RADIATA MANAGEMENT TECHNICAL NOTE
Site Productivity

Number:RSPTN-035
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Forest Management Practices and Soil Carbon

Summary

Both New Zealand and international studies show that the effects of plantation forest management on soil carbon (C) are usually restricted to surface soil layers (i.e., the top 10 cm or so) and are spatially variable. The change in mineral soil C stocks due to various forest management activities in New Zealand is usually in the order of 4 to 10 tonnes per hectare.

General trends observed from New Zealand studies were that:

- Forest floor C stocks increase with tree stocking rate, but mineral soil C may decline as tree stocking increases.
- Forest harvesting techniques that physically disturb the soil may cause the loss or displacement of soil C, whereas harvesting techniques that do not disturb the soil may help maintain soil C stocks.
- Removal of harvest resides (particularly when forest floor materials are also removed through disturbance) tends to reduce C stocks of surface mineral soils, whereas the retention of residues may lead to increased stocks in surface mineral soils.
- Some mechanical site preparation practices (usually involving physical disturbance and cultivation of the soil) can result in the loss of soil C.
- Applying fertiliser and retaining weedy vegetation cover can help maintain, or may even increase, soil C stocks.

There is potential for soil C stocks to be maintained or enhanced through the judicious selection and use of appropriate forest management practices. Nevertheless, there are corresponding risks to forest productivity in attempting to manage for soil C sequestration, and these risks would need to be carefully assessed and managed.

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Introduction

A range of site and stand management practices are currently employed within New Zealand's plantation forests. The potential exists for many of these practices to affect soil C stocks by changing the quantity or quality of organic matter inputs to the soil, causing physical disturbance of the soil profile, or by modifying soil moisture and nutrient levels.

New Zealand studies and some key international studies that include information on the effects of management practices on soil C and potential opportunities for mitigating soil C loss were reviewed in a report prepared for the Ministry of Agriculture and Forestry[1]. This Technical Note summarises that review, updating it with recent results from New Zealand studies. The review considered five forest management practice groups: silvicultural practices, forest harvesting, residue management, mechanical site preparation, and site improvement.

Silvicultural Practices

The relevant silvicultural practices include tree stocking, thinning and pruning, and tree species selection. The effect of tree species on soil C were reviewed in a recent FFR report [2] and are not discussed here.

Tree Stocking

Four studies have assessed the effects of tree stocking rates on soil and forest floor C stocks in New Zealand:

- A study in 18-year-old *P. radiata* at Tikitere agroforestry trial site near Rotorua [3] found soil C stocks (0-7.5 cm) decreased with increasing stocking rate from 40 tonnes per hectare under 50 stems per hectare to 30 tonnes per hectare under 200 stems per hectare. At 400 stems per hectare, soil C stocks were higher (32 tonnes per hectare).
- Subsequently a study on C stocks in forest floor materials (L and FH horizons) and mineral soils (0-50 cm), under two stocking densities (100 and 400 stems per hectare) at the Tikitere site at 23 years found [4] soil C stocks were marginally lower at 400 than 100 stems per hectare at all depths, but the differences were not significant. FH horizon C stocks under 400 stems per hectare (~ 10 tonnes per hectare) were almost double those

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in the FH horizon under 100 stems per hectare (5.7 tonnes per hectare).

- A study in the Waitaki catchment, central South Island[5], measured the effects of tree stocking on soil C in 10-year-old, first rotation *Pinus nigra* stands. Stocking (250, 500, and 750 stems per hectare) had no effect on soil C stocks to 30 cm depth.
- A study across a range of North Island forests at mid-rotation (between 18 and 21 years) [6] found forest floor organic matter levels generally increased with stocking. The study showed that an increase in stocking of 100 stems per hectare led to in an increase in organic layer mass of 0.677 tonnes per hectare.

The findings indicate that a reduction in mineral soil C that may occur along with increased stocking may be counteracted by C accumulation in the organic layer. However, further studies that measure soil C stocks to 30 cm depth and cover a greater range of soil and climatic conditions are required to confirm this.

Thinning and Pruning

No published studies have comprehensively assessed the impacts of thinning and pruning regimes on soil C stocks in New Zealand. Forest floor C stocks have been shown to decrease with increased thinning intensity in field studies in a number of countries, but there is little information from international studies on the effect of thinning on mineral soil C stocks [7]. The studies that have been undertaken are, in general, not relevant to New Zealand conditions.

A corollary of the finding that forest floor organic matter levels generally increase with stocking [6] is that increased thinning intensity may, in the long term, decrease organic matter stocks in the forest floor. Thinning and pruning regimes currently vary from forest to forest and could potentially lead to differences in organic matter inputs to the mineral soil that co-vary with site and climatic conditions.

Forest Harvesting

Harvesting removes biomass, can disturb the soil, and change the site microclimate, all of which can affect soil C storage. The affect may vary depending on the method of harvesting used [8].

There is much international information available on forest harvesting impacts on soil C stocks. A review that included a meta-analysis (73 observations from 26 publications) [9] found that on average, forest harvesting had little effect on soil, but large soil C losses have been reported [7]. These studies are restricted to high latitude northern coniferous forest regions and are not immediately relevant to New Zealand.

In New Zealand, the impacts of two forest harvesting methods (hauler- and ground-based) on soil C were studied before and after harvesting at the Puruki experimental catchment, central North Island[10]:

- Ground-based logging decreased soil C stocks in the top 10 cm by 3.1 tonnes per hectare. No change occurred with hauler-logging.
- Less intensive sampling of the effect of ground-based logging to a depth of 1 m was unable to detect any significant changes in soil C stocks.
- Additional sampling of the ground-based logging to 2 m depth showed no changes in soil C concentration, but results indicated that some mixing of topsoil and subsoil had occurred due to this harvesting.

Forest harvesting activities can, under certain soil texture and moisture conditions, result in soil compaction [11, 12]. In a New Zealand study across a range of 31 forest trial sites, it was found that after harvesting, disturbed (compacted) soil (0-10 cm depth) had a significantly ($P<0.05$) lower mean C concentration than undisturbed soil [13]. However, the more compacted soil had a significantly higher. ($P<.0.05$) bulk density and harvesting-related compaction resulted in a small increase in soil C stocks from 57 to 59 tonnes per hectare (statistical significance not determined).

No other published studies have examined the effects of different harvesting methods on soil C stocks in New Zealand. The findings at Puruki experimental catchment [10] suggest that the effects might differ considerably between different harvesting methods, with those that physically disturb the soil profile causing the loss or displacement of soil. However, these findings are limited to one site. More studies will be required to establish whether the effects observed above are consistent across a wider range of site conditions.

Residue Management

Removal of residues from a site can result from harvesting operations, bioenergy extraction or through burning post-harvest. The effects of harvest residue management on soil C have been studied in

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New Zealand at the Long Term Site Productivity Trial Series 1 sites (Woodhill, Tarawera, Kinleith, Golden Downs and Berwick Forests). Treatments investigated included residue retention (stem-only harvesting), residue removal (whole-tree harvesting), residue plus forest floor removal (forest floor disturbance), and, at one site (Woodhill), a double slash treatment which involved the placement of harvest residues collected from the residue removal treatment within plots with a normal quantity of residues already retained.

- At Woodhill Forest five years after treatment [14] no effects on the organic matter (rather than C) stocks of the soil to 90 cm depth were found despite large differences in forest floor stocks (82 tonnes per hectare under the 'double slash' treatment compared to 2.4 tonnes per hectare under the residue plus forest floor removal treatment).
- In contrast, at Tarawera Forest at 16-17 years after treatment, removal of harvest residues plus forest floor material resulted in [15] a reduction of C stocks in the forest floor, 0-10 cm soil, and total soil (0-30 mineral soil + forest floor) pools in comparison to the retention of harvest residues and forest floor materials. The C stock in the total soil pool was reduced by about 10 tonnes per hectare (a reduction of ~ 4 tonnes per hectare in forest floor and of ~ 5 tonnes per hectare in 0-10 cm soil) due to harvest residue plus forest floor removal.
- At Kinleith Forest 15 years after treatment [16] no change in mineral soil C stocks (0-10 cm or 0-30 cm) were observed. The forest floor C stocks were reduced in the residue removal and residue plus forest floor removal treatments, and increased under the stem only removal treatment.
- Further information is available for these sites and one additional site (Golden Downs, Nelson), from a study which examined the residue management effects on upper soil (0-25 mm) C concentrations and FH stocks at 8-16 years after the treatments were applied [17]. Soil C concentrations were lower where the forest floor had been removed than in the treatments where it had not been removed. The FH layer in the residue removal and residue plus forest floor removal treatments had, on average across the four sites, 4.4 and 8.4 tonnes per hectare less C, respectively, than where residues were retained.

Two studies by Huang *et al.* [18, 19] investigated impacts of forest residue management on light (labile) and heavy (stable) soil organic matter fractions and molecular characteristics within these fractions at Kinleith, Woodhill and Berwick Forests. The results demonstrated that increased residue return can increase the stable C pool in the heavy soil organic matter fraction of the upper soil through elevated input of more recalcitrant compounds from the litter and/or the light fraction soil organic matter. In addition, the Berwick study indicated that forest management practices can have long-term impacts on more labile organic fractions that may not be evident from whole soil analysis of C concentrations.

In considering the findings of the above experimental studies, it is apparent that much of the work has been on soils formed in very sandy (Woodhill Forest) or relatively coarse volcanic parent materials (Tarawera, Kinleith, or Kaingaroa Forests) under carefully applied, experimental management conditions. Therefore further work is needed to establish the effects of harvest residue management under a more complete range of soil, climatic and operational management conditions in New Zealand. Nevertheless, there is some strong evidence to suggest that the removal of harvest residues plus forest floor materials can result in the significant reduction of soil C stocks.

Substantial amounts of the C (in excess of 30 to 50 tonnes per hectare) contained in harvest residues can be lost to the atmosphere as a consequence of burning [20]. A meta-analysis of the effects of forest management on soil C[9] showed no overall effects of fire on mineral soil C. Similarly no evidence of C change in the top 10 cm of mineral soil under New Zealand conditions was found [20]. International studies have shown quite large losses in mineral soil C after fire [21], but these were undertaken in old-growth conifer forests in the north-western USA and may not be comparable to plantation grown *P. radiata* in New Zealand.

The impacts of mechanical manipulations of harvest residues (e.g. windrowing) on soil C stocks have not been comprehensively assessed in New Zealand to date, although one early study in 1978 by Ballard [22] partially investigated the effects of windrowing (discussed below).

Mechanical Site Preparation

An international review of forest management effects on soil C concluded that generally there is a net loss in soil C with site preparation[7], but results can vary depending on the amount of organic material mixed

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in [23]. The effects of site preparation on soil C stocks are likely to depend on the method used as well as the initial soil and site conditions. Therefore, studies elsewhere are unlikely to be relevant to New Zealand conditions or useful for addressing gaps in the limited New Zealand data.

Few studies have investigated the effects of different mechanical site preparation practices on soil C stocks in New Zealand. The effects of windrowing and skid site formation on soil properties of a 7-year-old *P. radiata* stand growing on a pumice soil in Kaingaroa Forest (central North Island) were studied by Ballard [22]. Lower C concentrations were found under skid sites, but not under inter-windrow areas, compared to undisturbed areas. It was estimated that almost 13 tonnes per hectare of C would be removed when 2.5 cm of topsoil was removed from inter-windrow and skid sites.

A study of the impacts of two different forest soil cultivation techniques (spot-mounding and line-ripping) on soil C at sites with contrasting soil conditions (Rotoehu in the Bay of Plenty and Lochinver in the central North Island) found [24]:

- Spot-mounding (Rotoehu) resulted in a significant reduction in C stocks of about 4 tonnes per hectare in the top 30 cm of mineral soil 15 months after cultivation.
- Line-ripping (Lochinver) had no significant effect on the C stocks in the 0-30 cm depth range 38 months after cultivation.

No other relevant studies have been undertaken in New Zealand to date. There is a need to determine the impacts of mechanical site preparation practices on soil C stocks across a wider range of soil and climatic conditions. Direct comparisons of alternative soil cultivation techniques on similar soils are also required to establish which are best in terms of conserving soil C stocks while continuing to function effectively to promote seedling growth.

Site Improvement

Fertiliser Application

The impacts of fertiliser application on soil organic matter (as opposed to soil C) were described recently in an FFR Technical Note [25]. Fertiliser inputs to the soil alter ecosystem processes such as the quantity or quality of organic matter inputs to the soil. The addition of fertiliser also affects organic matter decomposition. International studies have produced conflicting responses to fertiliser addition, some demonstrating increased mineral soil C pools following fertiliser application, while others have shown no change. The inconsistencies in the results of these studies are most likely a product of the complexity of soils, and the potential for various factors related to site characteristics and history to influence results significantly [25].

In New Zealand, on the sandy soils of Woodhill Forest, five years after harvesting there were no differences in the organic matter stocks of forest floor materials or soils (to 90 cm depth) between fertilised (receiving 200 kg N per hectare per year) and unfertilised plots[14]. However, trends in the data suggested that, over a longer time, the application of the N fertiliser may lead to increased stocks of organic matter in the soil[14]. In a subsequent study which measured C concentrations in forest floor materials at three North Island forests (Woodhill, Tarawera, and Kinleith Forests)[26], it was found that the application of N, P, and other fertilisers had little impact on forest floor C concentrations five years after harvesting.

Changes in soil C stocks after a longer time period after treatment have been observed. For example, a more than two-fold increase in the concentration of soil organic C in the 0-5 cm depth range after 10 years following the application of mixed fertiliser has been reported at Woodhill Forest[27]. However the nitrogen application rate (960 kg N per hectare over 10 years) in the mixed fertiliser in this study was high.

In contrast to the studies at Woodhill [14, 26], a mixed fertiliser (N, P, K, Mg, S, and Ca) application at 31 trial sites across New Zealand [13] led to a significant increase in topsoil (0-10 cm) C concentration measured after harvesting of 4-year-old densely-stocked plots.

Long-term fertiliser additions to a 15-year *P. radiata* trial in Kinleith Forest have been calculated to increase soil C inputs to the 0–5 cm soil depth by up to 9%, outweighing the increased loss of C via elevated decomposition rates [28]. However, this effect did not extend to lower soil depths [16]. The effect of long term nitrogen fertiliser additions on a wider range of New Zealand *P. radiata* forests showed no significant changes in soil C concentrations (0-2.5 cm) despite greater litter inputs, but did identify significant increases in the nitrogen concentration and decreases to the mineral soil carbon:nitrogen ratio [17]. This study indicated that the change in the soil organic matter after fertiliser addition can persist for some time after fertilisation has ceased [17].

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Herbicide Application

The use of herbicides to control weeds after harvesting and site preparation treatments has been shown to reduce soil C in a number of international studies [8]. These data mainly relate to the effects of herbicide in pines, and could be relevant for New Zealand conditions. As these studies have indicated, the retention of weeds after clear-cut harvesting and site preparation (especially prescribed burning) may assist in maintaining soil organic C stocks.

Two studies have examined the effects of weed control on soil C stocks in New Zealand:

- Lower soil C concentrations (0-10 cm) were found in the absence than in the presence of a pasture understorey in a *P. radiata* agroforestry site on the Canterbury plains [29]. No effect was observed in the 10-20 cm depth range.
- Grass growth post-harvest at a *P. radiata* site at Mahurangi Forest (north Auckland) was considered to be a major contributor to a significant increase of around 1.3 % in the C concentration of soil (0-10 cm) about two years after harvesting (change of ~ 10 tonnes per hectare)[12]. The decomposition of harvest residues that were retained on the site may also have contributed to the increase.

These studies suggest that the grassy/weedy understory vegetation that often occurs in plantation forests – particularly prior to canopy closure – may under certain circumstances help maintain or increase surface soil C stocks during stand establishment. Much more work is required to fully test this hypothesis under a range of New Zealand site and understory conditions.

Mitigation Opportunities for Forest Soils

Forest management opportunities that could help maintain or increase soil C stocks include:

- Retention of residues and forest floors.
- Retention of a grass or weed cover.
- Avoiding unnecessary soil disturbance or cultivation.
- Fertiliser applications.

Retention of Residues and Forest Floor Material

Wherever possible, forest floor materials and harvest residues should be retained on site to help maintain soil C stocks and nutrient supply. Further research may be able to identify areas and circumstances where forest floor removal by disturbance and harvest residue removal will not necessarily result in soil C stock reductions.

Retention of a Grass or Weed Cover

There are a number of indications that retention of 'weedy' vegetation through the harvest and re-planting phase contributes to an improvement in soil C stocks. Active retention of a grass or weed cover through the harvest phase seems a viable option for enhancing soil C or mitigating soil C losses. Management steps that can be taken include over-sowing of pasture species where 'weed' invasion is slow or limited, coupled with fertilisation if necessary, and minimising the herbicide application area around trees to that necessary to achieve good establishment.

Avoiding Unnecessary Soil Disturbance or Cultivation

Soil disturbance occurs during harvesting and when sites are cultivated in preparation for planting. The hauler and ground-based harvesting comparison at Puruki experimental catchment [10] is limited to one site, but results should be applicable to forests covering a large area of the central volcanic plateau of the North Island with similar soils. The results indicate there may be mitigation opportunities through use of hauler rather than ground-based logging techniques.

Cultivation generally leads to a reduction in soil C stocks, but the effects are highly site specific and dependent on the type of cultivation employed. Only two New Zealand studies on the effects of cultivation are available. Spot-mounding reduced soil C stocks and line-ripping had no effect on soil C stocks. The cultivation treatments are likely to cause similar trends at other sites, so information on the change determined from these data could be applied elsewhere to determine potential cultivation effects. As the mitigation opportunity arises from not cultivating sites, these treatments should not be applied unless necessary. Limited mitigation opportunities are likely to be available, as cultivation techniques like spot-mounding and line-ripping are generally applied to achieve adequate survival and productivity. The option needs careful consideration because gains arising from not cultivating are likely to be outweighed by productivity (and C sequestration in biomass) losses.

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Fertiliser application, especially N fertiliser, increases soil C stocks. However, further work still needs to be undertaken to consistently and systematically quantify the changes in soil C stocks (rather than just C concentrations) over longer periods following fertiliser application (as applied in management operations) under a comprehensive range of site conditions in New Zealand.

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