What do we know about the impacts of forestry on soil carbon in Scotland?

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Summary

This paper briefly summarises our state of knowledge concerning soils, soil carbon and the impacts of some forestry practices on soil carbon. We touch on the policy context relating to soils in Scotland and how they are treated in regulation and good practice guides, and we speculate on how our current understanding of soils and forestry practices could shape future policy. This treatise is relatively short for such a large topic, and we specifically focus on organic soils in the uplands.

Scotland's soils contain approximately 3,000 million tonnes of carbon in the top one metre of soil (**Figure 1**; Scottish Government, 2021). This means that a loss of just 0.34% of Scotland's soil carbon per year, in the form of carbon dioxide, would roughly double national greenhouse gas emissions (equivalent to 11 million tonnes of carbon per year). Preserving Scotland's soil carbon must be an urgent priority if we are to achieve the Scottish Government's commitment to reaching net zero CO_2 emissions by 2045 (Scottish Government, 2020). Whilst the government has abandoned its 2030 climate change targets, it would be prudent to keep as much of Scotland's soil carbon in the ground as possible, with foresters playing a role.

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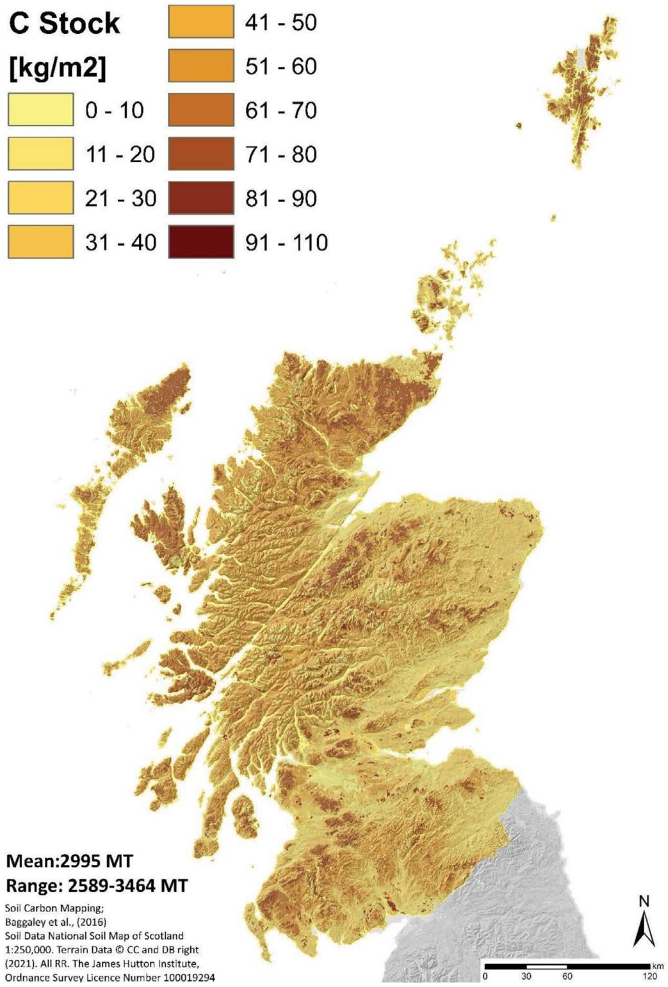


Figure 1, above: Soil carbon stocks to 1m depth (Adapted from Poggio & Gimona, 2014 by Scottish Government, 2021).

Scotland's organic soils

Of Scotland's soil carbon, 56% is in peatland, generally defined in Scotland as soils with an organic layer >50cm depth (Chapman et al., 2009). Deep peats aside, Scotland's soil carbon is mostly in carbon-rich organo-mineral soils such as peaty gleys, peaty podzols and humus iron podzols, common in the Scottish uplands. In the top metre, organo-mineral soils can contain 300-plus tonnes of carbon per hectare, approximately two thirds as much carbon as the top metre of deep peat (Vanguelova et al., 2013). In contrast, arable land in Scotland typically contains around 100 tonnes of carbon per hectare in the top metre (Vanguelova et al., 2013).

Soil type is an important factor in determining whether soils lose or gain carbon under forestry. This holds true from industrial forestry over multiple rotations, to newly created native forest on previously unforested land. The more carbon a soil contains, the more likely it is to lose carbon when disturbed; carbon-rich soils typically lose carbon under forestry, while carbon-poor soils typically gain carbon under forestry (Hong et al., 2020; Mayer et al., 2023).

Current policy context

The Scottish Government is committed to creating 15,000ha of new forest per year by 2025 (NatureScot, 2023). Much of the land afforested (Vanguelova et al., 2013) and land available for new planting (Brown, 2020) is on carbon-rich soils in the Scottish uplands (Scottish Government, 2021). Seventeen per cent of Scotland's peatlands and 21% of organo-mineral soils are currently forested (Vanguelova et al., 2018).

Neither the UK nor Scotland have overarching soil legislation; soil regulation stems from water-related law such as the Water Environment and Water Services (Scotland) Act (2003). No single Scottish governmental body is responsible for soils, and agencies such as Scottish Forestry, NatureScot and the Scottish Environmental Protection Agency (SEPA) deal with soils in relation to forestry practice, biodiversity and water quality.

The UK Forestry Standard (Forest Research, 2023) is the main reference for sustainable forest management, and deals with soils in relation to acidification, contamination, compaction disturbance, erosion, fertility and organic matter. Soil carbon guidance can be summarised as follows:

1. Minimise the soil disturbance necessary to secure management objectives, particularly on organo-mineral soils
2. Avoid establishing new forests on soils with peat >50cm depth and on sites that would compromise the hydrology of adjacent bog or wetland habitats
3. Forest creation on certain sites where deep peat soils have historically been highly modified may be considered if it complies with the relevant country policy
4. Consider the potential impacts of soil disturbance when planning operations involving cultivation, harvesting, drainage and road construction
5. Ensure that the removal of forest products from the site does not deplete site fertility or soil carbon over the long term and maintains the site potential
6. Consider the balance of benefits for carbon and other ecosystem services before making the decision to restock on soils with peat >50cm in depth.

In 2021, Scottish Forestry introduced stricter guidelines to limit medium- and high-disturbance cultivation techniques on soils with an organic layer >10cm in depth (Scottish Forestry, 2021). To reduce carbon emissions from soil disturbance, this proscribes techniques such as ploughing on deep peat, countering forest industry views that intensively cultivating peat and organo-mineral soils might be acceptable under certain conditions.

In 2018, Scottish Forestry launched a set of UKFS compliance procedures designed to deal with breaches of the UKFS (Scottish Forestry, 2018). We are unaware of any monitoring of UKFS in Scotland since these procedures were published, and the online register of UKFS breaches, due to go live in 2019, has not been published.

Sources of data on Scotland's soil carbon stocks

Existing data

The Scottish Soils Database includes several national datasets which underpin our knowledge of carbon stocks in Scottish soils (Scottish Government, 2021). Scotland has excellent data and mapping of soils compared to other countries, but the underlying surveys were developed iteratively over decades, beginning in the 1940s, and were not originally designed to quantify total carbon storage. The early soil surveys (known as Representative Soil Profiles of Scotland) were 'free surveys', meaning samples were taken in subjective locations based on the expert judgement of surveyors. The National Soil Inventory of Scotland (NSIS) in the 1970s and 1980s – partially repeated in 2007–09 (Chapman et al., 2013) – introduced systematic sampling on a grid, allowing for a robust assessment of changes in soil carbon stocks over time. However, spatial coverage of woodland soils in the NSIS is limited. Of the original 721 sampling locations, 25 were in woodland, and just five resampled in 2007–09 represented change to woodland from another land use (Chapman et al., 2013). Subsequent efforts were made to find locations in the wider Scottish Soils Database that had transitioned to woodland since the original sampling (Lilly et al., 2016) but this still left gaps: for example, none of these additional sites included broadleaf woodland. The UK BioSoil Network, established in 2006, is another key national soil carbon dataset but only includes woodland sites, so doesn't provide information on the impact of afforestation (Vanguelova, 2024b). Other soil carbon datasets relevant to forestry are more limited in scope, restricted to a few sites or limited soil depths. A scoping study on soil carbon sequestration by the Scottish Government provides a useful review of sources of Scottish soil carbon data (Scottish Government, 2021).

In addition to national datasets, a growing number of primary research studies aim to directly quantify the impact of forestry or forest management on soils in Scotland or in similar ecosystems (e.g. Friggens et al., 2020; Housego et al., 2024, in revision; Vanguelova et al., 2019). These studies contribute significantly to our understanding but often do not sample at enough sites to draw general conclusions. Because the amount of data from Scotland's historical surveys is limited, many studies rely on substituting 'space-for-time' – the assumption that adjacent forest areas of different ages, sampled today, reflect the changes that would have occurred through time. Space-for-time assumptions can be especially problematic when trying to understand the impacts of forest establishment on soil carbon, as nearby unforested areas do not necessarily represent the soil conditions that were present before a forest was established. Caution must be employed when interpreting these studies to avoid misleading conclusions.

Ongoing data collection

Forest Research is currently undertaking two evidence-gathering projects funded by Defra's 'Nature for Climate Fund.' One looks at the long-term effects of different intensities of ground preparation on soil carbon stocks following reforestation of peaty gley soils. The other is looking at the effects of low-intensity mounding – the approach recommended by current guidance – on peaty gley soils, by remeasuring Scottish BioSoil sites last surveyed in 2006 and 2012. In addition, the Woodland Carbon Code (WCC) project is measuring soil carbon stocks changes at WCC sites afforested in the past 20 years, which includes a selection of soil types and tree species, and ~100 BioSoil forest soil monitoring network plots in Scotland are being re-surveyed (Vanguelova, 2024a).

Barriers to collecting more data

Understanding the impact of forestry on soil carbon is challenging because it requires the quantification of small relative changes. A 10% loss of soil carbon over 30 years is a realistic scenario following low- to medium-disturbance cultivation of organo-mineral soils (Vanguelova et al., 2019) (note that a 0.34% soil carbon loss per year for Scotland as a whole would roughly double national carbon emissions). However, detecting change in soil carbon of a fraction of a per cent is near impossible, so repeat sampling often needs to be ten or more years apart for differences to be detectable. This is particularly true for Scotland, as most forestry occurs on organo-mineral soils, which are particularly spatially variable.

Figure 2, top right: Clearfell site, Dumfries and Galloway, 2024. © Ted Leeming
Figure 3, bottom right: Aerial view of restocking site with drains, Dumfries and Galloway, 2024. © Ted Leeming

High spatial variability also means a large number of samples are required to detect change (Vanguelova et al., 2013), which is labour-intensive and expensive. While the equipment involved in measuring soil carbon stocks is relatively cheap, the labour involved in time-consuming sampling and laboratory processing (such as measuring bulk density or carbon content) is expensive.

A further challenge associated with measuring changes to organo-mineral soils following forest establishment is changing soil horizons thickness, notably in the top litter layer and fermentation and humus horizons. Measuring and reporting changes in soil carbon to a fixed depth relative to the top of the litter layer or horizon may not give an accurate picture of soil carbon changes. The alternative is to sample by horizon, although different data sets (UK BioSoil versus NSIS, for example) use different approaches, making comparisons and synthesis of datasets more challenging. Finally, person power provides an additional barrier to soil data collection. There is a lack of professional expertise to survey soils, and this lack of soil scientists and surveyors appears to be a growing problem.

In summary, low spatial coverage of historical data, the highly variable nature of Scottish soils, the expense of sampling, and dwindling expertise all limit information on the impacts of forestry on soil carbon. Data on the impacts of afforestation are particularly sparse. As two leading soil researchers at Forest Research comment: 'There are presently insufficient measurements from a range of UK climate, land-use and soil type conditions to quantify with confidence soil carbon changes during afforestation' (Perks & Vanguelova, 2020).

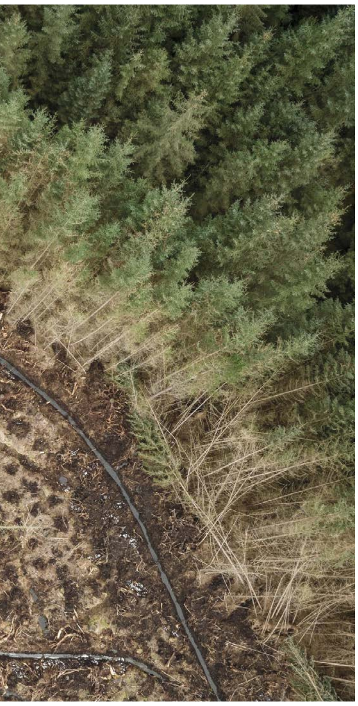
How does forestry influence soil carbon in Scotland?

Soils contain three quarters of forest carbon stocks (Vanguelova et al., 2013). Whilst carbon capture in woody biomass has been extensively measured and modelled, the effect of forestry on soil carbon stocks and fluxes is less well understood, with a complex picture emerging in Scotland (Sloan et al., 2018; Vanguelova et al., 2018, 2019). The impact of forestry on soil carbon is influenced by three factors: soil type, intensity of soil disturbance, and tree species (Vanguelova et al., 2018). We provide brief snapshots of the major impacts.

1. Soil type

In mineral soils such as in ex-arable and improved grassland, soil carbon stock tends to be stable. This is because more of the carbon stock – an estimated 65% – is stored as mineral-associated organic matter, bound to minerals and better protected from loss via processes such as decomposition (Sokol et al., 2022). Deep peats are at the opposite end of the spectrum – here, carbon accumulates as a thick layer of partially decomposed organic material, potentially sitting many metres above underlying mineral substrates. We know carbon in peat is vulnerable and easily lost if the peat dries out, going from a waterlogged, low-oxygen (anoxic) environment to an oxic environment where aerobic soil bacteria can decompose organic matter more rapidly (Loisel & Gallego-Sala, 2022). Organo-mineral soils are intermediate, defined as soils with a peat layer between 10–50cm. Organo-mineral soils may be relatively well or poorly drained, depending on the properties of the underlying mineral soils. When forests are planted on organo-mineral soils, there is often a loss of soil carbon from the organic horizons (Lilly et al., 2016; Vanguelova et al., 2018) which may or may not be compensated over time by carbon accumulation in surface litter or fermentation layers (Vanguelova, 2019; Friggens 2020), estimated to be 0.6tC ha^{-1}. However, carbon in the deeper soil horizons is a more reliable long-term carbon store than carbon in the litter layer (Sanaullah et al., 2011). We do not have a good understanding of why carbon is lost from organic horizons in these soils; this may be related to disturbance during cultivation, drainage or other biological processes associated with tree establishment.

Tree litter differs in quantity and composition from the previous vegetation cover, altering decomposition dynamics (Finzi et al., 1998; van Meeteren et al., 2007). Trees are associated with symbiotic mycorrhizal fungi (typically



ectomycorrhizal fungi), differing from grassland (typically arbuscular mycorrhizal fungi) and moorland communities (typically ericoid mycorrhizal fungi). A shift in the composition of the mycorrhizal fungi community can drive changes in soil decomposition dynamics. For example, ectomycorrhizal fungi can enhance the breakdown of soil carbon to release nitrogen for the tree in exchange for carbon from the tree (Clemmensen et al., 2021).

2. Intensity of soil disturbance by forestry practices

a) Afforestation

Afforestation of mineral soils such as ex-arable land does not result in significant release of carbon dioxide and can result in significant increases in soil carbon over long time periods (Ashwood et al., 2019; Benham et al., 2012; Poulton, 1996). This is partly because, relative to organo-mineral soils, mineral soils contain low levels of carbon (Vanguelova et al., 2013). Cultivation of peat soils results in losses of soil carbon (Chapman et al., 2013; Simola et al., 2012; Swain et al., 2010; Vanguelova et al., 2019; Zerva and Mencuccini, 2005), and losses increase with the intensity of forestry practices (Forest Research, 2021). Casado et al. (2022), combining data from the National Soil Inventory of England and Wales with data from the National Inventory of Woodlands and Trees, found that woodlands in their first rotation lost topsoil organic carbon at a typical rate of 2% per year for up to 40 years.

Drainage is an intensive forest practice and is effective in achieving rapid forest growth; Scotland has been draining peat for centuries (Evans et al., 2016; Zehetmayr, 1954), creating ditches that rapidly remove excess water from wet sites and help to dry peat soils (Anderson and Peace, 2017; Sloan et al., 2018). This intensity of upland and forest drainage is particular to the UK and Ireland (Evans et al., 2017) and lowering the water tables of peat soils leads to soil carbon losses (Vanguelova et al., 2018). Some is lost to the atmosphere as carbon dioxide via increased decomposition, while some is lost in drains as dissolved organic carbon, which eventually flows into rivers (Haddaway et al., 2014) – the presence of conifer plantations can double the quantity of carbon lost from peat soils into rivers compared with unforested catchments (Williamson et al., 2021). Chronosequences (sites sharing ecological attributes at different times) in Kielder Forest indicated carbon losses from peat under Sitka spruce plantations over multiple forestry rotations, with approximately 30% of original peat carbon lost over 30 years (Vanguelova et al., 2019).

Recent research raises questions about native woodlands planted on shallow peat and whether they are positive in respect of soil carbon over decadal timescales (Friggens et al., 2020; Matthews et al., 2020). Friggens et al. recorded a decrease in soil carbon relative to heather moorland control plots after 12 and 39 years in birch woodland on organo-mineral soils in north-east Scotland. Scots pine plots in the same experiment did not lose soil carbon, due to litter build-up from needle deposition. In the same vein, decreasing carbon in topsoil was recorded in a native woodland creation project in Glen Affric in the Scottish Highlands (Warner et al., 2022). Topsoil carbon decreases were linked to soil microbial and mycorrhizal community changes and increasing soil nitrogen (i.e. increased fertility). So, in the short-term, native trees might cause soil carbon losses on organic soils (Friggens et al., 2020; Warner et al., 2022).

When organo-mineral soils mix organic layers with underlying mineral layers, as with inverted mounding, soil carbon may move down the soil layers and may be sequestered by mineral soil underneath (Swain et al., 2010). This could mean that on certain site types – shallow peat overlaying mineral soils – carbon is moving down the soil profile, becoming more stable and less labile.

b) Natural regeneration

Natural regeneration does not normally involve ground preparation; thus there is less soil disturbance, resulting in less soil carbon loss (Matthews et al., 2020; Perks & Vanguelova, 2020). The long-term impacts of regenerating trees on organo-mineral soils, however, is unclear. Recent sampling at five sites in Deeside, Grampian, recorded soil carbon stocks in carbon-rich peaty podzols and humus-iron podzols under heather moorland, some 50% higher than soil carbon stocks under adjacent sparse 25-year-old Scots pine and birch regeneration. The organic horizon under trees was half that of open heather moorland. Soil carbon stocks in the top 10cm of the mineral horizon were similar, indicating the potential for soil carbon not to be relocated to deeper horizons (Housego et al., 2024, in revision).

c) Clearfelling

Clearfelling on organo-mineral soils can accelerate soil carbon loss – heavy harvesting machinery, often working large areas, disturb the soil and exacerbate soil compaction (see **Figure 2**), resulting in loss of organic matter and leaching of soil into watercourses (Dawson et al., 2007). Research shows significant carbon loss after clearfelling, though the rate of loss can vary, depending on practices such as residue management (Blanco, 2018; Clarke et al., 2015). An alternative to clearfelling – felling small coupes or tree selection – may be less damaging to soils. Results from a continuous cover forestry (CCF) plot in North Wales suggest that CCF could improve soil quality in comparison to even-aged clearfelling (Pitman et al., 2011) and could lead to more stable carbon stocks in the litter layer and negligible change in the mineral layer (Jandl et al., 2007). CCF management reduces or removes the need for large-scale forest soil disturbance, and carbon losses from soils may be less than in an even-aged clearfell system (Stokes et al., 2009).

d) Restocking

Restocking takes place after clearfelling, and with some 800,000ha of Scotland's existing forests planted on deep and shallow peats (Vanguelova et al., 2016) there is the potential for significant loss of soil carbon through oxidation and removal of the litter layer during operations to prepare clearfell sites for restocking. Restocking on organo-mineral soils using deep drains (see **Figure 3**), trench mounding and stump removal causes large-scale soil carbon loss (Smyth, 2023). This is severe in deep peats, where up to 75% of the topsoil may be disturbed (West, 2011). Using natural regeneration in restocking could significantly reduce soil disturbance and minimise carbon losses.

3. Tree species

Trees interact with soil carbon in several ways. Leaf litter produces an organic surface layer, typically leading to the development of the litter layer and, ultimately, deeper soil carbon. This litter layer is a contributor to soil carbon in forests (Laganière et al., 2010) and conifers tend to produce large quantities of needle litter that persist on the forest floor; deciduous tree leaf litter tends to decompose more quickly. Most soil studies concentrate on soil carbon changes in the top 30cm of the soil profile. A study of soil carbon under mature Scots pine stands, compared to adjacent open heather moorland on peat, found that soil carbon stocks in old-growth pine forests were 45% lower than on the moorland. However, the authors concluded, '[a] definitive statement on possible future changes in soil carbon balance as moorland progresses to forest cannot be made based on the existing information' (Chapman et al., 2003). A study of old-growth pinewood and moorland peaty podzols at Abernethy Forest Reserve in the Cairngorms (Wilson and Puri, 2001) reported old-growth Scots pinewoods to be greater carbon sinks than adjacent *Calluna* heath, with significantly larger stocks of soil carbon in the organic layer. This was because of Scots pine needle litter accumulation.

Discussion

The science of how forestry affects soil carbon is evolving, patchy and often difficult to interpret, but has developed rapidly during the last 30 years. We know that disturbance of deep peats as a result of cultivation leads to carbon losses, and that these losses can be dramatic. We know that the thicker the peat layer, and the more intense the disturbance, the heavier the loss. We can also be confident that degraded mineral soils will likely gain carbon under trees. However, there is much more uncertainty around the response of organo-mineral soils: how much carbon might be lost with cultivation, and how quickly soil carbon can recover through litter build-up. Importantly, some studies also suggest significant short- to medium-term soil carbon losses are possible with afforestation even without cultivation, but we currently cannot explain why these losses occur.

Whilst there is unanimity regarding the link between forest practice, soil disturbance and greenhouse gas emissions, industrial forestry interests argue that short-term carbon losses from soils are acceptable if trees grow rapidly. The timescales over which soil carbon losses are offset by tree carbon sequestration remain elusive, and measurements of soil carbon stocks and fluxes are more difficult and more expensive to quantify than woody biomass carbon uptake and storage. Focus on the time-to-carbon positive (the date where carbon sequestration by tree growth might exceed loss of soil carbon due to site management) is unhelpful for peat soils (Lawrence et al., 2021), partly because, currently, peats act as long-term carbon stores, and partly because the fate of carbon in softwood timber products is variable and often temporary.

Cultivating and planting mineral soils is far more carbon-efficient than planting organo-mineral soils, and forestry practices on organo-mineral soils require careful management to balance carbon sequestration with the risk of permanent soil carbon loss. Practices that minimise soil disturbance, such as natural regeneration, reduced drainage, lower-impact cultivation and selective, less intensive harvesting, are crucial to maintaining soil carbon stocks.

The commercial sector is primarily driven by investors seeking a return on investment. This incentivises practices with externalised costs, such as soil damage. Most foresters are, however, motivated by good forest management, and some see it as their professional responsibility to guide investors in this direction. Above all, the private sector interests want stability in regulatory guidance (Lawrence, 2021).

Soil and soil carbon are not given sufficient attention in the UKFS, and their management is indirectly handled through other forestry-related guidelines, such as those for water quality. This fragmented approach leaves soil management under-addressed in forest policy and practice. Whilst new cultivation guidance has recently been adopted, its development and acceptance were a painful and protracted process in which parts of the private sector resisted change and questioned soil/climate science (Lawrence, 2021). At the same time, government science proceeds very cautiously, possibly conscious that industrial forestry interests are one of its main customers. In the debates about forestry, soil carbon and regulation, most attention has focused on afforestation. Harvesting and restocking of existing sites, much of which are on deep and shallow peats, do not enjoy the protection that afforestation guidance adopted, and now would be a good time to put similar guidance in place for these forest practices. Arguably, the Scottish Government body best equipped to police forestry practice impacts on soil is SEPA, which has shown a willingness to put boots on the ground to survey forest sites and to call out bad practice (SEPA, 2023).

The forestry sector, both public and private, is making some adjustments to practice on its own account, but widely recognises that this is a problematic area which needs research, agreement on good practice, and regulation. More data would provide better understanding of the science of soil carbon dynamics, and firmer guidance and regulation, with enforcement, could ensure that Scotland's forest soil carbon stocks remain in the ground.

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