Appendix S1

Lucas E. Nave, Kendall DeLyser, Grant M. Domke, Scott M. Holub, Maria K. Janowiak, Brian Kittler, Todd A. Ontl, Eric Sprague, Eric B. Sucre, Brian F. Walters, Christopher W. Swanston

Disturbance and management effects on forest soil organic carbon stocks in the Pacific Northwest. *Ecological Applications.*

Section S1. Detailed Methods

All methods described herein follow Nave et al. (2021; this journal), as applied to the datasets supporting the present analysis for the Pacific Northwest.

Section S1.1 Meta-analysis- We searched for relevant publications using keyword searches and reference checks in the online Web of Science platform. Searches followed the syntax: [Geographic Term] + [Treatment] + Soil Carbon, where [Geographic Term] was “Washington,” “Oregon,” or one of the 17 ecoregional sections intersecting with these two states. [Treatment] terms were: forest management, timber, fire, afforestation, reforestation, reclamation, restoration, soil amendments, development, 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 larger-scale meta-analyses (Nave et al. 2009; 2010; 2011; 2013). These new keyword searches returned 1,880 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 17 ecoregional sections comprising our Pacific Northwest study area. Twenty-two publications met these criteria, in addition to 24 pre-2008 publications from our database.

To assemble the dataset 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 46 publications listed in Table S1 and identified with a * in the Appendix S1 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).

Papers reported soil organic contents as SOM, measured by loss on ignition (LOI), or as SOC, measured using elemental analyzers. Of the k=362 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. Published papers also differed in their units of reporting of SOC; namely, k=81 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 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 stocks 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 reported %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 categorizing reporting depths requires specific attention here. First, we recorded the genetic horizon (e.g., Oe, Oa, A, Bw1) 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 associated methods descriptions or USDA-NRCS soil series descriptions. Last, we aggregated these into master horizons (i.e., O, A, or B horizons) for use as the categorical variable corresponding to soil depth. When SOC was reported for increments greater than 50 cm total depth, we summed them and categorized them as “whole profiles.”

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), or subregional (S). Study numbers refer to points mapped in Figure 1 of the main article.

Study	**Citation**	**OM/OC**	**Units**	***k***	**Treat**	**Scale**	**Description**
1	Kraemer & Hermann 1979	M	S	7	F,H	S	A horizons 25 yr after fire or harvest in Douglas-fir stands throughout the Northern and Western Cascades
2	Bormann et al. 1981	M	S	9	A	L	O & A horizons in fir vs. alder-fir stands along a 40 yr chronosequence in the OR & WA Coast Ranges
3	Binkley et al. 1982	C	S	8	H	E	A horizons in two 30 yr Douglas-fir chronosequnces in the Western Cascades
4	Binkley 1983	C	S	4	A	E	A & B horizons in ~25 yr old fir vs. alder-fir stands in the Puget Trough
5	Cole et al. 1990	C	C	4	A	E	A & B horizons in 55 yr old fir vs. alder-fir stands in the Western Cascades
6,7	Binkley et al. 1990; 1992	C	C	8	A	E	A, B, & C horizons in ~50 yr old fir vs. alder-fir stands in the Western Cascades & OR Coast Range
8	Borchers & Perry 1992	C	C	2	H	E	A horizons 25 yr after harvest in a mixed fir stand in the Klamath Mountains
9	Van Miegroet et al. 1992	C	S	6	A	E	A & B horizons in 3 yr old fir vs. alder-fir stands in the Western Cascades
10	Tiedemann et al. 1998	C	C	4	A,H	E	O & AB horizons from a thinning X fertilization trial in a mid-rotation grand-fir stand in the Blue Mountains
11	Baird et al. 1999	C	S	9	F	L	O, A, & B horizons <1 yr after wildfire in mixed conifer stands in the Eastern Cascades
12	Cromack et al. 1999	C	S	1	H	E	O horizons 10 yr after harvest in a Douglas-fir stand in the OR Coast Range

Study	Citation	OM/OC	Units	*k*	Treat	Scale	Description
13	Law et al. 2001	C	S	5	H	L	O, A, B, C horizons & whole profiles ~20 yr after harvest in ponderosa pine stands in the Blue Mountains
14	Griffiths & Swanson 2001	M	C	6	H	L	O & A horizons 5, 15, 40 yr after harvest in Douglas-fir stands in the Western Cascades
15	Sanscrainte et al. 2003	C	C,S	4	H	L	O & B horizons 25 yr after harvest in subalpine fir-hemlock stands in the Northern Cascades
16	Piatek et al. 2003	C	S	4	H	E	A horizons 21 yr after harvest in a Douglas-fir stand in the Western Cascades
17	Sharrow & Ismail 2004	C	S	6	L	E	O & A horizons 11 yr after Douglas-fir establishment on former pasture land in the OR Coast Range
18	Fox 2004	C	C	7	A	L	A horizons from a factorial N*P*K fertilization trial in 23-20 yr old Douglas-fir stands in the Western Cascades
19	Prietzl et al. 2004	C	S	6	A	S	O horizons 8-15 yr after urea additions in managed Douglas-fir stands throughout western WA
20	Swanston et al. 2004	C	C	14	A	S	O & A horizons 10 yr after urea additions in 46-72 yr old Douglas-fir stands throughout western OR & WA
21	Holub et al. 2005	C	C	2	A	E	A horizons after 5 yr of annual wood or leaf litter additions in a Douglas-fir stand in the Western Cascades
22	Hatten et al. 2005	C	C	6	F	L	A & B horizons 2, 5, 27 yr after wildfires in pine-fir stands in the Eastern Cascades
23	Sartori et al. 2007	C	S	24	L	L	A & C horizons, whole profiles along a 10 yr poplar chronosequence on former cultivated lands in the Columbia Basin
24	Giesen et al. 2008	C	S	2	F	S	O & A horizons ~150 yr after stand replacing fire in Douglas-fir stands throughout the Western Cascades
25	Youngblood et al. 2008	M	S	3	F,H	S	O horizons 6 yr after fuel reduction treatments in pine-fir stands throughout the Blue Mountains
26	Shaw et al. 2008	C	S	5	H	L	O & A horizons 22-35 yr after harvesting in Douglas-fir stands in the Western Cascades of OR
27	Klopatek 2008	C	S	1	A	E	O horizons in ~55 yr old fir vs. alder-fir stands in the Western Cascades
28	Hatten et al. 2008	C	S	12	F	L	O, A, & B horizons 2 & 7 yr after prescribed fires in ponderonsa pine stands in the Blue Mountains
29	Cairns et al. 2009	C	S	6	H	L	O horizons & whole profiles 20, 60, & 100 yr after harvest in hemlock-fir stands in the Western Cascades

Study	Citation	OM/OC	Units	*k*	Treat	Scale	Description
30	Edmonds & Tuttle 2010	C	C	3	A	L	O & A horizons in ~53 yr old fir vs. alder-fir stands in the WA Coast Range
31	Powers et al. 2013	C	S	6	A	S	A & B horizons after >10 yr of understory herbicide in managed pine throughout the Southern and Eastern Cascades
32	Heckman et al. 2013	C,M	C,S	6	F	L	O & A horizons 2 yr after wildfire in pine-fir stands in the Klamath Mountains
33	Knight et al. 2014	C	S	7	A	E	O, A, B horizons & whole profiles after 5 yr of understory herbicide in managed Douglas-fir stands in the WA Coast Range
34	Shryock et al. 2014	C	S	20	A	S	O, A, BC horizons & whole profiles after urea additions in 26-33 yr old Douglas-fir stands throughout western OR & WA
35	Hatten et al. 2014	C	C	3	L	S	A & B horizons in >25 yr old Christmas tree plantations on former cultivated lands throughout western OR & WA
36	Homann et al. 2015	C	S	15	F,H	L	O & A horizons 1-15 yr after harvest or fire in Douglas-fir stands in the Klamath Mountains
37	Pingree et al. 2016	C,M	C	12	F	L	O horizons from a 36 yr wildfire chronosequence in Douglas-fir stands in the WA Coast Range
38	van Huysen et al. 2016	C	S	3	A	S	A horizons after 3 yr of P additions in Douglas-fir stands in the OR Coast Range
39	Cowan et al. 2016	C	S	6	F	E	A & B horizons 1 yr after wildfire in a pine stand in the Eastern Cascades
40	Bates & Davies 2017	C	S	16	F,H	E	A horizons 6 yr after fuel reduction treatments in juniper woodlands in the Northwestern Basin and Range
41	Pingree & DeLuca 2018	C	C	6	F	L	A horizons from a 36 yr wildfire chronosequence in Douglas-fir stands in the WA Coast Range
42	Page-Dumroese et al. 2018	C	S	14	A	E	A horizons 2 yr after organic amendments on 19 yr old mine spoil pine reforestation in the Blue Mountains
43	Hart et al. 2018	C	S	3	F,H	L	A horizons 16 yr after fire or harvest in ponderosa pine stands in the Blue Mountains
44	Gross et al. 2018	C	S	14	H	E	O, A, B, C horizons & whole profiles 14 yr after thinning a Douglas-fir stand in the Western Cascades
45	Matosziuk et al. 2019	C	S	4	F	L	O & A horizons 15 yr after prescribed fire in ponderosa pine stands in the Blue Mountains
46	Holub & Hatten 2019	C	S	45	H	S	O, A, B horizons & whole profiles 3 yr after harvest in Douglas-fir stands throughout western OR & WA

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[1]	geographic scale of study design	ecosystem, landscape, subregional
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	coniferous vs. broadleaved / mixed
MAT	mean annual temperature in degrees C	4.2 – 11.4
MAP	mean annual precipitation in mm	268 - 4770
Ecosection	ECOMAP section	Northern Cascades, Columbia Basin
Physiographic wetness	wetness or drainage index of site	poorly to somewhat poorly drained, moderately well to well drained, somewhat excessively to excessively drained
Elevation	elevation of site in meters above sea level	45- 1674
Slope_class	slope class of site	level to gently sloping, moderately sloping, strongly sloping

Variable	**Description**	**Examples and Ranges of Values**
Parent material	broad grouping of parent material type	igneous residuum, sedimentary residuum, till
Soil Series	individual series, complex, or association as mapped by USDA NRCS	Alderwood, Boistfort, Cumley
Soil Order	soil classification at the Order level (USDA)	Inceptisols, Andisols, Spodosols
Soil Taxon	soil taxonomy according to USDA system: Subgroup or Great Group	Andic Humudepts, Typic Palehumults
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, AE, AB, B, whole soil profile
Text_class	matrix texture class of sampled soil, specific to layer if possible	clay, sandy loam, silt loam, fibrous organic matter
IC	inorganic C percentage of the sampled soil layer	0 – 0.35
CTRL pH	mean pH of the sampled soil layer under control conditions	4.2 – 7.6
TRT pH	mean pH of the sampled soil layer under treatment conditions	3.9 – 7.7
Db_CTRL	mean bulk density of the sampled soil layer under control conditions	0.18 – 1.80
Db_TRT	mean bulk density of the sampled soil layer under treatment conditions	0.15 – 1.89
SOC_CTRL	mean SOC stock of the sampled soil in the control condition, in Mg ha-1	0.35 - 307
SOC_TRT	mean SOC stock of the sampled soil in the treatment condition, in Mg ha-1	0.01 - 265

[1] Scale refers to studies in which soils were sampled over areas of ones to tens of hectares (ecosystem), hundreds to thousands of hectares (landscape), or tens to hundreds of thousands of hectares (subregional).

Section S1.2 Synthesis of pedon and remote sensing data- We computed SOC stocks of individual genetic horizons in the USDA-NRCS National Cooperative Soil Survey, Kellogg Soil Survey Laboratory (KSSL) Database, in Mg C ha^{-1}, as the product of %SOC, Db, and thicknesses. Because soil horizons in NRCS databases 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 considerations that we have documented previously, including in this journal. We used the available C concentration data according to the following 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 estimating Db values for soils lacking them in this, and the meta-analysis dataset (Section S1.1). For gap-filling these missing values, we proceeded as follows. We extracted Db values for all n=235 O horizons in the KSSL Database, calculated as oven-dry whole-soil mass / field-moist whole-soil volume (db_fmst). Organic horizon Db did not differ by U.S. state or as a function of %SOC, but individual O horizon designations did differ. Therefore, for any O horizon lacking Db (whether in the NRCS pedon or meta-analysis dataset), 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=7,340 samples falling within the study area and possessing both measurements. This relationship had the best fit when modeled as an exponential decay function (r^2= 0.41; $P < 0.0001$). We applied this model to both datasets (meta-analysis and NRCS) to fill missing Db observations from their %SOC values. We then computed SOC stocks for each, in Mg C ha^{-1}, as the product of %SOC, Db, and thickness.

In our synthesis of geo-located soil pedons with remote sensing information, we only used pedons collected from 1989-present. For every pedon, we extracted land cover information 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 2019), and vegetation type and natural disturbance regime information from the GAP/LANDFIRE National Terrestrial Ecosystems layer (USGS 2016), including hierarchical vegetation classifications from the National Vegetation Classification System (USNVC 2019). We also extracted aboveground biomass C density (in Mg ha^{-1}) from the National Biomass Carbon Dataset (NBCD2000; only for pedons sampled 1997-2006; Kellndorfer et al. 2013), burned area extents from the Monitoring Trends in Burn and Severity (MTBS) layer (USGS and USDA 2020), and mean annual temperature (MAT) and precipitation (MAP) from PRISM's United States Annual Precipitation and Mean Temperature datasets (PRISM Climate Group 2015). In addition to these attributes extracted from GIS products, we also created a 30 m DEM from the National Elevation Dataset (USGS 2013) and from it derived each pedon's elevation, slope, and aspect, and topographic index according to the methods of Jones (2000). We placed DEM-derived slope percentages into three categories of level to nearly level, undulating to rolling, and hilly to steep, and converted slope aspects derived in degrees into 4 aspects (N, S, E, W).

We used NLCD, GAP/LANDFIRE, and MTBS layers as inputs to processes intended to improve data quality and statistical power by manually validating, reclassifying, and disambiguating subtle differences in land use, management, and disturbance. As in prior papers 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 and others have validated NLCD classifications against multiple independent sources and found NLCD to be 75-80% accurate (Marsik et al. 2018; Nave et al. 2018; 2021; USDA 2016). This level of accuracy leaves room for improvement, and furthermore, the forest land cover classes assigned in NLCD can be used more effectively when disturbances such as recent harvest or fire can be observed directly. Prior to beginning this analysis, we inspected high-resolution visible satellite imagery for every soil pedon geolocation in order to validate (and correct where necessary) the remote sensing derived land cover values. As with our prior analysis in this journal, we were specifically interested in differentiating pedons in forests harvested within recent decades from those in mature forests. When geo-located pedons were located within what appeared to be burn perimeters, we verified this using the MTBS layer; by the same token, MTBS (which extends back to 1984) also revealed some pedons that were located in areas of past fires that were no longer discernible from satellite imagery. Detailed descriptions of criteria used to infer land use or management from the combination of soil pedon description and associated remote sensing information have been repeatedly described in past publications (Nave et al. 2013; 2018; 2021).

In order to focus on the forests and woodlands of interest, we excluded pedons under the following NLCD land cover classes from our analyses: barren lands, cultivated lands, developed lands (including urban to suburban forests), areas apparently managed for pasture or forage production, and grasslands not supporting at least scattered, low-density woody vegetation (i.e., shrub/scrub cover). All other lands were considered representative of the range of forests and woodlands across the study area. We recognized pedons from harvested forests as those falling in areas of forest with signs of harvesting ranging from recent skidder trails, log decks or decking areas, to group selection openings, shelterwood belts or row thinning geometries, or distinct cutting boundaries against adjacent higher-density, higher-stature forest. In some cases we recognized past harvests as scattered, residual canopy dominants overtopping homogenous, lower-stature canopies. Overall, we estimate that forest pedons we identified as harvested were up to ~25 years since harvesting, as compared to the mature stands adjacent to the harvested pedon locations. This estimate compares reasonably with the average years since treatment for harvesting studies in the meta-analysis dataset (16 years). In general, we erred on the side of caution in categorizing a forest pedon as harvested, in order to avoid attributing to harvesting what may have been a pattern due to soil, hydrologic, or topographic influences or historic fire. Having begun with 1,722 pedons (8,196 individual horizons) from the study area, our final dataset for analysis included 1,146 pedons (5,547 individual horizons) specifically from forests and woodlands.

Section S1.3 FIA dataset- We complemented meta-analysis and NRCS pedon + remote sensing datasets with independent observational data 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 provide an equal-probability sample of forestlands across the conterminous U.S. (CONUS). There is one permanent plot on every ~2,400 ha across the CONUS, with each plot located randomly within a systematic hexagonal grid (20). The NFI design ensures that FIA data have no systematic bias with regard to forestland location, ownership, composition, soil, physiographic or other factors. Soils are sampled from a subset of these plots by first removing the forest floor and then sampling mineral soils as depth increments of 0-10 and 10-20 cm. 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 ecological sections comprising the study area. We set the single-condition criterion in order to exclude plots with obvious internal variation in factors such as stand age, slope, etc., which could 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. Altogether, our forest floor and mineral soil datasets were based on 194 and 130 NFI plots, respectively. As they are only sampled for forest and woodland plots, and have no Db or other data gaps, FIA data required no special handling or gap-filling techniques like those used in the NRCS pedon dataset.

The meta-analysis, NRCS pedon, and FIA plot datasets synthesized for these analyses are shared via the University of Michigan Research and Data Hub (https://mfield.umich.edu).

Section S2. Supporting Results

Table S3. Sample size and average thickness information across the three data sources used in this analysis. For published studies 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.

Published studies			**NRCS**			**FIA**		
Horizon	Thick (cm)	*k*	Horizon	Thick (cm)	*n*	Horizon	Thick (cm)	*n*
O	4	25	O	6	462	O	2	194
A	12	152	A	15	2154	A	10	129
A/E/B	26	4	A/E/B	19	480	A/E/B	10	122
B	26	58	B	26	3393			
BC & C	30	11	BC & C	32	1161			
Profile	87	29	Profile	108	1722			

Table S3 provides information about the soil depths reported across the three data sources used in this analysis, which may be used to assess the suitability of our attempts to harmonize across a wide range of sampling protocols for the sake of discussing soils from more or less distinct parts of the profile. Sections S1.1, S1.2, and S1.3 describe the methods and protocols associated with each of the three data sources. Similar to prior analyses (Nave et al. 2021), O horizons appear to be under-reported or under-encountered) for NRCS pedons, and when they are reported, tend to be better-developed than the average condition reported in the forest soils literature (published studies) or FIA Database. Topsoils (categorized as A horizons) were fairly consistent across the three data sources, averaging 12 and 15 cm for published papers and NRCS pedons, and fixed by protocol at 10 cm for FIA. Mixtures of A, E, and B horizons, or depth increments likely to consist of such mixtures, were only sporadically encountered in published papers or NRCS pedons. The FIA 10-20 cm depth increment likely contains mixtures of at least two of these three genetic horizons in most places, but for the sake of consistency in data presentation we report these as B horizons in the main paper. B horizons themselves, or depths most likely to correspond to B horizons, averaged 26 cm in thickness for both the published literature and NRCS pedon datasets. Published papers and NRCS pedons also agreed closely in the mean thickness of BC and C horizons. Whole soil profiles as reported in published papers tended to be shallower than NRCS pedons by an average of 20%.

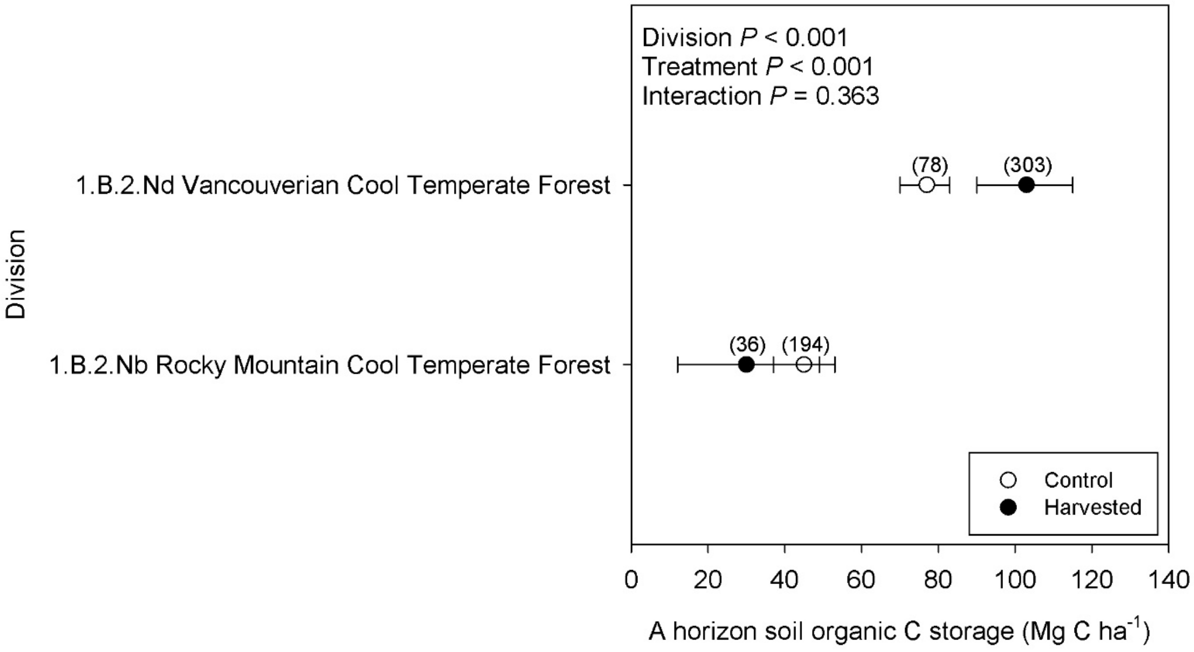

Figure S1. Topsoil SOC stocks for control and harvested pedons from the observational NRCS pedon + remote sensing dataset, for the two major vegetation divisions comprising the study area. Points plotted are means, 95% confidence intervals, and sample sizes.

Pedon data (from NRCS) and associated remote sensing information comprised the only one of our three data sources to indicate a significant effect of harvesting on SOC storage. At the ecoregional level, this effect manifested as significantly larger A horizon SOC stocks in recently harvested than non-harvested control forests. However, closer scrutiny revealed that the two major vegetation divisions in the ecoregion (USNVC 2019) showed divergent patterns (Fig. S1). Specifically, pedons in the Vancouverian Cool Temperate Forest had significantly larger A horizon SOC when harvested than under reference conditions, while A horizon SOC stocks were smaller under harvested than reference forests in the Rocky Mountain Cool Temperate Forest.

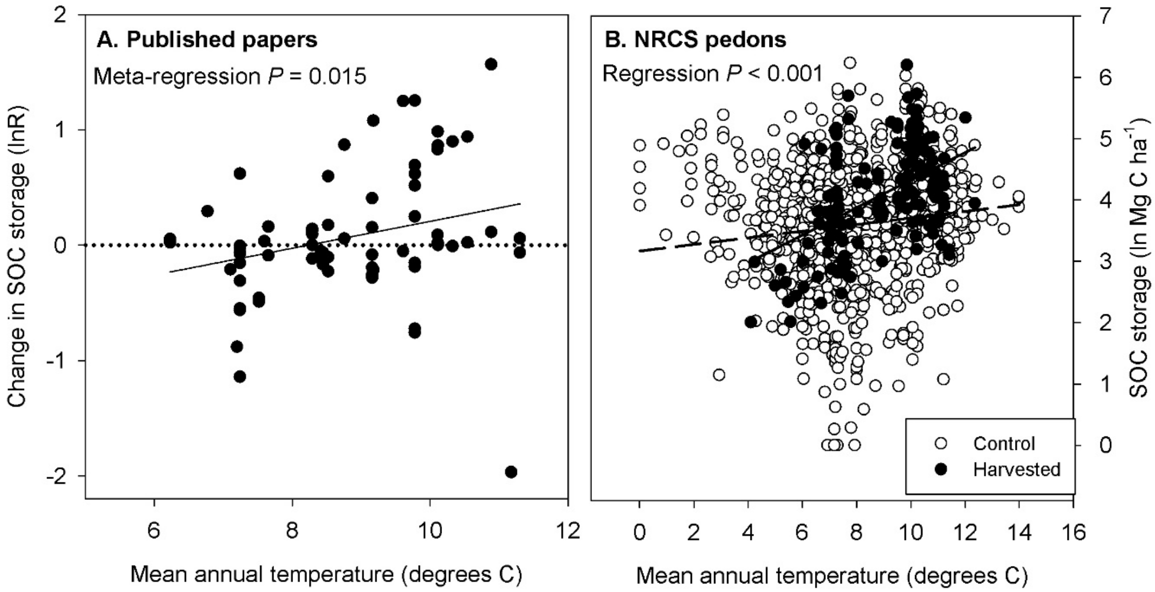

Figure S2. Relationship between mean annual temperature (MAT) and SOC storage in O and A horizons, in the context of harvesting. Panel A shows meta-analysis results as the proportional change in SOC storage due to harvesting, as a function of MAT. Panel B shows relationships between MAT and SOC storage for control (open circles, dashed regression line) and harvested (filled circles, solid regression line) forests. In panel B, regression slopes differed significantly (*P* < 0.001) for the control vs. harvested forests.

Meta-analysis of published literature and NRCS pedon + remote sensing data yielded complementary results regarding the influence of mean annual temperature on SOC storage in O and A horizons (Figure S2). Considered collectively, O and A horizons showed significantly more positive effects of harvesting in warmer climates (Fig. S2a). NRCS pedons showed positive relationships between O and A horizon SOC stocks regardless of treatment, albeit with significantly steeper slopes in harvested forests (Fig S2b).

Table S4. Example SOC management tactics for several categories of activities. These specific tactics tier to generalized strategies (strg.) and approaches (appr.) in Ontl et al. (2020; Table 1). Tactics are based upon our analysis, with other studies cited for further support, and are a subset of wider possible options. When possible, relevant studies are regional. See paper for more detailed discussion.

Management Category	Strg.	Appr.	Tactic	Basis for tactic / mechanisms of potential SOC impact	Relevant studies
Fire / Fuel	2,3	2.1, 2.2, 3.2, 3.3	In dry to moist forest types with extensive areas of overstocking, focus fuel reduction treatments on ridge tops and steep slopes (especially south-facing slopes)	Fire SOC vulnerability increases with stocking and steepness; S-facing slopes have less SOC to begin with and are more vulnerable to climate change driven and edaphic regeneration failure	Chmura et al. 2011; Ebel 2012; Peterson and Halofsky 2018; Stevens et al. 2014; Leverkus et al. 2021
Fire / Fuel	2,3	2.1, 2.2, 3.2, 3.3	In wet to moist forests, prioritize wildfire suppression efforts on strongly sloping landforms and landscapes	O horizon C losses in wildfires are greater on steep slopes than level to gently slopes; suppressing fire in steep settings will mitigate C losses & subsequent soil and ecosystem impacts	Bradstock et al. 2010; Doten et al. 2006; Jackson and Roering 2009; Wall et al. 2020; Wondzell & King 2003

Fire / Restoration	2,4	2.1, 2.2, 4.1, 4.2	In burned forests of any type, prioritize steep slopes for surface stabilization, organic amendment and reforestation activities	O horizon C losses in wildfires are greater on slopes than level areas; soil and ecosystem recovery are linked through soil water availability, which is enhanced by organic amendments	Bontrager et al. 2019; Jonas et al. 2019; Jurgensen et al. 1997; Neris et al. 2017; Robichaud et al. 2020
Fire / Fuel	2,3	2.1, 2.2, 3.1	In dry to moist forest types, implement prescribed burns in spring rather than fall	Spring burns decrease fuels with minimal SOC impacts; fall burns decrease fuels and SOC (due to drier soils in the fall)	Busse & Gerrard 2020; Hamman et al. 2008; Hatten et al. 2008; 2012; Switzer et al. 2012
Harvest / Fuel	2	2.1	In wet forests, chip or pile residues after harvests that generate large amounts of residue	Intact, distributed residues may increase fire spread; if not burned, piles increase soil moisture & seedling establishment success	Harrington et al. 2018; 2020
Harvest / Fuel	2	2.1	In dry to moist forests, utilize residues (as chips or biochar) for nearby soil amendment and reforestation projects	Direct SOC gains from amendments are further enhanced by their influence on reforestation success through increased soil water holding capacity	Avera et al. 2020; Dodson & Peterson 2010; Rhoades et al. 2020

Harvest / Fuel	2, 3	2.1, 3.3	In large-scale dry forest fuel treatments, fell and burn sub-merchantable conifers when they occur in dense patches	Fell-leave-burn treatments minimize dense ladder fuels with no to modest positive effects on SOC	Miesel et al. 2009; North et al. 2009; Stephens et al. 2012
Harvest / Fuel	2	2.1, 2.2	Restrict operations in space and time to protect soils vulnerable to physical disturbance	Ash-cap and fine-textured soils are most susceptible; limiting traffic, harvesting on frozen ground or at low moisture content mitigates disturbance	Angima and Terry 2011; Crawford et al. 2021; Nash et al. 2020
Harvest / Fuel	2	2.1., 2.2	Use proactive measures to prevent (e.g., slash armoring) or promptly ameliorate disturbance (e.g., tillage, amendment)	Residue armoring protects soil surface and distributes load; tillage can reverse compaction and in concert with soil amendments can restore SOC	Angima and Terry 2011, Page-Dumroese et al. 2010
Stand Management	6	6.6	In moist to wet forests in riparian settings, groundwater seeps, or limited accessibility, favor red alder at the expense of other hardwood species	Red alder can outcompete desirable conifers, but in N-limited or wet sites, its expansion can sequester SOC at no loss to production of commercial species	Atkinson et al. 1979; Miller and Murray 1978; Miller et al. 2005

Restoration / Reforestation	1, 2	1.2, 2.1	Prioritize areas with agricultural disturbance legacies (cultivation or livestock damage) for reforestation	Physical soil disturbance due to agriculture decreases SOC; reforestation increases SOC, especially on former croplands	Dumroese et al. 2019; Nave et al. 2018; 2019
Restoration / Adaptation	1, 4, 7	1.2, 4.1, 4.2, 4.4, 7.4	Reforest using future-adapted species mixtures on areas with fire-driven regeneration failures, especially on warm/dry sites	Tree species adapted to site, soils, and future climate are more likely to persist, maintaining the larger SOC stocks of forests as compared to shrublands	Halofksy et al. 2016; 2018; Haugo et al. 2010; North et al. 2019; Peterson & Halofsky 2018

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