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Mechanical site preparation for forest restoration

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Abstract Forest restoration projects have become increasingly common around the world and planting trees is almost always a key component. Low seedling survival and growth may result in restoration failures and various mechanical site preparation techniques for treatment of soils and vegetation are important tools used to help counteract this. In this article, we synthesize the current state-of-knowledge concerning mechanical site preparation for improved tree establishment when carried out in different forest restoration situations, point out critical research gaps and provide some recommendations for future directions. Mechanical site preparation often results in improved seedling survival and growth. However, if not intensive methods with much soil disturbance are used, it is a rather ineffective tool for controlling competing vegetation. Methods such as scarification, mounding and subsoiling also lead to multiple interactions among soil physical and chemical properties that affect plant survival and growth, and it may be difficult to determine the actual cause–effect relationship of any positive seedling responses. Most research to date on mechanical site preparation and plantation performance has been conducted using a few conifer tree species. Seedling responses differ among tree species and alternative species are often used during restoration compared to production forestry

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indicating a need for additional research for improved understanding. Several management objectives such as soil protection and increased biodiversity are many times relevant during forest restoration, and mechanical site preparation methods should be implemented carefully because they can have large impacts on the environment.

Keywords Afforestation · Ecosystem management · Rehabilitation · Regeneration · Sustainability

Introduction

The tree regeneration phase offers the best opportunity to change tree species and forest ecosystem structure, and this phase is an important initial step in restoration of forests. Without measures to improve soil conditions, control competing vegetation and reduce animal damage, artificial or natural forest regeneration often results in unacceptably low seedling performance. Low seedling performance, i.e. survival and growth, may result in substantial economic losses and various site preparation techniques are important tools to counteract this (e.g. Nyland 1996). This is usually achieved by using herbicides, mechanical site preparation, prescribed burning or mulching, which can be used singly or in combination (Prévost 1992; Sutton 1993; Iverson et al. 2008; Willoughby et al. 2009). Prescribed burning is limited seasonally by weather and fuel conditions, usually requires multiple applications, and may exacerbate competition problems when undesired or invasive vegetation is adapted to fire (Iverson et al. 2008; Rebbeck 2012). Mulching is rather expensive and is more common in urban plantations and in horticulture than in forest restoration projects. In general, forest managers prefer using herbicides to control competing vegetation because of their effectiveness and relatively low cost compared to available alternatives (Willoughby et al. 2009). However, there are substantial differences between countries and continents with regard to preferred site preparation methods (Ammer et al. 2011). In many European countries for example, public acceptance of chemical herbicides is low and certification systems generally discourage their use, prompting managers to examine alternative management practices such as mechanical site preparation (MSP) (Thiffault and Roy 2011). In addition to vegetation control, MSP may also be used as an important tool for improving physical soil conditions that limit tree regeneration or restoring site hydrology.

MSP is a broad category of site preparation methods typically involving use of large heavy machinery with certain attached implements to prepare an area and its soil for tree regeneration. Previously, MSP has mostly been used for increased productivity in traditional plantation forestry (Örlander et al. 1990). However, during the past decades there has been an acceleration of forest restoration activities around the globe (e.g. Stanturf and Madsen 2005; Perrow and Davy 2008), in which MSP methods are widely used. MSP is used for land reclamation following use for agricultural or surface mining operations, and for forest rehabilitation (e.g. Moffat and Bending 2000; Van Lerberghe and Balleux 2001; Querejeta et al. 2001; Parotta and Knowles 2001; Löf et al. 2006). See Stanturf (2005) for various concepts connected to forest restoration. While effects of MSP on regeneration in traditional plantation forestry is well documented and summarized (e.g. Örlander et al. 1990; Prévost 1992; Sutton 1993), no thorough synthesis of this topic has been conducted specific to use of MSP in forest restoration. As MSP can dramatically influence forest restoration outcomes, the aim of this review is to summarize and synthesize our current knowledge about effects on seedling performance in relation to MSP and to evaluate economic efficiency of MSP and its environmental impacts during forest restoration.

This review focuses on MSP for treatment of soils and vegetation by the three main types; scarification, mounding, and sub-soiling/ripping that are commonly used today. Although many times the first step in restoration scenarios, MSP types for only above ground purposes such as mowing, drum chopping, blading and piling, which are mainly used to clear a site from vegetation and slash, are not included in this review. In addition, intensive MSP methods such as deep plowing and terracing, which due to environmental reasons are seldom used nowadays, are touched upon only briefly.

Mechanical site preparation methods

There are several purposes for using MSP methods in advance of regenerating a site. Depending on the equipment used, MSP can include cultivating the soil layers: clearing unwanted vegetation and removing logging slash to facilitate planting or direct seeding (Nyland 1996). Depending on the site conditions, MSP may involve manipulating the soil conditions to improve microsites for seedlings by increasing or decreasing soil moisture as needed, increasing solar radiation, modifying soil temperature, increasing soil nutrient availability, reducing soil compaction and controlling competing vegetation (Prévost 1992). In addition, MSP may be used to reduce potential damaging effects from insects such as the pine weevil (*Hylobius abietis*) or from small mammals and birds feeding on seeds (Löf 2000; Birkedal et al. 2010).

Because large machinery most often is needed for MSP, it is most efficient in treating large areas and is therefore best suited for even-aged regeneration systems using artificial regeneration. For example, restoration of modern surface mining sites can be on an enormous scale including several square kilometers (Bradshaw and Hüttl 2001). For some tree species such as European beech (*Fagus sylvatica*), however, MSP is also used in uniform shelterwood systems to enhance natural regeneration by improving seedbed characteristics (Madsen 1995). MSP methods are many times used in combination to achieve multiple purposes. For example, sites prepared for conversion of Norway spruce (*Picea abies*) to broadleaves in southern Sweden are normally treated by piling of slash to ready the site for planting, which is then followed by disk trenching to prepare the soil (Löf et al. 2004). In Spain, terracing of hill slopes may be followed by subsoiling to improve water infiltration into the soil and plant root development (Querejeta et al. 2001). In afforestation of bottomland pastures or old fields in the US, mowing of vegetation may be followed by soil ripping, disking or mounding (Allen et al. 2004; Kabrick et al. 2005).

MSP for treatment of soils and vegetation can be carried out in three different ways or intensities; (1) continuous as connected tracks or areas, (2) intermittent with patches, mounds or subsoiling done at regular distances, or (3) directed where patches or mounds are placed at certain suitable areas. The choice of method may depend on soil type, topography and the degree of disturbance needed for regeneration or other restoration or conservation concern. For example, directed MSP may be selected in steep terrain or where rocky conditions prevent continuous or intermittent methods and where there is risk of soil erosion or other negative environmental impacts.

Site preparation for forest regeneration has essentially been practiced since humans began managing forests. Wild boars (*Sus scrofa*), for example, were domesticated several thousand years ago and the use of pannage (pasturing in a forest) to feed pigs was recorded from the antiquity in Europe and still has not totally disappeared. This practice facilitates beech and oak (*Quercus* spp.) natural regeneration (Peters 1997). In addition, prescribed burning has long been used for improved natural and artificial regeneration (Nyland 1996).

Several of the MSP methods (see below) commonly used during the last 50 years were already described in detail 150 years ago (e.g. Örlander et al. 1990; Sutton 1993 and references therein), although at that time manual or horse power were used instead of heavy machines. Following the introduction of the clear-cutting system in northern Scandinavia around 1950, various methods of MSP were developed and gradually introduced in practical forestry (Söderström 1976; Ritari and Lähde 1978). During the same time period, MSP methods were introduced for restoration of former mine sites and of Mediterranean dry sites (e.g. Moffat and Bending 2000; Barberá et al. 2005), and with the ready availability of gas and diesel machinery in the 1940s, MSP became integrated into forestry practices especially in even-aged management systems and intensive plantation culture. The three main types of MSP for treatment of soils and vegetation (i.e. scarification, mounding, and subsoiling/ripping) that are commonly used today are described below (Fig. 1). Depending on machinery and attached equipment they can all be carried out using different intensity as described above.

Scarification of the soil to remove vegetation and the upper organic layers and uncover bare soil can be achieved through several different techniques. Patch scarification (intermittent) and disc trenching (continuous) are among the most commonly used in boreal forests (Luoranen and Rikala 2012) (Fig. 1). Chaining, i.e. dragging heavy chains to remove vegetation and organic layers has approximately the same effect on the soil as disc trenching. Scalping is another word for patch scarification, although it is more related to the removal of grass sod to uncover bare soil during afforestation. Blading using mounted blades to uproot trees and scrubs may also be listed under scarification methods if the soil is also treated; it is then a continuous method that uncovers relatively large areas of bare soil. The purpose of scarification MSP techniques is to create desirable planting spots in mineral soil or in mixed mineral-organic soil. In addition, increased soil temperature and moisture resulting from this treatment provides advantages for seedling growth (Prévost 1992). Planting spots are normally below the original ground level, therefore temporary standing water may occur (Prévost 1992). Thus, different planting spots may be chosen depending on, for example, the moisture regime at the site (Boateng et al. 2011). Otherwise, scarification does not significantly influence soil structure.

In contrast to scarification techniques, mounding creates elevated planting spots and influences soil structure (Fig. 1) (Sutton 1993). Spot-wise mounding (intermittent) removes vegetation and the upper organic levels and results in inverted or mixed soil on top of either the organic layer or bare soil. Bedding is a continuous form of mounding to create beds with an elevated center. Plowing is another, more intensive, form of MSP methods that may be listed under continuous mounding because it also creates elevated planting

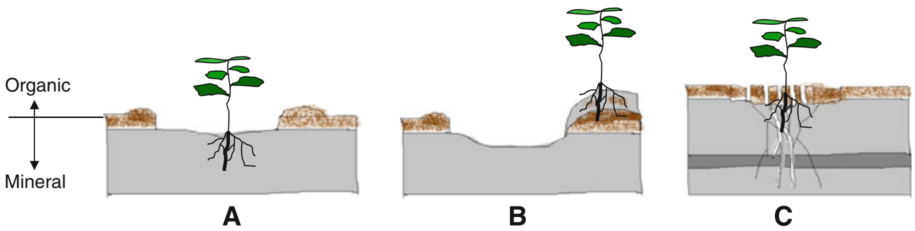

Fig. 1 Schematic description of three types of mechanical site preparation and their main effect on soil structure: scarification (**A**), mounding (**B**) and subsoiling (**C**). *Dark grey area* below mineral soil represent hardpan in **C**. Normal planting spots are indicated with a seedling. For **A** and **B** some authors recommend planting at the trench-berm interface (e.g. Boateng et al. 2011)

spots on ridges. The purposes of mounding MSP techniques are to create elevated planting spots free from water logging and with little vegetative competition. Also, increased soil temperature and nutrient availability, reduced soil bulk density, and good soil aeration are mentioned as advantages for root and seedling growth (Ritari and Lähde 1978; Londo and Mroz 2001; Kabrick et al. 2005). Mounds of different sizes may be created depending on the moisture regime at the site. Inverted site preparation, or hole-planting, where the mound is put back in the dug-out hole, are also sometimes listed under mounding techniques although the planting spot normally is not significantly elevated (Sutton 1993) (Fig. 2). Sometimes the latter technique is also called spot-tillage, or complete cultivation if the treated area is larger.

Subsoiling or ripping is a MSP method used for dry soils, reclaimed mined sites or for soils that have a compacted surface layer, but more often below the soil surface, that restricts root growth and plant development (e.g. Moffat and Bending 2000; Barberá et al. 2005; Palacios et al. 2009) (Fig. 1). Compacted layers may develop after long-term grazing regimes, working of soils during mining operations or as hardpans following agricultural land use. Without subsoiling, plantations may be stagnate after a few years despite positive early growth and establishment (Van Lerberghe and Balleux 2001). Subsoiling also is used to increase soil aeration, soil water infiltration and drainage, and to reduce soil bulk density. Subsoiling fractures soil structure without mixing of soil horizons and it is many times the first stage in a two-step site preparation process that also involves use of herbicides or other MSP methods to control vegetation and create suitable microsites for regeneration (Stanturf et al. 2004; Gwaze et al. 2007) (Fig. 3).

Fig. 2 Inverting site preparation by excavator (directed MSP) in southern Sweden to prepare planting spots for beech seedlings during conversion of Norway spruce to mixed broadleaved forests dominated by beech. Photo by Jörg Brunet

Fig. 3 Subsoiling (ripping) operation (continuous MSP) on a former agricultural field in the Lower Mississippi Alluvial Valley, southern USA. The rig is spraying a band of herbicide over the ripped row. Photo by Ray Souter

Casual factors behind seedling performance

Mechanical site preparation (MSP) types such as scarification, mounding and subsoiling influences both soil conditions and the intensity of competing vegetation, thus, the specific cause of any positive effects on seedling development is often not well elucidated (Margolis and Brand 1990). In addition, confounding effects such as altered herbivory by insects or browsing and predation from small mammals makes it even more difficult to correctly interpret survival and growth responses (Löf 2000; Birkedal et al. 2010). These responses may also vary with climatic conditions, site types and tree species (Prévost 1992). Thus, the choice of method in various forest restoration situations may be problematic; and depend on existing biotic and abiotic conditions and expected problems following any treatment sequence.

In general, earlier research (e.g. Bärring 1965; Söderström 1976; Söderström et al. 1978) on MSP and plant responses showed that performance of planted seedlings improves with increasing intensity of MSP. However, neither interfering vegetation nor insect damage was fully controlled in these early pioneering experiments and, thus, the conclusions regarding casual factors behind plant responses were rather speculative. In a classical study conducted during the late 1980s, Munson et al. (1993) showed the full influence from interfering vegetation on plant responses in connection with MSP. When vegetation was continuously controlled, i.e. every year, there was almost no additional positive growth effect in seedlings from scarification (Fig. 4). In the same experiment, there was also no additional effect of continuous fertilization. Therefore, and at many sites, any positive effects from increased soil temperature and mineralization rates during pure scarification seem minor. At most sites, the main influence on planted seedling performance following

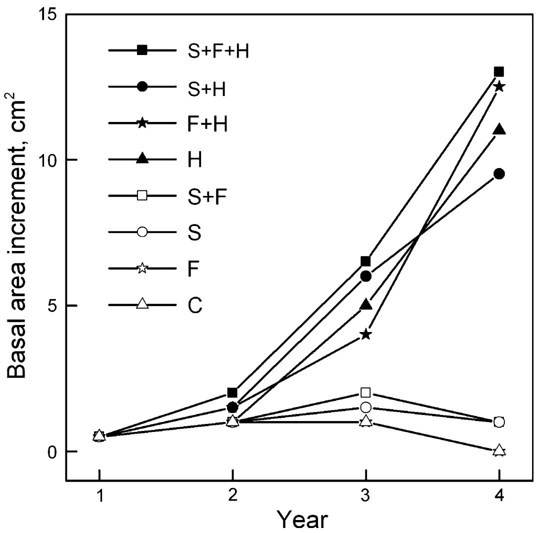

Fig. 4 The influence of combinations of scarification (*S*), repeated annual fertilization (*F*) and repeated annual herbicide treatment (*H*) and without any treatment (*C*) on the basal area increment on *Pinus strobus* seedlings during the 4 years following planting. Redrawn from Munson et al. (1993) where the experiment was conducted near Ottawa, southern Canada

scarification is decreased interference from vegetation, an effect that may be important during the critical seedling establishment period, but which is rather short-lived as exposed soil is rapidly re-colonized with vegetation. However, the above mentioned study was not carried out in the boreal forest where sometimes the humus layer may be 20–30 cm thick. For example, Thiffault et al. (2010) reported similar growth responses in planted seedlings from scarification and herbicide treatments 15 years following planting at a boreal site in eastern Canada.

Scarification may also sometimes improve conditions for germination of unwanted herbaceous and woody vegetation and, thus, aggravate the negative interference from surrounding vegetation on seedlings (Prévost 1992). Horsley (1991) found that mechanical application of herbicides by tracked vehicles to control competing vegetation in the understory of Allegheny hardwood forests actually caused high levels of competition after the shelterwood regeneration harvest was done. The metal cleats on the vehicle tracks segmented fern rhizomes that rendered ineffective the glyphosate treatment. Ferns proliferated after harvesting and dominated the ground flora to the detriment of the desired hardwood regeneration.

Although not the most efficient vegetation control method, scarification MSP may have other positive effects on plant performance. In Europe and parts of Asia, the pine weevil is a well-known destructive insect in reforestations, especially on conifer sites where, without protective measures, it may cause unacceptably high mortality of conifer seedlings following planting (Löf 2000). MSP by scarification provides some protection as long as bare soil surrounds the seedlings (Petersson et al. 2005). MSP by mounding provides better protection against the weevil by causing more soil disturbance, although continuous insecticide treatment provides the best protection (Örlander and Nilsson 1999). This effect of pine weevil damage on tree seedlings performance is tree species and site dependent, however, and they prefer to feed on conifer tree species much more so than on broadleaved tree species (e.g. Löf et al. 2004). In addition, outside its distribution area, on former agricultural land or on former broadleaved forest sites, the pine weevil is not a problem for regeneration and, thus, not relevant at all forest restoration sites.

Enhanced seed survival and germination during natural regeneration or direct seeding of a number of tree species is another example of the positive effects of scarification and mounding (Karlsson 2001; Madsen 1995; Löf and Birkedal 2009). Contact with bare soil facilitates water uptake by seeds and small seedlings, which otherwise may suffer desiccation in the organic layer, and therefore enhances both seed and seedling survival (Prévost 1992). As seed production varies substantially between tree species and years, and because patches of bare soil are rapidly re-colonized with vegetation, the effect of MSP on natural regeneration depends on when the operation is carried out and in which ecosystem (Karlsson 2001). A unique application of scarification in conservation of oak forests in the US is to increase the number of acorns that get incorporated into the soil and organic layers of forest understories, and thereby increase the number of established seedlings by protecting the acorns from desiccation, and perhaps reducing their susceptibility to predation by small mammals. After a good acorn crop was on the ground, Lhotka and Zaczek (2003) used a small brush rake mounted on a crawler dozer to substantially reduce the density of the sugar maple midstory while incorporating acorns in the upper soil layer. Similarly, Rathfon et al. (2008) used a small tractor-pulled disk to scarify the upper soil layer in the understory of oak forests to incorporate acorns that were on the ground. They followed this with a combination of herbicide treatments to reduce the midstory density. In both of these studies, scarification significantly increased the density of new oak seedlings and midstory removal improved oak survival. Finally, since MSP may improve conditions for seed germination of a number of herbaceous and woody species, it may also increase biodiversity (see below under impacts on environment).

The relative importance among growth factors differs between regions and this influences which MSP method is preferred. The Boreal forest is characterized by low productivity, primarily resulting from a short growing season, low temperatures and poor soil nutrient availability (Tamm 1991). In contrast, water becomes more limiting to plant growth in the Temperate, Mediterranean and Tropical zones, where growing seasons are longer and higher temperatures promote greater mineralization rates in more productive habitats (Kramer and Boyer 1995; Blondel and Aronson 1999). Thus, mounding may create elevated planting spots with increased soil temperatures and improve soil drainage and moisture conditions for seedlings at northern boreal sites (Sutton 1993), whereas on Mediterranean dry sites, elevating planting spots created by mounding and fertilization may be negative for seedling performance (Varelides and Kritikos 1995). In the Mediterranean region, subsoiling may have been a better choice of MSP method to increase the amount of available soil water. Changing climatic conditions between years and variation between site types including amounts of vegetation may also affect the outcome of plant responses following MSP (Nilsson and Örlander 1995; Gemmel et al. 1996).

In contrast to scarification, and in experiments at relatively wet or cold sites where vegetation has been controlled, mounding itself may have a more significant positive effect on seedling growth (Sutton 1993; Löf et al. 2006). In general, this growth response has been correlated to increases in soil temperatures, available soil nutrients, soil aeration, and nutrient seedling uptake, yet decreased soil moisture and soil density (Knapp et al. 2006; Löf and Birkedal 2009). The specific cause of positive effects in seedlings, however, is likely difficult to determine. Alternatively, it is the combination of changes that causes the effect. Similar to mounding, subsoiling may have a positive effect on plant performance through increased rooting depth and water uptake at drier sites (e.g. Querejeta et al. 2001; Palacios et al. 2009), and improved drainage at compacted or wet sites (Van Lerberghe and Balleux 2001). In contrast to scarification and mounding, subsoiling does not reduce competition from herbaceous vegetation (Querejeta et al. 2001).

Most research investigating MSP and plant performance has been conducted using a few conifer tree species with the goal of increased productivity in traditional plantation forestry or during restoration where the conifer species is looked upon as a relatively easily established nurse tree species to improve soils and the environment for other tree species (e.g. Prévost 1992; Sutton 1993; Pausas et al. 2004). The outcome in terms of seedling performance following MSP is very much dependent on tree species, site and situation. Furthermore, according to our knowledge there are no replicated experimental investigations that evaluate the effects of MSP throughout several vegetation zones. Our understanding of MSP and plant performance is therefore limited to a few tree species and knowledge is lacking regarding seedling performance following various MSP methods in relation to climate. If the goal of forest management is to implement MSP on a broader scale for forest restoration, research in these areas becomes more important. To better understand the causes for any positive seedling responses to MSP, this research should include a wide spectrum of sites and tree species.

Forest restoration and seedling performance

Afforestation of former farmlands

Human population increase and degradation of forests over large areas is normally followed by cultivation of agricultural crops on marginal lands, not well suited for sustainable crop production (Weber 2005). Afforestation by artificial regeneration or by natural invasion of trees often occurs first on those marginal sites as a consequence of land use change, shifts in agriculture practices and depopulation of rural areas. Thus, afforestation of former farmland is carried out on a variety of soil types, including dry and wet sites in uplands and floodplains. Although land is considered marginal from an agricultural perspective, sites may still be productive and competition between herbaceous vegetation and newly established seedlings is many times a main problem for successful afforestation (Van Lerberghe and Balleux 2001; Navarro Cerrillo et al. 2005). As cropfields revegetate damage to trees may occur from small mammals, especially voles, who find suitable habitats among the weeds (Bärring 1967). Another problem for successful afforestation may be plow-pans or deeper layers of clay that restricts root growth (Stanturf et al. 2004).

With water logged soils it may be necessary to construct a system with open ditches to remove excess water before planting (Van Lerberghe and Balleux 2001). Deep plowing down to 60–70 cm may also be used to remove excess water through furrows. Elevated planting spots are then available on top of the ridges formed from construction of the furrows. This may be combined with subsoiling to further increase soil drainage, and with a system of ditches. In the latter case, the ditches must be dug after plowing, so as not to hamper the plowing, and to ensure that the furrows run directly into the ditches. In cases where soil texture itself causes low permeability, i.e. soils with fine texture and clay content, it may be necessary to further reshape the soil surface. Mounding, sometimes called bedding, is typically performed utilizing plows where soil is turned inward from two directions to create elevated planting spots. There are several studies showing improved seedling performance, i.e. survival and growth, with use of this method on former farmland having excess water (e.g. Patterson and Adams 2003; Stanturf et al. 2004). However, bedding does not always result in improved seedling performance where coarse textured soils are naturally well-drained (Kabrick et al. 2005).

If plantations are established on farmland immediately removed from agricultural production and on moderately fertile soils, MSP is often not practiced because herbaceous vegetation has not yet colonized the sites (Gardiner et al. 2002). However, subsoiling may be needed to break plow-pans where they have developed (Stanturf et al. 2004). For example, subsoiling may improve soil moisture availability, root development and soil exploitation for planted seedlings (Miller 1993; Bocio et al. 2004; Dey et al. 2008). In addition, seedlings may tolerate competition from herbaceous vegetation better after subsoiling and significant increases in seedling survival and growth have been found for several tree species following implementation of this MSP method on former farmland (Berry 1986; Russell et al. 1997; Self et al. 2010). However, subsoiling on former farmland does not always improve seedling performance and the outcome may depend on soil type and climate (du Toit et al. 2010). Where fields have been removed from agricultural use for several years prior to regeneration, MSP methods such as disking or deep plowing are practiced to reduce competition from herbaceous vegetation and remove small mammal habitat (Gardiner et al. 2002; Örlander et al. 2002).

Post planting MSP using harrowing of topsoil between planting lines to reduce competition is sometimes used, but needs to be carried out every year to improve seedling performance (Cogliastro et al. 1997). For example, Seifert et al. (1985) observed that disking for two consecutive years, the year before and after planting, or using a combination of disking for 2 years and raised beds improved height and diameter increment of planted 1–0 swamp chestnut oak (*Quercus michauxii* Nutt.) on poorly drained flat pastures in southeastern Indiana, US. In contrast, where Groninger et al. (2004) used only a single disking to prepare a bottomland former cropfield for the planting of 1–0 green ash (*Fraxinus pennsylvanica* Marsh.), they found that it did not affect seedling height or diameter growth after 3 years in southern Illinois, US. Others have reported that MSP by disking upland pastures, old fields and deforested areas once did not improve survival or growth of planted hardwood bareroot seedlings, and infact promoted the development of competing vegetation (Horsley 1985; Jacobs et al. 2004). Multiple cultivations with a disk in a single season did generally improve initial height and diameter growth of 1–0 planted stock compared to no MSP, but the significance of the difference depended on the tree species in an afforestation study in southeastern Indiana, US (Seifert and Woeste 2002). MSP methods that remove top soil, i.e. deep plowing, and create seedbeds with mineral soil have also been shown to improve natural regeneration of birch (*Betula* spp.) on former farmlands in Sweden, whereas MSP treatments that preserved top soil enhanced germination of herbaceous species (Karlsson 1996).

Afforestation using deep plowing to 60–70 cm soil depth on poor sandy soils was common practice in western Denmark (Neckelmann 1976) and Mediterranean countries (Navarro-Garnica 1975). Due to burial of topsoil containing seeds from weeds, burial of organic matter with high water holding capacity and breakage of any plow pans, survival and growth of seedlings are normally improved (Madsen et al. 2005). However, this MSP method is now seldom used due to environmental reasons. Plowing to break up dense grass mats has also been shown to be beneficial for seedling performance elsewhere (Otsamo et al. 1995; du Toit et al. 2010). However, the same method may not show similar effects during initiation of the second rotation (Smith et al. 2001).

Forest restoration of dry sites with focus on Mediterranean ecosystems

Mediterranean ecosystems in Europe have been modified and degraded by human activities such as timber cutting, agricultural land use and extensive grazing in combination with natural factors such as soil erosion and fire for thousands of years. This has led to severe land degradation over large areas (Albaladejo 1990; Blondel and Aronson 1999). In addition, in similar ecosystems in California, soil compaction is commonplace in areas subjected to continuous grazing for approximately 150 years (McCreary and Cañellas 2005). Water is a limited resource and these environments are characterized by periods of severe moisture stress and high radiation. Soils are also poorly developed, shallow (20–40 cm), stony, poor in organic matter and sometimes with impermeable horizons (Albaladejo 1990; Puigdefábregas 1998). The restoration goals in these areas are to protect soils from erosion, increase soil fertility and to restore natural vegetation and forests.

During the early phase of forest restoration on these sites it is important to establish regeneration with uniform seedling performance to facilitate management and avoid problems such as patches of soil erosion. However, the semiarid conditions may cause low seedling survival due to drought, resulting in non-uniform stocking and low restoration success. In Mediterranean areas, the purpose of MSP during restoration is therefore to improve deep penetration of roots, increase soil infiltration of water and nutrient availability, reduce water runoff and to control competing vegetation (Roldan et al. 1996; Querejeta et al. 2001; Barberá et al. 2005; Palacios et al. 2009). Traditional MSP methods include subsoiling (i.e. deep ripping to 50–70 cm soil depth) (Fig. 5), mechanical terracing (2–3 m wide in combination with subsoiling) and mechanical and manual holes for planting (ca 40 × 40 × 40 cm) (Rojo et al. 2002). The most intense MSP method is terracing, which was commonly used from 1970 until the end of the 1980s, but it is controversial from an environmental point of view and is rarely used nowadays (see environmental impacts).

Subsoiling MSP or mechanical preparation of planting holes (spot tillage) has been shown to improve performance of planted seedlings due to increased rooting depth that enables roots to reach sustainable water reserves (Querejeta et al. 2000, 2001; Castillo et al. 2002). The combination of using high quality seedlings following nutrient loading, planting early in the season and using subsoiling seems to be an efficient strategy for improved seedling performance (Palacios et al. 2009) (Fig. 6). Through vigorous root growth, seedlings may reach sustainable water reserves before any drought later in the

Fig. 5 A *Quercus ilex* plantation following subsoiling (continuous MSP) on former agricultural field in southern Spain. Photo by Rafael M. Navarro

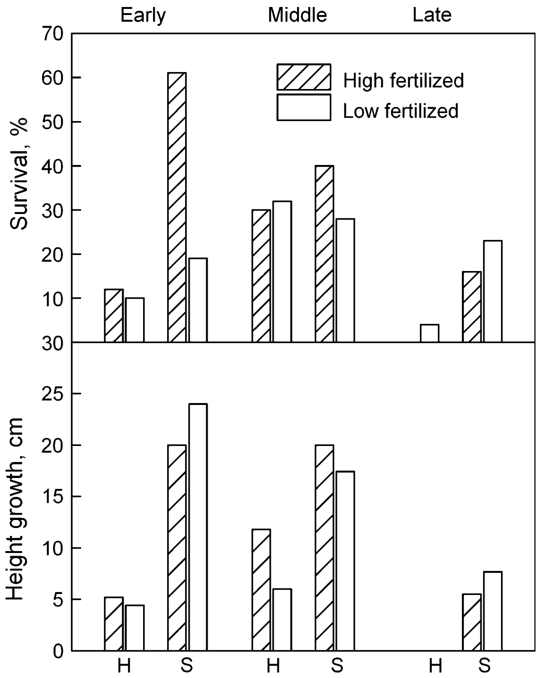

Fig. 6 Mean survival rate (*top box*) and height growth (*lower box*) after 2 years of high fertilized and low fertilized *Quercus ilex* seedlings planted in early season, middle season and late season with two types of soil preparation—manually prepared holes (*H*) and subsoiling (*S*). Redrawn from Palacios et al. (2009) where the experiment was conducted in southern Spain

season. However, MSP methods in Mediterranean countries are still a controversial issue between foresters and ecologist (see environmental impacts). At sites already colonized with herbaceous vegetation, disk ridging and disk harrowing (similar to disk trenching), may be negative for seedling growth due to stimulated re-colonization of that vegetation (Varelides and Kritikos 1995). The future use of alternative and less intense MSP methods such as intermittent subsoiling and small terracing and use of smaller machines will hopefully minimize the undesirable and irreversible impact that conventional soil preparation techniques may produce (Navarro-Garnica 1975; Maestre and Cortina 2004; Cortina et al. 2011).

Similar land degradation as in Mediterranean ecosystems also has occurred elsewhere, e.g. in Asia including China and in Africa (Stanturf and Madsen 2005; Perrow and Davy 2008). Vegetation in these arid areas is fragile and vulnerable to degradation. Increasing population along with the high demand for more food for humans and animals and fuel wood in combination with drought and soil erosion has sometimes led to desertification.

Reclamation of mine sites

Restoration of sites where surface mining of e.g. bauxite, coal and lignite, have been completed is increasingly common throughout the world (Parotta and Knowles 2001; Sharma et al. 2004; Kew et al. 2007; Zipper et al. 2011). Exposed spoils and waste dumps may contain toxic elements and these sites are prone to wind and water erosion, and water runoff that may reduce water quality in adjacent water bodies (Bradshaw and Hüttl 2001). Restoration is thus important, and forests on many of these sites have largely been replaced by persistent herbaceous species. However, during the last decades, forest restoration has often been preferred since forests provide more ecosystem services such as timber, carbon storage, watershed and water quality protection, and habitats for pre-disturbance plants and fauna (Zipper et al. 2011). Forest restoration of former mine sites is a difficult task. In many places the topsoil is removed and buried under masses of spoil and waste dump; soil chemistry and texture may not be suitable for sustainable tree growth and the operations and handling of the soils many times results in soil compaction (Showalter et al. 2010).

When mine soils become compacted, mine operators are advised to loosen them using subsoiling equipment prior to plating trees (Zipper et al. 2011). There are many examples of improved performance of planted seedlings following subsoiling on such sites. For example, Skousen et al. (2009) showed that subsoiling significantly improved survival and growth of *Juglans nigra, Liriodendron tulipifera, Quercus rubra* and *Prunus serotina* 7 years following planting. However, in the same study there was no improved plant performance of *Fraxinus americana* following the same treatment. Others have also shown better plant development after subsoiling, and sometimes after extended time-periods (Ashby 1996). Similar to restoration in Mediterranean ecosystems, higher survival and growth after subsoiling is probably due to better conditions for root growth and more available water caused by improved infiltration and collection of water. Due to dense and hard sub-soil horizons, deep subsoiling (1.5 m) may sometimes be necessary for improved plant performance (Kew et al. 2007). Kost et al. (1998) found that subsoiling to 30 cm soil depth was not enough to loosen subsoil horizons on coal mine soil in eastern USA.

In some cases, research has questioned the long-term efficiency of subsoiling because re-compaction of soils at mine sites may occur (Moffat and Bending 2000). Alternative methods that may better avoid soil compaction include loose tipping of soils (similar to mounding) (Fig. 7) or complete cultivation of soils using an excavator. Moffat and

Fig. 7 Planting operation following loose dumping of soil during mine reclamation in eastern USA. Photo by Justin Schmal

Bending (2000) showed results from several sites in the UK where loose tipping in mounds and complete cultivation resulted in improved seedling performance 5 years following planting compared to subsoiling. In the same study, root development in terms of increased rooting depth and occupied soil volume was also improved. As in many cases with MSP methods, they also found differences in responses to treatments between tree species.

Stand rehabilitation

The goal of stand rehabilitation through natural regeneration, artificial planting or seeding with native tree species is often to restore forest structure in e.g. homogenous forest monocultures (Harrington 1999). Increased biodiversity, stand stability, adaptation to climate change and promotion of a sustainable economy are reasons for such restoration (e.g. Hartley 2002; Spiecker et al. 2004).

Following disturbances such as major blowdowns, seeds of various tree species normally germinate in the resulting pits and mounds created by uprooted trees (e.g. Ilisson et al. 2007). Similar conditions can be created with different MSP methods to improve natural regeneration following clear-cutting or beneath shelterwoods. Scarification and mounding may improve natural regeneration of wind-dispersed tree species such as *Betula* spp., especially during years with good seed production (Prévost 1997; Karlsson 2001; Karlsson and Nilsson 2005; Elie et al. 2009). In contrast, for tree species that depend on well-developed advanced regeneration, MSP may damage regeneration by reducing seedling density (e.g. Prévost 1992).

In Europe, the conversion of pure conifer stands into mixed stands with broadleaves has been a major challenge during the last decades (Spiecker et al. 2004) (Fig. 2). Scarification on clear-cuts somewhat improved survival of planted *Betula* seedlings, but had little effect on growth (Bergquist et al. 2009). In the same study, survival of *Quercus* seedlings was not improved by MSP. On the other hand, mounding may improve both survival and growth, and in some cases this MSP method has been equally effective as repeated herbicide treatment to increase growth in seedlings (Löf et al. 2006) (Fig. 8). Similar findings have been reported during restoration of *Pinus palustris* stands in North America (Knapp et al.

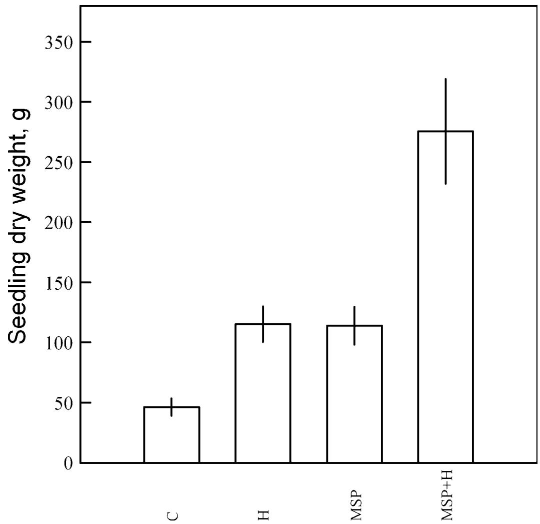

Fig. 8 Mean *Quercus robur* seedling dry weight 3 years following planting in four treatments. The treatments were: control (*C*), repeated herbicide treatment of ground vegetation (*H*), mounding site preparation (*MSP*) and the combination of mounding site preparation and repeated herbicide treatment (*MSP+H*). Redrawn from Löf et al. (2006) where the experiment was conducted in southern Sweden

2006). Mounding has also successfully been used during planting for restoration of coastal swamp forest in South America (Zamith and Scarano 2010). Underplanting with valuable tree species under a shelterwood or partial overstory has been proposed as a method that meets more objectives during rehabilitation than planting on clear-cuts (Paquette et al. 2006). Here light is the most limiting factor although root competition from shelterwood trees is an additional factor that influences seedling performance (Petritan et al. 2011), especially on xeric sites or in Mediterranean climates. In general, responses in seedling survival and growth are therefore less pronounced following MSP beneath shelterwoods compared to clear-cuts (e.g. Gemmel et al. 1996; Löf 2000).

Direct seeding of large seeded and valuable tree species for stand rehabilitation has been proposed as a means to lower regeneration costs (e.g. González-Rodrígues et al. 2011). Similar to planting, mounding may improve for example growth in *Quercus* seedlings following direct seeding (Löf and Birkedal 2009). Granivorous rodents, however, may find and consume buried seeds and their predation may put the whole regeneration operation at risk (Dey et al. 2008). Scarification of normal intensity does not protect the seeds from this predation (Birkedal et al. 2009). MSP through intermittent mounding or intensive soil scarification (similar to blading) may reduce the predation somewhat (Birkedal et al. 2010). However, even more intensive MSP methods should probably be used to protect regeneration from predation (Johnson 1981), which raises concerns from an environmental point of view.

Economic efficiency

The management goals for forest restoration differ from those for reforestation. In the latter case, stand replacement is most often scheduled to minimize the period between harvest and crop tree establishment. Here, MSP is important because it is designed to improve tree establishment and early survival and growth and many times results in larger land expectation values although economics are affected by rotation length and discount rate (Hawkins et al. 2006). During forest restoration early survival and growth is still important, but are normally not optimized in order to simultaneously achieve other goals such as improved soil protection and biodiversity; therefore economic evaluations are more complex. In addition, subsidies many times play an important role during restoration projects, which also increases complexity in economic evaluations and influences the choice of methods during implementation. However, ecological and economic goals are not mutually exclusive during forest restoration (Stanturf et al. 2001). Public landowners and small non-industrial landowners are not only interested in multi-purpose management including biodiversity and soil protection, but are also interested in timber production. The latter may be capable of producing a financial return sufficient to ensure the long term maintenance of the restored sites (Bradshaw and Hüttl 2001). Therefore, efficient establishment of tree stands and woody vegetation during forest restoration is important as failure leads to unnecessary costs and potentially to restoration failures or extended time periods for achieving restoration success.

The body of research on MSP during reforestation for increased production is large and diverse and the majority of this literature focuses on operational, biological and ecological aspects of MSP. In contrast, research examining the economics of MSP is far less developed (Hawkins et al. 2006; Ahtikoski et al. 2010), and there is even less research on economic efficiency following MSP during forest restoration. However, some knowledge from reforestation situations can also be used during forest restoration. For example, Uotila et al. (2010) compared the economic results from two different MSP methods in Finland. They used several interest rates and found that an intermittent method (spot mounding) resulted in lower total management costs compared to disc trenching. Although disc trenching is a less expensive method compared to spot mounding, the latter method resulted in less costs for young stand operations to control unwanted vegetation. Furthermore, spot mounding resulted in higher incomes from first commercial thinnings due to better growth in seedlings and trees. In another study conducted in shelterwoods of different densities by Granhus and Fjeld (2008), the time consumption for manual planting between two intermittent methods, patch scarification and inverting MSP (or hole planting), and an untreated control were compared. They found that MSP greatly reduced the time required for planting, i.e. greater ease of planting, and that the largest reduction occurred with the inverting MSP. A similar conclusion was drawn by Suadicani (2002) during conversion of Norway spruce stands although there were no differences between various MSP methods.

Other goals, e.g. biodiversity or soil protection, may be of higher or equal priority to stand productivity of timber during forest restoration. Few studies involving MSP have at the same time taken into account effects on seedling performance, economical costs and the ecological consequences. However, in a multi-criteria evaluation during restoration of *Pinus nigra* forests in Spain, Espelta et al. (2003) concluded that subsoiling (ripping) alone without other soil or vegetation management methods was the top ranked alterative as it combined low economic cost with low ecological impact but still resulted in reasonably good survival and growth of seedlings. In a study by Gan et al. (1998), respondents indicated greater willingness-to-pay for stands created without site preparation, i.e. less homogenous stands. Although herbicides, and not MSP for soil treatment, were included in the latter study, the result indicates that the non-timber values might be higher in stands without intensive vegetation management control.

A preferable method to establish trees during forest restoration may be to use MSP in a few spots in combination with the use of large seedlings. Even if larger seedlings cost more to produce and plant, large seedlings normally have a significantly higher survival following planting and compete better with vegetation than smaller seedlings (e.g. Jobidon et al. 2003; Cuesta et al. 2010; Dey et al. 2008). Probably, less intensive MSP could be used in combination with larger seedlings as well. However, to our knowledge little research and no economic evaluations have been conducted using such alternative management methods during forest restoration.

Impacts on environment

Depending on the intensity, site preparation using MSP can lead to impact over relatively large areas and deep soil disturbance. In general, there is a loss of carbon from soil following MSP, which tends to increase with increased soil disturbance (Jandl et al. 2007 and references therein). At treated areas, organic matter is often mixed with or buried beneath the mineral soil and, thus, exposed to different conditions of decomposition and mineralization compared to untreated areas. The soil disturbance changes the microclimate and stimulates the decomposition of soil organic matter (Johansson 1994). However, performance of seedlings and carbon sequestration are also favored by MSP in most studies, and this may balance or outweigh the carbon losses from soils in the overall ecosystem response (Jandl et al. 2007). Therefore, to avoid unnecessary losses of carbon from soils following MSP, the chosen technique and intensity is important. Hence, to minimize soil disturbance, intermittent or directed MSP should be chosen instead of continuous methods.

There is a risk that at later stages of stand development, growth may be retarded because of leaching of elements from the ecosystem due to MSP (Lundmark 1988). Although nutrient pools may be affected (e.g. Yildiz et al. 2009), there are few studies that have shown that MSP has negatively affected long-term productivity of crop trees. However, at sites where there is a risk for soil erosion, sites with low fertility and with low soil organic matter, harvesting and MSP in combination with wet weather may cause major physical disturbances, soil compaction and erosion (Miwa et al. 2004). For example in steep forest lands in northern Spain, mechanized forest operations including down-slope plowing significantly increased soil losses, with effects on site productivity (Edeso et al. 1999). Terracing has also been reported to cause soil erosion in Mediterranean areas (Maestre and Cortina 2004). Most MSP methods can cause soil erosion if not carefully implemented and adapted to the specific site characteristics and climate (Alcázar et al. 2002). In addition, without protection zones of trees and vegetation and careful harvesting and scarification, leached nutrients and organic matter may also affect water quality in adjacent streams (Ahtiainen 1992).

Mechanical site preparation may influence biodiversity, at least in the short-term, but effects on biodiversity following MSP are probably more dependent on management of e.g. the overstory or land use history in the surrounding areas than on MSP itself. In Norway spruce dominated landscapes in southern Sweden, exposed mineral soil after disc trenching increased the amount of regenerated broadleaved tree species during the first years after treatment (Karlsson and Nilsson 2005). However, management such as pre-commercial thinning and any browsing pressure will probably influence the dynamics of tree species more through the rotation. Simmons et al. (2011) reported that mounding in temporarily flooded environments created several microhabitats that created a more diverse plant community. Haeussler et al. (2004) stressed, however, that site preparation may alter plant diversity initially but over time the plant communities showed a strong resilience against disturbance from MSP. The effect of MSP on biodiversity is also dependent on the intensity of site preparation. For example, Espelta et al. (2003) showed that intensive vegetation control affected the populations and diversity of small mammals in Spain. Amphibians, in particular, may suffer from intensive site preparation (Hartley 2002). Little is known about effects of MSP on below-ground fauna. However, Thornton and Matlack (2002) indicated that it takes a relatively long time ($\sim$50 years) for nematode diversity to recover after intensive soil disturbance.

Forestry practices, especially MSP, have a great potential to damage ancient remains (Dolk Fröjd and Norman 2007). For example, graves, pits in the ground used as hunting traps, mounds of stones from former agricultural land use, remains from charcoal stacks and tar piles may all be hidden under the organic soil layer in the forests. Ancient remains may also be hidden under agricultural topsoils and be damaged by intensive MSP methods such as deep plowing (Madsen et al. 2005). In forests, Dolk Fröjd and Norman (2007) reported that as much as 43 % of ancient remains were damaged during harvesting operations in Sweden and that as much as 65 % were damaged when MSP also was carried out. They also reported that the most serious damages on ancient remains were caused by MSP. Directed MSP was the least threatening method because the disturbed area was relatively small and it was easier to avoid ancient remains compared to use of intermittent or continuous MSP (Torstensdotter Åhlin 2001).

Conclusions

Forest restoration projects have become increasingly common around the world and planting trees is almost always a key component. Low seedling performance caused by e.g. competing vegetation, excess water or drought, or compacted soils may result in restoration failures and various MSP methods using heavy machinery are important tools used to help counteract this. MSP methods for treatment of soils such as scarification, mounding and subsoiling are old methods that were introduced in large scale in forestry with the ready availability of gas and diesel machinery in the 1940s and were most commonly used during the 1970s and 1980s. The different types of MSP may be implemented in isolation or in combinations, and with or without herbicides. Due to environmental problems following operations caused by large areas of soil disturbance, MSP methods did get a somewhat bad reputation. However, recently they have attracted new attention. Mainly because public acceptance of chemical herbicides is nowadays low and certification systems generally discourage them, and therefore managers nowadays are looking for alternative site preparation practices.

Although MSP methods are regarded as rather weak tools for vegetation control, they influence both the amount of competing vegetation and the soil conditions. Methods such as scarification, mounding and subsoiling also lead to multiple interactions on soil physical and chemical properties that affect plant performance, and it may thus be difficult to determine the actual cause–effect relationship of any positive seedling responses. Furthermore, these responses may also vary with climatic conditions and site types. The choice of method in various forest restoration situations may therefore be problematic and depend on existing abiotic and biotic conditions and expected problems following any treatment sequence. Finally, most research on MSP and plant performance has been conducted using a few conifer tree species. However, seedling responses between species differ and most often other tree species are used during restoration compared to production forestry. Therefore, the scientific basis for implementing MSP during forest restoration is rather weak and we need more research for improved understanding. This research should include a wide spectrum of sites and tree species.

Several management objectives such as timber production, soil protection and increased biodiversity are normally relevant simultaneously during forest restoration, and therefore economic evaluations of MSP are complex. However, the few existing reports on the subject indicate that intermittent or directed MSP methods may be more beneficial from an economic point of view compared to continuous methods, which are more intensive and cause larger soil disturbance. Biodiversity may at least temporarily increase following MSP and there are surprisingly few reports that show a negative impacts following MSP on long-term productivity of trees. However, especially continuous methods may have large negative impacts on the environment causing soil erosion, impaired water quality in adjacent streams and damaged ancient remains. Therefore, MSP methods should be implemented carefully and adapted to site conditions. With the exception of MSP causing soil erosion, seedling performance seems to increase with increased soil disturbance. During any development of new MSP techniques for the future, intermittent or directed methods to achieve relatively large soil disturbance on a limited area seems to be a promising starting point. MSP may then lead to a combination of little environmental impact with improved seedling performance.

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