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Deep soil ploughing for afforestation: a review of potential impacts on soil and vegetation

GEDIMINAS SURVILA, IVETA VARNAGIRYTĖ-KABAŠINSKIENĖ * AND KĘSTUTIS ARMOLAITIS

Lithuanian Research Centre for Agriculture and Forestry, Liepų str. 1, LT-53101 Girionys, Kaunas district, Lithuania
** Corresponding author: iveta.kabasinskiene@lammc.lt*

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Abstract

Deep ploughing – which inverts, covers, or mixes soil organic layer (forest floor) and surface mineral A horizon into the mineral subsoil, burying the upper soil horizon in deeper layers, and disrupting pedogenic processes – is a debatable topic in forest plantation management. Overall, this review article aimed to identify the impacts of deep ploughing on the properties of forest plantations, adapting experiences from the agricultural sector. This paper examines the main impacts of deep ploughing technology on soil physical, chemical, and biological properties, ground vegetation, and tree aboveground and belowground biomass in afforested former agricultural land. Analysis of the published literature shows that deep ploughing can be used under different climatic and soil conditions, but it induces site-specific changes in soil properties and vegetation. Mechanical site preparation during afforestation and reforestation should follow the requirements of sustainable soil management, to avoid negative effects on the environment and biodiversity. Based on this analysis, we suggest key indicators that may be specific to deep ploughing responses in afforested sites and can contribute to risk assessment, aimed at achieving sustainable forest management. To date, most studies on mechanical site preparation for forest plantation have been performed using a few conifer tree species; therefore, it is important to expand empirical studies.

Keywords: deep tillage, soil horizon mixing, soil properties, vegetation response

Introduction

The goal of plantation forestry is to produce industrial timber for local use and global markets, and to reduce timber shortages in the near future, thereby meeting some basic needs of society (Sedjo 2001, Barua et al. 2014, McEwan et al. 2020). Along with meeting the demand for timber, the successful development of forest plantations is associated with environmental requirements, carbon sequestration measures, and protection of biodiversity and soil and water quality (Burger 2009, Innes 2013). Common practices show that plantation forestry is developed by planting or sowing native or introduced species through afforestation or reforestation (Freer-Smith et al. 2019, FAO and UNEP 2020).

Overall, plantation forestry is useful for afforestation of former agricultural and degraded lands, and for carbon sequestration and biodiversity (Sedjo 2001, Paquette and Messier 2010, Pawson et al. 2013). Soil cultivation is an important process that affects the physical, chemical, and biological properties of the soil, and leads to different plant growth responses, regardless of where it is applied (i.e. in agricultural or forest land) (Matthesen and Damgaard 1997, Akinci et al. 2004, Hansen et al. 2007, Alcántara et al. 2017, Schneider et al. 2017). Deep ploughing or subsoil ploughing has been widely used to reduce soil strength in agricultural soils (Akinci et al. 2004), but there is little data on the effectiveness of this method for tree growth, especially in habitats with different soil conditions. According to some authors, deep ploughing is ploughing to a depth of 30–45 cm or even deeper (60–120 cm), depending on soil type (Matthesen and Damgaard 1997, Luscombe et al. 2006, Russell 2009, Hussein et al. 2019). In all cases, pedogenic processes are disrupted and the soil profile is greatly altered compared with naturally created vertical horizons formed by long soil formation processes under a range of physical, chemical, and biological processes.

In Europe, deep ploughing dates to the 1950s, and this technology was mainly used in agriculture (Russell 2009). Although, nowadays, efforts are being made to limit cultivation in agriculture to reduce greenhouse gas emissions and to achieve good soil management, the use for forestry is debatable. Site preparation for forest regeneration has been practiced since humans began managing forests, and it is a recurring theme in forest policy groups (Löf et al. 2012, FPG 2019). For many years, soil cultivation was recommended as best practice for the establishment of tree plantations on all soil types. Deep ploughing is rarely used due to environmental concerns; however, it should be carefully considered as an alternative technology when planning afforestation of former agricultural land (Matthesen and Damgaard 1997, Hansen et al. 2007, Malinauskas and Urbaitis 2010, Smal et al. 2019). Owners of newly established forest plantations may have questions about the suitability of former agricultural land for the forest because soil has been ploughed for many years. A layer of compacted soil (ploughpan), which has been formed on former agricultural soil due to intensive and repeated ploughing, can hamper successful afforestation by slowing down root penetration and water penetration (Malinauskas and Urbaitis 2008). Some authors argue that soil ploughing up to 60 cm deep before afforestation of agricultural land could be preferred because it provides better weed control compared with other technologies (Hansen et al. 2007). However, many other issues remain unaddressed.

This study aimed to review the main impacts of deep ploughing technology, used for the establishment of forest plantations, on the physical, chemical, and biological properties of soil, including soil organic carbon (SOC) stocks, as well as ground vegetation development, and aboveground and belowground tree biomass growth. We should emphasise that this study contributes to the concept of potential deep ploughing for forest plantations, but we did not analyse the reliability of specific empirical studies. More specifically, we further give the examples from Lithuanian study on afforestation after deep soil ploughing.

Materials and methods

For this study, an impact of deep ploughing is defined as changes in the physical, chemical, and biological properties of the soil, or response of ground vegetation and tree growth. Due to the lack of forestry studies directly related to the topic, this review article was based on relevant references from both forestry and agricultural sectors. The analysis of the potential effects involved systematising the results from different published studies, searching them mainly in the multidisciplinary databases, such as Scopus and Web of Science, and publisher databases, such as ScienceDirect (Elsevier). The search was organised while including the main keywords, such as *deep soil ploughing/tillage/plowing/cultivation*, *deep ploughing and soil properties/changes*, *vegetation response/changes, plantation/tree/root growth/survival*. 'Deep ploughing' is taken here to include soil ploughed deeper than 30(35)–50(80) cm, without emphasising the effect of specific ploughing depth on exact parameters but assessing and describing the potential effects.

The search was limited to references published in the past 40 years, from 1980 to 2020. General issues, which are not based directly on the effects of deep ploughing on forest plantations, were cited from previous literature reviews (Hamza and Anderson 2005, Mahajan and Balachandran 2012, Blouin et al. 2013, Prem et al. 2016, Feng et al. 2020).

Identified impacts were classified as effects of deep ploughing on physical and chemical soil proper-

Figure 1. Examples of soil profiles: **A** – unploughed Planosol (regenerated coniferous forest), and **B** – deep ploughing performed up to 55 cm on Planosol (Scots pine plantations planted in 2012) (Photos: Gediminas Survila)

ties; effects of deep ploughing on biological soil properties; and vegetation responses to deep ploughing. The effects were classified as either positive or negative in relation to site sustainability. Some of the identified effects were site- (different soil texture, fertility, etc.), or climate- (different air temperature, water regime, etc.) dependent, and it was not possible to identify clearly whether the effect was positive or negative, thus, some effects could be classified as uncertain under specific conditions.

The reviewed studies are provided in the text and in the summary table, including the possible effects generalised from the analysed references. Translations of the texts cited in the review are mainly unofficial versions made by the authors.

To provide more specific data about the impact of deep ploughing on Lithuanian sites (in this case, mineral Planosol according to IUSS Working Group WRB (2015) is shown as an example), four composite samples of mineral soil (0–10 cm, 10–20 cm, 20–40 cm, and 40–80 cm layers) were sampled for the determination of SOC concentration (ISO 1995). The non-ploughed soil and deep ploughed soil profiles at sandy Planosol are shown in Figure 1. The example of the deep ploughs, which were used for the establishment of the experimental plots for afforestation of former agricultural abandoned land in Lithuania, is given in Figure 2.

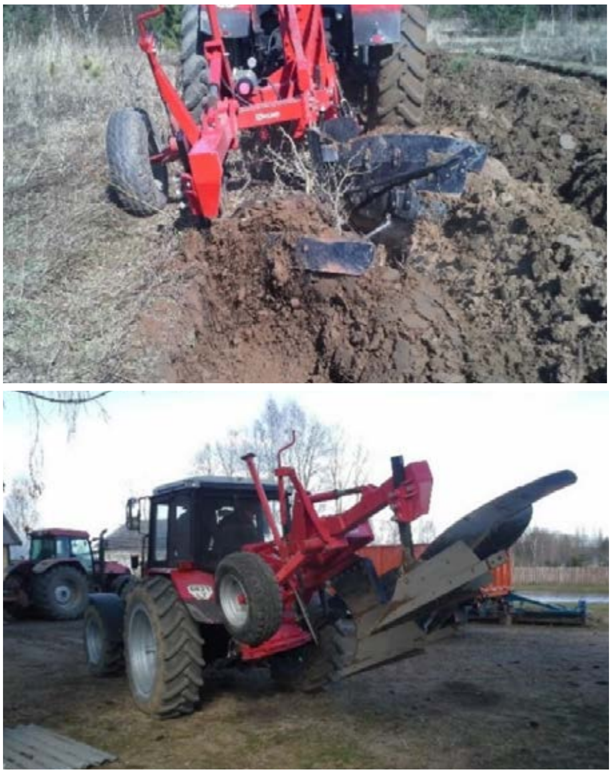

Figure 2. Example of deep inversion ploughing with Bovlund-80 deep ploughs (Photos: Gediminas Survila)

Effects of deep ploughing on soil physical and chemical properties

Ploughing is one of the oldest technologies through which soil is inverted, loosened, compacted, mixed, and crushed (Prem et al. 2016). During deep ploughing, the subsoil horizons enter the soil surface, and the upper soil horizon (topsoil) is buried in deeper soil layers, and the process ends with deep-soil mixing throughout the profile (Schneider et al. 2017). In most cases, deep ploughing is best suited for even-aged regeneration systems using artificial regeneration. Ploughing has a direct impact on factors that influence plant nutrient dynamics as it stimulates the mineralisation of soil organic matter (SOM). Soil nutrients can be reduced by ploughing more deeply than in conventional soil preparation. For example, ploughing to 30 cm reduced surface soil total N, and extractable K and P (Pywell et al. 2002), also reduced SOC, pH values, and exchangeable Ca (Madeira et al. 1989). Soil mixing resulting from deep ploughing can affect the distribution of mobile nutrients such as NO_3-N and SO_4-S, and the leaching of higher NO_3 concentrations can occur (Randall and Iragavarapu 1995, Jiao et al. 2004). It is well established that soil properties are highly dependent on the SOM content: higher quantity and better quality of organic matter lead to better supply of nutrients to the plants (Gan et al. 2020). If required, deep ploughing is effective for reducing topsoil fertility in former agricultural land (Glen et al. 2016).

Site cultivation can affect soil physical properties for many years, sometimes for more than one rotation (Evans 2009). Deep cultivation or ploughing, turns SOM into soil to increase decomposition and add nutrients from the SOM to the mineral soil. The increasing content of SOM in the soil during deep ploughing reduces the soil bulk density and increases soil porosity (Hamza and Anderson 2005). However, several studies have demonstrated that intensive ploughing deteriorates soil structure and enhances soil erosion (Kladivko 2001). Longer term benefits include not only a reduction in bulk density, as such practices increase infiltration capacity and soil aeration, but also improvements in moisture storage. The potential mechanism through which trees benefit from ploughing has been associated with increased nutrient mineralisation and availability (Silgram and Shepherd 1999). This technology, through which the mineral soil is turned over, not only mixes the SOM, but also increases oxygen in the soil, thereby speeding up the decomposition of the organic matter and making more oxygen available for the plant roots. Deep ploughing has been associated with a reduction in erosion when clay-rich subsoil enters silt-dominated topsoil (Alcántara et al. 2017). Ploughing should be avoided on heavy soils, except for restoring soil physical conditions. Several authors have shown ploughing as a promising method for increasing tree growth when soil is compacted (Heninger et al. 2002, Holub et al. 2013). A decade post-ploughing use after soil compaction showed a minor but not significant increase in tree volume, basal area, and basal area growth (Holub et al. 2013). Similarly, a study by Heninger et al. (2002) showed ploughing to be effective at restoring productivity to detrimentally compacted soils.

Due to the deeper roots of forest trees and their higher biomass content in the forest, the peculiarities of root formation in the forest are different from those of crops (Jackson et al. 1996), making it difficult to compare different land uses.

With increasing emphasis on forest-based SOC sequestration, it is known that the processes of stabilisation and degradation of SOM are influenced by soil genesis, meteorological conditions, and cultivation techniques (Janzen et al. 1998, Liaudanskienė 2009). Naturally, carbon from annual litter of leaves or needles, dead wood and roots enters the subsoil, and, further, dissolved organic carbon (DOC) is released by leaching, or bioturbation (Rumpel et al. 2012), while deeper burial of carbon-rich soil material occurs due to deep ploughing.

Changes in land use and/or land management can greatly affect SOC stocks and, therefore, soil C response to land-use changes, at least partially, depends on the previous land use (Guo and Gifford 2002). Previous studies indicate that SOC stocks could increase by 12–13% per 100 years if 30% of the agricultural land in Europe was afforested (Powlson et al. 1998). Similar results were obtained in studies conducted in Lithuania, when the impact of afforestation of infertile lands on SOC changes was assessed (Aleinikovienė et al. 2007, Armolaitis et al. 2007). It was also found that SOC stocks increased or did not change after afforestation of infertile arable sandy soils, while SOC stocks decreased in continuously arable sandy soils.

The studies on soil SOC are often limited to the 30 cm depth topsoil; however, more than half of the world's SOC is concentrated in the soil deeper than 30 cm (Hiederer and Köchy 2011, Batjes 2014, Alcántara et al. 2017, FAO 2018). Otherwise, the higher carbon storage capacity in subsoil appears to several reasons. The first one, despite the decrease of SOC concentrations in deeper soil layers, SOC stocks are higher than those in the topsoil because of the higher soil mass (Lorenz and Lal 2005). The second one, slower SOC mineralisation in deeper soil layers occurs due to specific environmental conditions: the lower variability of soil moisture and temperature, and the lower oxygen content (Lorenz and Lal 2005, Rumpel and Kögel-Knabner 2011, Beare et al. 2014). The third one, the SOC in the subsoil has not been exchanged with the atmosphere for a long time (Gleixner 2013, Mathieu et al. 2015). Wordell-Dietrich (2016) showed slower decomposition of additional SOC inputs in the subsoil compared to the topsoil. This process depended on the lower SOC content, which resulted in a lower density of decomposing microorganisms and thus a lower possibility of any SOC present being mineralised (Don et al. 2013). Lower oxygen concentrations in the subsoil and less disturbance via drying-rewetting and freeze-thaw cycles via ploughing have been identified as reasons for higher SOC stability in subsoils (Rumpel and Kögel-Knabner 2011). As noted by Feng et al. (2020), subsoiling significantly increased SOC by 8–9%. Deep ploughing did not facilitate SOC sequestration to a significant extent for the whole soil profile, although it did significantly increase SOC in the 20–50 cm layer (Figure 3). However, some authors argue the opposite, that intensive ploughing which accelerates the conversion of soil macro-aggregates is the main cause of SOC loss (Lal 2007). Smal et al. (2019) showed that the SOC stocks in the former plough layer decreased in the first decade after afforestation, and then gradually increased. Previous studies indicate that the use of deep ploughing is a highly effective long-term SOC sequestration tool (Alcántara et al. 2016) and improves long-term soil fertility (Baumhardt et al. 2008). A study by Alcantara et al. (2016) showed that 36–48 years after the use of deep ploughing in mineral soils, 3–183% higher SOC stocks were found in 0–100 cm soil layer because the carbon that accumulated in the topsoil was not fully mineralised in the deeper layers, and SOC accumulated continuously in the newly formed, mixed topsoil. Because deep ploughing enters large amounts of SOC into the subsoil and facilitates deep rooting, SOC stocks in afforested lands can be expected to increase over time.

It is important to note that differences between deep ploughing methods were less important than the presence of root-restricting soil layers (Schneider et al. 2017). The risk of negative deep ploughing effects was the highest in the sites with light textured silt soil. In dry seasons, positive deep ploughing effects were greater than in average years. In soils with stable soil structure and root-restricting layers, deep ploughing can be an effective tool to reduce drought stress on plants, and, therefore, it can improve plant resilience to climate change. For example, this can be determined in Planosol with sandy mineral topsoil when loam is inverted on the surface.

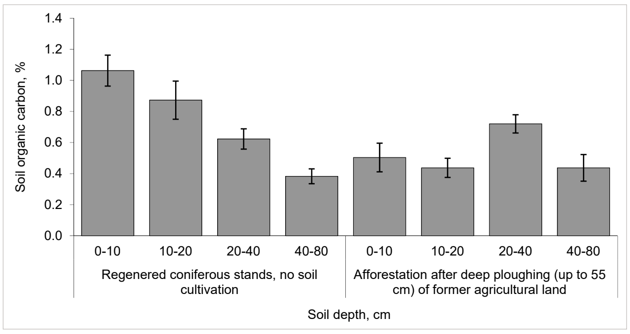

Figure 3. The mean (error bars show standard error of the mean) concentration of soil organic carbon (%) at different mineral soil layers in regenerated forest on non-ploughed soil, and in afforested site, established after deep soil ploughing in 2012; the soil was classified as non-fertile Planosol at both sites (IUSS Working Group WRB (2015); also see Figure 1) (Unpublished data, Gediminas Survila PhD project, 2019–2023)

Effects of deep ploughing on soil biological properties

Due to high diversity and abundance, the soil organisms – microbes, micro, meso, macro, and megafauna – are directly related to the soil functions (FAO et al. 2020). Clear relationships between vegetation, SOM, and soil microbial communities exist in natural forests (Merilä et al. 2010). However, these relationships may be drastically changed when deep ploughing is applied before planting trees. To date, only few studies have examined the effect of different ploughing practices on soil microbial community structure (Van Groenigen et al. 2010, Navarro-Noya et al. 2013).

As a first phase, soil micro, meso, and macrofauna physically decompose plant residues and allow soil microorganisms to release nutrients and energy bound to plants (FAO et al. 2020). For example, the more the earthworms in the soil, the more the organic matter, and the better the soil structure. Earthworms depend on the availability of sufficient food (debris, plant debris) close to the soil surface (Blouin et al. 2013), but this changes greatly if deep ploughing is used. Although there is no consensus, some studies have shown that deep ploughing increases the activity of earthworms and other beneficial soil organisms, which relates to the formation of soil structure, aeration, and water permeability and the abundance of plant-promoting rhizobacteria and mycorrhizae in the subsoil (Fenner et al. 1993). However, deep ploughing kills earthworms directly, mechanically destroys their burrows, and buries their food supply.

The main biological benefit of mixing organic matter with the subsoil is to promote plant growth and improve soil biodiversity (Hahn and Quideau 2013). Among other biological components, the soil fauna contributes to the mineralization of plant litter, promoting microbial function (microbial biomass, fungal:bacterial ratio) (Lavelle et al. 1997, Coleman and Crossley 2004).

Soil microorganisms (mainly bacteria, actinomycetes, and fungi) are also important for the decomposition of plant litter, which has multiple functions in the forest floor, such as preventing soil erosion, microclimate fluctuations, soil compaction, etc. (Lavelle et al. 1997, Sayer 2006, Bani et al. 2018). Prior studies have noted the importance of soil microorganisms and enzyme activity for soil quality, as well as the ability to activate soil nutrient availability and increase plant productivity (Pajares et al. 2011). It is obvious that any change in soil physical and chemical characteristics, including those induced by deep ploughing, may affect soil microorganism and enzyme activities, and change their ability to decompose organic residues, produce antibiotics, and supply food sources for organisms (Mahajan and Balachandran 2012). Therefore, biochemical nutrient processing and soil improvement are impaired. First, ploughing affects microbial access to fresh carbon in the subsoil, releases previously inaccessible organic carbon (OC), and changes soil water and gas distribution, affecting microbial metabolic rates (Salomé et al. 2010).

Following other studies, the soil fungal community responded more to soil cultivation than the bacterial community and, similarly, fungal abundance was significantly reduced due to soil ploughing, while bacterial abundance was only slightly affected (Sun et al. 2018).

Vegetation response to deep ploughing

The changes in vegetation induced by deep ploughing could be roughly grouped into the following: (1) changes in ground vegetation; (2) changes in aboveground tree parameters; and (3) changes in belowground tree parameters, mainly including fine roots.

Basically, the ground vegetation in forest ecosystems could compete with young trees during the regeneration phase (Balandier et al. 2006) but stabilises the topsoil and reduces nutrient leaching (Hansen et al. 2007). During ploughing, weed roots are mechanically broken, weed seeds enter deeper soil layers, and weed growth is disrupted. Once weeds are removed, the tree seedlings cannot take up the available nitrates, which can increase nutrient losses (Hansen et al. 2007). Hjelm et al. (2018) concluded that removal of weeds helped avoiding the problems when poplar plantations were established.

However, in some cases, ploughing changes the soil microclimate (especially, topsoil thermic regime), which can promote seed germination of different weed species (Mohler 1993).

Following Scandinavian forestry practice, deep ploughing to more than 50–60 cm depth improved plantation success in the short term, keeping areas free from vegetation in the first growing season (Matthesen and Damgaard 1997). Danish studies showed that deep ploughing decreased the vegetation cover to 50% in the first growing season in afforested sites (Matthesen and Kudahl 2001). Jones et al. (2010) identified slow colonisation of natural vegetation when nutrient-rich topsoil layer was covered with 40–50 cm of mineral soil, and the first plants (*Carex arenaria*, *Cirsium arvense*, *Equisetum arvense*, *Ranunculus repens*, etc.) occurred from 8 to 15 months after the disturbance.

By deep ploughing, the soil is usually prepared once in order to loosen the subsoil, improve water permeability and root penetration, thus creating better conditions for plant growth. Schneider et al. (2017) concluded that the average deep ploughing effect on yield was slightly positive (6%) and resulted in a 20% yield increase in soils with root-restricting layers. Deep ploughing can also improve the resilience of crops during drought (Schneider et al. 2017). Malinauskas and Urbaitis (2010) concluded that deep ploughing provided favourable conditions for the growth of seedlings and increased rooting depth. A study performed in Ireland showed improved early growth of Sitka spruce and Douglas fir in ploughed sites compared with that in unploughed ones (Hendrick 1979).

Decreased soil moisture availability and changes in soil N cycling induced by soil compaction and loss of SOM have affected photosynthesis, and, therefore, it may also potentially influence tree growth.

When preparing the soil for afforestation, deep ploughing results in a higher survival rate of planted trees because of better water availability, i.e. oxygen and carbon-rich layer with high water-holding capacity is observed in deeper soil layers (Hansen et al. 2007). In addition, Coll et al. (2007) highlighted the significant competition for soil N and the need to control belowground vegetation to minimise root competition, thus the weed control could be helpful in this case. Schilling et al. (2004) reported that root architecture was primarily influenced by subsoiling treatments, regardless of surface ploughing or machine planting.

Nordborg et al. (2006) analysed influence of different site preparation treatments, including deep soil cultivation to 50 cm deep, on total N and OC stocks in soil, ground vegetation, trees (*Pinus contorta*, *Picea abies*, *Pinus sylvestris*) and roots. Ten years after the deep soil ploughing, no effects on N stocks in vegetation and the biomass allocated to needles, stems and roots were found, but the higher tree C and N stocks and total tree biomass were found. Malinauskas and Urbaitis (2008) analysed the growth of trees and roots in Scots pine, Norway spruce, and birch plantations, established using a ploughpan on former agricultural soils. The study showed that deep ploughing provided better conditions for the growth of roots and increased their rooting depth. Notably, the growth of aboveground tree was directly related to root growth.

Tree roots and especially the most active fine roots (< 2 mm in diameter) are important for water and nutrient uptake and ecosystem function (Fitter 1982, Jackson et al. 1990, Bardgett et al. 2014, McCormack et al. 2017, Mucha et al. 2020). Although fine tree roots account for less than 2% of tree biomass, they can contribute to 75% of primary production in mature forests annually, making them important for forest carbon, nutrient, and water cycling processes (Gill and Jackson 2000, Brunner and Godbold 2007). Fine roots are concentrated on the soil surface and decrease steadily with increasing soil depth (Macinnis-Ng et al. 2010, Jian et al. 2015). Studies performed in the plantations of six tree species established on agricultural land have shown that the highest fine root density was concentrated at a depth of 0–40 cm (Jian et al. 2015). Otherwise, fine roots are known to develop very plastically in response to changing environmental conditions (Meier and Leuschner 2008). Deep ploughing causes substantial changes in root distribution. For example, shallow ploughing caused the root concentration in the 0–20 cm layer, and deep ploughing resulted in the root distribution in the 20–75 cm soil layer (Madeira et al. 1989).

The importance of fine roots for carbon and nutrient metabolism under various conditions has been studied quite extensively. Fine root biomass has been found to vary with climate, stand age, tree species, and soil fertility (Ostonen et al. 2007a, Comas and Eissenstat 2009, Kalliokoski et al. 2010, Mucha et al. 2020). For example, higher fine-root biomass was found in nitrogen-deficient soils, and fertilisation reduced specific root length (Finér et al. 2007, Helmisaari et al. 2007, Ostonen et al. 2007b). In previously ploughed forest soil, it is reasonable to assess the spatial distribution of fine roots in the soil to elucidate soil properties and possible changes in these properties and to assess the long-term uptake of plant nutrients and water (Tanskanen and Ilvesniemi 2007). The distribution of fine roots in ploughed forest sites has shown that SOM, produced by root exudates and fine root turnover, is distributed unevenly in the profile, thus altering the properties of the inverted soil. However, the study by Madeira et al. (1989), showed that different soil ploughing techniques did not affect tree biomass production between 18 and 30 months after planting.

Potential benefits and disadvantages of deep ploughing

To summarise the topics covered in the paper, the benefits and drawbacks of deep ploughing in forest plantations were summarised in Table 1. Overall, deep soil ploughing could create favourable conditions for tree planting and ensure low plantation maintenance in the future. A tree survival and growth depend on the complex properties of the soil, as soil fertility, microclimate (moisture and temperature regime), and the abundance and growth of competing plants and their effects on forest plantations, these aspects were mainly analysed in this study.

As mentioned above in this paper, deep ploughing aims to reduce soil compaction, breaking down the hardpan and reducing soil density. Several studies have shown that deep ploughing creates better conditions for plant growth. In this case, plants form a deeper root system, with easier rooting and better conditions for absorbing water and nutrients. Deeper loosening of the soil results in improved aeration properties, easier planting of seedlings, and effective weed control. It was also noted that this technology can be applied to a variety of climatic and soil conditions (Hansen et al. 2007, Schneider et al. 2017, Hussein et al. 2019). Some authors pointed out that increasing the ploughing depth by 1 cm increases energy consumption by 5–7%, and such ploughing requires high labour per hectare of soil (Civikaitė 2019, Lekavičienė et al. 2019).

Generally, more often in agriculture, ploughing usually brings a lot of benefits: the soil is loosened, the plants are easier to plant or sow, and the plant litter enters deeper soil horizons, the weeds are destroyed, etc. Typically, soil ploughing aims to reduce soil compaction, rip the hardpan, and reduce the soil bulk density, thereby encouraging deeper rooting of plants, improving soil infiltration, and stimulating tree growth through better soil aeration, and water and nutrient availability, and it is a suitable practice for weed control (Busscher and Bauer 2003, Bulmer and

Table 1. Summary of potential benefits and disadvantages of deep ploughing on forest plantations

Benefits of deep ploughing	Disadvantages of deep ploughing
Impact on soil	
• Reduced soil compaction / eliminated high-density subsoil (ploughpan) (Heninger et al. 2002, Akinci et al. 2004); • Improved soil water use / enhanced soil water retention capacity / improved localised drainage around the plants / improved moisture availability, especially on dry sites (Hansen et al. 2007, Russell 2009); • Increased porosity / improved soil aeration, water infiltration and water storage / lower runoff (Hamza and Anderson 2005); • Improved soil thermal regime (Mohler 1993); • Improved absorption / uptake of water and nutrients, especially potassium and mineral nitrogen (N); • Intensified nutrient mineralisation (Silgram and Shepherd 1999); • Deep N placement in soil reduces N oxide emissions (Liu et al. 2006); • Translocation of SOC from topsoil into subsoil / Enlarged available SOC storage space / significantly increased SOC stocks in the long-term (Hansen et al. 2007, Rumpel et al. 2012, Wordell-Dietrich 2016, Alcántara et al. 2016, Feng et al. 2020); • Improved long-term soil fertility (Baumhardt et al. 2008, Alcántara et al. 2016).	• Reduced total soil N content / soil microbial biomass N in the topsoil (Pywell et al. 2002); • Disrupted pedogenic processes / disrupted soil natural structure (Schneider et al. 2017); • Litter removal from the soil surface (Rumpel et al. 2012); • Increased SOM decomposition/mineralisation when forest floor is inverted into the subsoil / decreased SOM decomposition/mineralisation when surface mineral A horizon is inverted (Silgram and Shepherd 1999); • Destroyed nutrient balance / changed optimum nutrient turnover (Glen et al. 2016); • Nutrient loss due to leaching and accelerated surface runoff, wind, and water erosion with high risk of increased nitrates in soil water (Randall and Iragavarapu 1995, Kladivko 2001, Jiao et al. 2004, Hansen et al. 2007); • Reduced / changed diversity, abundance, and biological activity of soil organisms (Fenner et al. 1993, Hahn and Quideau 2013, Sun et al. 2018); • Disrupted microbial access to fresh carbon in subsoil; • Destroyed bioturbation process (Rumpel et al. 2012).
Impact on vegetation	
• Effective weed control: weed uprooting / reduced weed competition / destroyed existing undesirable vegetation or buried an unwanted seed bank (Matthesen and Damgaard 1997, Matthesen and Kudahl 2001, Busscher and Bauer 2003, Bulmer and Krzic 2003, Hansen et al. 2007, Russell 2009, Hjelm et al. 2018); • Reduced vegetative competition for water, nutrients, sunlight, and space (Matthesen and Damgaard 1997); • Improved plant root penetration and growth – plants are able to form a deeper root system / easier rooting (Schilling et al. 2004, Malinauskas and Urbaitis 2008, 2010, Schneider et al. 2017); • Improved survival, growth and health of tree seedlings / improved early growth (Hansen et al. 2007, Holub et al. 2013, Hahn and Quideau 2013); • Rapid early growth of pioneer tree species (Hendrick 1979, Matthesen and Damgaard 1997); • Protection against plant death in dry season (Schneider et al. 2017).	• Promotes seed germination of weed species due to changed thermal and water regime (Mohler 1993); • Decreased biodiversity, at least at a local scale; • Disrupted fine root development / changed root distribution (Madeira et al. 1989); • Delayed recovery of native vegetation.
Technological aspects	
• Easier seedbed preparation / planting of tree seedlings (Russell 2009); • Can be applied to a variety of climatic / soil conditions (Hansen et al. 2007, Schneider et al. 2017, Hussein et al. 2019); • Deeper soil mixing is important for long-term responses (Tanskanen and Ilvesniemi 2007, Baumhardt et al. 2008, Alcántara et al. 2016); • Successful treatment for sandy topsoil of arable land in dry season (Schneider et al. 2017).	• Higher risk of sand deflation (erosion) (Kladivko 2001); • Increased energy consumption / high labour costs per hectare of soil (Civikaitė 2019, Lekavičienė et al. 2019).

Krzic 2003). Few studies have examined the response of specific tree species to the use of deep ploughing, and these showed rapid early growth of European larch (*Larix decidua* Mill.), black alder (*Alnus glutinosa* (L.) Gaertn. L.), and other pioneer trees after deep ploughing (Matthesen and Damgaard 1997). However, there is still a need for studies on tree species other than pioneers, as well as the long-term effects on soil fertility when deep ploughing is used. Socio-economic aspects must also be considered when deciding on forest management practices. Applying technological solutions to different soil types or biomes can lead to unforeseen risks.

This review article, however, is subject to several limitations. First, this study presents generalised and potential advantages and risks of deep ploughing. We did not analyse individual effects observed in the studies with specific ploughing depths. Second, differences between agricultural and forest plants could lead to variation in responses of varying intensity and duration.

Conclusions

This study summarises the empirical evidence on the ecological effects of deep soil ploughing and suggests specific indicators for deep ploughing responses in afforested sites, contributing to risk assessments for sustainable forest management. This review highlights key aspects of deep soil ploughing, which is a practice where the soil is usually cultivated deeper than 30–45 cm, typically with the aim of reducing soil compaction, and encouraging deeper plant rooting and growth through improved soil aeration, water infiltration, and nutrient availability. Selecting the appropriate ploughing method can eliminate limiting factors such as high-density subsoil (ploughpan), intensive accumulation of organic litter, vigorous weed cover, or soil compaction induced by harvesting machines. Although deep ploughing can be used under different climatic and soil conditions, the responses of soil and vegetation to deep ploughing were found to be site specific. Mechanical site preparation during afforestation and reforestation should be carried out carefully and in accordance with the requirements of sustainable soil management, to mitigate any adverse effects on the environment and protect biodiversity. Finding a compromise between the advantages and disadvantages, deep soil ploughing destroys soil functionality, and the changes associated with it continue for at least 30 years. This is also important because most studies on mechanical site preparation and forest plantation performance have been conducted using a few conifer tree species; therefore, it is appropriate to conduct more local experimental studies.

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