GLOBAL SYMPOSIUM ON SOIL ORGANIC CARBON, Rome, Italy, 21-23 March 2017

The effect of forest harvest on soil carbon: a global meta-analysis

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Abstract
Forest soils represent a substantial portion of the terrestrial carbon (C) pool, and changes to soil C cycling are globally significant not only for C sequestration but also for sustaining forest productivity and ecosystem services. To quantify the effect of harvesting on soil C, we used meta-analysis to examine a database of 945 responses to harvesting collected from 112 publications from around the world. Harvesting reduced soil C, on average, by 11.2%. There was substantial variation between responses in different soil depths, with greatest losses occurring in the O horizon (-30.2%). Much smaller but still significant losses (-3.3%) occurred in top soil C pools (0-15 cm depth). In very deep soil (60-100+ cm), a significant loss of 17.7% of soil C in was observed in harvested soils. The response of soil C to harvesting varies substantially between soil orders, with greater losses in Spodosol and Ultisol orders and less substantial losses in Alfisols and Andisols. The publications in this analysis were highly skewed toward surface sampling, with a maximum sampling depth of 36 cm, on average. Sampling deep soil represents one of the best opportunities to reduce uncertainty in our understanding of the response of soil C to harvest.

Keywords: Forests; Deep soil; soil organic matter; meta-analysis; soil orders; forest management

Introduction, scope and main objectives

Forest ecosystems contain 1240 Pg C, which represents as much as 80% of aboveground terrestrial C and 70% of soil organic C [1–4]. The net balance of soil C in forests relies upon large input rates (61.4 Pg C year^{-1}) and respiratory losses (60 Pg C year^{-1}), which represent a substantial yearly turnover in the soil C pool [5]. By decreasing detrital inputs and increasing respiratory outputs, forest harvest and land-use change can have substantial impacts not only on ecosystem function, but atmospheric chemistry and global climate.

Deep soils store substantial quantities of C with as much as 38% of soil C found below 1 m, globally [3]. While it has traditionally been assumed that this millennially-aged, deep soil C is minimally responsive to human activities, it has been shown that this deep soil C responds just as much to warming [6] and the introduction of fresh, labile materials [7] as surface soil. In addition to direct losses of C through in situ respiration, advances in freshwater research suggest that substantial quantities of soil C are mobilized to streams, rivers, and lakes, constituting a second pathway for soil C mineralization to the atmosphere [8,9].

Recent estimates of the transfer of C from terrestrial systems to freshwaters has more than doubled from 0.9 to 1.9 Pg C year^{-1} [10]. Moreover, as the extent of human disturbance increases, the age of riverine dissolved organic matter also increases in watersheds around the globe [11]. This gives credence to the hypothesis that mobilization of soil carbon to freshwater through human activities represents an additional source of fossil carbon to the modern carbon cycle.

Currently, protocols for ecosystem C monitoring poorly assess soil C. In many protocols, soil C is either limited to surface sampling (20 cm), not required, or excluded entirely [12]. Inclusion of soil C in ecosystem models is also crucial. For example, the payback period for C when substituting forest bioenergy for coal increased by 25 years when soil was included [13].

Because the response of surface and deep soil C to harvest has been inconsistent in the literature, this study used meta-analysis to systematically examine:

- The effect of forest harvest on surface and deep soil C
- Differences in response between soil types
- The recovery period for soil C after harvest

Methodology

A database of the response of soil C to forest harvest was compiled from 112 publications from around the globe. To be included in the meta-analysis, articles and reports had to report both control and harvested treatments. Potentially useful predictors and metadata were recorded for each publication, including time since harvest, additional levels and intensities of treatment (such as whole tree removal), and the soil depth. The meta-analysis estimates the magnitude of change in soil C using the ln-transformed response ratio (*R*), which is defined as

$$ln(R) = ln\left(\frac{\overline{X^T}}{\overline{X^C}}\right)$$

where $\overline{X^T}$ is the mean soil C value in the harvested treatment and $\overline{X^C}$ is the mean soil C value of control observations for a given set of experimental conditions at a specific site and depth. *R* is a unitless measure of effect size which was back-transformed to represent the percent change in soil C relative to the control.

Results

Across all studies, harvesting led to a significant average decrease in soil C of 11.2% relative to control (Fig. 1). Whether the response to harvest was reported as pools or concentrations had a large impact on the estimated effect of harvest on soil C, with a significant difference (16.2%) between mean response of studies reporting C concentration (%, mg g^{-1}, etc.) and studies reporting C pools (Mg ha^{-1}, tons ha^{-1}, etc.).

O horizons lost 30.2% of their carbon as a result of harvesting. Losses from top soil were much smaller, although the estimated loss when reported in pool units was significant (-3.3%). The overall effect in very deep soil (60-100+ cm) was significant, with an average loss of 17.7%. Unfortunately, this region of the profile was not frequently sampled (21 response ratios out of 945 total), and consequently the 95% confidence interval is quite wide.

The effect of forest harvest on soil C differs significantly between soil types. No significant loss in mineral soil C was seen in Alfisols, Inceptisols, and Mollisols, while substantial mineral soil losses were observed in Spodosols (-9%) and Ultisols (-12%). Significant overall soil C losses occurred in Entisols, Mollisols, and Oxisols, although these soils had very few responses recorded in the literature. Soil C increased following forest harvest in Andisols by 24%, though only 9 responses in the database covered this soil type. Finally, the recovery of soil C following harvest differs among soil types (Fig. 2).

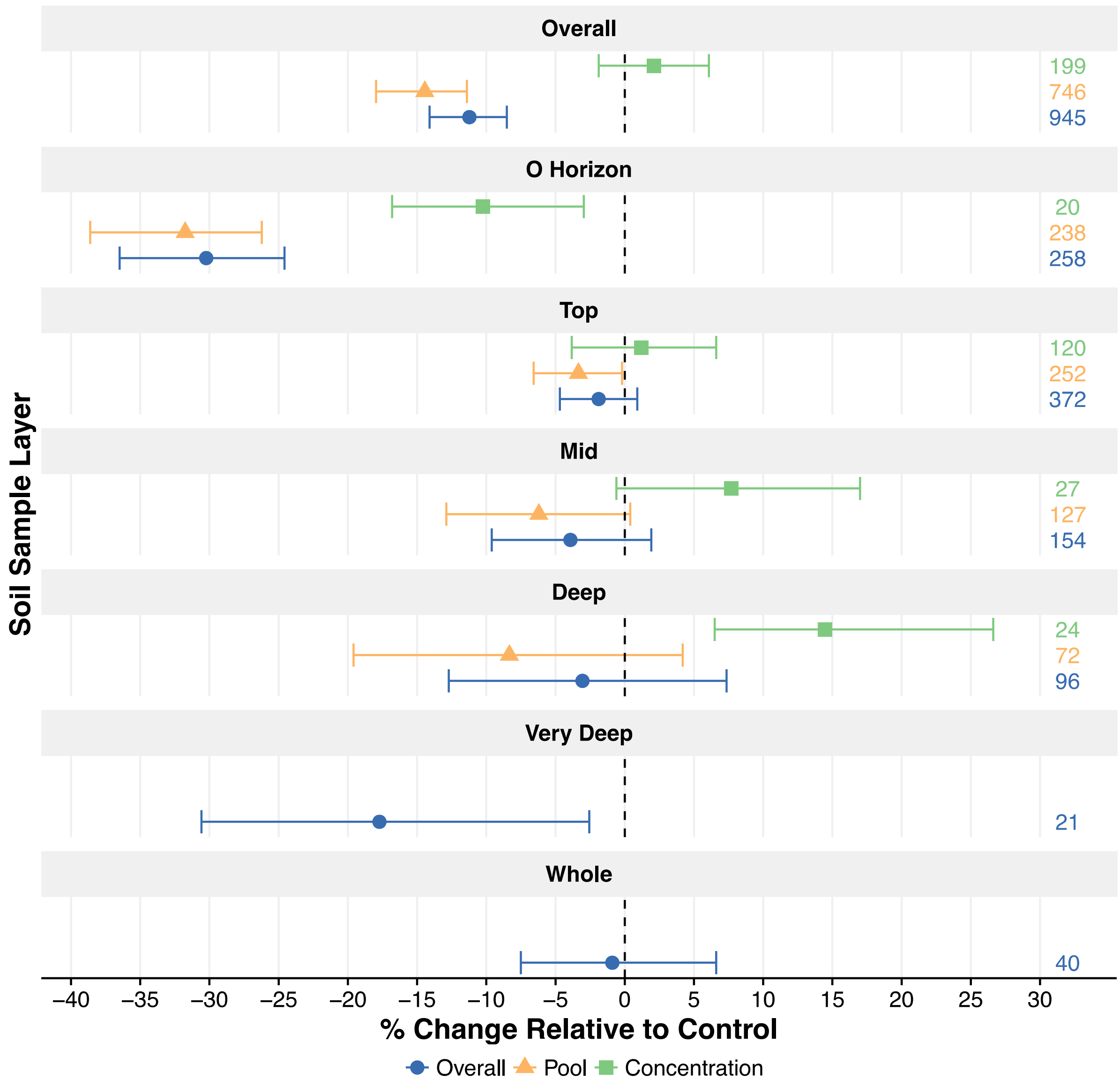

Fig. 1: Response of soil C to forest harvesting, overall and faceted by soil depth. All points are mean effect size estimates ± 95% confidence intervals. The number of effect sizes in each group is listed on the right. Mean effects with confidence intervals overlapping 0% show no significant change due to harvesting. The depths for soil depth groups are: top soil [0-15 cm], mid soil [15-30 cm], deep soil [30-60 cm], and very deep soil [60-100+ cm]. Reproduced from [14]**.**

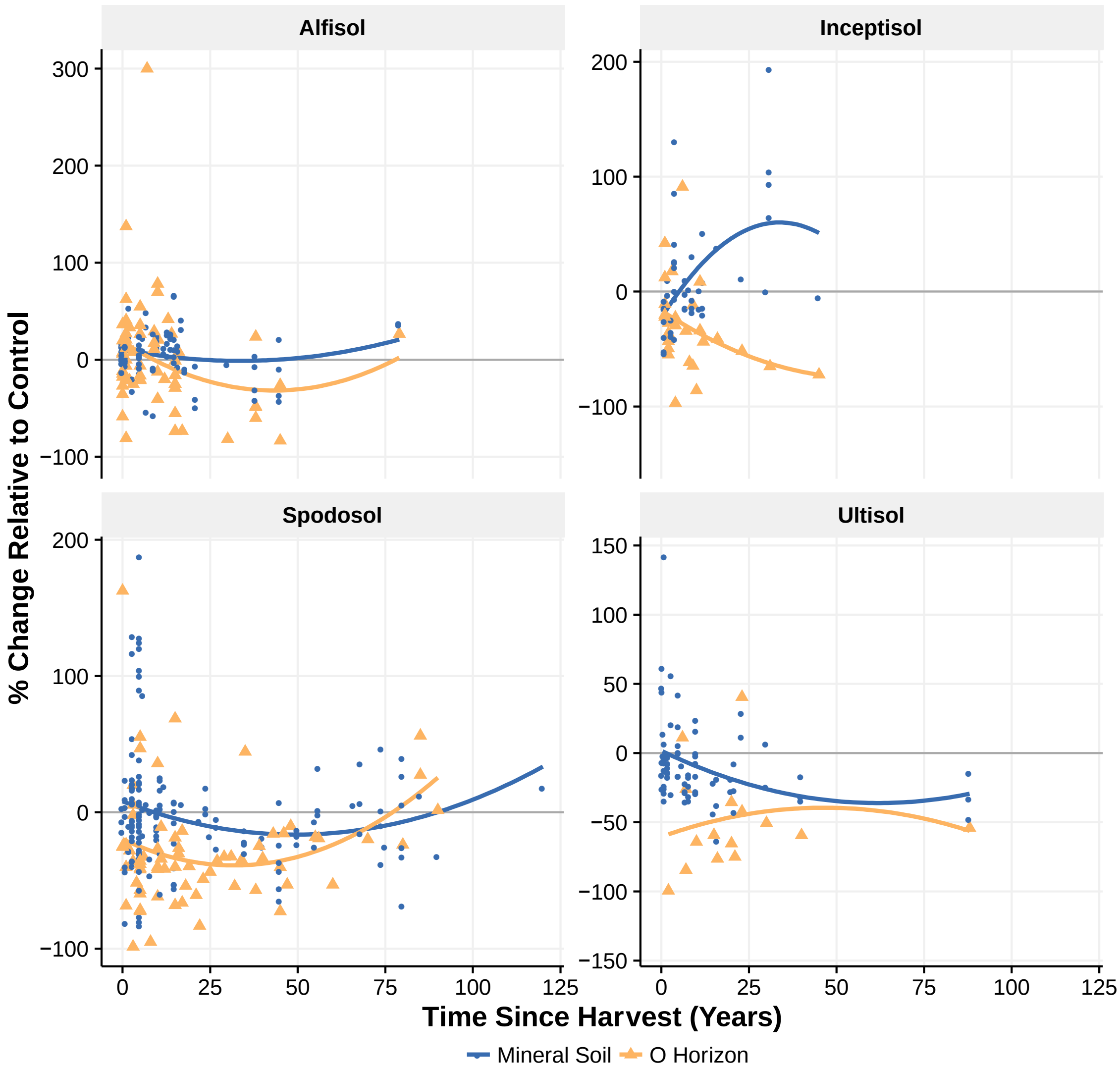

Fig. 2: Temporal patterns in both O horizon (yellow triangles) and mineral soil (blue circles) C pools for Alfisol, Inceptisol, Spodosol, and Ultisol orders. Other orders are not show due to inadequate sampling over time. Regression lines show trends with time using a second order polynomial (Time + Time^2). For the overall model, F=9.205 on 7 and 532 degrees of freedom, Adj. R^2 = 0.1, *p* < 0.0001. Reproduced from [14]**.**

Discussion

These results suggest that much additional research is necessary to fully understand the effect of forest harvest on soil C, globally. Due to the sheer size of the forest soil C pool, small relative changes in soil C can result in large absolute losses of C either to the atmosphere or freshwater systems. While this meta-analysis shows a significant and substantial loss in very deep soil, the small number of observations in the literature suggest that substantially more observations need to be made in field research plots in a variety of soil types around the world.

In general, sharper losses occur quickly in O horizons, while mineral soils may continue to lose C over 25 years after harvest. Despite greater losses in C, O horizons recover more quickly that mineral soils to disturbance. In Spodosols, O horizons recovered around 75 years after harvest, while mineral soil C pools took 85-100 years to recover. For Inceptisols, there is insufficient data to calculate a full recovery period. However, little sustained loss in mineral soil is evident in these soils, while O horizon losses continued for at least 45 years post-harvest. The response to harvest was most muted in Alfisols, with mineral soils retaining C over time and O horizons recovering within 50-75 years after harvest.

Conclusions

Forest soils represent the majority of soil C on the planet, and this C is sensitive to human management efforts. Consequently, utmost care should be taken to utilize less intensive management practices where possible and to carefully consider the soil when designing national policies for bioenergy and forest products. Conclusions and recommendations from this analysis:

- For modeling: surface and deep soil should be included in carbon balance assessments and ecosystem C models
- For monitoring: in addition to gathering sufficient samples to overcome spatial heterogeneity, long-term monitoring efforts should include some ongoing deep sampling (1+ m). Insufficient sampling of deep soils is one of the largest gaps in global soil C data.
- For reporting: national assessments of soil C should report the depth of soil sampled, bulk density measurements, and C pool size rather than concentration alone.

References

1. Dixon, R. K.; Brown, S.; Houghton, R. A.; Solomon, A. M.; Trexler, M. C.; Wisniewski, J. Carbon Pools and Flux of Global Forest Ecosystems. *Science (80-.).* **1994**, *263*, 185–190.

2. Prentice, I. C.; Farquhar, G. D.; Fasham, M. J. R.; Goulden, M. L.; Heimann, M.; Jarmillo, V. J.; Kheshgi, H. S.; Le Quere, C.; Scholes, R. J.; Wallace, D. W. R. The carbon cycle and atmospheric carbon dioxide. *Clim. Chang. 2001 Sci. Basis* **2001**, 183–237.

3. Batjes, N. H. Total carbon and nitrogen in the soils of the world. *Eur. J. Soil Sci.* **1996**, *47*, 151–163.

4. Jobbagy, E. G.; Jackson, R. B. The uplift of soil nutrients by plants: Biogeochemical consequences across scales. *Ecology* **2004**, *85*, 2380–2389.

5. Schimel, D. S. Terrestrial ecosystems and the carbon cycle. *Glob. Chang. Biol.* **1995**, *1*, 77–91.

6. Fang, C. M.; Smith, P.; Moncrieff, J. B.; Smith, J. U. Similar response of labile and resistant soil organic matter pools to changes in temperature. *Nature* **2005**, *433*, 57–59.

7. Fontaine, S.; Barot, S.; Barre, P.; Bdioui, N.; Mary, B.; Rumpel, C. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature* **2007**, *450*, 277-U10.

8. Bianchi, T. S.; Garcia-Tigreros, F.; Yvon-Lewis, S. A.; Shields, M.; Mills, H. J.; Butman, D.; Osburn, C.; Raymond, P.; Shank, G. C.; DiMarco, S. F.; Walker, N.; Reese, B. K.; Mullins-Perry, R.; Quigg, A.; Aiken, G. R.; Grossman, E. L. Enhanced transfer of terrestrially derived carbon to the atmosphere in a flooding event. *Geophys. Res. Lett.* **2013**, *40*, 116–122.

9. Raymond, P. A.; Bauer, J. E. Riverine export of aged terrestrial organic matter to the North Atlantic Ocean. *Nature* **2001**, *409*, 497–500.

10. Cole, J. J.; Prairie, Y. T.; Caraco, N. F.; McDowell, W. H.; Tranvik, L. J.; Striegl, R. G.; Duarte, C. M.; Kortelainen, P.; Downing, J. A.; Middelburg, J. J.; Melack, J. Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems* **2007**, *10*, 171–184.

11. Butman, D. E.; Wilson, H. F.; Barnes, R. T.; Xenopoulos, M. A.; Raymond, P. A. Increased mobilization of aged carbon to rivers by human disturbance. *Nat. Geosci.* **2015**, *8*, 112–116.

12. Buchholz, T.; Friedland, A. J.; Hornig, C. E.; Keeton, W. S.; Zanchi, G.; Nunery, J. Mineral soil carbon fluxes in forests and implications for carbon balance assessments. *Glob. Chang. Biol. - Bioenergy* **2014**, *6*, 305–311.

13. Zanchi, G.; Pena, N.; Bird, N. Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy* **2012**, *4*, 761–772.

14. James, J.; Harrison, R. The Effect of Harvest on Forest Soil Carbon: A Meta-Analysis. *Forests* **2016**, *7*, 308.