Supporting Information. Nave, L.E., K. DeLyser, G.M. Domke, M.K. Janowiak, T.A. Ontl, E. Sprague, B.F. Walters, and C.W. Swanston. 2021. Land use and management effects on soil carbon in the U.S. Lake States, with emphasis on forestry, fire, and reforestation. Ecological Applications.

Appendix S1

Section S1. Detailed Methods

S1.1 Meta-analysis- We searched for relevant publications using keyword searches and reference checks in the online Web of Science platform. Keyword searches followed the syntax: [Geographic Term] + [Treatment] + Soil Carbon, where [Geographic Term] was a U.S. state name or one of the 22 ecoregional sections, and [Treatment] terms were: forest management, timber, fire, afforestation, reforestation, reclamation, restoration, soil amendments, development, and site preparation. We limited our searches to publications from 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). These new keyword searches returned 1,638 papers, which we assessed against our inclusion criteria of: 1) reporting control and treatment values for soil C stocks or concentrations, 2) providing adequate metadata to constrain locations and use as potential predictor variables in meta-analysis, 3) presenting novel response data not included in previous studies, and 4) having a study site located within one of the 22 ecoregional sections comprising our Lake States study area. Twenty publications met these criteria, in addition to 19 pre-2008 publications from our database.

To assemble the data set needed for meta-analysis, we extracted control and treatment SOC values, and used these to calculate effect sizes (as the *ln*-transformed response ratio R), from the 39 publications listed in Table S1 and identified with a * in the Supporting Information Literature Cited. We revisited all papers already in our database (i.e., those published prior to 2008) and performed data extraction anew, concurrently with the new (post-2008) papers collected through new literature searches. We then performed 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 decided to perform 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 assumptions of a weighted meta-analysis. Broad 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.

Papers reported soil organic contents as SOM, measured by loss on ignition (LOI), or as SOC, measured using elemental analyzers. Of the *k*=595 response ratios calculated for use in effect-size meta-analysis, 35 were measured as SOM; we assumed for all of these that 50% of the lost mass was organic C and multiplied each LOI value by 0.5 to estimate SOC concentration (Nave et al. 2013). Published papers also differed in their units of reporting of SOC; namely, *k*=35 reported SOC as a concentration (e.g., percent of mass) rather than as the SOC stock (or storage, Mg ha^{-1}) of interest to our analyses. When SOC concentrations were accompanied by bulk density (Db) data, we calculated SOC storage directly as the product of C concentration (%), bulk density (g cm^{-3}), and the thickness of the reported horizon or sampling layer (cm), and scaled to SOC storage in in Mg ha^{-1}. When papers reporting SOC concentrations did not report Db, we gap-filled according to Section S1.2 and then calculated SOC stocks from the measured %C and layer thickness and predicted Db values.

We extracted potential predictor variables from each paper to address the principal study objectives of identifying factors that predict variation in SOC responses to land use or management. When necessary, 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 (https://soilseries.sc.egov.usda.gov/osdname.aspx). 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. The complete list of attributes extracted from, or assigned to, the published studies is available in Table S2. Our strategy for handling variable 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.

Table S1. Descriptions of published studies synthesized for meta-analysis. Column "OM/OC" reports whether soil organic contents were reported as organic matter (M) or organic carbon (C); "Units" reports whether organic contents were reported as concentrations (C) or stocks (S); *k* denotes the number of response ratios calculated from the data published in the study. Treatments (Treat) are land use change (L), soil amendments (A), harvest (H), and fire (F); scale refers to the geographic extent of the study design as single ecosystem (E), landscape (L), subregional (S), or regional (R).

Study	**Citation**	**OM/OC**	**Units**	***k***	**Treat**	**Scale**	**Description**
1	Leisman 1957	C	C	12	L	S	A & C horizons from a 51-yr mine spoil reforestation chronosequence across northern MN
2	Bockheim et al. 1986	M	S	5	A	E	O, A, & B horizons & whole profiles 4 yr after fertilization in a *Pinus* plantation in WI
3	Alban & Perala 1990	C	S	22	H	S	O horizons & whole profiles 1-8 yr after harvesting for a network of *Populus* stands in MN & MI
4	Alban & Perala 1992	M	S	7	H	E	Whole profiles from *Populus* stands 0-72 yr after harvest in MN
5	Hansen 1993	C	S	8	L	R	A, B, & C horizons & whole profiles 4-30 yr after afforestation for a network of *Populus* stands in WI, MN, ND, SD, IA
6	Schaetzl 1994	M	S	14	F	E	O & A horizons from a 90-yr fire chronosequence in MI
7	Pregitzer & Palik 1997	C	S	4	L	E	A & B horizons for 20-46 yr old *Pinus* plantations on former cropland in MI
8	Stone & Elioff 1998	C	S	4	H	E	O, A, E, & B horizons 5 yr after *Populus* harvest in MN
9	Grigal & Berguson 1998	C	S	5	L	S	O, A, E, & B horizons 4 yr after hybrid *Populus* plantation harvests in MN
10	Brosofske et al. 2001	C,M	S	15	H	L	O, A, E, & B horizons 5-13 yr after harvesting in 6 forest cover types in WI
11	Paul et al. 2003	C	S	5	L	S	Whole profiles 50 yr after forest, cultivation, & reforestation land use changes in OH
12	Rothstein et al. 2004	C	S	40	F	L	O, AE, & BC horizons, & whole profiles from a 52-yr postfire *Pinus* chronosequence in MI

Study	Citation	OM/OC	Units	k	Treat	Scale	Description
13	DeGryze et al. 2004	C	S	20	L	E	A, E, & B horizons & whole profiles 10 yr after forest, cultivation, & reforestation land use changes in MI
14	Coleman et al. 2004	C	S	37	L	R	A horizons 2-10 yr after forest, cultivation, & reforestation land use changes in WI, MN, IA
15	Gallo et al. 2005	C	C	6	A	L	O & AEB horizons 2 yr after N additions to northern hardwood stands in MI
16	Sartori et al. 2007	C	S	8	A	E	A & B horizons & whole profiles 5 yr after wood ash additions to a hybrid *Populus* plantation in MI
17	Morris et al. 2007	C	S	25	L	E	O, A, B, & C horizons & whole profiles ~50 yr after forest, cultivation, & reforestation land use changes in MI
18	Pregitzer et al. 2008	C	S	24	A	R	O, A, B, & C horizons & whole profiles after 10 yr of N additions to northern hardwood stands across northern MI
19	Grossmann & Mladenoff 2008	M	C	3	H, F, L	L	AE horizons 26-55 yr after harvest, fire, or cropland reforestation in WI
20	Tang et al. 2009	C	S	12	H	L	A, B, & C horizons & whole profiles for a 26-yr post-harvest *Populus* chronosequence in WI
21	Scharenbroch et al. 2010	C	S	4	L	E	A & B horizons 33 & 36 yr after two types of forest encroacment into grassland in WI
22	Bradford & Kastendick 2010	C	S	39	H	L	O & AEB horizons for a 50 yr post-harvest *Populus* chronosequence in MN
23	Woodruff et al. 2010	C	C,S	7	F	L	O horizons for stands 1, 30, or 65 yr after wildfires in MN
24	Rothstein & Spaulding 2010	C	S	8	H	L	O, AE, & B horizons 5-15 yr after harvesting *Pinus* stands in MI
25	Trettin et al. 2011	C	S	12	H	L	O, EB, & BC horizons & whole profiles 11 yr after harvest & site prep treatments in mixed conifers in MI
26	Jurgensen et al. 2012	C	S	24	H	E	O, A, & B horizons 13 yr and 29 yr after harvest in northern hardwoods & *Pinus* stands in WI & MN, respectively
27	Powers et al. 2012	C	S	58	H	L	O & AEB horizons for ~100-yr, 1x vs. 2x harvested *Pinus* chronosequences in MN
28	Forrester et al. 2013	C	S	4	H	E	O & AE horizons 2 yr after harvesting northern hardwoods in WI

Study	Citation	OM/OC	Units	k	Treat	Scale	Description
29	Klockow et al. 2013	C	S	9	H	S	O, A, & EB horizons 1 yr after harvest treatments in *Populus* stands across northern MN
30	Lajtha et al. 2014	C	S	2	A	E	A horizons after 50 yr of annual organic matter amendments to a broadleaved forest in WI
31	Kurth et al. 2014	C	S	48	H	S	O & AEB horizons 15 yr after harvest treatments in *Populus* stands in MN & MI
32	Gahagan et al. 2015	C	S	20	L	E	O, A, B, & C horizons & whole profiles 63 yr after *Pinus* or 81 yr after broadleaved reforestation on old croplands in MI
33	Currie et al. 2016	C	S	9	L	S	O, OA, & C horizons 10-50 yr after urban development or reforestation across southern MI
34	Kolka et al. 2017	C	S	12	F	L	O, AE, & B horizons 1 yr after wildfire in MN
35	Ziter & Turner 2018	C	S	1	L	L	AEB horizon for urban reforestation in WI
36	vandenEnden et al. 2018	C	C	4	A	E	AE horizons after 10 yr of annual organic matter amendments in MI
37	Kazanski et al. 2019	C	S	6	A	L	AE horizons after 12 yr of annual N amendments in MN
38	Premer et al. 2019	C	S	4	H	S	AEB horizons 20 yr after harvest treatments in *Populus* stands across northern MI
39	Nave et al. 2019a	C	S	48	H, F	L	O, AE, E, B, & C horizons & whole profiles for 103-yr harvest and 78-yr fire chronosequences in MI

Table S2. Variables extracted from and categorized for the published studies used in the meta-analysis.

Variable	**Description**	**Examples and Ranges of Values**
Data source	page(s), table(s), and figure(s) in the pdf containing the metadata and response data	2-4, T1, F2
Parameter	organic matter response parameter	organic matter, organic carbon, total carbon
Units	reporting units of the organic matter response parameter	%, Mg ha^{-1}
Sampling	sampling design of the study	pre vs. post-treatment sampling, paired treatment vs. control, chronosequence
Method	method for analytical determination of organic contents	elemental analyzer, loss on ignition
Scale	geographic scale of study design	landscape, regional
Treatment	general land use or management treatment	soil amendment, harvest and site preparation, fire, land use change
Practice descriptor 1	specific practice details for the land use or management treatment	cropland vs. reforesting cropland (land use change), regeneration vs. partial (harvest), prescribed vs. wildfire
Practice descriptor 2	second set or more refined practice details for land use or management treatment	residue removal vs. retention (harvest), low vs. high-severity fire
Practice descriptor 3	third set or more refined practice details for land use or management treatment	disking surface after harvest, form of N added for fertilizer
Time	time since treatment	years (if reported)
Plant functional type	functional vegetation type of the forest ecosystem studied	broadleaf vs. coniferous / mixed forest
MAT	mean annual temperature in degrees C	3.1 - 10.2
MAP	mean annual precipitation in mm	598 - 982
Ecosection	ECOMAP section	Northern Highlands, Eastern Upper Peninsula
Landform	broad grouping of landform type	moraine, lacustrine plain

Variable	**Description**	**Examples and Ranges of Values**
Physiographic wetness	wetness or drainage index of site	poorly to somewhat poorly drained, moderately well to well drained, somewhat to excessively drained
Elevation	elevation of site in meters above sea level	190 - 505
Slope_class	slope class of site	level to gently sloping, moderately sloping, strongly sloping
Aspect	aspect class of site	in cardinal directions
Parent material	broad grouping of parent material type	outwash, fine glaciolacustrine deposits
Soil Series	individual series, complex, or association as mapped by USDA NRCS	Argonne, Kalkaska, Rubicon
Soil Order	soil classification at the Order level (USDA)	Spodosols, Alfisols, mixed Inceptisols and Alfisols
Soil Taxon	soil taxonomy according to USDA system: Subgroup or Great Group	Typic Hapludalfs, Entic Haplorthods
LAT,LONG	latitude and longitude	in decimal degrees
Depth	depth range of the sampled soil layer in cm	0-10, 5-15, 0-20
Portion of profile	master horizon (known or probable) as reported or inferred from depth range of layer	O, A, E, AE, B, whole soil profile
Text_class	matrix texture class of sampled soil, specific to layer if possible	clay, sandy loam, silt loam, sapric muck
IC	inorganic C percentage of the sampled soil layer	0
CTRL pH	mean pH of the sampled soil layer under control conditions	2.3 – 7.5
TRT pH	mean pH of the sampled soil layer under treatment conditions	2.1 – 8.4
Db_CTRL	mean bulk density of the sampled soil layer under control conditions	0.80 – 1.66
Db_TRT	mean bulk density of the sampled soil layer under treatment conditions	0.72 – 1.72

Variable	Description	Examples and Ranges of Values
SOC_CTRL	mean SOC stock of the sampled soil in the control condition, in Mg ha-1	0.1 - 178
SOC_TRT	mean SOC stock of the sampled soil in the treatment condition, in Mg ha-1	0.1 - 237

S1.2 Synthesis of pedon and remote sensing data- We computed SOC stocks of individual genetic horizons in the USDA-NRCS NCSS Database, in Mg C ha^{-1}, as the product of %SOC, Db, and thicknesses. Because soil horizons in the NCSS Database can contain multiple variant forms of soil C concentration or Db, or can completely lack one or the other of these variables, our SOC stock computations required many decisions and steps. We used the available C concentration data according to the following preferences and criteria: (1) if available, % organic C = % SOC; (2) if % total C and % inorganic C available, then % total C - % inorganic C = %SOC; (3) if % total C is available and pH <7.0, then % total C = % SOC. Regarding Db, our first use of these data was in developing estimated Db values for soils lacking them in this, and the meta-analysis data set. For gap-filling these missing values, we proceeded as follows. We extracted the Db values for all n=235 O horizons in the NCSS Database, calculated as oven-dry whole-soil mass / field-moist whole-soil volume (db_fmst). Organic horizons have traditionally been under-represented in Soil Survey and the NCSS Database, especially outside regions that have organic soils; indeed, 122 of these 235 observations were from the Lake States which are a well-known region of organic soil development (Boelter and Verry 1977). Organic horizon Db did not differ by U.S. state or %SOC, but individual O horizon designations did differ. Therefore, for any observed O horizon lacking Db (whether in the NRCS pedon or meta-analysis data set), we used the mean Db value for the most closely matched designation (e.g., Oe, Oa, O horizon as a whole), along with the measured %SOC and thickness, to compute the SOC stock. For mineral soils, we derived an equation to predict Db (as oven-dry fine earth mass / oven-dry fine earth volume) from %SOC for the n=5,716 samples possessing both measurements. This modeled relationship, following many others that have noted the significant inverse relationship between %SOC and Db (e.g., as we used in Nave et al. 2018, 2019b), was slightly stronger (larger adjusted R^2, lower SE of estimate) when including depth in the profile. The two-variable model explained 32% of the variation in measured Db values, and was significant at P <0.001, so we applied it to both data sets to fill missing observations. We computed SOC stocks of each horizon, in Mg C ha^{-1}, as the product of %SOC, Db, and thickness. For horizons spanning 100 cm, we assumed a homogenous vertical distribution of SOC within them, and truncated the bottom depths of such horizons. We set this 100 cm reporting depth in order to make comparisons of SOC stocks to 1 m (or refusal) across profiles.

To synthesize geo-located soil pedons with remote sensing information, we only used pedons collected from 1989-present. We extracted land cover from the most closely coincident version of the National Land Cover Dataset (NLCD; Vogelmann et al. 2001; Homer et al. 2004; Fry et al. 2011; Homer et al. 2015; Dewitz et al. 2019), aboveground biomass C density (in Mg ha^{-1}) from the National Biomass Carbon Dataset (NBCD2000; Kellndorfer et al. 2013), mean annual temperature (MAT) and precipitation (MAP) from PRISM's United States Annual Precipitation and Mean Temperature data sets (PRISM Climate Group 2015), and Land Type Association, (LTA) a physiographic attribute developed for each of the Lake States to categorize the ecological units (in terms of parent material and topography) at scales that tier beneath the ECOMAP system (Corner and Albert 1999; Hanson and Hargrave 1996; McNab et al. 2007, WI

Dept. Natural Resources 2002). For the southern portion of Michigan's Lower Peninsula, LTA classifications are not available; here we extracted surface geologic information for every geo-located pedon from the spatially explicit Quaternary Geology of Southern Michigan data product (Farrand et al. 1982). For remaining portions of the overall study area (i.e., small areas of ND, SD, IA, IL, IN, OH) we extracted parent material and landform information from Soller et al. (2012). In addition to these attributes extracted from existing GIS products, we also created GIS layers and extracted derived values from them for every pedon, including, from a DEM based on the National Elevation Dataset (USGS 2013), each point's elevation, slope, and aspect, and topographic wetness index (TWI) as generated according to Tarboton (1997) using the TauDEM toolbox (Tarboton 2015).

We used most GIS-based attributes as a starting point in processes intended to improve data quality and statistical power. The most critical of these relates to validating, reclassifying, and disambiguating land cover and land use. As in prior analyses (e.g., Nave et al. 2018; 2019b), we assumed that land cover for soils sampled between 1 January 1989 and 31 December 1996 was reasonably represented by the NLCD1992 product; soils from 1997 to 2001 were represented by NLCD2001; soils from 2002 to 2006 by NLCD2006; soils from 2007 to 2011 by NLCD2011; soils from 2012 to present by NLCD2016. In past assessments, we have compared NLCD land cover classifications at pedon geolocations to the (inconsistently) available vegetation or management notes accompanying the pedon data, and found NLCD to be 75-80% accurate, similar to values reported in other large-scale assessments (Marsik et al. 2018; Nave et al. 2019b; USDA 2016). However, this level of accuracy leaves room for improvement, and furthermore, the land cover classes assigned in NLCD can be used more effectively when land use can be observed or inferred. We described our approach for inferring a land use change—cultivation to forest—from soil descriptions and remotely sensed land cover in past analyses (Nave et al. 2013; 2018). In the present analysis, we similarly differentiated among pastures that have been permanent pastures, were formerly cultivated, or have switched dynamically between pasture and cultivation during recent periods. Similarly, by inspecting high-resolution satellite imagery, it was possible to differentiate forest plantations, or forests harvested within recent decades, from adjacent mature forests. We inspected imagery for each of the 1,709 soil pedons, and classified whether the land cover assigned to each point by NLCD was likely to have accurately represented land cover at the time of pedon sampling. Similar to our past assessments, 76% of the NLCD-based assignments appeared to have been accurate overall; accuracy scores for aggregated land cover classes are presented in Table S3. Where assignments were inaccurate, we reclassified them to represent the probable land cover condition at the time of soil sampling. Thereafter, in order to make the most efficient use of the data for our ecoregional assessment of land use and management effects, we assigned each geolocation into a more refined category reflective of the dominant land use and management condition.

Table S3. Summary of land cover product accuracy and reclassifications for the geolocations of NRCS pedons. Reported are the initial accuracy as a percentage of the total pedons (%TRUE), as well as the absolute numbers of pedons for which initial NLCD land cover assignments were inaccurate (FALSE) vs. accurate (TRUE). Also reported is the number of pedons falling into each land cover group before and after reclassification for accuracy.

Land Cover Group	**%TRUE**	**FALSE (*n*)**	**TRUE (*n*)**	**Initial pedons (*n*)**	**Reclassified pedons (*n*)**
Barren Land	67	1	2	3	7
Cultivation	87	79	528	607	587
Developed	16	65	12	77	29
Forest	81	117	484	601	650
Shrub/Scrub	0	5	0	5	0
Grassland/Herbaceous	11	51	6	57	0
Pasture/Hay	75	55	168	223	240
Herbaceous Wetlands	53	14	16	30	38
Woody Wetlands	87	12	80	92	158
Water	67	2	4	6	0
Other	13	7	1	8	0
ALL CLASSES	76	408	1301	1709	1709

We next discuss several points related to our accuracy assessment and reclassification process because they contextualize the interpretation of our results, may be of value to future researchers, and are important to the ongoing refinement of our data synthesis techniques. The most important of these is a caveat. Although based on experience with regional geography, history, patterns of land use and management, and air photo and map interpretation, our assessment of land cover classes was subjective. We were able to improve upon the algorithm-based methods used to derive the NLCD products but a residual unquantified error rate still exists in our land cover assignments and resulting land uses. This error likely obfuscates our ability to detect land use effects on SOC, but does not directionally bias any of our results or inferences. The second caveat is that the classes we inherited and refined from NLCD are often themselves ambiguous (or temporally dynamic) in ways that cannot be ascertained without years of on-the-ground observation. Lines between the grassland vs. pasture/hay, or pasture/hay vs. cultivation provide good examples- a location may appear to be one or the other of these classes, only because e.g., the day after the imagery was taken the grassland was mowed for hay, or plowed for cultivation. The "wetland" class also provides examples: lands that qualify as wetlands (soil, hydrology, vegetation) may be subsumed under other land cover classes; similarly, some lands with forest cover in the Lake States are wetlands but barring investigation it is not possible to classify them as such. Another caveat relates to the spatial resolution of the geo-located soil pedon vs. the remote sensing products, which themselves have differing levels of resolution. In some cases, we noted non-forest land cover classes possessing substantial aboveground biomass C stocks; in nearly all cases this appeared to derive from a geo-located soil pedon whose land cover, e.g., cultivated field was accurately represented by the NLCD assignment (NLCD being a 30 m pixel size), but located close to a forest edge and therefore registering the aboveground biomass density associated with the 250 m pixel size of the NBCD2000 product.

Regarding our assignments of land use based upon land cover and soil pedon information, we next offer criteria and descriptions for our categorization process.

Barren lands- Barren lands have little to no vegetation, apparently persisting in this manner over longer time frames than would be the case for active construction or development. Barren in this context is a passive term, in contrast to areas where the lack of vegetation is due to active modification of the land surface, removal of soils or sediments, or intended replacement with built features. Examples from the Lake States include sediment barrens, dunes, beaches, sand blowouts, and areas of historic peat mining (i.e., organic soils removed down to underlying mineral substrate).

Cultivation- Cultivated lands are the most readily recognized from imagery, whether by analyst or algorithm, and across the Lake States cultivation is a long-term stable land use. Even for those limited cultivated lands that transition to other uses, such changes are perceptible through features such as the persistence of old field lines or fencerows during oldfield reforestation, or through the familiar regional pattern of commercial, residential, and exurban development into previously agricultural areas.

Developed- We classified pedons falling in developed lands into three groups. Pedons from developed- open lands were from parks, golf courses, and large areas that are predominantly herbaceous (rather than forested) and which appear to be regularly managed through activities such as mowing, raking, or landscaping. Developed- forest lands were forest lands in a landscape-level setting that is low-density developed or higher, i.e., suburbs but not exurbs. We intended the developed- forest category to capture lands covered with forest that experience higher rates of human use, runoff and material inputs, localized higher rates of atmospheric deposition, urban meso- or micro-climates, and invasive species than forests in more rural or wildland settings. We placed all other developed lands into a miscellaneous developed category; these included pedons from suburban or higher density lawns, city street rights of way, active development sites, and ongoing industrial and or extractive activities (e.g., salvage yards, gravel pits).

Forest- We subsumed the shrub/scrub category into forest in the Lake States, recognizing that apparent shrublands in this region are recently harvested forests, young forests establishing on former agricultural lands, or woody wetlands. Within the forest category, we preserved NLCD cover type classifications (deciduous, coniferous, mixed) when possible, but recognized four additional types of forest land, useful for assessing land use change and management impacts.

First, when a pedon fell under forest, but possessed an Ap horizon, we assumed it represented reforestation on formerly plowed land. In some cases, such pedons appeared in windbreaks, shelterbelts, or broadleaved plantations (e.g., bioenergy plantations). Second, when a pedon fell under forest cover that was obviously low-density and low-stature, in a geometric configuration (e.g., a rectangular old field), and lacking an Ap horizon, we assumed it represented reforestation of (never-cultivated) pasture or hay land. Third, we recognized pedons from harvested forests as those falling in areas of forest with signs of harvesting ranging from active or recent skidder trails, log decks or decking areas, to group selection openings, shelterwood belts or row thinning geometries, or clear regeneration-cut boundaries against adjacent higher-density, higher-stature forest. In some cases we recognized past harvests as residual canopy dominants overtopping lower-stature canopies. In general, based upon familiarity with forests and forestry in the Lake States, we estimate our assignments into the harvested forest category to correspond to forests no older than 20-30 years (and quite often younger), as compared to adjacent more mature stands. This estimate compares favorably with the average years since treatment for harvesting studies in the meta-analysis data set (26 years), suggesting general comparability of these two data sources. In general, we erred on the side of caution in assigning forests to the harvested condition, in order to avoid attributing to harvesting what may have actually been a soil, hydrologic, or topographic pattern. The fourth and final condition of forest that we recognized is one of the most visible, save for cultivation- the "pines in lines" appearance of conifer plantations, ranging in apparent age from 1-3 decades to much older (80-100 yr), owing to the history of plantation reforestation projects during the post-land-clearing through Depression era in the Lake States.

Pasture/hay- Owing to the scarcity of native, non-managed grasslands in the Lake States, we subsumed the grassland/herbaceous category most often into the pasture/hay category (or occasionally into barren land, harvested or reforesting forest classes). We recognized three types of pasture/hay lands. First, pedons with no Ap horizon and under stable perennial herbaceous cover at the time of aerial imagery represent permanent pasture/hay. In the Lake States, these lands are typically too wet or too rocky for cultivation. Second, pedons with Ap horizons and under stable perennial herbaceous cover at the time of imagery fell into a category that we created to incorporate long-term pastures that were previously cultivated, cultivated lands temporarily (~10 yr) in Conservation Reserve Program or other soil conservation programs, and rural yards (including barnyards). For the third type, we recognized pedons classified by NLCD as pasture/hay or grassland, and with Ap horizons, but subsequently under cultivation at the time of more recent imagery, or lacking the appearance of stable perennial herbs as lands that dynamically switch between pasture/hay and cultivation. Common cues of pasture/hay use in aerial imagery included rectangular field edges, mowing lines, hay windrows or bales, livestock troughs or wallows, and isolated shade trees.

Wetlands- Our approach to classifying wetlands had some similarities to forests. When a pedon was classified by NLCD as forest, but soil taxonomic information indicated a drainage class of poorly or very poorly drained, we reclassified it to woody wetland. If a pedon in an area classified by NLCD as woody wetland possessed an Ap horizon, we assumed it to represent woody wetland reforestation on formerly cultivated land. When a pedon fell in an area of woody wetland bearing evidence of recent harvesting (see the *forest* section), we classified it as a harvested woody wetland. In few cases, pedons in areas classified by NLCD as herbaceous wetland possessed sufficient woody vegetation that we reclassified them to woody wetland. Herbaceous wetlands generally thus included marshes, open muskegs, sloughs or swales (i.e., of dune-swale complexes), and shallow prairie potholes. In a limited number of cases, NLCD algorithms assigned pedons to the open water category; we assumed that assignment to be an artifact of temporal mismatch (e.g., seasonally high water levels) with pedon sampling and assigned those pedons into the herbaceous wetland category. We also reclassified grassland/herbaceous pedons with drainage classes of poorly or very poorly drained to the herbaceous wetland category.

In terms of other reclassifications and modifications of initial GIS data, we parsed Land Type Association and surface geology attributes for every pedon into a set of discrete parent material and landform groups, respectively. For example, Landtype Association (LTA) names customarily bear names such as “Watton-Sixmile Moraine” or “Merrill Outwash Plain,” which correspond to landforms of “moraine” and “plain,” and parent materials of “till” and “outwash,” respectively. We also concatenated each pedon’s parent material and landform into a physiographic group cross product (e.g., “till moraine,” “outwash plain”), to arrive at a more consistent, statistically replicated classification for these factors. We placed DEM-derived slope percentages into NRCS classes of nearly level, undulating to rolling, and hilly to steep, and converted slope aspects derived in degrees into 4 cardinal aspects (N, S, E, W). Lastly, for year 2000 aboveground biomass values, we followed our previous standard and only extracted biomass estimates from NBCD2000 for pedons sampled between 1997 and 2006. Our final data set for analysis included 1,709 pedons, consisting of 10,608 individual horizons (2,993 with measured Db, 191 with mean O horizon Db, 7,424 with predicted Db) across the study area.

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

Section S2. Supporting Results

Table S4. Sample size and average thickness information for the reporting depths used to test harvest impacts on forest SOC storage. For published data analyzed with meta-analysis, observations are paired, thus *k* is the number of treatment:control pairs for each depth. For NRCS and FIA data, sample sizes (*n*) are the number of geo-located pedons or NFI plots (respectively) falling under control and harvested conditions.

Published studies			**NRCS**				**FIA**			
Horizon	Thick (cm)	*k*	Horizon	Thick (cm)	Control *n*	Harvest *n*	Horizon	Thick (cm)	Control *n*	Harvest *n*
O	3	108	O	15	113	17	O	4	329	35
A	12	22	A	10	627	71	A	10	229	32
E	13	8	E	18	488	63	E	10	229	32
B	26	21	B	25	1815	233				
BC & C	56	10	BC & C	49	988	135				
Profile	73	33	Profile	86	701	86				

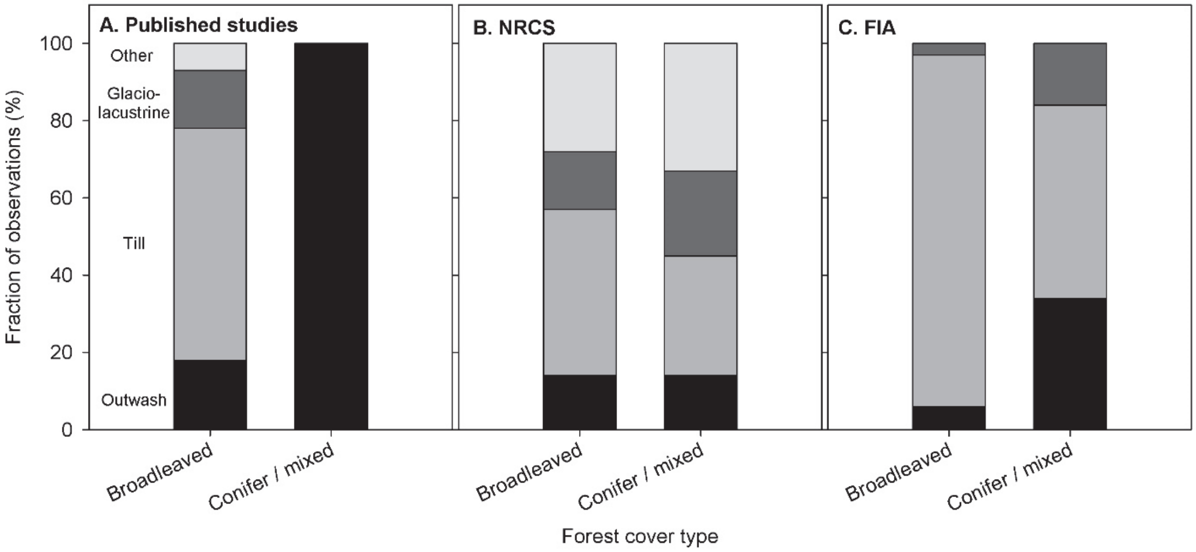

Figure S1. Distribution of two forest cover types (broadleaved vs. coniferous/mixed) across parent materials for published studies (A), NRCS (B), and FIA (C) datasets. Values are presented as the percentage of total observations.

Table S5. Potential SOC management tactics, by management activity. These specific tactics tier to the generalized approaches in Ontl et al. (2020; Table 1, Menu of adaptation strategies and approaches for forest C management). Tactics are based upon our analysis and other studies, and represent a subset of wider possible options, many of which are encompassed in existing BMPs and restrictions on State and Federal lands in the Lake States. When possible, relevant studies are regional.

Management Category	Strg.	Appr.	Tactic	Basis for tactic / mechanisms of potential SOC impact	Relevant studies
Harvest	2	2.1	Conduct mechanized harvesting on vulnerable soil textures only during intermediate moisture, frozen (>15 cm), or snow-covered (>30 cm) conditions	Physical damage to SOC that is protected by soil structure is most likely when soils are overly wet or dry; impacts are mitigated when structure is protected by freezing or snowpack	Berger et al. 2004; Block et al. 2002; Kolka et al. 2012; Sealey & Van Rees 2019; Shabaga et al. 2017; Stone 2002
Harvest	2	2.1	On soils most vulnerable to structural degradation, restrict mechanized travel to the minimum number of trails and roads, optimize # of transits, use more & smaller landings	Substantial structural impacts occur with the first machine pass and are thereafter relatively small; soil impacts are the product of mass & number of transits; smaller landings have lower relative area	Ampoorter et al. 2012; Bustos & Egan 2011; Cambi et al. 2015; Parkhurst et al. 2018; Reichert et al. 2018; Slesak & Kaebisch 2016
Harvest	2	2.1	For identifying soil structural impacts, use physical measurements rather than visual estimates whenever possible	Penetrometers, bulk density, & remote sensing more sensitively detect changes in soil structure (e.g., density & strength) than visual protocols	Marra et al 2018; Steber et al. 2007; Zenner et al. 2007
Harvest	2	2.1, 2.2	On soils with O horizons, use slash mats and rubber-tired (not tracked) machines to preserve O horizons and minimize mineral soil exposure; route trails parallel to slope gradients	Skid-steering machines scrape away surface organic horizons, exposing mineral soils to thermal and hydrologic modifications that may stimulate decomposition, runoff and C flux, especially through flow incision	Maghdi et al. 2016; Polotrak et al. 2018

Harvest	2	2.1, 2.2	On soils lacking organic horizons, use slash mats and tracked (or super-wide-tired) machines to minimize compaction and rutting	Tracks and wide tires distribute mass more than tractor-tired equipment, mitigating compaction and rutting which destroy SOC-protecting soil structure, increase runoff & erosion	Allman et al. 2015; Borchert et al. 2015; Gerasimov and Katarov 2010; Haas et al. 2016; Vega-Nieva et al. 2009
Harvest	2	2.1	Broadcast residues (if possible, chipped) on impacted sites such as forwarder trails, decking and landing areas, and haul roads	Spreading woody residues can help protect the mineral soil surface from thermal and hydrologic modification; C subsidies from residues may sustain C cycling in diminished horizons through the post-harvest recovery period	Belleau et al. 2006; Corns & Maynard 1998; Webster et al. 2016;
Harvest	2, 6	2.1, 6.1	During processing of individual trees, position residues (e.g., tops, limbs, reject logs) over areas of exposed mineral soil	Maintaining residue cover over exposed mineral soils mitigates insolation and increased soil temperatures that favor decomposition	Rousseau et al. 2018; Slesak 2013
Harvest	2	2.1	Return bark, but not bioenergy ash, from processing facilities to harvested forests	Bark & ash are process waste products high in inorganic nutrients that limit productivity, but high pH of ash enhances decomposition	Campbell & Tripepi 1992; Hannam et al. 2019; Preston & Forrester 2004
Harvest	2	2.1, 2.2, 5.1	On wet sites, fell or redistribute residues in areas prone to saturation or ponding	Placing organic materials in waterlogged conditions promotes their persistence; this may be most effective on fine-textured glaciolacustrine soils where SOC gains are more probable	Blonska et al. 2019; Falsone et al. 2012; Puhlick et al. 2016
Harvest	5	5.1, 5.2	For aspen cuts on glaciolacustrine sites with high water tables, remove residues, and maintain high residual basal area along skidder & forwarder	Glaciolacustrine soils are least likely to lose SOC. Risk of aspen decline may increase with thick residues and high water; maintaining RBA sustains stand water loss via transpiration and may	McNabb et al. 2001; Perrette et al. 2014; Sewell et al. 2020

			trails and haul roads	mitigate wetness-driven impacts	
Harvest`	2	2.2	Orient high-basal area-removal harvest patches with long axes running from E to W (rather than N-S)	East-west orientation of forest openings creates edges that maximize shading and cooling, snowpack augmentation, and hydrologic C redistribution	Gabriel et al. 2013; Schaetzl et al. 2015; Schatz et al. 2012; Verry et al. 1983;
Harvest	2	2.1	Wash adhering soil off of machines before moving from earthworm-invaded to uninvaded timber sales, but do not require washing for machines moving between uninvaded areas	Earthworms, which are more common in deciduous stands on finer-textured, higher pH soils than on conifers or sandy and acidic soils, eliminate organic horizons and also decrease SOC storage in mineral horizons	Crumsey et al. 2013; Gundale et al. 2005; Kurth et al. 2014; McFarlane et al. 2013; Shartell et al. 2013
Harvest, fire	2	2.1, 2.2	On sloping landforms, use contour felling & leave strips of residues or un-treated forest. If slopes are compound, configure surface control features to connect, collect, and stabilize mobilized materials.	Contour strips and patches of tree canopies, roots, and residues can retain soil moisture, slow surface runoff and stabilize transported materials, thus retaining C and nutrients on-site	Jourgholami et al. 2020; Simard & Lajeunesse 2015; Valentin et al. 1999; Wallbrink et al. 2002
Restoration	7	7.2	Focus pine plantation to barrens restoration efforts on soils with the least surface organic matter, using summer burning	Forest floor loss is key to restoring barrens; overall impacts on profile SOC (plantation < native pine) are smaller for profiles with thinner forest floors	Quigley et al. 2020, James et al. 2018
Restoration	6	6.2	Limit number of stand entries for converting pine plantations to pine parklands or barrens	Repeat entry has increasing impacts on soil physical properties; low-SOC plantations may be more vulnerable	Tarpey et al. 2008

Restoration	6	6.2	Delay thinning pine plantations where O horizon development is desired	Forest floor SOC decreases with age after thinning in ~40 year old stands	Powers et al. 2012
Restoration	2	2.1	Protect the soil surface during pine plantation harvesting if prescribed fire is to follow	O horizons are nonlinearly susceptible to compound disturbance in a harvest + fire context	Fraver et al. 2011
Restoration	2	2.1	In soils high in base cations, use harvest rather than fire (or harvest + fire) to restore early-successional habitat	Soils high in base cations release large quantities of basic ash and increase pH, inhibiting podzolization and stable SOC accumulation	Barrett & Schaetzl 1998; Nave et al. 2019a
Restoration	3	3.1, 3.3	Use combination of mechanical treatments and low-intensity prescribed fire to reduce fuels and fire risk in vulnerable landscapes	Harvesting & residue treatments vs. prescribed fires remove different classes of fuels & are more effective in combination at reducing total fuel loads and risk	Busse et al. 2013; Gilmore et al. 2003; Kalies & Kent 2016
Fire	3	3.2, 3.3	In peatlands or upland-peatland complexes, prioritize wetland margins (especially on outwash) for wildfire suppression	SOC stocks in peatlands on low-lying outwash and glaciofluvial landforms are resilient to fire; peatlands at upland-wetland interfaces are vulnerable to permanent hydrologic and SOC impacts	Flanagan et al. 2020; Ingram et al. 2019; Schaffhauser et al. 2017 Wilkinson et al. 2020
Fire	3	3.2, 3.3	In peatlands, prioritize minerotrophic ecosystems rather than ombrotrophic ecosystems for wildfire suppression	Minerotrophic peatlands are more susceptible than ombrotrophic peatlands to permanent ecosystem change and retrogressive C stock declines	Magnan et al. 2019; Rowe et al. 2017; Schiks et al. 2016
Fire	3	3.2, 3.3	In uplands, prioritize deciduous rather than coniferous forests for wildfire suppression	Greater amounts of SOC are in stable pyrogenic forms under conifers than under deciduous cover	Miesel et al. 2015; Preston et al. 2017; Santos et al. 2017

Reforestation	1, 7	1.2, 7.4	In mineland reforestation, utilize tree species and fungal symbiont inocula tolerant of site-specific extreme soil conditions	Mine soils may have high ionic or heavy metal concentrations, extreme pH, or other problems that inhibit tree establishment and SOM accumulation	Baum et al. 2002; Babu et al. 2014; Davidson 1981; Hall 1980; Lorenc-Plucinska et al. 2013
Reforestation	2	2.5	In mineland reforestation, utilize site-specific soil amendments to remedy nutrient deficiencies or unfavorable physical properties (e.g., low porosity, high density)	Mine spoils and soils may have limited organic matter or depth to parent material, requiring surface amendments to establish trees and initiate organic matter accumulation	Asensio et al. 2014; Chambers & Wade 1992; Indraratne et al. 2020; Vega et al. 2005; Walker 2008

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