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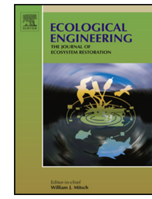

A comparison of different soil transfer strategies for restoring a Mediterranean steppe after a pipeline leak (La Crau plain, South-Eastern France)

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ABSTRACT

Among the techniques used for the restoration of terrestrial ecosystems, soil transfer has already produced encouraging results for re-establishing species-rich grassland plant communities. On August 7 2009, a serious oil pipeline leak occurred in the La Crau steppe in south-eastern France. In 2010, more than 5 ha of steppe vegetation were then destroyed by the excavation, and removal of polluted soil. Restoration of the site was achieved by transferring 72 000 t of identical soil from a nearby quarry. Soil was applied in four treatments, each with a different degree of profile complexity. After three years (2011, 2012 and 2013), our results show that the replacement of the soil to include horizon similar to the reference steppe allows recovery of the vegetation in terms of composition, similarity and species richness of the steppe vegetation during this period. The ecological engineering guidelines aimed at limiting the transit time of the soil and the reconstitution of its vertical layer organisation resulted in the improved recovery of the vegetation without colonisation by non-target species. This system may further benefit from reintroduction of traditional sheep grazing to promote sustainability following the restoration of the steppe vegetation.

1. Introduction

In Western Europe, semi-natural grasslands such as dry grasslands generally have a high level of biodiversity (Gibson, 2009), because they are subject to stress regimes (drought, low temperature, impoverished soil, etc.) and disturbance (fire, grazing, mowing, etc.). They can accommodate numerous biological groups (WallisDeVries et al., 2002; Piqueray et al., 2007; Gibson, 2009) having a rich diversity of animal and plant species at both local and regional scale (Willems, 2001; Poschold and WallisdeVries, 2002). It is common to find 30 to 40 species of plants per square metre and up to 80 species with the bryophytes (Bobbink and Willems, 1987; Hutchings and Stewart, 2002; Römermann et al., 2005).

However, since the second half of the 20th century, there has been a drastic decline in the range and quality of habitats of these grasslands (Dzwonko and Loster, 1998; Lee et al., 2001; Adriaens et al., 2006). This decline has been observed in the north-west and centre of Europe in Great Britain, the Netherlands, Belgium, France and Germany (Kiehl et al., 2010). This is mainly due to changes in land use (urban sprawl or agriculture intensification), to landscape fragmentation and invasion by non-native species (Saunders et al., 1991; Poschold and WallisDeVries, 2002).

In an attempt to put a stop to these serious losses, management systems have been introduced in many grasslands for conservation purposes (Wells, 1969; WallisDeVries et al., 2002; Janišová et al., 2011). However, after major soil disturbance, the vegetation recovery of these ecosystems can be very low (Bischoff, 2002; Donath et al., 2003; Hutchings and Booth, 1996; Coiffait-Gombault et al., 2011; Römermann et al., 2005; Forey and Dutoit, 2012), and it is then necessary to introduce ecological restoration to speed up the natural recovery (Clewell and Aronson, 2013).

Strong disturbances, due to changes in land use, can completely destroy the soil and the vegetation. These disturbances are generally caused by human engineering projects such as construction of roads, buildings, quarries or pipeline laying. For this, numerous ecological restoration techniques have been introduced, such as soil transfer. Soil transfer, applied in bulk, by spreading or in turf

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(whole or fragmented), has already produced encouraging results over short periods for the reestablishment of species-rich plant communities (Worthington and Helliwell, 1987; Pywell et al., 1995; Bullock, 1998; Vécrin and Muller, 2003; Kiehl et al., 2010; Jaunatre et al., 2014b). Soil transfer is the translocation of soil material and its native biota. It involves the removal of the soil substrate and its assemblage of species from an intact donor site to an area requiring restoration. The purpose is to aid in the reestablishment of a functional community following disturbance (Bullock, 1998), and it may be applied to disturbances of small or large areas (Pywell et al., 1995; Jaunatre et al., 2014b). Using this method, it is possible to bypass both the biotic and abiotic filters that constrain the establishment and development of plant communities. The removal of a soil from a donor site to a location in need of restoration allows the transfer of physico-chemical elements (nutrients, fine and coarse particles, etc.) but also soil organic matter (litter, humus, etc.). Similarly, the fauna (pedofauna) and the flora (seeds, algae, clones, etc.) as well as the microbial biomass (bacterial, algal and fungal) are transferred (Clewell and Aronson, 2013). Perennial plants with vegetative reproduction, which play a structure-building role in the community, may also be transplanted as well as a part of the soil structure and a part of the plant community structure (Manchester et al., 1999).

Soil transfer also enables the rapid re-creation of a habitat corresponding to the reference ecosystem if the donor site is indeed close to the one that was originally degraded and/or destroyed (Bullock, 1998). This has already been demonstrated for certain grasslands in Great Britain where positive results were achieved (Bullock, 1998; Box, 2003; Trueman et al., 2007). For example, in 18 experiments, the rate of transfer for plant species ranged from 54% to 91% after 3 to 7 years with a high success rate in particular for the transfer of turf (Bullock, 1998) which may be as high as 100% after 5 years for a dry grassland restored using this method in Great Britain (Trueman et al., 2007).

On the other hand, this technique is certainly not sustainable, since soils are not considered a renewable resource. Soil transfer should limited to particular cases where the destruction of the soil of the donor site is planned, generally independently of the soil transfer operation (Bullock, 1998; Bruelheide and Flintrop, 2000; McLean, 2003; Vécrin and Muller, 2003). In some case, the soil transfer may not always require an independent donor site. For example, during the installation of a pipeline, the soil which has been removed, can be immediately transported and then placed on a site that is being restored. The direct transfer or hauling avoid or minimise any losses of seed or vegetation propagule viability, soil structure or microbial biomass (DePuit, 1984; Pfannenstiel and Wendt, 1984; Andersen et al., 2008). Transfer of large quantities of soil requires the use of civil engineering methods (use of worksite earth moving equipment, transport trucks, etc.) and involves hydrocarbons consumption, pollutants emission (CO_2, NO_x, etc.), soil compaction and alteration during transportation.

The use of techniques associated with ecological engineering (Mitsch and Jørgensen, 2004) and aimed at economising and/or preserving the soil resource have thus been recommended in order to limit the environmental impact of this kind of restoration technique and to increase the chances of success. For soil, this involves transferring only a few blocks which would act as the kernel of recolonisation while allowing the recovery of the donor site (Good et al., 1999; Kiehl et al., 2010; Jaunatre et al., 2014a). Also, the soil dilution by inoculation on the host site of soil transferred in bulk (ratio of 1 to 2, 1 to 3, etc.) allows to economise the soil and restore a larger area than if the soil has been removed from a donor site and replaced in a receiver site of equal size (Vécrin and Muller, 2003; Jaunatre et al., 2014a). Finally, in order to preserve the soil (organic and physico-chemical composition, structure, etc.), it should be transferred at the right time (spring or autumn in Western Europe) as quickly as possible and without stocking to avoid any alteration (deterioration, destruction of the pedofauna and pedoflora, colonisation of the stockpiles by undesirable species, etc.).

In south-eastern France, the La Crau steppe represents a good example of Mediterranean dry grassland possessing high plant species richness (Molinier and Tallon, 1950; Devaux et al., 1983; Römermann et al., 2005; Buisson and Dutoit, 2006). In fact, this steppe vegetation is the result of a regime of particular stress and disturbance induced by the shallow red Mediterranean soil (red fersialitic soil) and by the Mediterranean climate interacting with centuries of sheep grazing and a succession of prairie fires (Devaux et al., 1983; Cherel, 1988; Badan et al., 1995; Henry, 2009). Although this environment is partly protected through the establishment of a National Natural Reserve in 2001 on 7400 ha, extensive areas today require active restoration (Buisson and Dutoit, 2006; Coiffait-Gombault et al., 2011; Jaunatre et al., 2014a) as recovery of the steppe vegetation after changes in land use is extremely slow (Römermann et al., 2005; Buisson et al., 2006; Dutoit et al., 2013a,b).

Among the areas to be restored is at the heart of the La Crau steppe and the natural reserve, an area of 5.5 ha which was recently destroyed by leakage of an oil pipeline on 7 August 2009 (Wolff, 2013). The surface, the soil, the geological agglomerate and the ground water were polluted by the spillage of more than 5400 m^3 of crude oil. Consequently, restoration has consisted of the excavation and removal of the polluted soil (72 000 t) to a specialised treatment centre.

To fill in this excavated area, a same type of soil was transferred from a nearby active quarry. In order to maximise the chances of success, we have undertook the transfer (1) during a rainy period of spring 2011 in order to enhance the regeneration of the plants (annual and perennial species), (2) in real time without stocking to avoid soil deterioration in the stockpiles, the destruction of the pedofauna and pedoflora and the enrichment of the piles with seeds of undesirable species, (3) at a ratio of 1 to 1 integrating the reconstitution of soil in different degrees of profile complexity derived from the pedogenesis of the red fersialitic soil. Without our guidelines, only the altered bedrock would have been transferred homogeneously over the whole area and for the full depth (at least 40 cm) of the area to be restored using geological materials furnished by the nearby alluvial quarries. We proposed these guidelines for the first time in order to provide the basis for maximising the development of the steppe vegetation identical to that previously damaged.

Here, we measured the recovery of the steppe vegetation as a function of different treatments of soil replacement. The aim is to measure the impact of these methods on the composition, richness and species diversity over the three years following soil replacement (2011–2013), and also on the similarity of composition and structure with a reference steppe community surrounding the excavated area. By testing the importance of maintaining the vertical organisation of the main pedological layers (topsoil, subsoil, altered bedrock), we seek to determine whether it is necessary to replace all the soil including the topsoil or whether it is preferable to render the soil as oligotrophic as possible by not replacing it and only leaving on the surface the subsoil or the altered bedrock. Our hypothesis is that the replacement of topsoil may favour, in addition to the development of the desired target species, also the establishment of species not targeted by the restoration because not typical of the reference steppe ecosystem (ruderal, ubiquitous, invasive species, etc.) from the transferred soil permanent seed bank or the surrounding seed rain of the donor site. This would also make it possible to make the most use from a non-renewable resource, which is the soil of the intact steppe grassland.