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The effect of tillage management and its interaction with site conditions and plant functional traits on plant species establishment during meadow restoration

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ABSTRACT

The restoration of grasslands is a key management practice that supports biodiversity across Europe. On species poor grasslands and ex-arable fields, the establishment of plant species is often limited by the availability of habitat niches, in particular space to germinate. We investigated the impacts of full inversion tillage and its interaction with site conditions and functional traits on the abundance of 51 plant species sown into a 2 ha ex-arable site in Poland. Soils of the donor site were characterized by high levels of heterogeneity in terms of water content and plant availability of N, P and K. One year after sowing the cover of species typical of semi-natural grasslands was significantly higher on the tilled plots than on the non-tilled plots. However, in the case of widespread generalist species the tillage of soil resulted in no significant effect on their establishing percentage cover. The establishment of plants on the tilled area was more successful where soils were relatively rich in mineral N. It was also more successful for species with low Ellenberg's N values. Species indicative of moist soil established poorly where the soil was tilled. This study has clear implications for the applied restoration of grasslands, demonstrating a vital role of soil tillage to promote the establishment of species typical of semi-natural grasslands. This is particularly important where seed mixtures may contain both desirable and undesirable competitive species that would disproportionately benefit from the absence of tillage management.

1. Introduction

During the restoration of species-rich grasslands, sowing seeds of the target species is often preceded by plowing, rotovating, harrowing or other methods of mechanical soil disturbance that aim to break up the old vegetation cover and help deplete the soil seed bank (Edwards et al., 2007; Long et al., 2014; Pywell et al., 2007; Schnoor et al., 2015; Wagner et al., 2011). The main theoretical basis for applying mechanical soil disturbance before sowing is that gaps in vegetation are necessary for the regeneration of plant populations. A gap is a competition-free space for seedlings where the requirements for dormancy-breaking, germination and establishment are fulfilled, while the effects of predators, competitors and pathogens are reduced (Bullock, 2000; Grubb, 1977; Harper, 1977). However, the openings created with available farming equipment (e.g., a plow) are different in size, duration, and character from the natural gaps in grasslands that temporarily appear as a result of plants death, livestock trampling and dung deposition. One of the major differences is that with the use of agricultural machinery plant-free spaces at the scale of whole fields can be created almost instantaneously, whereas naturally occurring gaps in grasslands are typically just a few centimeters or decimeters across (Bullock, 2000; Grubb, 1977). Therefore in ecological terms, seedbed preparation for grassland restoration can be considered to be large scale vegetation disturbance that substantially modifies conditions for the establishment of plants by exposing them to direct insolation, wind, air temperature fluctuations, and drying of soil surface.

On emergence, many seedlings of grassland plants require protection from these extreme environmental conditions (Gibson, 2009). It remains unclear the extent to which the presence of few shoots of non-target species co-emerging in a tilled restoration area may provide such protection. Moreover, herbaceous litter, removed through mechanical disturbance of old vegetation, has been shown to promote seedlings

Abbreviations: Ellenberg's nitrogen (nutrients) indicator value, ENIV; Ellenberg's moisture indicator value, EMIV

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emergence by keeping the soil surface moist (Thompson, 1987). However, for some species this surface vegetation litter can act to inhibit species emergence (Donath et al., 2006; Goldberg and Werner; 1983). How soil tillage promotes the establishment of plant species particularly in response to underlying soil conditions remains an important issue in restoration ecology. In the context of the restoration of temperate grasslands, plowing, rotary cultivation and harrowing prior to sowing, have all been shown to increase the rate of target species establishment from sown seed mixes, and in most cases this response was promoted by higher disturbance levels (Donath et al., 2007; Edwards et al., 2007; Hofmann and Isselstein, 2004; Hopkins et al., 1999; Poschlod and Biewer, 2005; Schmiede et al., 2012). However, these studies have typically either focused on a very limited number of species or are related to specific habitat types (e.g., Donath et al., 2006; Edwards et al., 2007; Hofmann and Isselstein, 2004; Hutchings and Booth, 1996). Therefore, the effects of tillage and their interactions with soil conditions on plant species establishment during grassland restoration has remained largely unexplored.

The intrinsic reasons for the differences in establishment success among grassland plant species following sowing into tilled soil when compared to undisturbed sward also need further elucidation. The evidence for such differences has been collated since the 1950s (Black, 1958), but an overwhelming majority of the experiments focus on the importance of small gaps, not larger openings typical of large scale mechanical disturbance. Differences in survival have been observed at either the germination or the seedling emergence stage, but when both these stages of the establishment process were considered together, the results were often complex and inconsistent (Bullock, 2000). In general, the published literature indicates that seed size may be of particular importance in this process. Large seeds are assumed to provide individuals with a competitive advantage in dense turf, as seed reserves allow the seedlings to tolerate prolonged periods of intense competition from the established vegetation (Burke and Grime, 1996; Donath et al., 2006; Goldberg, 1987; Gross, 1984). Where large areas of bare ground are created, differential species establishment on disturbed soil vs. intact vegetation is often better explained by species association with fertile or infertile soils (Pywell et al., 2003), specific ecological guilds (Hopkins et al., 1999; Pywell et al., 2003), tolerance to water stress (Bullock, 2000), as well as again in seed size (Donath et al., 2006). It is also possible that specific leaf area (SLA) may play a role, as low SLA allows young plants to persist during summer drought, while high SLA, by contrast, helps species establishing into existing swards with shady conditions (Lambers et al., 2008).

This paper describes a study investigating the initial establishment of 51 grassland plant species during grassland restoration in response to tillage and mowing management as it interacts with soil moisture and the availability of mineral nutrients. The sown species are characteristic of a wide range of semi-natural vegetation types typical of the surrounding dry calcareous grasslands, mesic lowland meadows, and *Molinia* semi-wet meadows. The study was split into two parts. The first part assessed species level responses and asked how much tillage (temporal vegetation removal) promotes the establishment of plant species introduced by sowing, and how many and which species establish successfully within the sward. In the second part, we tested whether the success of species establishment on tilled soil vs. intact vegetation is associated with their functional traits, realized habitat niche or other soil conditions. Assuming that the main effect of tillage lies in the alleviation of the competitive effect from established vegetation on species establishment, we hypothesize that (H1) this measure favors the establishment of competitively weak species which are typical of low-productive, semi-natural grasslands; (H2) that under dry conditions tillage poses the risk of drought, especially to those species, which are typically associated with wet habitats, whereas this measure should be beneficial to all species in moist sites. With respect to the effect of functional traits of species, we hypothesize that (H3) tillage is more beneficiary for the establishment of small-seeded, small-stature, and low-SLA species, which are less capable of growth under dense canopies dominated by grasses.

2. Material and methods

2.1. Design of the experiment

A 2-ha experimental site was located in abandoned fields in Bagno Serebryskie Nature Reserve, East Poland (51°10′16″N, 23°32′01″E). The terrain is almost flat with height differences of ca. 1 m and mean elevation of 178 m above sea level. The climate of this area is warm, humid continental (Köppen's classification, www.physicalgeography.net), with 574 mm mean annual rainfall and mean annual air temperature of 7.5 °C. For 1.5 ha of the site the underlying soils were Rendzic Cambic Leptosol, with the remaining 0.5 ha – Mollic Gleysol (IUSS Working Group WRB, 2007). Before 1990 the area had been used as an extensive grassland, but was converted to arable agricultural in 1991 and then abandoned in 2005. Soon after the abandonment the former fields were colonized by ruderal and common grassland plants (Appendix A). In the autumn of 2008 the whole area was mown and divided into ca. 8-m-wide strips. Every second strip of land was moldboard plowed, so that the Ap horizon of the soil (average depth of 24 cm) was completely inverted. In this way, 11 parallel strips of plowed land, separated with 11 strips of uncultivated land, were created (Fig. 1a). The introduction of desired plant species was delayed for a year with the aim of reducing the weed burden to a manageable level (UK Rural Development Service Staff, 2010). This was achieved by leaving the plowed area in furrows throughout the winter so that the perennating organs of unwanted plant species were exposed to frost. In the following growing season shallow disking or harrowing was carried out every 5–6 weeks from June to October to progressively exhaust the weeds' food reserves by stimulating regrowth from the rootstock after each cultivation, and homogenize the seedbed.

In December 2009, the experimental area was hand-sown with seed mixture collected by means of vacuum harvesting from nearby meadows that represented *Molinietalia* and *Arrhenatheretalia* orders and *Festuco-Brometea* class (Kącki et al., 2013). The sowing was conducted in bands perpendicular to the plowed lines, again in ca. 8 m wide strips separated by 8 m. These created a lattice work of intermittent tilled and untilled strips going in one directions, overlain with intermittent sown and unsown bands going in the other direction (Fig. 1a). This lattice of sowing and tillage management allowed us to establish four experimental treatments (Fig. 1b) in a replicated 2 (± tillage) × 2 (± sowing) experimental design. These treatment levels were: 1) control with neither soil tillage or the addition of vacuum harvested seed, 2) tillage only, 3) vacuum harvested seed addition only, 4) tillage and vacuum harvested seed addition. Each of these four treatment levels was positioned in adjoining 8 × 8 m plots to form a replicate block. Nineteen replicate blocks (representing 76 experimental plots) were randomly located within this lattice of tillage and sowing management.

The vacuum harvested material was thoroughly homogenized and sampled for the analysis of species composition. Seedling emergence tests, which were conducted in a greenhouse, showed that the material contained 70 plant species (see Appendix B). Within the vacuum harvested seed mix 33 species were already identified as being present in the experimental area before sowing. Plant species transfer was planned to maximize the probability that all the species present in the vacuumed seed mix were sown on every experimental plot, and that seed number of each species was similar across the plots. To achieve this, large amount of seeds were sown with a 5:1 ratio of donor to receptor site area used. Seeds were harvested twice in the growing season and harvesting was continued until the majority of seeds were collected from plants. The harvested seed mix was carefully and thoroughly homogenized during sowing.