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NATURE-BASED SOLUTIONS FOR A CHANGING WORLD

Review

Improved forest management as a natural climate solution: A review

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Abstract

1. Natural climate solutions (NCS), a set of land management, conservation and restoration practices aimed at mitigating climate change, have been introduced as cost-effective strategies to increase carbon (C) sequestration in terrestrial ecosystems. Improved forest management (IFM) has been identified as one NCS for working forests with substantial climate change mitigation potential. However, there is a disconnect between the policy and carbon markets context and the scientific evidence for verifiable C benefits. Further, forest soil C—the largest forest C pool—has largely been excluded from current forest management guidelines and has not been included in the IFM discourse.
2. Herein, we assess the evidence for the potential of specific IFM practices to sequester C in live forest vegetation and store it in both live and dead organic matter, and forest soil. We review IFM approaches that can enhance forest C storage, and links to best management practices and silvicultural systems to offer guidance for practitioners and researchers in the Great Lakes region of the United States. Finally, we discuss the current challenges and opportunities in including soil C in forest C management guidelines and frameworks.

KEYWORDS
carbon management, forest carbon, forest management, improved forest management, land use, land management, natural climate solutions, silviculture, soil carbon

1 | INTRODUCTION

Land management strongly affects the ability of ecosystems to sequester and store carbon (C). Natural climate solutions (NCS), a set of land management, conservation and restoration practices aimed at mitigating climate change, have been introduced as cost-effective tools that increase C sequestration in terrestrial ecosystems (Fargione et al., 2018; Griscom et al., 2017), while also sustaining biodiversity and other ecosystem services. Of the NCS activities identified, forests pathways for NCS, in particular reforestation, avoided forest conversion and improved forest management (IFM), have the potential to contribute as much as 50% of the total C sequestration possible through NCS globally (Fargione et al., 2018; Griscom et al., 2017). For example, in 2018, forests in the conterminous United States sequestered 211 Tg C (774 Tg of carbon dioxide), offsetting 11.6% of the total annual greenhouse gas emissions in the United States (EPA, 2020). To date,

TABLE 1 Glossary of forest management and silviculture terms used in this article

Afforestation	Trees are introduced to an area that has previously not been forested.
Extended rotation	Extending the time between harvests, that is, longer rotation length.
Mean annual increment (MAI)	Stand volume divided by the stand age, that is, average growth of the stand per year.
Regeneration	Re-establishment of the stand, through natural (from existing seeds, samplings in the stand) or artificial regeneration (planting, direct seeding).
Retention harvesting (also known as variable retention)	Harvesting system in which some structural elements are retained at the time of harvest, such as mature trees (as seed trees) and dead wood to increase the structural complexity of the stand. This practice usually involves stands that are even-aged.
Rotation [length]	Time in between final harvests, that is, time period between stand establishment and final harvest.
Selection systems	Individual trees or smaller groups of trees are removed instead of all trees in a stand, producing of several age classes. The practices included are commonly referred to as uneven-aged forest management.
Thinning	Removal of specific trees or age-class of trees to improve the growth or health of the remaining trees.

TABLE 2 Glossary of C terms used in this article

Carbon flux	Flow (i.e. movement) of C from or to the C reservoir (units of mass/time, e.g. Pg C year^{-1}), that is, a transfer of C from one pool to another, resulting in removal of C from the prior.
Carbon pool (stock, storage)	Reservoir of C (units of mass, e.g. Pg C) in plant biomass, oceans and soil.
Carbon sequestration	The process of removing C from the atmosphere and storing it in a C reservoir (i.e. biomass, soil). For example, in soil, C storage is the result of dead organic matter accumulating.

IFM as an NCS has only included a limited number of forestry practices, namely extended rotations (i.e., extending the time between final harvests) (Fargione et al., 2018; see Table 1), which underestimates the potential contribution of IFM to forest-based C sequestration and storage. Moving beyond extended rotation could improve the ability for forests to store and sequester C, as recognized by existing forest-based NCS analyses (D'Amato et al., 2011; Janowiak et al., 2017; Ontl et al., 2020).

In the United States, timber harvesting is the most extensive disturbance across forestlands both in terms of area and C impacts, and 89% of the timber harvested annually comes from private lands (Oswalt et al., 2019; Williams et al., 2016; Woodall et al., 2015). Thus, decisions around forest and land management alter the role of forests as a C sink. Forest management, defined as applying appropriate, sustainable practices to a forest to achieve certain outcomes (i.e., timber, recreational opportunities, etc.), can influence C sequestration by (1) increasing forest cover (reforestation or afforestation), (2) maintaining existing forest cover (avoided deforestation) and (3) managing existing forests (e.g., Fahey et al., 2010; Ryan et al., 2010). Although US forests at present are C sinks (see Table 2) (EPA, 2020; Hudiburg et al., 2019; Law et al., 2018; Oswalt et al., 2019; Pan et al., 2011), large uncertainty remains about the future persistence and magnitude of this sink under rotational, single-species forest management (Wear & Coulston, 2015).

IFM could provide an important approach to increasing C sequestration in forested systems (Fargione et al., 2018 , but effective implementation will need to be expanded to forestry in practice. Early definitions of IFM, and analyses of its potential as a NCS (Fargione et al., 2018), included only extended rotations (Table 3(b). However, extending harvest rotation might entail the risk of climate-induced disturbances such as storm damage or insect outbreaks (Anderegg et al., 2020; Diaz et al., 2018; McKinley et al., 2011; Ryan et al., 2010), thus risking reductions in forest C stocks (Wear & Coulston, 2015). In contrast, other IFM strategies—not currently considered in existing NCS analyses—are commonly used in the forest industry and protocols applied in the C markets (Table 3(a)), including silvicultural systems such as selection and retention harvesting. Yet, they remain largely unassessed for their C sequestration potential by research communities in forestry. For example, the forestry protocols of the California Cap-and-Trade Program (California Air Resources Board, 2015) — the only emissions trading system where forest offsets are traded in the United States—are carefully developed and vetted, but remain mostly untested in forestry (Marland et al., 2017), in part due to the youth of the Program. Further, 95% of the forest offsets issued in the California Cap-and-Trade-Program originate from IFM projects (California Air Resources Board, 2020; Marland et al., 2017). Finally, since the introduction of forest C offset credits, the definition of IFM has largely been shaped by entities tied to the California Cap-and-Trade-Program and Voluntary Offset Market (Tables 3(a)). Although markets are certifying (i.e.,issuing offsets to) IFM projects, the empirical evidence of the long-term C benefits of given IFM practices remain to be tested (Marland et al., 2017).

Although the importance of managing live trees (and standing and downed dead wood) in forest ecosystems as NCS has been established, large uncertainty remains on how to manage and potentially increase forest soil C storage in managed forests. In forestry, practical forest management guidelines used within the United States include best practices for mitigating impacts of forest management activities on soil productivity (Cristan et al., 2016), but have thus far overlooked forest soil C as a management objective (Case et al., 2021). As soil accounts

TABLE 3 Definitions of improved forest management (IFM) in (a) protocols by state and government agencies, and non-governmental organizations associated with forestry and/or existing C markets, and (b) in published peer-reviewed literature. We consider whether below-ground C components are included in those existing definitions or standards

(a)		
Publication	**Definition of IFM**	**Below-ground or soil C included**
Verified Carbon Standard (VERRA, 2012, 2013)	Uses CARB's definition (see below).	Soil C is not included; changes in soil C pool considered de minimis as a result of rotation extension.
California Air Resources Board (CARB, 2015)	In this protocol, IFM is defined as forest management activities that increase C stocks on forested land relative to baseline levels of C stocks. Eligible management activities include (but are not limited to): • increasing the overall age of the forest by increasing rotation ages • increasing the forest productivity by thinning diseased and suppressed trees • managing competing brush and short-lived forest species • increasing the stocking of trees on understocked areas • maintaining stocks at a high level In addition, all forest projects are required to establish and/or maintain forest types that are native to the project area.	Below-ground biomass C (tree) is included. Soil C is included if (1) site preparation activities involve deep ripping, furrowing, or ploughing where soil disturbance exceeds 25% of the project area over the project life, or (2) mechanical site preparation activities are not conducted on contours. No crediting of increased soil C is allowed, however.
American Carbon Registry (ACR, 2018, 2019)	IFM is defined as activities to reduce greenhouse gas (GHG) emissions and/or enhance GHG removals, implemented on lands designated, sanctioned or approved for forest management (e.g.,production of sawtimber, pulpwood and fuelwood).Eligible IFM project activities include: • conversion from conventional logging to reduced impact logging • conversion of managed forests to protected forests ("stop logging") • extending rotation lengths in managed forest • conversion of low-productive forests to high-productive forests • increasing forest productivity by thinning diseased or suppressed trees • managing competing brush and short-lived forest species • increasing the stocking of trees on understocked areas (including lands not historically managed as forest but meeting the applicable "forest" definition due to percent tree cover or other factors)	Below-ground biomass C (tree) included. Soil C is not included, considered de minimis (i.e. below the threshold of 3% of the final calculation of emission reductions or removals) and is assumed not to change significantly as a result of IFM activities.
Climate Action Reserve (CAR, 2019)	Uses CARBs definition (see above), and in addition, IFM includes: • growing older forests • stocking improvement • retention of the best-growing trees • avoiding damage to retained trees at harvest	Below-ground biomass C (tree) included. CAR follows CARBs guidance on soil disturbance (see above). Soil C is assumed not to change significantly as a result of most IFM activities. However, all IFM projects must use standardized guidance to account for potential soil C emissions (i.e. losses) associated with management activities.
(b)		
Publication	**Definition of IFM**	**Below-ground or soil C included?**
Miller et al. (2014)	IFM methods include extending harvest/rotations, minimizing disturbances to forest floor, stocking of long-lived/climate-adaptive tree species and natural disturbance risk management.	No

(Continues)

TABLE 3 (Continued)

(b)

Publication	Definition of IFM	Below-ground or soil C included?
Griscom et al. (2017)	Natural forest management includes improved plantations, and IFM methods highlighted include: • extension of harvest cycles • reduced-impact logging • shifting production from native forests to plantations	Below-ground (tree) biomass is considered, total ecosystem C pool estimates assume no change in soil C under natural forest management.
Fargione et al. (2018).	IFM includes both natural forest management and improved plantations. The maximum mitigation potential proposed is reached by halting harvesting in natural forests (i.e., on lands under uneven-aged and/or less intensive management) until the stand reaches its biological optimum rotation length.	Below-ground biomass C (tree) included, total ecosystem C pool estimates for IFM assume little or no change in soil C as result of IFM practices.

TABLE 4 Definition of improved forest management proposed by this synthesis

	Proposed definition	Silvicultural management practices
Improved forest management (IFM)	IFM encompasses a range of silvicultural management actions that incorporate above- and below-ground biomass C components, as well soil C stocks.	Extended rotations Thinning for stand improvement and fuel management Promoting uneven-aged forest management (including partial harvesting) Facilitating stand re-establishment/regeneration and seedling survival Avoiding logging damage to remaining trees Species selection: retaining native species, and if possible, diversifying species in stand Minimizing soil disturbance and extensive soil damage: compaction, mixing and displacement Retain coarse woody debris (stumps, downed trees, snags) in a stand

for an estimated 56% of the total ecosystem C on managed lands in the conterminous United States (Domke et al., 2017; Table 4), accounting for soil C when assessing the potential for IFM to store C is essential.

Herein, we identify specific silvicultural practices that could serve as the foundation for IFM. The importance of forest management in maintaining and enhancing terrestrial C sinks has been established (e.g., McKinley et al., 2011), but guidance for implementation of C management in practical forest management is needed—including consideration for a wide array of ecosystem services (Ontl et al., 2020). Considering a wider range of IFM strategies for forestry in practice, such as those currently implemented and researched in silviculture, and highlighted by entities tied to the C market could help with the C storage task at hand. In this synthesis, we offer specificity to IFM through reviewing published literature, forest offset protocols and existing silvicultural practices that are relevant for IFM drawing from examples from the Eastern and Midwestern United States, particularly from the Great Lakes region. In addition, we assess potential strategies to include soil C as a management component in IFM, and limitations for the adaptation of these considerations. Finally, we highlight the opportunities and challenges associated with forest C offset market access for landowners. Overall, this synthesis highlights opportunities to expand the contribution of IFM as an NCS to sequester and store more C in terrestrial systems, and provide co-benefits for water quality, habitat and biodiversity.

2 | DEFINING IFM

In the last decade, C storage and sequestration has emerged as an important forest ecosystem service (e.g., reviewed in Ontl et al., 2020). Silvicultural practices that integrate multiple goals are of interest to stakeholders in forestry (Miller et al., 2014; Miller et al., 2015), thus developing management options that respond to multiple objectives (e.g.,timber, C, wildlife habitat) is important. Next, we review existing silvicultural approaches and practices that could be considered IFM drawing from examples in literature.

2.1 | IFM as a tool in managing existing carbon stocks

2.1.1 | Extended rotation

To date, the primary focus of IFM as a NCS has been on extending rotation times, and other practices have not been evaluated. For this reason, we briefly review the benefits and risks of extended rotations for C.

When C is considered a forest management objective, the value of delaying harvest (i.e.,extending the rotation time) is higher as C accumulates in the woody biomass as the existing trees grow larger (Harmon, 2001; McKinley et al., 2011; Ryan et al., 2010). Rotation length, that is, the time between final harvests, is determined by management objectives and is an integral part of forest management planning in managed forest stands. In these stands, the harvesting interval is often dictated by economics: stands are logged when they reach the culmination of mean annual increment. In the short term, extending the time between harvests (i.e.,extending rotations) is an attractive option, particularly in managed plantation, where extending the rotation length could potentially offer high C storage returns for a low or no net cost as management actions (i.e.,harvesting) are delayed (Fargione et al., 2018; Griscom et al., 2017). Outside of plantation forestry, extended rotations have been used to create structural and ecological attributes in younger stands lacking old-forest elements (D'Amato et al., 2010; Silver et al., 2013). For example, in northern Minnesota, USA, extended rotations combined with thinning treatments, accelerated the advancement to larger tree diameter classes, and generated diameter distributions more closely resembling those found in old-growth stands (Silver et al., 2013). Finally, the management strategy with the largest impact on C sequestration (e.g., modifying thinning regimes versus extending rotations) may also vary by stand type (i.e., the dominant species), timber prices and wood production (i.e., site class) (Galik & Jackson, 2009; Sohngen & Brown, 2008).

Extending rotations is not always feasible and face a risk of reversal caused by disturbances (Galik & Jackson, 2009). For example, extending rotations may increase the risk of losing C from disturbances, such as fire, prior to harvest if there is significant fuel build-up in the stand (McKinley et al., 2011), or if the forest type has other aspects that make it vulnerable to climate risks that could result in widespread mortality. For these reasons, we next highlight other promising strategies drawing on examples from silviculture practiced in the Eastern and Midwestern US forests.

2.1.2 | Managing stand density

Silvicultural practices that could be considered IFM should align with sustainable forest management practices, which aim to maintain the health of the stand (thinning of diseased trees and management of competing vegetation), increase the vigour of existing trees (selection and retention harvesting) and minimize harvest damage (Table 3(b)). Selection systems—in which individual trees or smaller groups of trees are removed instead of all—produce forests of several age classes and are commonly referred to as uneven-aged management (Table 1). Selection systems can be used either to maintain uneven-aged conditions or to create them in even-aged stands. Retention systems, usually practiced in even-aged stands, and similarly to selection systems, aim to sustain more of the ecological conditions and processes characteristic of a natural forest (Palik et al., 2014). This is achieved by introducing or maintaining a level of complexity in the stand structure through biological legacies (e.g., large trees), which can potentially sustain higher levels of biodiversity and forest ecosystem functioning, including C storage and sequestration. Intermediate silvicultural treatments, such as thinning, that aim to improve the growth of residual trees can decrease the total C storage in the short-term, but could have C increasing benefits in the long term; by increasing the vigour and health of the remaining trees and their resistance to bark beetles and pathogens; by removing diseased trees (salvage logging); by shifting species composition in the stand, potentially toward more climate-adapted species; and by introducing structural complexity to the stand (Hoover & Stout, 2007; Ontl et al., 2020). In recent years, structural enhancement treatments (i.e., practices that enhance forest habitat attributes such as multi-layered canopies, standing dead trees, downed large woody debris and a full range of tree sizes) have emerged as tools to increase C storage in red pine stands and northern hardwood-conifer stands (Palik et al., 2014; Ford & Keeton, 2017). In addition to younger and developing stands, thinning treatments are also increasingly being applied to older, managed forest stands in attempts to increase residual tree vigour, reduce fuel loads, alleviate drought pressure and to promote structural complexity and increase resistance to climate change impacts such as drought (Hoover & Stout, 2007; D'Amato et al., 2010; Law et al., 2012; Silver et al., 2013). Some stands can be more suitable to thinning than others. For example, in northern Minnesota thinning to different basal area densities had little influence on C storage in red pine stands, but C storage decreased with increasing treatment intensity in northern hardwood stands (Powers et al., 2011; D'Amato et al., 2011), thus thinning may provide greater C storage potential in the latter (Powers et al., 2011). In a thinning experiment in the Northeastern hardwood forests, stands that were thinned from below (i.e., smaller trees were removed) had greater volume production and C sequestration rates than stands where larger trees were removed (Hoover & Stout, 2007).

2.2 | Forest soil C: Considerations and knowledge gaps

Much of the focus in forest management and silviculture has been on live and dead above-ground biomass. Yet forest soils are a significant pool of C: an estimated 55%–60% and 60%–85% of total C is stored in the soil in temperate and boreal stands, respectively (Domke et al., 2017; Nave et al., 2018; Pan et al., 2011). Furthermore, soil accounts for 56% of the total ecosystem C on managed lands in the conterminous United States (Domke et al., 2017). Thus, considering the impact of different harvesting practices on forest soil C should be a critical piece of the NCS puzzle in forests. Reviewing existing definitions and standards for IFM, we find that, to date, IFM has largely not considered soil C in the C accounting when assessing NCS potential (Bossio et al., 2020; Fargione et al., 2018).

Forest harvesting, intentionally or unintentionally, often disturbs the organic (O) horizon and exposes mineral soil, which may result in reductions in forest soil C, as a result of soil mixing (as organic matter deeper in the mineral soil is exposed and decomposed) (Cao et al., 2019;

Harmon et al., 2011; Nave et al., 2010). Experiments focusing on forest soil find that forest harvesting lowers forest soil C by 8%–11%, depending on forest type (hardwood and coniferous/mixed): the effects are most pronounced on the surface layers (forest floor and O-horizon) where C stocks can be reduced by 20%–36%, whereas mineral soil responses to harvest have been less pronounced (James & Harrison, 2016; Nave et al., 2010). Soil surface recovery from harvest can take several decades or more (James & Harrison, 2016; Nave et al., 2010). Despite the potential for changes in soil C dynamics, only a handful of past publications have highlighted minimizing harvest-induced forest soil disturbance as a part of IFM efforts (Nave, et al., 2019; Ontl et al., 2020; Swift, 2012).

Harvesting intensity is an important factor in determining the extent of soil disturbance and affects stand C stocks directly (removing C in biomass) and indirectly (causing disturbance in soil); thus, we expect that IFM also influences C loss following harvest, as well as post-harvest soil recovery rates. As more intense harvesting methods tend to cause greater soil disturbance, there is variation in soil C response to harvesting among different harvesting strategies (Binkley & Fisher, 2020; Hume et al., 2017; James & Harrison, 2016; Jandl et al., 2007; Mayer et al., 2020; Nave et al., 2010; Nave, DeLyser, et al., 2019). Clearcutting generally results in reduction in stand soil C stocks, particularly if whole-tree harvesting (i.e., slash is removed with timber) and/or stump harvesting is practiced (Mayer et al., 2020; Thiffault et al., 2011). The effects of harvesting are most pronounced in the surface of the soil, particularly in the organic layer, and are largely driven by disturbances caused by logging equipment and site preparation (Kaarakka et al., 2018; Mayer et al., 2020; Thiffault et al., 2011). In the United States, previous syntheses indicate that thinning reduces C stocks in the O horizon; but no consistent conclusions have been reached for the mineral soil C stock (Cao et al., 2019; James & Harrison, 2016; Johnson & Curtis, 2001; Nave et al., 2010). It is possible that more intense harvesting combined with site preparation will affect deeper soil layers, and potentially C pools there (Kaarakka et al., 2018), but much uncertainty remains about the harvest-induced changes deeper in the mineral soil in part due to the lack of sound experimental data (James & Harrison, 2016).

Evidence for the effects of IFM strategies outside of extended rotations on forest soil C dynamics are rare, particularly on partial harvesting and that of uneven-aged forest management. Recent syntheses conclude that management of stand density (i.e., thinning) has small effects on forest soil C stocks (Mayer et al., 2020; Zhang et al., 2018). In the Northeastern United States, partial and complete harvesting treatments (light thinning, heavy thinning and clearcutting) were reported to have no effect on forest floor and mineral soil C (Hoover, 2011). Similarly, a study in a lowland mixed species stand found no difference in mineral soil C stocks following selection, shelterwood and clearcutting treatments (Puhlick et al., 2016). All of these findings suggest that a less intense management action could be considered in stands where maintaining and/or increasing soil C stocks is of interest (Jandl et al., 2007; Powers et al., 2012). Thinning and selection harvesting increase the number of logging operations in the stand, and logging equipment can cause soil compaction, redistribution of the forest floor organic matter and vertical dislocation of soil organic matter and pose a risk of damage to remaining trees. The use of skid trails, protecting soil with timber mats, particularly on wet sites, and timing harvest to winter months are operational examples that could be considered for protecting forest soil at harvest.

2.3 | Moving forward

2.3.1 | Bringing forest soil into the fold

Reviewing the status of IFM for forest C management, we identify that very little research exists on the effects of the many IFM practices on forest C beyond that on extended rotations and outside the realm of C markets. In existing IFM approaches, namely extended rotation, the most focus has been on above-ground C despite the importance of below-ground C as long-term C storage. Considering that forest soil in the conterminous United States contains on average 112.9 Mg C ha^{-1} to a depth of 1 m in contrast to approximately 53.6 Mg C ha^{-1} in above-ground biomass (EPA, 2020), maintaining forest soil and its components well into the future—including C—should be a climate mitigation and adaption priority (Bossio et al., 2020; Nature Geoscience, 2020).

Given the foundational role of soil both as a repository of future forest productivity, and as the largest C pool in forest ecosystems, including soil C into forest management guidelines should be a priority. In managed ecosystems, soil C stocks can be increased by: (1) increasing the rate of C addition to the soil, which removes CO_2 from the atmosphere, and/or (2) reducing the relative rate of loss (as CO_2) via decomposition (Paustian et al., 2019), which might also slow nutrient turnover and tree growth. One way to achieve this in managed forests, is to retain logging residues and coarse woody debris, such as stump and coarse roots, that comprise the largest biomass component in many productive forests, in the stand following harvest (Kaarakka et al., 2018; Table 4).

Efforts to include forest mineral soil C—the largest forest soil C pool—into national inventories are underway (Bulmer et al., 2019; Domke et al., 2017; 2019). Yet, the lack of accessible and comprehensive forest soil C data has resulted in soil C being exempted from forest and land management C policy reporting and accounting (Bossio et al., 2020). For example, in the compliance offset protocol developed by the California Air Resources Board, forest soil C is included in the final estimation of IFM project C stocks (i.e., within the offset project boundaries) only if the management activity involves soil preparation on more than a quarter of the project area (Table 3(a)). Otherwise no crediting of increased soil C is allowed (i.e. soil is assumed not to sequester C), however (Table 3(a)). One of the reasons is tied to the practical implications; indeed, soil C mapping can present an added cost to the already costly assessment of forest C stocks needed for the market verification documents. Measuring soil C can further add to these costs; to detect meaningful changes in soil C, sampling frequency has to be high (Domke et al., 2017). Moving forward, future research should seek to understand how soil is shaped by different silvicultural practices, and at what spatial and temporal scales. Long-term, coordinated experiments should be established across a range of forest ecosystem and soil types, particularly in regions where existing forest C offset projects are located, including in the Great Lakes region.

2.3.2 | Expanding IFM opportunities for landowners

Despite the potential climate benefits, IFM can be costly compared to more established practices such as clearcutting. Thus, incentives for landowners to switch to and adopt IFM practices are needed, particularly to compensate for additional management costs associated with IFM and opportunity costs (e.g. from delaying harvest or forgoing some harvest-related profits from wood). Expanding financial incentives for practitioners in forestry to adapt IFM methods are important to offset these opportunity costs. In addition, several other barriers for entry into C markets remain. Family forest owners control 36% of the forestland in the United States, this is more than any other ownership group (Butler et al., 2016). Yet low C prices, long-term contracts and the lack of awareness of C market opportunities persist as barriers for C market participation within this ownership group (Miller et al., 2015; Marland et al., 2017; Ruseva et al., 2017). Existing forestry offset project across the contiguous United States have an average size of 22,240 acres (9000 ha) (Anderson et al., 2017). In contrast, family forest landowners in the United States own on average 67.2 acres of forestland (Oswalt et al., 2019). Furthermore, feasibility studies have indicated that small-scale forest owners do not meet the requirements for offset project permanence, accounting and monitoring, and are struggling with the rising costs of both the C inventory and accounting, as at least 1500–5000 acres are required to balance the transaction cost of participating in the offset market, depending on the stocking of the land (Kerchner & Keeton, 2015; Miller et al., 2014; White et al., 2018). Finally, project development and verification costs are high (more than $100,000 and $45,000, respectively), pushing market participation out of the reach of many family forest owners in the United States. Only a few states in the United States have programs in place to assist landowners in managing forest C: California, Michigan and Oregon (American Forest Foundation, 2019; Miller et al., 2015). However, only California has a market where landowners can sell forest C offsets (American Forest Foundation, 2019; Hamrick & Gallant, 2017; Miller et al., 2015). Supporting market participation and access, and increases in the demand for forest offsets could increase forest offset prices (Marland et al., 2017), and provide new avenues of revenue for family forest owners.

2.3.3 | IFM in the context of climate change

With an uncertain climate future, however, past forest management practices might become increasingly disconnected with the task at hand, that is, sustaining forest and the resources they provide into the future (Jandl et al., 2019; Ontl et al., 2020; Thom & Keeton, 2020). Under current management practices, stresses posed by climate change may exceed the ability of the forests to adapt (Duveneck et al., 2014), as recognized in the forestry community (Handler et al., 2014; Halofsky et al., 2018; Ontl et al., 2020; Swanston et al., 2016). As such, a number of tools aimed at integrating forest C into practical management while providing natural resource managers and landowners with strategies and approaches for helping forests adapt to climate change, have emerged as of late (Janowiak et al., 2017; Nave, DeLyser, et al., 2019; Ontl et al., 2020; Swanston et al., 2016). For example, maintaining existing C stocks, reducing the risk of C losses from disturbance and enhancing C sequestration through forest alterations (i.e., species selection from native species or increasing species diversity) (Ontl et al., 2020) are some of the strategies that should be incorporated into the guidance for IFM. Some of the specific silvicultural practices could include practices that aim to improve the vigour and health of the forest stand (i.e., thinning), practices that aim to protect the stand from extensive disturbance, including the soil, and practices that retain coarse woody debris in the stand (Table 4). Finally, in the context of climate change, forest management can indeed create conditions in a stand that alleviate some pressure on trees.

3 | CONCLUSIONS

Land management and conservation management practices such as NSC, including IFM, could provide an important approach to increasing C sequestration and storage in forested systems in the United States, but effective implementation in practice will need to be built on insights from research. Further, currently IFM remains unconnected to practical and operational forest management. To develop forest NCS pathways to their fullest potential and to be considered in forest management decision-making, we recommend establishing a stronger evidence base for the verifiable C benefits of existing silvicultural practices. Our synthesis highlights several opportunities to build these connections. First, we propose establishing clear definitions for silvicultural practices included in IFM, beyond extended rotation. Second, a majority of forest C projects under the offset market are considered IFM, a source of data that can help link specific silvicultural practices to their C sequestration potential. Finally, soil C has been largely excluded as a management component in practical forestry, and thus far existing IFM projects have not considered soil C in the C accounting when assessing NCS potential. Moving forward, future research should focus on understanding the cumulative effects of forest management (or silvicultural practices) on all ecosystem C components, including on soil C.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

Lilli Kaarakka, Laura E. Dee and Meredith Cornett conceived the idea. Lilli Kaarakka led the writing of the manuscript with support from Laura E. Dee. All authors contributed to different drafts, including the final, and gave approval for the publication of the final manuscript.

DATA AVAILABILITY STATEMENT

This manuscript does not include any data.

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