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Is plant diversity on tractor trails more influenced by disturbance than by soil characteristics?

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ABSTRACT

Despite broad recognition that forest machinery access systems impact plant diversity, previous studies have largely focused on skid trails. As a consequence, how tractor trails (dead-end single-use trails) influence plant diversity is poorly understood. In particular, knowledge is lacking on whether fine-scale understory diversity is better indicated by tractor-trail disturbance or by the environment. We investigated the relative importance of tractor-trail disturbance conditions and soil characteristics, as well as their effects on ground floral diversity in four oak forest types (a high forest and three coppice-with-standard forests) in the northern half of France. Subplots representing five types of disturbance conditions were placed on both recent (<12 years) and older (⩾12 years) tractor trails at two locations – (trail center and wheel track), and an off-trail control subplot was added. At each subplot, we measured soil moisture, penetration resistance (PR) and bulk density (BD), and the last two were used as proxies for soil compaction. We also recorded the abundance of all vascular plants below 2 m in height on each subplot. Plant diversity was calculated based on CSR plant strategy (C-competitors, S-stress tolerators and R-ruderals), seed bank persistence, and light and moisture preference. We found that compared to controls, PR and BD were significantly greater on both old and recent tractor trails; soil moisture was greater on recent tractor trails. Comparing models showed that tractor-trail disturbance mattered more than did the soil characteristics for the diversity of most ecological groups (except for woody species richness). Compared to controls, tractor trails favored the richness of the short-term seed bank, C-strategy, CSR-strategy, heliophilous and hygrophilous herbaceous species; and abundance of heliophilous, CSR-strategy and hygrophilous herbaceous species. Furthermore, compared to controls, both richness and abundance of mesophilous herbaceous species strongly increased on recent tractor trails and strongly decreased on old tractor trails. Concerning effects of soil characteristics, only one non-negligible (positive) relationship was found: between BD and the richness of heliophilous woody species. Since plant diversity is affected by tractor trails, and since plant recovery is very slow on trails, long-term studies on their impact are needed.

1. Introduction

Understanding the mechanisms that determine biodiversity patterns and community assemblages has been central to community ecology for decades (Chase, 2003). According to current theory, disturbance regime and resource availability are considered the key factors structuring plant communities (Takafumi and Hiura, 2009). In highly perturbed areas, disturbance may sometimes override the influence of the local environment (Baeza et al., 2007). However, some studies have also found relatively strong relationships between floristic diversity and local environmental variables, even in disturbed areas (Hix, 1988). Therefore, the relative importance of disturbance - here considered as both the immediate and lasting effects of a given perturbation - and current environmental conditions has often been investigated when studying biodiversity mechanisms in disturbed forest areas (Baeza et al., 2007; Brosofske et al., 2001; Forey et al., 2008; Takafumi and Hiura, 2009).

The influences of anthropogenic disturbance are of particular relevance in European temperate forests, which have been subjected to conversion and logging for centuries (Spiecker, 2003). During the last decades, forest management has evolved from manual felling and logging towards mechanized harvesting. Mechanized timber harvesting relies on access systems (e.g. roads, skid

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trails, tractor trails, etc.) (Jarret, 2004). Forest roads are required to enter the stands; their construction and maintenance use exogenous materials whose properties contrast with existing soils. Skid trails - frequently parallel and straight - are created by clearing vegetation during stand regeneration to provide easy, repeated access from forest roads to stand interiors throughout the forest rotation (Avon et al., 2013). Although the term "skid trails" appeared about half a century ago (e.g. Dyrness, 1965), few studies clearly define what this means in their research (Avon et al., 2013; Buckley et al., 2003; Cimon-Morin et al., 2010; Ezzati et al., 2012; Naghdi et al., 2007; Wei et al., 2015a). In several studies, "skid trails" have been called "haul roads" (Buckley et al., 2003), "skid paths" (Perkins, 1980), "snig tracks" (Croke et al., 1999), "bulldozer paths" (Pinard et al., 2000) or even "tractor trails" (Madej, 2001), among other denominations. Another kind of machinery trail is created by harvesting machines entering the stands from skid trails to haul out logs from the precise cutting points. Some studies call these "secondary skid trails" (Cimon-Morin et al., 2010; Panayotou and Ashton, 1992) or "other skid trails" (Krueger, 2004). However, calling them "skid trails" may be misleading because they are different from main skid trails in terms of the disturbance frequency associated with them; indeed, such trails are usually used only once, while the very aim of skid trails - at least in France - is to confine repeated disturbances to specific areas (Akbarimehr and Jalilvand, 2013). That is why we have chosen to hereafter call "tractor trails" dead-end single-use trails.

Mechanized harvesting has become an important ecological issue for tree stand vitality and the conservation of biological diversity – all the more so that biodiversity is one of the six criteria of sustainable forest management in Europe (MCPFE, 1998). In previous studies on the influence of access systems on plant diversity, the presence of roads and skid trails has been shown to favor the introduction or development of heliophilous, often ruderal, non-forest or exotic species (Avon et al., 2013; Buckley et al., 2003; Wei et al., 2015a; Zenner and Berger, 2008). Yet the ecological impact of tractor trails is still a rather neglected issue; few studies to date have focused on tractor-trail disturbance and its impacts on plant diversity (Baltzinger et al., 2011; Buckley et al., 2003; Cimon-Morin et al., 2010; Deconchat, 2001). Unlike forest roads and skid trails, whose creation is systematically designed prior to forest operations, tractor trails are not planned; they are created directly in the forest by equipment operators during logging. As a result, tractor trails are irregularly distributed within stands and can potentially be found anywhere in a forest. Few studies have quantified the surface area covered with tractor trails in managed forests but available figures range from 3% in Baltzinger et al. (2011) to 16% in Buckley et al. (2003). Forest managers have trouble controlling, or even detecting, tractor trails due to the disappearance of their superficial traces over time. Although more equipment passes occur on skid trails than on tractor trails, several studies on skid trails have shown that the greatest disturbance occurs during the initial passes, and that the degree of disturbance does not increase, or only very little, with the number of passes (Da Silva et al., 2008; Han et al., 2009; Soltanpour and Jourgholami, 2013). Furthermore, on tractor trails, as on roads and skid trails, the recovery process following the soil disturbance (e.g. compaction) caused by the harvesting equipment may take several decades (Ezzati et al., 2012; Hattori et al., 2013). It is therefore important to evaluate the severity of tractor-trail disturbance, the environmental changes induced by these trails and their impact on ground floral diversity.

Effects of road or skid-trail disturbances on plant diversity have often been detected by comparing the diversity on and off roads or skid trails (Avon et al., 2010; Buckley et al., 2003). Yet, this general comparison may hide important processes. For example, we do not know which specific properties of tractor trails determine disturbance severity and its impact on plant diversity. Tractor-trail age - i.e. time elapsed since the trail was created - could reflect disturbance history. Contrary to skid trails which are usually all created at the same time in a given stand (during the regeneration phase), the creation of tractor trails is not confined to a specific period; logging/thinning operations occur at irregular intervals to control stem density and favor the growth of the most valuable trees. Therefore, trail age usually varies within a stand. Moreover, the machinery force exerted on a tractor trail is uneven depending on with-in trail location. Within-trail location - on the wheel track or between wheel tracks - is also an important factor which could reflect fine-scale disturbance gradients within a given tractor trail (Brais and Camiré, 1998; Wei et al., 2015a). We may assume the vegetation disturbance effect on recent tractor trails to be more severe than on old tractor trails (age effect), and more severe on wheel tracks than between wheel tracks (location effect). Finally, how these two factors combine may also change the impact of tractor trails.

In addition to the immediate physical destruction of the vegetation caused by the equipment's passage, lasting changes in the micro-site environment may also affect ground flora on tractor trails. To our knowledge, no previous studies have assessed the relative importance of disturbance and local environmental factors on ground floral diversity in the context of a forest tractor-trail access system. The local environmental conditions (e.g. canopy opening, higher soil compaction, soil nutrient loss, etc.) might change during the creation of tractor trails, as it does on roads and skid trails (Buckley et al., 2003; Coffin, 2007; Wei et al., 2015a), and these changes would ultimately influence ground floral diversity. Although canopy openings above tractor trails are usually not as large as the ones above skid trails (Buckley et al., 2003), significant variations in other local environmental factors such as soil compaction and soil moisture content may occur, which in turn would affect ground floral diversity. Soil compaction (a reduction in the volume of a given mass of soil (Gliński and Lipiec, 1990) is one of the major consequences of mechanized harvesting (Ampoorter et al., 2010; Naghdi et al., 2010; Solgi and Najafi, 2014). Furthermore, the recovery process after soil compaction may take several decades (Ezzati et al., 2012; Hattori et al., 2013). Inconsistent results have been found for the effects of soil compaction from skid trails on plant diversity. For example, Roovers et al. (2004) demonstrated that the intensity of soil compaction was highly (negatively) correlated with species cover and composition. On the contrary, the reduction in Douglas-fir tree seedling growth on skid trails was unrelated to the percentage increases in soil bulk density in Heninger et al. (2002). Wei et al. (2015a) even found that bulk density positively affected heliophilous species richness on skid trails, while soil penetration resistance was positively related to shrub abundance. Soil moisture has been described in many studies as an important fine-scale factor affecting plant growth and diversity (Beckage et al., 2000; Gálhidy et al., 2006; Wei et al., 2015a). In Wei et al. (2015a), soil moisture on skid trails was positively correlated with the richness of low- and high-humidity species, shade-tolerant species and transient-seed-bank species. A significant relationship between soil moisture and compaction has been found in several previous studies (e.g. Akbarimehr and Naghdi, 2012). Nonetheless, knowledge is still lacking concerning the respective role of soil compaction and moisture content on tractor trails play in ground floral diversity.

In conclusion, tractor trails differ from skid or other trails in the purpose and the way of their creation, the frequency of usage, the distribution pattern and trail-ages within stands. Furthermore, knowledge is lacking on disturbance degree, local environmental conditions on tractor trails and their relative importance in