires, reforestation, and other forest-related land use and management activities at broad scales (Laganiere et al. 2010; Lorenz and Lal 2014; Nave et al. 2010; 2011; Thiffault et al. 2011). The value of these generalizations from SOC management syntheses is considerable. However, the papers that have generated these foundations of our current understanding share one common, problematic finding: they recognize that place matters, at some scale in the wide gap between broad synthesis and site-specific study. Definitive exceptions exist to many generalized rules, and even the strongest generalizations can be irrelevant, inaccurate, or out of context when applied to a specific ecoregion, landscape, or project. There is thus need to harness the synthesis tools that so effectively address questions of SOC management at broad patterns, at scales that apply to more targeted decision making by land users, forest managers, and policy makers.

It is now possible to use synthesis techniques to address SOC management at intermediate, and indeed increasingly localized scales. This potential exists due to the abundance of information now available and the flexibility of the tools themselves. For example, meta-analysis synthesizes individual studies differing in many ways, but each possessing paired comparisons (treatments) to reveal overall patterns and sources of variation (Hedges et al. 1999). The ability of meta-analysis to quantitatively synthesize individual studies with their own unique designs makes it a robust tool for identifying trends operating across those sites, and at rooting out sources of variation between them. However, even large meta-analyses are constrained by the origins of the studies they synthesize, making them good for knowing what is happening at select sites, but unable to extend their inferences into the vast intervening spaces where the diversity of soils, ecosystems, and management regimes remains un-represented (Gurevitch et al. 2001). In light of this limitation, it is possible to validate and contextualize these "intensive site" meta-analysis results with observational data collected much more widely, such as through soil survey or national forest inventory programs. Observational datasets lack experimental control, may not possess desired ancillary variables, and incorporate sources of variation that may obscure or confound the true treatments of interest (e.g., types of management). Nonetheless, such datasets allow for treatment comparisons over much wider areas, and ancillary variables can be harmonized from additional sources to create synthesis datasets that complement the more direct meta-analysis in scale, scope, and approach. This particular combination of scientific approaches has proven useful in moving from broad patterns (e.g., Nave et al. 2010; 2018) to the specific soils, landscapes, and land use and management regimes of distinct ecoregions (Nave et al. 2019b), and holds the potential to produce more nuanced applications in many more.

The U.S. Lake States—i.e., those with extensive Great Lakes shorelines and abundant inland lakes—may appear on the surface a rather provincial, limited arena for a multi-methods synthesis of land use and management impacts on SOC. However, even in its narrowest definition, this region is comprised of three states (MN, WI, MI), that span over 3 billion years of bedrock geology (King and Beikman 1974), have areas that were glaciated during the Quaternary either not at all or repeatedly up until less than 10,000 years ago (Leverett 1932), span five-fold mean annual temperature (MAT) and two-fold mean annual precipitation (MAP) gradients (Midwestern Regional Climate Center 2020), include soils from 8 of the 12 USDA Taxonomic Orders (Soil Survey Staff 2020a), and range from central interior deciduous forest, to boreal conifer forest and wetlands, to savannah and parkland, to tallgrass prairie (McNab et al. 2007). These three states, at 6% of the land area in the conterminous U.S. (CONUS), represent 7% of the forest area and 9% of forest SOC stocks to 1m (Domke et al. 2017), and comprise a significant forestry industry, employing >125,000 people and with an annual economic output of $60B (USD) (Swanston et al. 2018). Thus, at a national level, the influence of the U.S. Lake States on forest C is outsized to their area, and their wide-ranging lands and management regimes make them a worthy target for an ecoregional assessment that addresses place-based uniqueness, and downscales generalizations to scales where they may be applicable. Furthermore, the physiography, soils, and ecosystems of the U.S. Lake States bear much in common with two of the three most important forested provinces of Canada (Ontario and Quebec), where land use and management considerations are largely similar. In this regard, an ecoregional assessment focused on the U.S. side of the international border may nonetheless be applicable on the other, just as studies from similar ecosystems in Canada can inform practices and impacts in the U.S. (e.g., Kishchuck et al. 2016).

In general, land use and management can affect SOC stocks via a range of mechanisms. The most direct and negative mechanisms are the oxidation of SOC (through fire) and the physical destruction of soil structure that protects SOM from decomposition (Six et al. 2002; von Lutzow et al. 2006). The latter occurs when soils are physically mixed (e.g., through agricultural tillage or removal for mining activities), can occur when soils are compacted or displaced by mechanized forestry operations, and may occur with fire if soil heating is sufficient to eliminate SOM from structural elements such as aggregates (Bormann et al. 2008; DeGryze et al. 2004; Shabaga et al. 2017; Six et al. 2000). These direct impacts can lead to sustained, indirect SOC decreases through wind and water erosion, especially for cultivated, burned, or severely harvest impacted soils that lack litter or vegetative cover (Certini 2005; McEachran et al. 2018; McLauchlan 2006). Other indirect, continuous mechanisms for SOC loss may include: 1) a period of diminished organic matter inputs, e.g., through tree mortality, agricultural or forest harvest removals; 2) increased soil temperature and moisture that stimulate decomposition, e.g., through loss of shading or litter cover; 3) biogeochemical mechanisms, e.g., pH changes that increase enzyme or substrate availability or bacterial activity, incorporation of labile C into previously stable SOM via leaching, root or fungal exudation (Adkins et al. 2020; Andersson and Nilsson et al. 2001; Baath et al. 1995; Johnson et al. 2010; Ojanen et al. 2017; Slesak 2013; Slesak et al. 2010; Ussiri and Johnson 2007). Land use and management also have some potential to increase SOC stocks through mechanisms that are the reverse of these negative impacts. For example, minimizing soil disturbance and erosion through less frequent tillage or the protection of the soil surface, promoting vegetation that sustains or increases organic matter inputs to the soil, and directly adding (or redistributing) surface organic matter are associated with sustained or increased SOC stocks in agricultural and forest soils (Guo and Gifford 2002; Vance 2000). In the U.S. Lake States, the relative importance of these mechanisms across land use and management regimes likely corresponds to the degree and duration of soil disturbance, with annual cultivation at one end of the continuum, subtle biogeochemical shifts after a light forest harvest at the other, and combinations of direct and indirect mechanisms for typical fires or harvests in the intermediate. That said, all of these mechanisms have considerable knowledge gaps, not least including why some appear to be more important in some settings than others. In this regard the mechanistic literature is much like the review literature on SOC management, in that both will benefit from analyses targeted at intermediate scales.

The present study is intended to narrow the applied science knowledge gap in the realm of land use, forest management, and SOC in the U.S. Lake States, and was motivated by four objectives. First, place land use and management impacts in the context of other sources of variation in SOC stocks, such as physiography and soil properties. Second, quantify the impacts of land use and forest management on SOC stocks, in terms of magnitude, variability and sources thereof. Third, qualify these quantitative estimates using multiple complementary approaches where possible, in order to assess degree of confidence in them. Finally, provide scientifically defensible operational considerations for natural resource professionals wishing to incorporate SOC into their planning and management.

2. Methods

2.1 Study area- For the purposes of synthesizing data from the U.S. Lake States in an ecologically meaningful context, we defined the study area as all of the ecological sections present in MN, WI, and MI (Figure 1). Ecological Sections tier immediately beneath the

Province level in the U.S. Department of Agriculture-Forest Service (USDA-FS) ECOMAP hierarchical ecosystem classification system (Cleland et al. 1997; McNab et al. 2007). Thus, these three states include a total of 22 sections, some of which extend into portions of adjacent states (ND, SD, IA, IL, IN, OH) possessing the same climate and physiography. This approach allowed a potentially wider geographic scope from which to synthesize data, while ensuring that data falling outside of the three states' political boundaries were still representative of climatic, physiographic, soil, and vegetation characteristics present within them. Section-specific descriptions are beyond the scope of this paper and are available in McNab et al. (2007). Broadly, the study area records a long-running historical geology from some of Earth's oldest bedrock (Precambrian volcanics nearly 4 billion years old) exposed on the Canadian Shield of its north-western extent, to more recent (<300 million years old) Paleozoic sedimentary bedrock nearer the Michigan Basin of the southeast (King and Beikman 1974). Over two-thirds of the study area, bedrock formations lay buried beneath unconsolidated sediments >30 m thick and ranging in depositional age from tens of millions to <10,000 years old, with the youngest deposits originating during Wisconsinan glaciation (Soller et al. 2012). On these landscapes, which possess >240,000 inland lakes and ponds and >130,000 km of perennial streams and rivers (USGS 2020), soils from 8 of 12 USDA Taxonomic Orders are represented (Soil Survey Staff 2020a). Organic soils (Histosols) occupy approximately 1% of the study area and are extensive in low-lying and poorly drained landscape positions; Entisols (10-15%), Inceptisols (5-10%), and Spodosols (10-15%) have formed in relatively younger and/or coarser parent materials, and Alfisols (35-40%), Mollisols (25-30%), Vertisols (1%), and Ultisols (<1%) have formed in relatively finer and/or older parent materials. Mean annual temperature ranges from <3 degrees in the far NW, to 11 degrees in the SE, and across the same span MAT ranges from <500 to >1,000 mm yr-1 (Midwestern Regional Climate Center 2020). A strong physiographic boundary approximately bisects the study area from NW to SE, with forests and forestry more strongly represented to the north, and agricultural land uses to the south. In the north, forest types and land use history are generally similar across the study area, with contemporary cover of aspen-birch, mixed pine, northern hardwoods, and spruce-fir cover types that established following widespread forest cutting and burning of the later 19^{th}-early 20^{th} centuries (Nave et al. 2017). Modern forest management began around the middle of the 20th century, with typical regimes including regeneration harvests in early-successional deciduous or mixed cover types

(40-80 year rotations), periodic selection or shelterwood harvesting in longer-lived northern hardwood cover types, and thinning – regeneration harvest cycles in plantation conifers (Bates et al. 1993; Gahagan et al. 2015; Gerlach et al. 2002; Palik et al. 2003; Stone 2002). In the southern ~½ of the study area, the predominant (agricultural) land uses are cultivated row crops, increasingly irrigated in western or coarse-soiled areas, or tile-drained in south-eastern areas with finer soils, and pasture or hayland (USDA 2015).

2.2 Approach- In this analysis, we applied and refined methods described previously (Nave et al. 2010; 2013; 2018; 2019b; Ontl et al. 2019). These methods are four-fold: (1) effect size meta-analysis of data from published literature; (2) synthesis of soil pedon observations with remote sensing information; (3), analysis of national forest inventory (NFI) data from plots in which soils, biomass, and other ecosystem properties were measured; (4) literature review of strategies, approaches, and tactics of forest C management. Datasets supporting these components are available via the University of Michigan Research and Data Hub (https://mfield.umich.edu).

2.3 Meta-analysis- We synthesized data from 39 papers identified through literature review, which are summarized in Appendix S1: Table S1. We have described our literature review and statistical methods in past papers, and detail them in Appendix S1: Section S1.1. In brief, we limited our searches to 2008-2019, in order to add the papers found through new searches to those already in our database from previous meta-analyses (Nave et al. 2009; 2010; 2011; 2013). To be included, each paper had to: 1) report control and treatment values for SOC stocks or concentrations, 2) provide adequate metadata to constrain locations and use as potential predictor variables, 3) present novel response data not included in previous studies, and 4) be located within one of the 22 ecoregional sections comprising our U.S. Lake States study area. Twenty publications met these criteria (of 1,638 reviewed), in addition to 19 pre-2008 publications from our database.

We extracted control and treatment SOC values from each paper and used these to calculate effect sizes (as the *ln*-transformed response ratio *R*). We revisited pre-2008 papers already in our database and performed data extraction anew, concurrently with the papers collected through new literature searches. We used unweighted meta-analysis to estimate effect sizes and bootstrapped 95% confidence intervals (Hedges et al. 1999) using MetaWin software (Sinauer Associates, Sunderland MA, USA). We selected unweighted meta-analysis *a priori* in order to maximize data availability (weighted meta-analyses require sample size and variance statistics in every paper), and because we did not assume that the assembled data met the parametric preconditions of a weighted meta-analysis. Treatments of interest included forest harvesting (and associated post-harvest practices), fire management (wildfire and prescribed fire), and land use change (comparisons of native forests or wetlands to other land uses, e.g., cultivation, reforestation after cultivation, wetland restoration, developed lands). Several papers reporting soil amendments and SOC in forests were found, but were too few to analyze quantitatively.

We standardized response data using correction factors and prediction equations to address two common problems in the literature, namely, the occasional use of loss on ignition (LOI) as a metric of SOM, and the reporting of SOC values as concentrations rather than the SOC stocks of interest to our analysis. Our correction factors (for LOI) and prediction equations (for estimating bulk density from C concentration) followed methods we have used previously (Nave et al. 2019), and are detailed in Appendix S1. Our meta-analyses were mostly aimed at using the *ln*-transformed response ratios (of treatment SOC : control SOC stocks), although we present some results as the actual SOC stocks from the published literature.

We extracted predictor variables from each paper to test factors that may predict variation in SOC responses to land use or management. We looked up missing information (e.g., study site characteristics) in other publications from the same sites, or using information about the soil series reported from those study sites obtained from the web-based interface for the USDA-Natural Resources Conservation Service (USDA-NRCS) Official Soil Series Descriptions (Soil Survey Staff 2020b). Given the lack of standardization across studies in details such as soil sampling depth and parent material, it was necessary to create categories for many attributes, in order to parse variation within and between studies into sufficiently replicated groups for meta-analysis. Appendix S1: Table S2 contains the complete list of attributes extracted from, or assigned to, the published studies. Our strategy for categorizing reporting depths requires specific attention here. First, we recorded the genetic horizon (e.g., Oe, Oa, A, Bs1) or sampling increment (as depth range in cm) for each SOC value. Next, for soils reported as depth increments, we correlated each specified depth increment to its probable genetic horizon, based upon USDA-NRCS soil series descriptions. Lastly, we created broad master horizon groups (e.g., O, A, B, AEB, BC) for use as the categorical variable corresponding to soil depth. When

SOC was reported for depths of 50 cm or deeper, we termed those observations “whole profiles;” when possible, we also summed individual reporting layers reaching 50 cm or deeper to compute whole profile SOC.

Similar to Nave et al. (2019), our efforts to obtain predictor variables and assign studies to groups were more involved than past analyses (e.g., Nave et al. 2010), but we used the information essentially the same way. Namely, we used meta-analysis to identify significant predictors of variation in SOC responses, which is done statistically by parsing variation into within-group (Q_w) and between-group heterogeneity (Q_b), and inspecting corresponding P values. Grouping variables that have large Q_b relative to Q_w are significant ($P < 0.05$) and explain a larger share of total variation among all studies (Q_t). However, the statistical significance of P values is only one way to assess significance of meta-analysis results. In our meta-analysis, we were as interested in identifying groups that are significantly different from zero percent change (e.g., in response to harvest), in terms of their 95% confidence intervals, as we were interested in groups that were significantly different from each other (e.g., soil textures differing in their responses to harvest).

2.4 Synthesis of pedon and remote sensing data- We complemented the experimental strength of meta-analysis, which generates high-confidence inferences for a limited number of sites, with a synthesis of data for >1,700 locations across the study area. These data came from geo-located soil pedons from the USDA-NRCS National Cooperative Soil Survey (NCSS) Database, and included latitude, longitude, soil taxonomy, and physical and chemical properties of individual genetic horizons according to Schoeneberger et al. (2012) and Burt et al. (2004). Data from the NCSS Database span many decades of soil survey; to synthesize geo-located pedons with remote sensing information, we only used pedons from 1989-present so that pedons could be matched to temporally discrete GIS products in the same manner as Nave et al. (2018; 2019b).We extracted the following attributes for geo-located NRCS pedons, from data products detailed in Appendix S1 Section S1.2: land cover, aboveground biomass C stocks, mean annual temperature and precipitation (MAT and MAP, respectively), landform and parent material, and topographic parameters including elevation, slope, aspect, and topographic wetness index. Our final dataset for analysis included 1,709 pedons (10,608 individual horizons) across the study area.

2.5 NFI dataset- We further complemented our meta-analysis and NRCS pedon + remote sensing datasets with an additional, independent observational dataset derived from the USDA-FS National Forest Inventory (NFI). The NFI plots that are the basis for data from the Forest Inventory and Analysis (FIA) program derive from an equal-probability sample of forestlands across the CONUS. There is one permanent plot on approximately every 2,400 ha across the U.S., with each plot placed randomly within a systematic hexagonal grid (McRoberts et al. 2005). Soils are sampled from a subset of these plots, according to a protocol in which the forest floor is first removed, and mineral soils are then sampled as depth increments of 0-10 and 10-20 cm. The NFI plot design ensures that FIA data have no systematic bias with regard to forestland location, ownership, composition, soil, physiographic or other factors. For this analysis, we queried the FIA Database for records of forest floor and mineral soil SOC stocks (Mg C ha^{-1}) for all single-condition plots in the ECOMAP ecological sections comprising the study area. We set the single-condition criterion in order to exclude plots divided along sharp boundaries into conditions of different stand age, slope, wetness, etc, such that local variation in such factors would misrepresent conditions at the actual location of soil sampling. As an additional constraint, we only utilized the most recent observation of each long-term NFI plot, and only plots observed since 2000, in order to make FIA data reasonably concurrent with the NRCS pedon and remote sensing data described above. For the sake of assessing harvest impacts, we used NFI plots with stand ages <25 yr vs. >25 yr as the threshold for defining recent harvest, based on the mean time since harvest of meta-analysis studies (26 yr) and our estimated time since harvest for the NRCS pedons + remote sensing information (20-30 yr; see Appendix S1 Section S1.2). Altogether, our datasets for forest floors and mineral soils were based on 364 and 261 NFI plots, respectively.

2.6 Statistical analysis of NRCS and FIA data- To complement the non-parametric meta-analysis of published literature data, we used data transformations and parametric statistics to analyze NRCS and FIA data. These two observational datasets derived from fundamentally different sources, but they were sufficiently similar to be analyzed using a consistent set of techniques. Owing to their typically right-skewed distributions, we used *ln*-transformations to normalize response variables; in graphical representations of results, we present back-transformed means and 95% confidence intervals. We used t-tests or ANOVAs (with Fisher's Least Significant Difference) to test for significant differences between *ln*-transformed group means, e.g., for harvested vs. reference forests, or for topsoil SOC stocks for soils from different texture classes. We used simple linear regressions to test for significant relationships between continuous variables (e.g., mean annual temperature and SOC stock). In all cases, we set $P < 0.05$ as the *a priori* threshold for accepting test results as statistically significant. In addition to these formal P value statistical analyses, we used the proportion of observed variation (e.g., in SOC stock) that could be explained by a grouping (e.g., soil texture) or continuous (e.g., MAT) variable to rank the explanatory power of each individual analyzed factor, as the sum of squares between groups divided by the total sum of squares (SS_b / SS_t). In the case of continuous relationships, this fraction is approximated by dividing the regression sum of squares by the total sum of squares.

3. Results

3.1. Sources of variation in forest SOC across the U.S. Lake States

Across the study area, spatial variation in forest SOC stocks was most explained by soil properties including texture and taxonomic order, less so by geographic factors including ecosection, parent material and landform and their cross product (physiographic group), and least of all by management (Table 1). These results were consistent whether assessed only at the surface (topsoils, A horizons) or for whole soil profiles. In the case of topsoils, climate parameters (MAT, MAP) and elevation were also statistically significant predictors of variation, albeit with even less predictive capacity than management. Among dominant soil orders, Histosols, Mollisols, and Inceptisols had large SOC stocks, while Alfisols, Spodosols, and Entisols had smaller SOC stocks, generally in that order. Most of these differences were statistically significant, whether for topsoils or whole profiles. Textural variation in SOC stocks was significant for topsoils and whole profiles, with the largest SOC stocks for silty to clayey soils, intermediate SOC stocks for loamy soils, and the least SOC in sandy soils. Till, lacustrine, and drift-mantled bedrock parent materials (and ecosections where these parent materials were extensive) had large SOC stocks, while outwash, aeolian, and alluvial, residual and colluvial parent materials (and ecosections) had small SOC stocks. In terms of management, harvested forests had significantly smaller topsoil SOC stocks than non-harvested forests. Harvested and non-harvested forests did not differ in whole profile SOC stocks, but whole profile SOC stocks were significantly smaller for conifer plantations than harvested or non-harvested forests.

3.2 Overall impacts of harvest on SOC

Meta-analysis of published studies and NRCS pedon data, both of which sampled to considerable depths, indicated that harvesting did not impact SOC stocks of whole profiles, illuvial (B) or parent material (C) horizons (Figure 2). However, all three datasets (published studies, NRCS, and FIA) concurred that overall, mean topsoil (A horizon) SOC stocks were significantly smaller in harvested than control forests. The magnitude of this effect ranged from -17 to -20% across the three approaches. FIA data also suggested significant harvest decreases in SOC in the forest floor and 10-20 cm depth increment, though the corresponding horizons (O and E, respectively) in the NRCS dataset did not exhibit significant harvest effects.

Data availability for assessing harvest impacts varied by data source, sampling depth, and treatment. Reporting depths were closely comparable across data sources, with few exceptions (Appendix S1: Table S4). Topsoils (A horizons) averaged 12 cm thick in published studies, 10 cm for NRCS pedons, and were fixed (by protocol) at 10 cm for FIA. Eluvial (E) horizons averaged 13 cm for published studies, 18 cm for NRCS pedons, and were fixed at 10 cm for FIA data. Deeper soils were not sampled for FIA, but published studies and NRCS had similar mean values for B horizons (26 and 25 cm, respectively), BC and C horizons (56 and 49 cm, respectively), and whole soil profiles (73 and 86 cm, respectively). Organic horizon thicknesses did not closely correspond across data sources, tending to be considerably thicker when (infrequently) reported for NRCS pedons than for published studies and FIA data, respectively, which corresponded closely (3 and 4 cm, respectively).

3.3 Sources of variation in harvest impacts

The experimental designs of published studies, each of which attempted to minimize confounding factors in its attempt to detect harvest impacts at some carefully selected site(s), provided the most rigorous dataset for identifying which factors mediate harvest impacts on SOC. According to meta-analysis of these studies, soil texture, forest cover type, depth in profile, and parent material were the strongest predictors of the substantial study-to-study variation in harvest impacts (Figure 3). Of these four variables, texture and cover type were the most significant in terms of their proportion of total variation explained (Q_b/Q_t). Portion of profile sampled and parent material fell outside the *P* value threshold for significance of Q_b/Q_t values, but more importantly revealed several groups that differed significantly from 0% change.

In terms of textural trends, harvesting on the finest soils (silt loam and clay + clay loam groups) was associated with significant SOC stock increases (Fig. 3A). Harvesting on intermediate textures including sandy loams and loams was associated with significantly and marginally lower SOC stocks, respectively, while SOC stocks of the coarsest mineral soils (loamy sands and sands) did not differ with harvesting. In terms of forest cover type, harvesting was associated with significantly lower SOC stocks in coniferous and mixed forests, but not broadleaved forests (Fig. 3B). In terms of the depth distribution of harvest impacts (*cf.* Fig. 3C vs. Fig. 2A), harvesting was associated with statistically significant declines in SOC storage in topsoils (A horizons) and O horizons; E horizons showed variable and insignificant tendencies towards decreased SOC stocks. Portions of the profile that included B, BC, or C horizons showed no net change in SOC storage, and neither did profile total SOC stocks change with harvesting. In terms of parent materials (Fig. 3D), harvesting on soils formed in glaciolacustrine deposits was associated with increased SOC stocks. Storage of SOC in soils formed in till was not affected by harvesting. Harvesting on soils formed in mixtures of outwash and till, or pure outwash, was associated with significant SOC stock decreases.

The NRCS and FIA data from forests across the study region provided two independent means to validate the meta-analytic findings that harvest impacts varied with texture, parent material, and cover type. The overall, statistically significant harvest decrease in topsoil SOC across the three approaches (Fig. 2), coupled with the lack of any consistent harvest impact for other horizons or whole profiles, directed further exploration to topsoils specifically, using the extensive NRCS and FIA data. In contrast to meta-analysis (Fig. 3A), NRCS and FIA indicated that the impact of harvesting did not depend upon topsoil texture (two way ANOVA interaction terms of P=0.36 and P=0.12, respectively), but did indicate that texture itself had a significant influence on topsoil SOC stocks (Figure 4). Data were more limited for FIA (n=261) than NRCS (n=698), but both datasets detected the same pattern of sandy topsoils holding the least SOC. The more abundantly replicated NRCS data exhibited more numerous significant textural differences, with sands holding the least SOC, loamy sands and sandy loams having moderately small topsoil SOC stocks, loams, silts, and silt loams having moderately large SOC stocks, and the finest soils having the most topsoil SOC. The occasional presence of organic materials in the 0-10 cm FIA reporting layer indicated that some fraction of the time, Oa horizons were collected and included in this layer, which otherwise correlated well to the A horizons of the other two datasets (Appendix S1: Section S3.2 and Table S1). With reference to meta-analysis results, the finest soil textures, which showed positive impacts of harvesting (Fig. 3A), also had the largest topsoil SOC stocks (Fig. 4A). Sandy loams, which were the only group to show a significant meta-analytic decrease with harvesting (Fig. 3A), held modest SOC stocks (Fig. 4A).

Topsoil SOC stocks responded differently to harvest depending on parent material in the NRCS dataset (Figure 5A), which corroborated the meta-analysis in showing that outwash soils were negatively impacted by harvesting (Fig. 3D). The NRCS dataset further indicated that topsoil SOC stocks were smaller in outwash than till or glaciolacustrine parent materials. Aeolian deposits, not reported in the published literature, exhibited a negative harvest trend similar to outwash (Fig. 5A). The meta-analytic trend of increased SOC with harvesting on glaciolacustrine materials (Fig. 3D) was not supported by the NRCS dataset. Physiographic group categories used for FIA do not explicitly identify parent material, but broadly mirrored the patterns for corresponding parent materials in the NRCS dataset, with topsoil SOC being least for xeric (typically deep, sandy soils such as outwash), and greatest for hydric soils (often organic, dense till or fine glaciolacustrine materials). The significant overall impact of harvest on topsoil SOC did not depend upon physiographic group in the FIA dataset.

Meta-analysis indicated that harvesting was associated with diminished SOC stocks under coniferous and mixed forest cover, but not under broadleaved forest cover. However, NRCS pedon and FIA plot data indicated that topsoil SOC stocks, and harvest effects upon them, did not differ by forest cover type (results not shown). Exploring the distribution of forest cover types across parent materials revealed several important but not statistically testable patterns that provide critical context for the meta-analysis results (Appendix S1: Figure S1). Specifically, all published studies of coniferous/mixed forests were on outwash parent materials (Appendix S1: Fig. S1A). This contrasted with NRCS and FIA data, both of which indicated that coniferous and mixed forests were evenly distributed across parent materials (Appendix S1: Figs. S1B, S1C). Similarly, aeolian, alluvial/ colluvial/ residual, and bedrock parent materials were rare in the literature, but appreciable proportions of both cover types occurred on these (other) parent materials in the NRCS dataset. FIA physiographic groups of xeric, mesic, or hydric grossly approximate the outwash, till, and glaciolacustrine parent materials for published studies and NRCS pedons, but due to its differing scheme, a larger share of FIA data fell into the mesic category, which extends into xeric and hydric groups at its extremes. Whether compared to NRCS pedon or FIA plot data (results not shown), there was similar evidence of publication bias in the distribution of coniferous/mixed forests across soil textures. Overall, these non-testable results indicated that apparent meta-analytic "conifer effects" (Fig. 3B) are confounded with outwash parent materials and coarse soil textures.

3.4 Fire impacts on SOC storage

Meta-analysis indicated that fires had an overall negative but highly variable effect on SOC storage. Sampling depth was the strongest predictor of this variation, 42% of which was explained by the portion of the profile sampled (Figure 6). Decreases in SOC were largest for O, intermediate for A, and least for E horizons, while B horizons showed no effect of fire, and mixtures of A, E, and B horizons, or B and BC horizons showed net SOC increases. Soil organic C stocks of whole soil profiles were not impacted by fire. There were no significant differences in impacts as a function of fire type (wild vs. prescribed) or reported severity (high vs. low). According to meta-analysis, nearly all other tested predictor variables were significant predictors of variation, though with data originating from only 5 published papers, trends appeared to be confounded with specific studies or sites. It was not possible to address fire effects on SOC storage using NRCS or FIA data.

3.5 Land use impacts on soil C storage

Meta-analysis indicated that most land use changes had no detectable impacts on SOC storage, and those that did differed in their direction, magnitude, and variability (Figure 7). Because O horizons were sporadically reported (k=12 out of 149 total response ratios) and extremely variable (95%CI of effect size was -99.4%, +1,171%), meta-analysis trends are presented here only for mineral soils. Among mineral soils, changes in SOC storage were positive but still highly variable for reforestation on former minelands. Paired comparisons of native forests (never cultivated) to cultivated lands, as a meta-analytic representation of deforestation, indicated significant SOC losses. Paired comparisons of forests recovering on formerly cultivated lands to cultivated lands, as a representation of cropland reforestation, indicated no significant change in SOC. Other comparisons tested with meta-analysis, including reforestation on grassland, pasture, or hayland, or comparisons of urban forests to lawns, suggested these land use changes had no net impact on SOC stocks (data not shown).

Soil-land use observations from the NRCS dataset corroborated one of the trends detected with meta-analysis of published land use change studies and revealed how soil physical properties influence land use in ways that could obscure detection of other trends using observational data. These trends emerged from comparisons of topsoil properties across land uses increasing in intensity from native forests to barren lands (Figure 8). Parenthetically, we highlight here a distinction between unvegetated "barren lands" (as defined in Appendix S1), and "pine barrens" or "barrens" which are common terms for low-density, *Pinus*-dominated forests in the U.S. Lake States that do not meet the criteria of "barren land" but which are also relevant to these statistical comparisons and their management implications. Regionally, of the 5 land uses, only barren lands had significantly different SOC stocks, which were smaller than cultivated lands, forests regrowing after cultivation, plantations established on (never-cultivated) native forest lands, and native forests (Fig.8A). Although limited in areal extent and thus sparsely replicated in the NRCS dataset, barren lands corresponded to conditions captured in the meta-analytic mineland reforestation comparison, and generally indicated a four- to five-fold potential for SOC increase, as compared to native forests. Most other tested topsoil properties differed with land use across this gradient of intensity. Lands actively under cultivation had the smallest sand contents (Fig.8B) and highest pH (Fig.8C) of all uses, while barren lands, forest plantations, and native forests had large sand contents and low pH. Forests regrowing on formerly cultivated lands had intermediate sand contents and pH. Similar trends existed for silt, clay, and rock contents (all ANOVA $P<0.05$; results not shown), with fine textured, low-rock soils being preferentially cultivated, native forests occurring on coarser and rockier soils, and forest regrowth on croplands occurring on intermediate textures. At the whole profile level, SOC stocks did not differ for lands under cultivation (mean=113 Mg C ha^{-1}), forests regrowing after cultivation (93 Mg C ha^{-1}), or native forest (95 Mg C ha^{-1}), but plantations and barren lands (55 and 8 Mg C ha^{-1}, respectively) did differ from these land uses and from each other.

Four ecosections had sufficient data density for statistical comparisons (two-way ANOVAs) aimed at probing the consistency of regional trends within distinct subregions, those being the Western Superior Uplands, Northern Lower Peninsula (Michigan), South Central Great Lakes, and North Central U.S. Driftless and Escarpment. Despite differing significantly from each other in topsoil SOC stocks, silt, sand, rock, and pH, each of these distinct ecosections mostly duplicated the trends observed across the entire study area. Those trends were: cultivated topsoils having significantly smaller sand and larger silt, clay, and pH values; forest topsoils having significantly larger sand and smaller silt, clay, and pH values, and forests regrowing after cultivation having intermediate values. Topsoil rock content was the exception, showing a significant land use * ecosection interaction. Specifically, the South Central Great Lakes and Western Superior Uplands corroborated the regional land use trends, the Driftless section (which had lower rock contents than all other sections) showed no difference in rock content with land use, and in Michigan's Northern Lower Peninsula, cultivated topsoils had the largest rock contents and forests had the least rocky topsoils.

4. Discussion

4.1 Inferences and Implications

By using three complementary approaches to assess forest management and land use effects on SOC storage in the U.S. Lake States, we are able to assess the significance and applications of our findings in three critical ways. First, by examining whether the three approaches concur, diverge, or are ambiguous, we can qualify our key findings with ratings of our confidence in them. Second, by critically appraising statistical results as one measure of significance, and the magnitude and variability of change as another, we can address the degree to which our results are scientifically significant vs. meaningful in an applications context. Finally, because potential applications of our work range from site-level operations planning to regional- or wider-scale C accounting, we can address how the implications of our findings may depend upon the scale of their application. We organize this discussion around Table 2, which summarizes the key findings of our synthesis.

The most important inference of our analysis comes from the finding that place-based factors, such as soil order, texture, and physiography explain much more of the variation in SOC stocks than land use or management practices. This result is significant in statistical and applied terms, across scales, and as the basis for any consideration from site-level planning up to regional land sector C budgets. The controlling influence of fundamental soil and physiographic factors on SOC stocks argues for refining existing soil and land classification resources (e.g., soil maps, terrestrial ecosystem unit inventories) into tools for identifying vulnerabilities, anticipating impacts and opportunities in forest SOC management. Applied in this way, such tools can be used to tailor operations according to site-specific factors when SOC is a management priority. Acknowledging that place matters more than practice to forest SOC also demonstrates why rules of thumb are problematic. Even "safe" ones—e.g., generalizations from wider-scale analyses such as substantial harvest reductions in forest floor SOC (Nave et al. 2010)—do not apply to individual sites, or in the case of the U.S. Lake States, even entire ecoregions. Ultimately, even increasingly refined syntheses cannot address every condition with confidence, thus local information and professionals' personal experience will remain critical even as the science continues to provide tools that better support the planning of management and operations.

Acknowledging that management has the evident capacity to alter forest SOC, within the constraints of fundamental site factors, we report with confidence that harvesting on average has no impact on whole profile SOC. Given this, the soil as a component of a forest ecosystem—of which the fundamental unit is the pedon or profile—is not affected from an ecosystem C accounting perspective. The resistance of profile SOC to harvest impacts may allow those concerned with forest management, policy, and C accounting in the U.S. Lake States to focus on more uncertain terms in the forest sector C budget, such as the fate of harvested wood products (Domke et al. 2012; Smyth et al. 2018), or on more specific considerations. Such considerations may include steps to protect against topsoil SOC losses, which emerged as a robust general trend across our three approaches, and tailoring those steps towards the specific conditions in which topsoil SOC losses are most likely. On average, topsoils in the U.S. Lake States lost 17-20% of their SOC across our three datasets, but this average value masks underlying variation in which some soils tend to lose, and indeed some topsoils tend to gain SOC with harvesting. The statistically significant average condition, represented by even a 20% reduction in topsoil SOC, still has no applied significance to C accounting, given that topsoils hold 15-30% of profile total SOC stocks. It is significant in its application to the site, where a decrease of this magnitude could negatively impact hydrologic, biogeochemical, and other ecosystem functions tied intimately to SOC (Vance et al. 2014; 2018). In this context, the apparent vulnerability of topsoil SOC to harvest is highly relevant to professionals concerned with the site itself and its long term trajectories, especially on soils and sites identified as particularly vulnerable.

If topsoil SOC losses can be considered a "rule of thumb," then expecting these overall average losses will only be appropriate in rare cases in the U.S. Lake States where site-specific information is not available. On the other hand, if topsoil SOC losses are treated as an indication of risk, to be mitigated as appropriate through operational adjustments, then soil parent material and texture information will inform the need for site- or project-specific adjustments. Our findings related to specific parent materials and textures range from high to medium confidence, given their level of support across datasets. We have high confidence that soils formed in outwash are most likely to exhibit topsoil SOC losses, because this result emerged clearly from both meta-analysis (Fig. 3D) and NRCS pedon (Fig. 5A) datasets. Our methods cannot identify mechanisms for the vulnerability of topsoil SOC in outwash soils, but these may include the fragile soil structure, wide climatic extremes, and indirect relationships with water holding capacity and plant nutrient cycling that tend to place outwash sites on the low-productivity end of the spectrum in the U.S. Lake States (Host et al. 1988; Koerper and Richardson 1980; Nave et al. 2017; Powers et al. 2005). Further to our high confidence in topsoil SOC declines on outwash, we have medium confidence that intermediate-textured soils- particularly sandy loams, which are frequently associated with outwash materials, are likely to exhibit topsoil SOC losses. Our confidence in this inference is only medium as the meta-analytic pattern (Fig 3A) was not supported by the extensive NRCS or FIA soil texture data (Fig 4).

In contrast to the apparent vulnerability of topsoil C in outwash and intermediate-textured topsoils, we have medium confidence that harvesting on the finest-textured soils, which usually occur on glaciolacustrine parent materials, may cause modest relative increases (Figs. 3A, 3D). These fine soils, including textures of silt, silt loam and finer, can also occur on till parent materials (which did not respond to harvest); thus the sites where fine soils are most likely to respond positively to harvest are those where harvesting is done on lacustrine plains, lake-washed till plains, or shallow ponded meltwater depressions. Although these trends for fine glaciolacustrine soils appear to indicate potential C benefits through forestry—i.e., relative SOC increases (Fig. 3D) for soils with large baseline SOC (Fig. 5A)—the potential for these benefits may be tempered by considering fine glaciolacustrine soils in their ecological and operational context. Ecologically, because these soils are high in SOC, water and nutrient holding capacity to begin with, they are unlikely to support more productive forests with a modest relative SOC increase (Belanger and Pinno 2008; Lavkulich and Arocena 2011; Magrini et al. 2007; Pinno and Belanger 2011). Furthermore, from an operations perspective, glaciolacustrine landforms are usually at the hydric end of the physiographic spectrum, making them difficult to access and their soils vulnerable to physical impacts such as rutting, and compaction (Kolka et al. 2012).

Literature examining fire effects on soils highlights the rarity of long-term studies, especially for regions in which fires play modest and/or suppressed roles in ecosystem disturbance regimes, such as the U.S. Lake States (Bedison et al. 2010; Miesel et al. 2012; Patel et al. 2019). Our inferences into fire impacts on SOC storage are limited by this lack of research, and by our inability to use NRCS or FIA data to assess fires using an observational design. Nonetheless, our meta-analysis demonstrates that fire does impact SOC, albeit highly variably and in ways that must be considered in whole-soil context. Profile total SOC stocks are generally not affected by fire, but this overall average result masks fire-induced changes in the depth distribution of SOC. On average, surface horizons—especially O and A horizons—exhibit statistically and ecologically significant SOC declines, even as deeper soils show no net change or even SOC increases (Fig. 6). Given that post-fire recovery of ecosystems services can be inhibited by the loss of surface organic matter (Certini 2005; Neary et al. 1999), the net impact of this surface loss – subsurface gain pattern may be negative from other standpoints, even if its overall SOC effects are neutral. In addition, fire-driven changes in SOM composition that are in addition to (or independent of) changes in SOC amount can have important ecosystem consequences, including altering the overall residence time SOC and its role in nutrient or pollutant sorption (Kolka et al. 2014; Miesel et al. 2015). Ideally, additional research may reveal factors mediating SOC responses to fire that we were unable to address with our meta-analysis, but this is anything but certain. It is well known to fire managers that factors influencing fire behavior, even when known, are highly dynamic, spatially variable, and hence difficult to predict. Topography, meteorological conditions of the year, season, day, and hour, and the abundance, size, and composition of fuels across the burn area all drive variation in fire severity (Finney et al. 2011; Sullivan 2017). Many of these factors are beyond control, but management can still provide the ability to mitigate fire impacts on SOC, whether proactively through forestry or prescribed burning, during initial attack, or through targeted asset deployment during long, large burns. Similarly, deploying firefighting assets to targeted portions of a large fire for reasons that have nothing to do with C for its own sake, but which protect vulnerable soils as an additional benefit, can mitigate its overall C impacts. By the same token, the U.S. Lake States include ecosystems where stand-replacing fires are the long-term dominant disturbance type (Heinselman 1973; Schulte and Mladenoff 2005); where these occur and impacts include the loss of surface organic matter, SOC losses may be a natural, unavoidable, or even desired result.

In the U.S. Lake States, it is difficult to attribute SOC stocks to specific land uses, and even more challenging to assess the impacts of land use change on SOC stocks. These difficulties largely derive from limited opportunity to study the real process of interest (land use change), especially over the multi-decadal and longer timescales needed to reveal changes in SOC stocks (McLauchlan 2006; Nave et al. 2013). Even meta-analysis, which uses studies that mostly attempt to address a single factor (e.g., land use) while holding other sources of variation (e.g., soil texture) constant, is limited by the availability of experimental designs and direct comparisons of changing land uses. Our observational comparisons of NRCS pedons (Fig. 8 and section 3.5), indicate that soils used for different purposes inherently differ in properties that influence SOC stocks, independent of land use. These differences in soil properties explain current and historic patterns of land use and suggest how results from the published literature may also be influenced by non-random land use. If in any subsection of the U.S. Lake States, or across the region at large, forests are allowed to persist on sandier, rockier, more acidic soils, while soils with properties favoring greater primary production, water and nutrient retention, and organo-mineral stabilization are used for cultivation, then comparing SOC for soils used for forest vs. cultivation may create a misleading results. Such results may include failing to detect real land use impacts that are masked by textural influences acting in the opposite direction. If we assume that published studies adequately control for confounding sources of variation (e.g., texture) and rely on meta-analysis alone, even its findings offer little nuance (Fig.7). Forest conversion to cropland was largely historical (Leverett and Schneider 1912; USDA 2015), and forests now recovering on cultivated croplands have not apparently made meaningful SOC recoveries in the region. Reforestation appears to be highly effective at increasing SOC on barren mining substrates, though our high confidence in this result is tempered by the limited areal extent of these lands and the questions of what became of the C pools held in these ecosystems through their conversion to industrial land use activities. Nonetheless, the recovery of many ecosystem services on mined lands depends upon SOM formation (Akala and Lal 2001; Larney and Angers 2012). Forestry-based reclamation may therefore be justified for lands that have not been successfully reclaimed, for reasons that are not distinctly because of SOC but which result in SOC accumulation as an additional benefit (MacDonald et al. 2015; Policelli et al. 2020).

Regardless of their ability to support inferences into SOC change through land use change, observational comparisons of SOC stocks across land uses can help prioritize lands for management. For example, across the U.S. Lake States, forest plantations are on the sandiest, rockiest, most acidic soils of all (except for barren lands, Fig. 8), and hold significantly less profile SOC than native forests (section 3.1). Given the depth of this difference in SOC stocks, it is unlikely to reflect plantation forestry so much as it reflects the history of plantations in the U.S. Lake States, where many plantations result from reforestation and rehabilitation of the lands least productive, most badly burned or eroded following historical, region-wide, land use changes and disturbances (Brown 1966; Conrad et al. 1997; Crow et al. 1999; LeBarron and Eyre 1938; Lundgren 1966). Because these low-diversity, structurally homogenous conifer plantations are extensive and still have not recovered their potential SOC (compared to native forests), they offer an appealing target for management. Careful tactics may transition these systems to more desired ecological or climate-adapted conditions (Nagel et al. 2017; Quigley et al. 2020) while maintaining their SOC stocks, or at least deliberately attempting to mitigate SOC losses. These tactics may be further informed by other patterns in our analysis that reflect bias in the underlying data distribution, which when recognized as such are a useful way to reveal management opportunities and knowledge gaps rather than a problem in the interpretation of results. For example, the apparent meta-analytic "conifer effect," which reflects SOC vulnerability related to soil texture and parent material rather than coniferous vegetation (Figs. 3-5, Appendix S1: Fig. S1), may point to a need for the most cautious management in plantations on outwash plains with sandy loam soils, hence low SOC stocks and greatest vulnerability to harvest. In terms of knowledge gaps, the publication bias connecting coniferous / mixed forests entirely to outwash parent materials highlights a need for further research on, e.g., the effects of harvest on SOC in coniferous forests on till or glaciolacustrine parent materials.

4.2 Management Applications

We have reported overall that place has a stronger influence than practice on SOC stocks and their responses to management. However, many practitioners have less capacity to adjust where actions are taken than how they are implemented if they wish to consider SOC. Recognizing this, we detail in Appendix S1 a set of options and related references for place-based tactics to mitigate SOC vulnerability, or enhance probability of SOC gain (Appendix S1: Table S5). These options for matching SOC management tactics to site conditions augment a menu of climate adaptation strategies and approaches for forest C management. The *Practitioner's Menu of Adaptation Strategies and Approaches for Forest Carbon Management* (Ontl et al. 2020) helps resource professionals identify climate-informed management actions that maintain or enhance forest ecosystem C stocks and sequestration rates. In its strategies, approaches, and example tactics, the *Practitioner's Menu* emphasizes the aboveground portions of forest ecosystems broadly. In Appendix S1, we offer tactics relevant to the U.S. Lake States, and SOC in particular. Recognizing that any list of potential tactics is essentially limitless, we provide a focused, defensible subset of examples, the majority of which tier to the adaptation approaches of reducing impacts to soil nutrient cycling or hydrologic functioning. The link between these approaches and our example tactics recognizes that factors such as texture and parent material often influence the impacts of soil disturbance on SOC and other soil properties concurrently. This link is more than implicit; it explicitly demonstrates how actions that are already often taken to mitigate other soil impacts also affect SOC. In this regard, one function of our tactics menu is to provide managers the capacity to show informed intent in planning or executing prescriptions, because protection of SOC may come at no additional cost to existing restrictions or best management practices (BMP's). This is important because there are many guidance and regulatory frameworks already used by forest managers in the U.S. Lake States, which frequently overlap but rarely include SOC as an explicit target (e.g., Cristan et al. 2016; Minnesota Forest Resources Council 2013; USDA-FS 2012). Other tactics in our menu tier to approaches from Ontl et al. (2020) that recognize how changing management options, such as the timing, level or type of disturbance, or treatment of residual biomass influence SOC based on soil properties. These include actions relating to the implementation of prescribed fire, fuel management, harvest entry cycles, or reforestation. Our example tactics emphasize extensive (rather than intensive) forest management, as it is more representative of the management regimes in the region (Grigal 2000). Furthermore, extensive activities such as single-entry harvests likely have less impact on

SOC over a stand's lifetime than multiple, more intensive activities, and allow for achieving SOC objectives with less investment than repeated entries. Overall, this menu of example tactics is a starting point; as it is applied and refined for a widening range of conditions it will support the goal it shares in common with our synthesis as a whole: undertaking forest management in the U.S. Lake States with knowledge of its impacts on SOC, and how to mitigate them.

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Supporting Information

Additional supporting information may be found online at: [link to be added in production]

Open Research

The meta-analysis, NRCS pedon, and FIA plot data sets used for analyses are available from the University of Michigan Research and Data Hub at https://mfield.umich.edu/dataset/land-use-and-management-effects-soil-carbon-lake-states-emphasis-forestry-fire-and.

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Table 1. Predictors of SOC stocks in topsoils (A horizons; left) vs. whole soil profiles (right) for forest lands across the study region, based on analysis of NRCS pedon and harmonized remote sensing data. Factors are ordered in descending predictive capacity in terms of the sum of squares between / total sum of squares (or in the case of continuous relationships, regression sum of squares / total sum of squares). Regarding the number of observations for each variable, not all attributes were available for every soil, and not every soil profile possessed an A horizon.

	A horizons			**Whole profiles**		
Factor	*n*	SS_b/SS_t	*P*	*n*	SS_b/SS_t	*P*
Texture class	688	26	**<0.001**	484	9	**<0.001**
Soil order	439	16	**<0.001**	484	10	**<0.001**
Ecosection	715	13	**<0.001**	807	8	**<0.001**
Physiographic group	715	8	**<0.001**	808	4	**<0.001**
Parent material	715	6	**<0.001**	808	2	**<0.001**
Landform	715	5	**<0.001**	808	3	**<0.001**
MAT	715	3	**<0.001**	808	0	0.15
MAP	715	2	**<0.001**	808	0	0.193
Management	715	1	**0.044**	808	1	**0.007**
Elevation	715	2	**<0.001**	808	0	0.101
Slope class	715	0	0.349	808	0	0.275
Aspect class	715	0	0.603	808	0	0.463
Abovegr. L. Biomass	261	1	0.213	332	0	0.475
Topogr. Wet. Index	714	0	0.401	808	0	0.889

Table 2. Synthesis summary. Major inferences have more (+) or less (-) confidence based on support across datasets; low-confidence or highly specific inferences are omitted.

Major inference	+/-	Management, C accounting, & policy considerations
1. Place influences SOC more than practice	+	Land use & management can only slightly change SOC within the stronger constraints & wider variation of site-specific natural factors; carbon-informed planning and operations take into account these factors
2. Harvest does not impact profile SOC	+	Harvesting generally does not affect soil C in terms of ecosystem C accounting; policy and management may be effectively directed towards site-specific considerations or other terms in the overall C budget
3. Topsoil SOC is vulnerable to harvest	+	A 15-20% decline in SOC in the portion of the profile that represents 15-30% of profile SOC is not significant from a C accounting perspective, but can impact C cycling, hydrologic processes, & ecosystem productivity, especially on some sites
4. Outwash soils are most likely to lose topsoil C with harvest	+	Small baseline SOC stocks of outwash mean that proportional decreases have little impact on ecosystem C budgets, but could have substantial impact on soil C cycling, hydrologic processes, & ecosystem productivity
5. Glaciolacustrine soils may gain topsoil C with harvest	-	Large baseline SOC stocks of glaciolacustrine materials mean that proportional increases have a potentially large impact on ecosystem C budgets, but little impact on soil C cycling, hydrologic processes, & ecosystem productivity
6. Intermediate-textured topsoils may lose C with harvest	-	Caution may be most appropriate where these soils occur on outwash, with which they are frequently (but not always) associated
7. Fine-textured soils may gain topsoil C with harvest	-	Potential C gains may be greatest where these soils occur on glaciolacustrine parent materials, which may have access limitations due to wetness

8. Fire does not change profile SOC stocks	+	Fire generally does not affect soil C in terms of ecosystem C accounting; policy and management may consider interactions between altered SOC depth distribution and other ecosystem impacts
9. Fire may alter SOC depth distribution	-	Potential impacts of surface C losses on C cycling, hydrologic processes, & ecosystem productivity may be more important than C gains at depth
10. Reforestation of minelands increases SOC	+	Limited extent, C loss with prior conversion may temper net C gains, but positive impacts of increased SOC on hydrologic processes and ecosystem productivity at the site level are important
11. Deforestation for cropland decreases SOC	+	Widespread extent of this largely historic change had major impact on regional C budget, contemporary relevance is limited
12. Cropland reforestation has not increased SOC	-	Crop-to-forest transitions have yet to exhibit net overall SOC increases; SOC stocks and regional C budgets will only be positively affected if native forest SOC levels are actually attainable after long-term cultivation
13. Forests and cropland reforestation occur on coarser soils	+	Preferential cultivation of fine soils and forest allocation to coarse soils may limit upper potential for SOC gain given overarching textural control of SOC
14. Plantations occur on soils low in SOC	+	Preferential (historic) reforestation prioritized vulnerable sites; contemporary management may incorporate SOC vulnerability and opportunity

Figure captions

Figure 1. Map of study area. Shaded polygons are USDA-FS ECOMAP Sections. Numbered point locations, which are approximate, represent papers reviewed for the meta-analysis. The two

smaller point sizes are papers with ecosystem-specific and landscape-level designs, respectively; the two larger point sizes are papers with sites arrayed across a subregional or regional scale, respectively (see Appendix S1: Table S1). Blue triangles and red squares show locations of NRCS pedons, and FIA plots (approximate), respectively.

Figure 2. Soil organic C stocks for control vs. harvested observations from the published literature used in the meta-analysis (A), NRCS (B) and FIA (C) datasets. In each panel, control forests are open symbols and harvested forests are filled symbols. Plotted are sample sizes, back-transformed means and 95% CIs, and mean effect sizes (as percent change from harvest relative to control) and associated *P* values.

Figure 3. Proportional changes in soil C storage with harvesting, by soil texture (A), forest cover type (B), portion of the soil profile sampled (C), and parent material (D). Plotted are *P* values for Q_b / Q_t, means, 95% CIs, sample sizes, and dotted reference lines indicating 0% change in soil C storage.

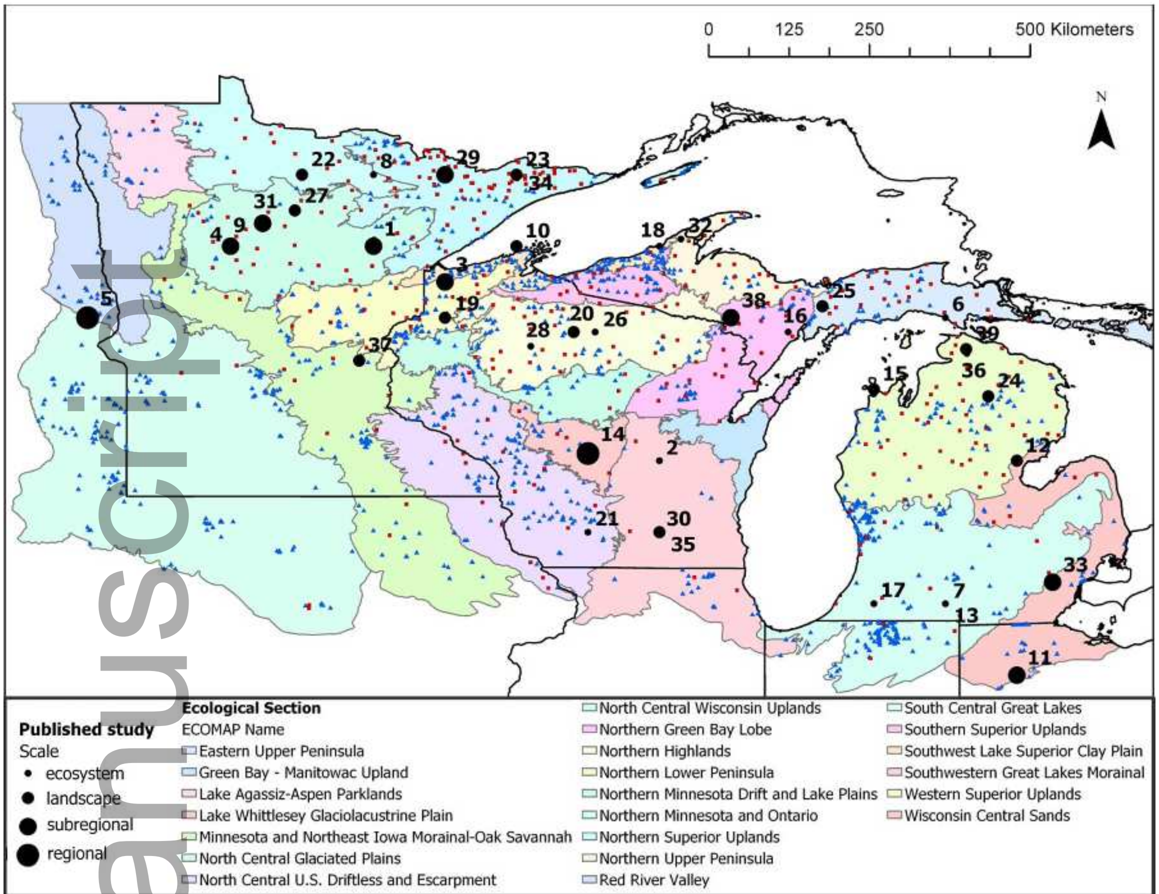
Figure 4. Topsoil (A horizon) SOC stocks, by texture class, in the NRCS (A) and FIA (B) datasets. Plotted are sample sizes, back-transformed means and 95% CIs, and lowercase letters indicating significant differences between textures within each dataset.

Figure 5. Topsoil (A horizon) SOC stocks, by parent material in the NRCS (A) and physiographic group in the FIA (B) datasets. Plotted are sample sizes, back-transformed means and 95% CIs, and lowercase letters indicating significant differences between the parent materials or physiographic groups comprising each dataset. In (A) control forests are open symbols, harvested forests are filled symbols, and significance of treatment (TRT) within each parent material is indicated accordingly.

Figure 6. Proportional changes in soil C storage, by portion of the profile sampled, associated with fire. Points are means, bars are bootstrapped 95% CIs, sample sizes are in parentheses, and the dotted reference lines indicate no net change in soil C stocks.

Figure 7. Proportional changes in soil C storage associated with land use change. Points are means, bars are bootstrapped 95% CIs, sample sizes are in parentheses, and the dotted reference lines indicate no net change in soil C stocks. Note x-axis breaks.

Figure 8. Topsoil SOC stocks (A), sand contents (B), and pH (C) from NRCS data as a function of land use. Plotted are sample sizes, means and 95% CIs. Lowercase letters denote significant differences between land uses for each soil property.



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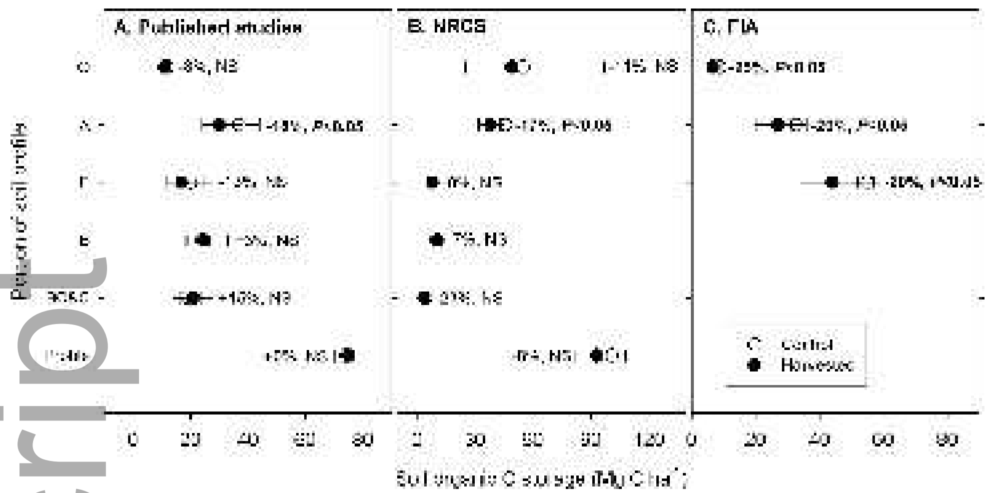

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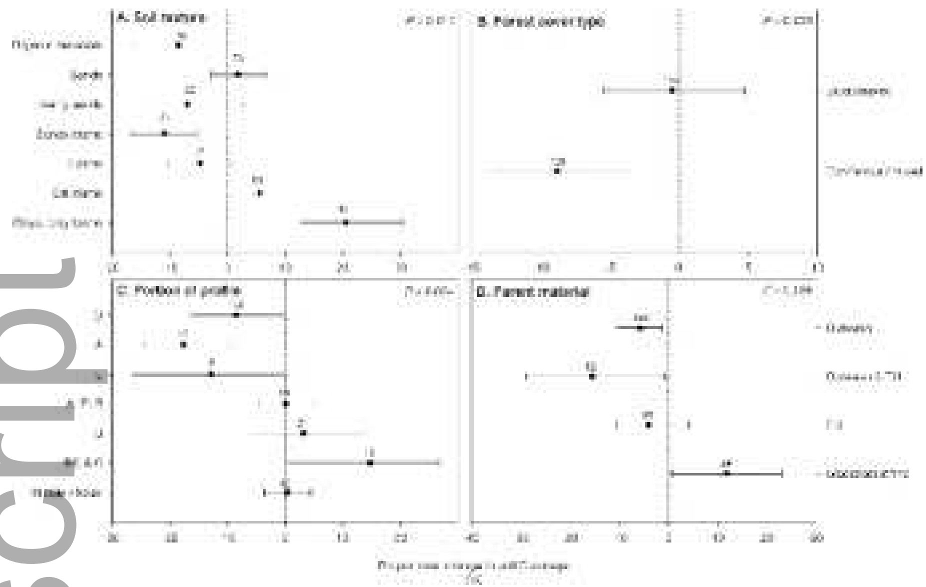

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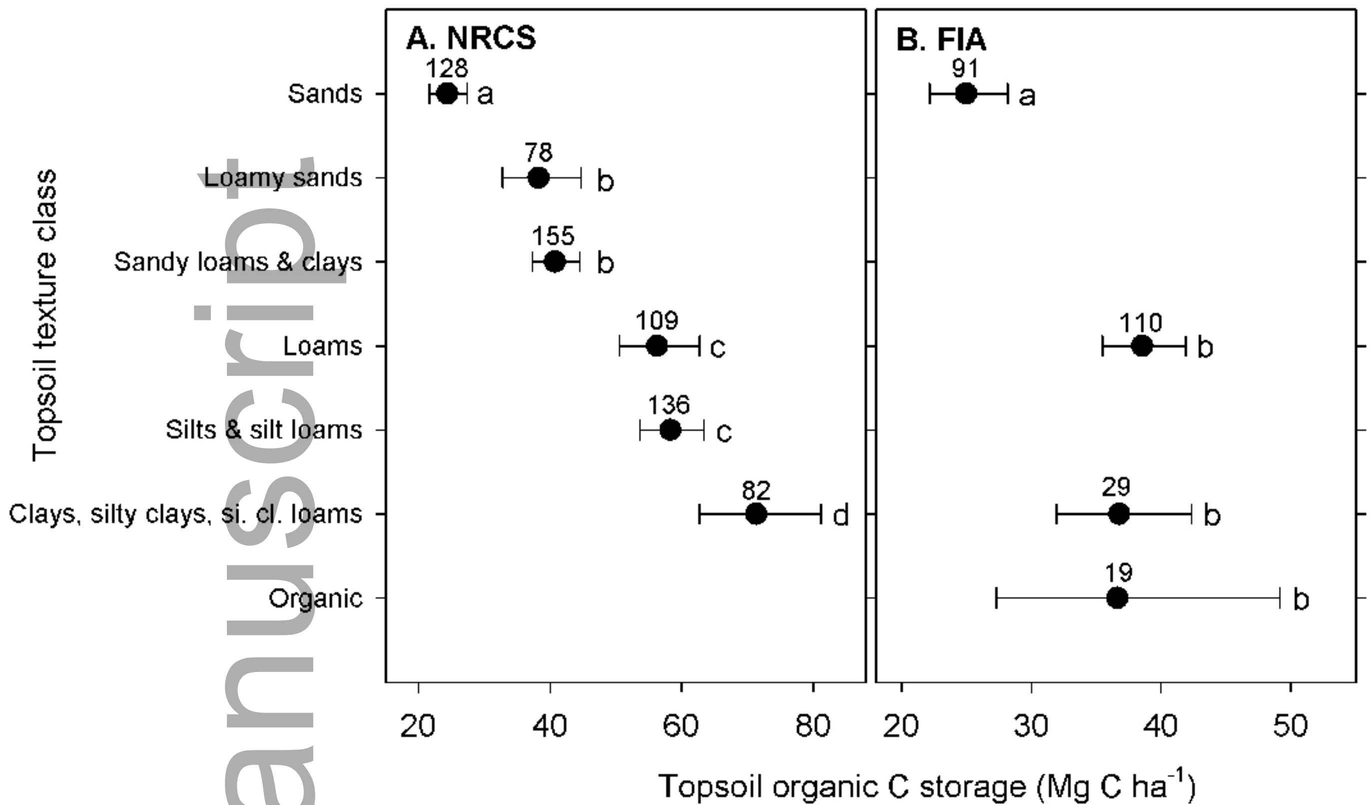

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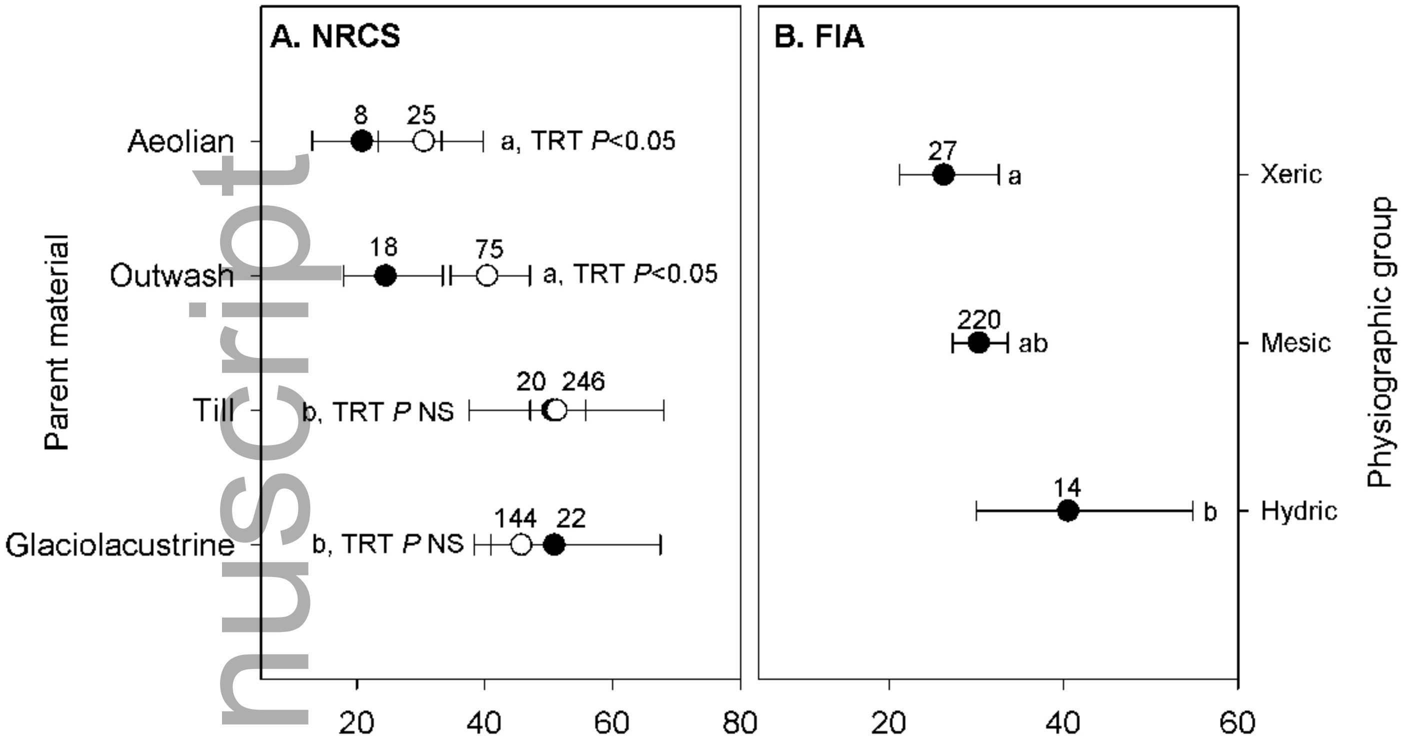

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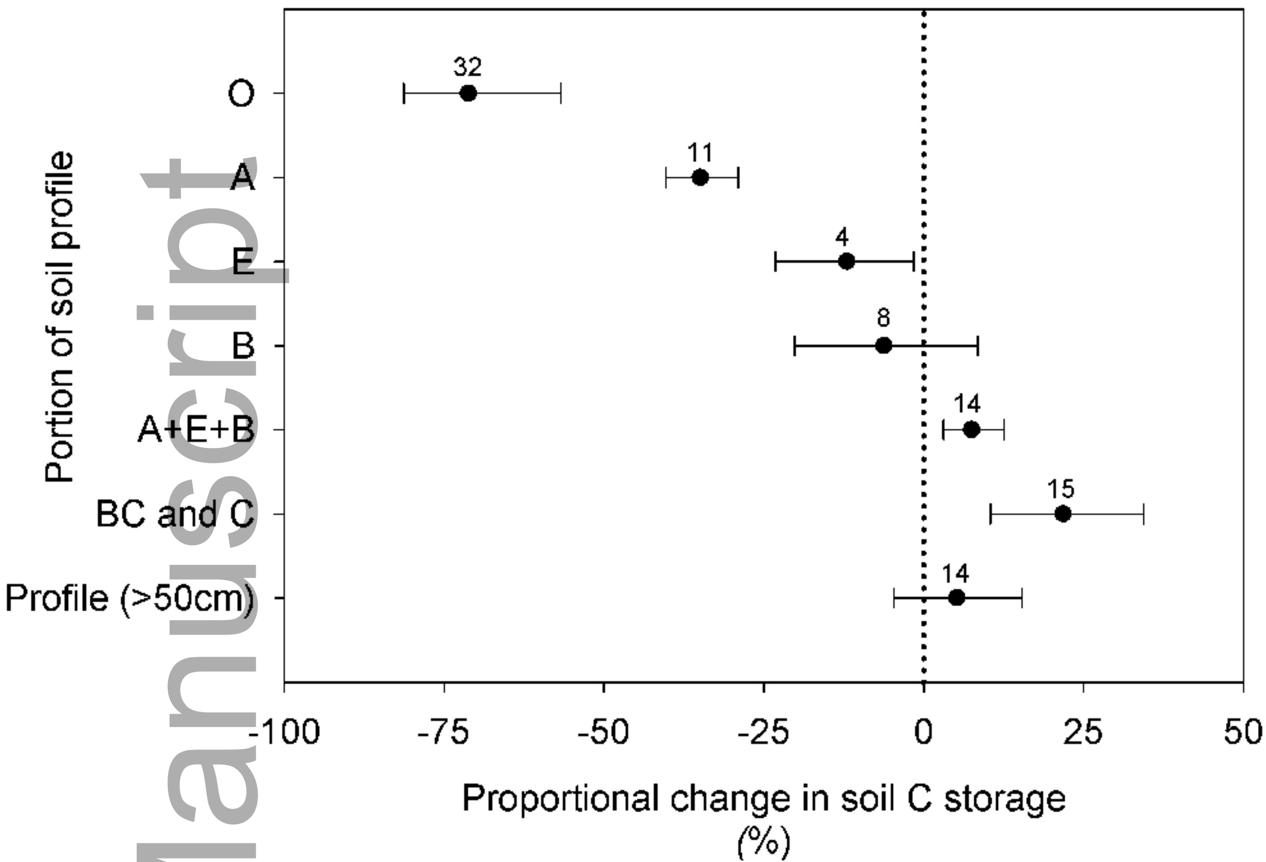

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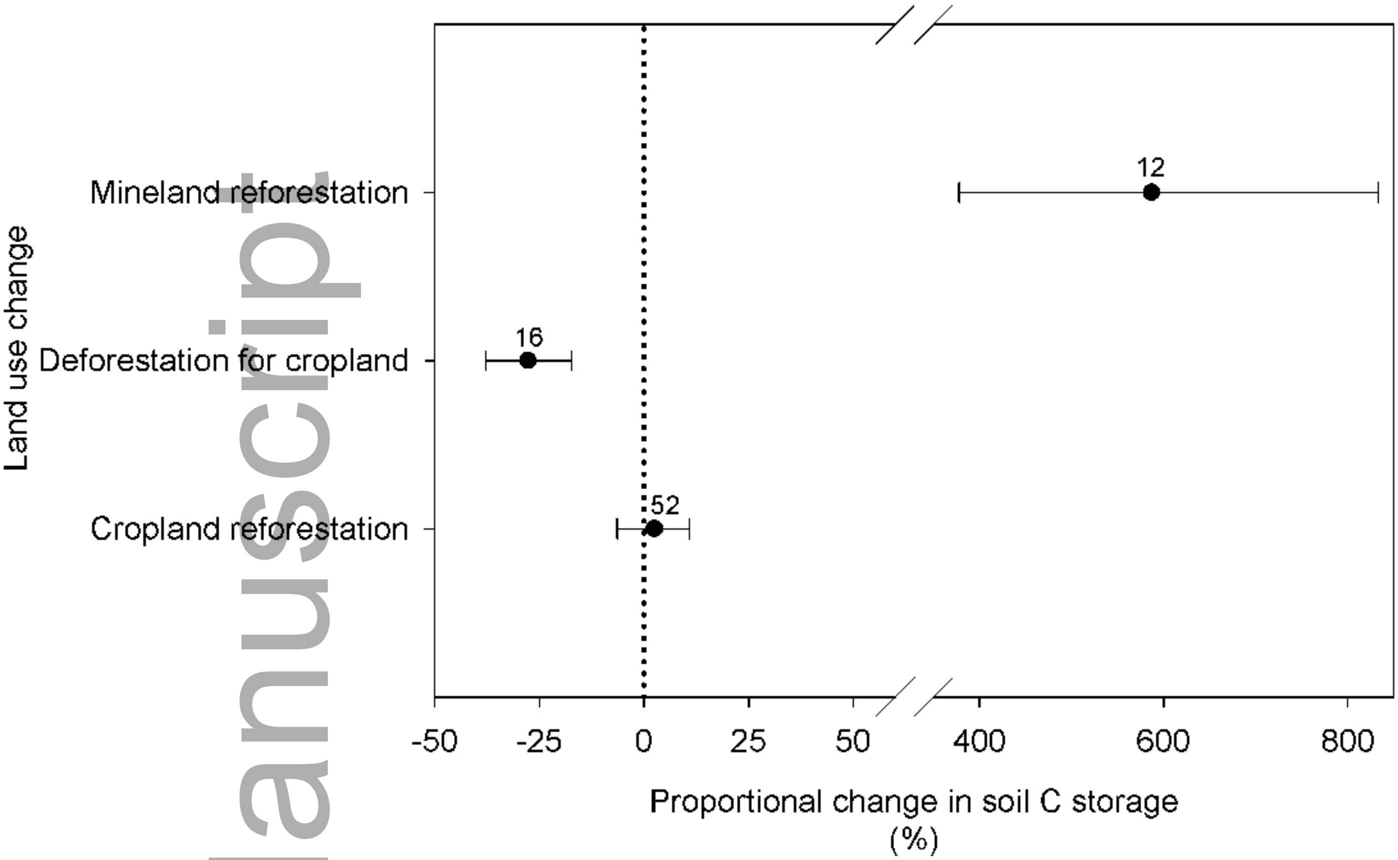

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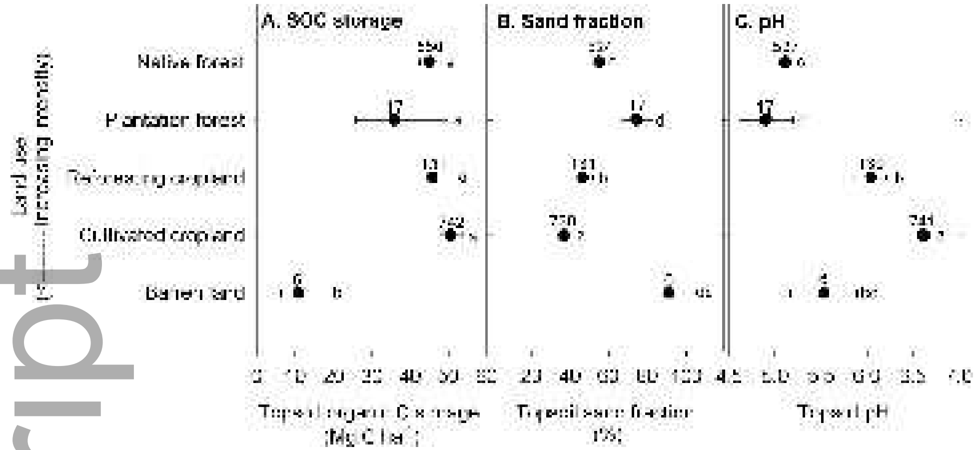

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