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Comparison of translocation methods to conserve metallophyte communities in the Katangan Copperbelt, DRC

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Abstract

In Katanga, Democratic Republic of Congo, unique metallophyte communities supporting numerous endemic species occurred on the highly mineralized copper cobalt (Cu-Co) hills throughout the province. These hills are economically valuable mineral reserves, mining activities represent therefore a threat to the long-term persistence of these communities. *Ex-situ* conservation program was set up by a mining company to rescue and conserve the diversity of Cu-Co communities until restoration activities are initiated. Two kind of Cu-Co communities, the steppe and the steppic savanna were translocated using topsoil spreading and whole-turf translocation. In this study we assessed the effectiveness of these two techniques in conserving Cu-Co communities and their potential use in future restoration programs. More than two years after the translocation, whole-turf translocation appeared to be the better technique for *ex-situ* conservation of endemic Cu-Co species. Not only did whole-turf successfully translocate numerous target species that were not present in the topsoil areas, but it also resulted in fewer ruderal and non-target species compared to topsoil spreading. Topsoil spreading recorded low seedling emergence from seed bank due to large proportions of dormant seeds or the absence of a seed bank, especially for the steppic savanna. Restoration of the steppe, is currently more successful than for steppic savanna where the lack of dominant and structuring species likely contributed to divergence in species composition compared to reference ecosystem. Our study stress the fact that tropical old-growth grasslands, which require probably several centuries to assemble, are difficult to restore or translocate.

Keywords: assessment, copper flora, mining, old-growth grasslands, restoration, Southeastern Congo, topsoil spreading, whole-turf translocation

Introduction

Metal-rich habitats support very unique plant communities, and usually contain rare and specialized taxa adapted to high concentration of metals (Whiting et al. 2004; Jacobi et al. 2007; Faucon et al. 2010). As these communities often occur on economically-valuable mineral deposits, many are threatened by quarrying and mining activities (Whiting et al. 2004). As opportunities for *in situ* conservation of metallophyte communities are often limited, there has been increasing attention on *ex-situ* conservation methods including use in phytostabilisation (Shutcha et al. 2010) and ecological restoration (Whiting et al. 2004; Faucon et al. 2012; Saad et al. 2012).

In Katanga, Democratic Republic of Congo, unique metallophyte communities supporting numerous endemic species have evolved on the highly mineralized copper cobalt (Cu-Co) hills throughout the province (Duvigneaud and Denaeyer-de-Smet 1963; Séleck et al. 2013; Faucon et al. 2010; Copperflora.org 2012). These communities, referred to as Cu-Co clearings, represent old growth grasslands (Veldman et al. 2015) that require centuries to assemble and are characterized by a diversity of herbaceous species and forbs, and are maintained by fire and edaphic factors that limit tree growth (Bond and Parr 2010; Lehmann et al. 2011; Parr et al. 2014; Veldman et al. 2015). In Cu-Co ecosystems, plant communities and associated endemic species are distributed along a soil metal concentration gradient (Séleck et al. 2013). The two main plant communities are the steppe and the steppic savanna. Typically, the steppe is located in the upper part of the hill and is characterized by shallow soils with high metal concentrations (Cu-EDTA of 3 500-10 000 mg $Cu.kg.soil^{-1}$) and a large number of endemic species. The steppic savanna occurs along the lower slopes on deeper sols with lower metal concentrations (1 000-3 500 mg $Cu.kg.soil^{-1}$) (Saad et al. 2012; Ilunga et al. 2013; Séleck et al. 2013).

The Cu-Co clearings are generally located on hills that possess economically valuable mineral reserves, and the DRC government has divided much of Katanga province into private mining concessions which are leased to commercial mining companies. The DRC mining code requires lessees must to exploit all viable reserves within the concession. Although several Cu-Co species have received IUCN conservation status, there are currently no DRC governmental conservation initiatives or policies relating to the protection of Cu-Co communities in Katanga. Accordingly, mining activities represent a threat to the long-term persistence of these communities and associated endemic species.

Co-Cu communities have limited capacity to naturally recolonize areas disturbed by mining, not only due to the physical alteration of suitable soils and substrates (Ash et al. 1994; Wong 2003; Yuan et al. 2006) but also because tropical old-growth grassland species tend to have low success establishing from seed and poor colonization ability (Zaloumis and Bond 2011; Le Stradic et al. 2014; Veldman et al. 2015). Rather, they rely on strong resprouting capacity, investment in underground storage/root systems, and clonal growth (Veldman et al. 2015). Lack of target species source, either in the seed bank or in the surrounding, may also limit the recolonization of degraded areas by native species, often to the benefit of ruderal and/or invasive species (Ash et al. 1994; Bakker et al. 1996; Bradshaw 1997; Bakker and Berendse 1999; Wilson 2002; Shu et al. 2005; Kiehl 2010) Thus, active restoration is the only strategy for re-establishing Cu-Co communities in disturbed sites (Hutchings and Booth 1996; Bischoff 2002; Kiehl et al. 2010), which imply, first, to conserve these communities and second, to develop techniques to restore its.

Two plant translocation techniques include topsoil transfer (hereafter "topsoil spreading") (Rochefort et al. 2003; Cobbaert et al. 2004; Jaunatre et al. 2012) and community translocation (hereafter "whole-turf translocation ") (Bullock 1998; Butt et al. 2003; Trueman et al. 2007; Box et al. 2011). Topsoil spreading has been used in the rehabilitation of quarries and mines in temperate ecosystems, and involves collecting topsoil from a donor site in native habitat and spreading it on a receptor area. This technique allows for the transfer of seeds, propagules, roots, and soil microorganisms that are present in the native topsoil. However, temporarily stockpiling topsoil prior to spreading reduces effectiveness of this technique, as it has been demonstrated that stockpiled topsoil exhibits loss of viable seeds and reduction in germination potential as a function of storage time (Rivera et al. 2012). Whole-turf translocation involves the transfer of intact vegetation mats from the donor site to a receptor site (Bullock 1998). As this technique transfers entire intact mats with plants and attached root systems and soils, it was first drawn in a conservation context to move communities that would otherwise have been completely wiped out (Bullock 1998; Milton et al. 1999; Good et al. 1999; Bruelheide and Flintrop 2000; Butt et al. 2003; Trueman et al. 2007; Box et al. 2011). It can be used as a strategy to create communities that closely resemble the original state (Bullock 1998; Box 2003). This technique is effective but more expensive (Kirmer et al. 2009; Török et al. 2011) than topsoil spreading which demand less technique and time.

The Tenke Fungurume Mine (TFM) is implementing a long-term conservation program for the Cu-Co communities and associated species of concern (SoC) within its concession in Katanga. SoC include species identified as strict endemic, broad endemic, and threatened and metallophyte species (Faucon et al. 2010). A primary component of this program is the incorporation of Co-Cu communities in the restoration of waste dumps and open pits during mine closure, but restoration opportunities are limited during active mining. TFM has established a system of *ex situ* “artificial ecosystems” (AEs) to rescue and temporarily conserve the diversity of Cu-Co communities and associated SoC until restoration activities are initiated. They should allow acting as sources of propagules for future ecological restorations of closed mine. TFM has utilized both topsoil spreading and whole-turf translocation in the development of the AEs, thereby providing an opportunity to assess the effectiveness of these techniques in conserving Cu-Co communities and their potential use in future restoration programs.

The present study compares the effectiveness of whole-turf translocation and topsoil spreading as means to conserve the steppe and steppic savanna communities of copper clearings. As these plant communities are expected to have low seed banks and persistent bud banks (Veldman et al. 2015), we hypothesized that whole-turf translocation would be more successful than topsoil spreading in preserving the diversity of Cu-Co communities and associated endemic species.

Material and methods

Study site

The study site is located in the TFM mining concession in central Katanga, DRC. The concession, covering ca. 1000 km², hosts more than 40 copper clearings distributed along two parallel low ridges between the cities of Tenke (10.61°S; 26.12°E) and Fungurume (10.62°S; 26.32°E) (altitude around 1300 m). The climate is classified as subtropical humid (Cwa) according to the Köppen’s classification (Köppen 1900) with hot and humid summers (November to March) and generally mild to cool dry winters (April to October). Annual rainfall is around 1300 mm (of which 1200 mm fall during the rainy season). Mean annual temperature is about 20 °C. Temperatures range from 15–17°C reaching lows of 5°C at night at the beginning of the dry season, and highs of 31–33°C in September–October.

Reference ecosystem

Kavifwafwaulu hills supported extensive Cu-Co clearings (Appendix 1) and served as the donor site for salvage efforts conducted prior to mining. Kavifwafwaulu represents the reference ecosystem for this study. This hill supported approximately 12ha of clearings dominated by steppic savanna on gentle slopes (~5°) forming a dome (Séleck et al. 2013). A vegetation survey was carried out at the peak of vegetation in March 2009; absolute percentage cover of each vascular plant species was recorded in 36 1m² plots. Plots were distributed to cover both the steppe and the steppic savanna along the Cu-Co gradient (Séleck et al. 2013) with 6 plots in the steppe and 30 plots in the steppic savanna. The number of plots was sufficient to record most of the species in each community.

For both restoration techniques, receptor sites were constructed to match as best as possible with the donor site conditions. Since the reference Kavifwafwaulu hill presented gentle slopes, similar gentle slopes were recreated on the receptor sites (Appendix 2,3,4,5). Donor and receptor sites are closed and share the same environmental conditions in term of elevation, precipitations and temperature. There are no large herbivores or livestock in the region and the main perturbation is fire which burns both donor and receptor sites almost every year.

Topsoil spreading

Topsoil spreading was completed during the dry season (June to August) in 2011. The top 20cm of Kavifwafwaulu topsoil layer was stripped with a bulldozer and stored at the edge of the area for a short time. Approximately 50 cm of mineralized subsoil was also stripped with a bulldozer. Topsoil and subsoil were loaded, transferred, and spread at the receptor site which was a rock stockpile with less than 0.1% of Cu content (i.e. waste dump). A 20cm of topsoil from the steppe and the steppic savanna communities at Kavifwafwaulu were spread over a 50 cm layer of corresponding subsoil from Kavifwafwaulu, on strips of 10m x 75m and 13m x 75m, respectively (Appendix 2 and 3).

Whole-turf translocation

Whole-turf translocation was conducted during the 2010-2011 rainy season (i.e. from September to January). The receptor site consisted in a fallow and was prepared by removing the upper soil layer and spreading a layer of subsoil from the donor site, and 20 cm of highly Cu-Co mineralized rocky siliceous substrate for the steppe community and 20-100 cm of lowly mineralized talceous-clay substrate for the steppic savanna community (Appendix 4 and 5). Methodology used for whole-turf translocation followed Bruelheide and Flintrop (2000) using ca. 40 cm deep vegetation mats. Vegetation mats were extracted via backhoe from six different areas of steppe (around 40m² each) and twelve areas of steppic savanna (10 areas of around 100m² and 2 areas of around 200m²) at the donor site. These areas were selected in order to maximize the species richness and the number of SoC. Vegetation mats ranging in size from 0.2 m^2 to 1 m^2 were transported to the receptor site by truck, unloaded, and set in place manually. Vegetation mats from steppe were placed in a 40m x 6m strip and steppic savanna in a 40m x 34m strip (Appendix 4 and 5). Gaps between mats were filled with topsoil from the reference ecosystem.

Vegetation monitoring

Metric for vegetation monitoring of recreated communities included percentage cover of vascular plants and total number of species (species richness). For topsoil spreading, 7 and 10 m² permanent quadrats were established in the steppe and steppic savanna areas, respectively and monitored at the end of the rainy season (March) in 2012 and 2013. For whole-turf translocation, 14 and 42 m² permanent quadrats were established in the steppe and steppic savanna areas, respectively. Monitoring was conducted at the end of the wet season in 2011, 2012 and 2013 and percentage cover of vascular plants was recorded in each quadrat. In addition, species richness (species lists) was recorded for both habitat types and translocation methods.

Data analysis

Mean species richness (number of species/m²) and mean vegetation cover were compared using Generalized Linear Models (glm) with a Poisson distribution for richness and a Gaussian distribution for vegetation cover. To assess differences in community composition between vegetation type and translocation technique, a first Correspondence Analysis (CA) was run (162 points x 158 species) to assess differences between the reference and translocated ecosystems over the years.

While multivariate analyses are useful to distinguish differences between translocated *versus* intact communities, three additional indices were calculated using the 'CommStructIndices' function (Jaunatre et al. 2013) on species abundances to assess the magnitude of observed differences: Higher Abundance Index (HAI), Community Structure Integrity Index (CSII), and normalized Community Structure Integrity Index ($CSII_{norm}$) (Jaunatre et al. 2013). HAI measures the proportion of the species abundance in the assessed communities which is higher than in the reference community. HAI is positively influenced by the increase in non-target species and by the decrease in the overall abundance of community. CSII measures the proportion of species abundances in the reference community represented in the assessed communities. The CSII and the $CSII_{norm}$ increase toward the reference community value only when target-species abundance increases. When indices of the assessed communities are significantly different from the reference we can conclude that abundances of the assessed community are different than in the reference. Neither CSII nor the $CSII_{norm}$ are influenced by the increase in non-target species abundance. $CSII_{norm}$ is a normalized version of CSII allowing for comparisons of CSII values across diverse reference communities (Jaunatre et al. 2013). After checking conformity to parametric conditions (i.e. normality and homoscedasticity), we performed Analysis of variances (ANOVA) followed by Tukey HSD post-hoc tests to compare indicators between translocation technique for each community. In order to have an easy reading abundance graph, log of mean abundances were represented. For the steppic savanna, for clearness purposes only species which occur in more than 3 quadrats are represented.

All analyses were performed with R version 3.0.0 (R Development Core Team, 2011) using function ‘ComStructIndices’ for indices calculation and a modified version of ‘structure.plot’ for plotting (Jaunatre et al. 2013).

Results

Plant species richness, vegetation cover and plant community evolution

On the original Kavifwafwaulu hill, 143 plant species were recorded during the vegetation survey in 2009, and in 2013, overall, 129 plant species were registered for the whole-turf translocation and 64 for the topsoil spreading Plant species richness by square meter varied significantly according to the technique used in the steppe (glm procedure $z = 29.40$, $p < 0.001$) and in the steppic savanna ($z = 63.99$, $p < 0.001$, Figure 1a). Both in the steppe and in the steppic savanna, lower species richness by square meter were recorded on topsoil spreading compared to the reference community (5.71±0.28 and 9.10±0.52 mean number of species.m^{-2} ± standard error for the steppe and the steppic savanna using topsoil spreading respectively and 11.00±0.73 and 14.60±0.73 mean number of species.m^{-2} for the steppe and the steppic savanna reference respectively, $p<0.001$, Figure 1a) whereas the same number of species was recorded in whole-turf translocation and reference (10.85±0.34 and 14.00±0.45 for the steppe and the steppic savanna using whole-turf translocation respectively, Figure 1a). In the steppe, no difference in vegetation cover percentage was observed between topsoil spreading (69.28±22.25, mean vegetation cover percentage ± standard error), whole-turf translocation (73.75±3.12) and reference (55.83±6.37) ($F = 2.64$, $p=0.09$, Figure 1b). For the steppic savanna vegetation, cover was similar in topsoil spreading (77.00±6.63) and reference (82.33±1.93) but it was slightly higher in whole-turf translocation (90.41±1.18) than in reference ($F = 8.38$, $p < 0.001$, Figure 1b).

The Correspondence Analysis showed that, for the steppe vegetation, whole-turf translocation allows to reach a plant community similar but more homogeneous than the reference (Figure 2). For the steppic savanna, communities present in whole-turf translocation and reference ecosystems were still different after two years (Figure 2). Topsoil spreading did not allow reaching communities similar to the reference neither for steppe nor for steppic savanna: for the steppe, topsoil communities were close to the reference but still different after two years (Figure 2) while steppic savanna topsoil community was clearly distinct from the reference steppic savanna (Figure 2). In whole-turf translocation, steppe remained quite similar to the reference over the three years of monitoring (Figure 3a) while the steppic savanna community diverted from the reference over time (Figure 3a).

For both vegetation types, communities on topsoil tend to become more different from the reference over the three years of survey (Figure 3b).

Characteristics of communities obtained using topsoil spreading and whole-turf translocation.

Steppe

After 2 years, the steppe on topsoil spreading presented a significantly higher HAI (Higher Abundance Index) due to an overall abundance decrease compared to the reference community (F=17.29, p<0.001, Figure 4 & 5) while it remained the same for whole-turf translocation. For the two techniques, few non-target species (i.e. species observed in the translocated community but not present in the reference) were observed, as only *Drimia calcarata*, present in the whole-turf translocation, was not observed (likely a “false” absence) in the reference ecosystem (Figure 5). The low CSII values meant that target species (i.e. species present in the reference) abundances in whole-turf translocation were globally similar to the ones of the reference. Two species, *Ocimum vanderystii* and *Hyparrhenia cf. diplandra*, were missing (Figure 5). In topsoil spreading, abundances of some target species were however much different than in the reference (F= 10.31, p<0.001, Figure 4 & 5), higher abundances of *Eragrostis racemosa, Bulbostylis cupricola, Haumaniastrum robertii* and *Bulbostylis pseudoperennis* were recorded in topsoil communities (Figure 5). In another hand, 13 species present on reference ecosystem were missing in top soil communities (Figure 5). Whole-turf translocation allows to translocate numerous Species of Concern (SoC) 10 out to 11 SoC present on the reference, only *Ocimum vanderystii* failed to be translocate into the whole-turf translocation (Figure 5, Table 1). Topsoil spreading permits the transfer of 7 SoC among whom 2 SoC presenting low abundances (*Crotalaria cobalticola* and *Sporobolus congoensis*, Figure 5, Table 1) but 4 SoCs failed to establish in the topsoil.

Steppic savanna

For steppic savanna, for the two techniques the HAI differed significantly from the reference (F=61.36, p<0.001, Figure 4): an HAI increase reflects higher percentage cover of numerous non target species especially in topsoil spreading compared to reference (Figure 4 & 6) such as *Bulbostylis cupricola, Haumaniastrum robertii* or *Celosia trigyna*, which are SoCs but not present in the reference community, and the ruderal species *Digitaria cf. diagonalis and Setaria sphacelata* (Figure 6). CSII values show that target species abundances in whole-turf translocation and topsoil spreading communities were very different from the reference, especially for topsoil spreading (F=89.36, p<0.001, Figure 4). Looking at community composition, we notice an important lack of common and structuring species in both translocated communities, especially for topsoil spreading, (Figure 6) such as *Cryptosepalum maraviense, Tristachya bequaertii*, *Loudetia simplex, Crotalaria argenteotomentosa* and

Droogmansia pteropus among others. Some over-abundances of target species were also observed such as *Andropogon schirensis, Trachypogon spicatus Eragrostis racemosa, Monocymbium ceresiiforme, Hyparrhenia cf. diplandra*, *Ocimum fimbriatum* or *Rhytachne rottboellioides* (Figure 6). Whole-turf translocation allows establishment of more steppic savanna SoC compared to the topsoil spreading which allowed the translocation of only one SoC, *Triumfetta welwitschii var. rogersii* (Figure 6, Table 1). Seven SoC were recorded in the whole-turf translocation, however three of them (*Ocimum vanderystii, Diplolophium marthozianum* and *Triumfetta welwitschii* var. *rogersii*) presented low abundance compared to the reference (Figure 6, Table 1). *Triumfetta likasiensis, Basanthe kisimbae, Acalypha cupricola* and *Sporobolus congoensis* failed to be translocated either by whole-turf translocation or topsoil spreading (Table 1).

Comparisons between communities

According to the $\mathrm{CSII}_{\mathrm{norm}}$ values, whole-turf translocation is a technique allowing to reach similar abundances of target species for the steppe (Figure 4), whereas this was not verified for the steppic savanna ($F=10.31$, $p<0.001$, Figure 4) where $\mathrm{CSII}_{\mathrm{norm}}$ differ between the reference and the whole-turf translocation. For both vegetation types, topsoil spreading showed not to be a technique allowing the recovery of target species abundances (Figure 4). Higher value of $\mathrm{CSII}_{\mathrm{norm}}$ underlined that steppe translocation using either the whole-turf translocation or topsoil spreading present more successful results than steppic savanna translocation ($F= 89.36$, $p<0.001$, Figure 4).

Discussion

All Cu-Co community translocation actions from Kavifwafwaulu aimed to translocate a maximum of biodiversity and to re-establish similar communities and associated endemic plant species *ex situ*. The study results indicate that after two years, whole-turf translocation sites had a similar number of species by square meter compared to the reference ecosystem, while topsoil spreading sites had significantly lower species richness. Both translocation techniques resulted in equivalent or higher vegetation cover compared to the reference ecosystem. However, species richness and vegetation cover alone are not sufficient measures of success as they do not inform on species composition of translocated communities, specifically the occurrence of endemic species. We therefore assessed whether target species, particularly endemic species, were effectively translocated and whether translocated community structure was similar to the reference. The study results indicate that whole-turf translocation was the more effective technique, particularly for steppe communities which support the largest proportion of endemic species. It is important to note that both methods are limited for some species present in low abundance in the reference ecosystem, since they are easily missing in topsoil or in vegetation mats and then did not establish in translocated ecosystems. That is why, for the steppic savanna, we have discussed mainly the most common species in the reference ecosystem (i.e. present in at least 3 quadrats) and which should have been translocated with topsoil spreading or whole-turf translocation.

Although topsoil spreading has been demonstrated to be a successful restoration method for temperate vegetation communities and ecosystems (Good et al. 1999; Rokich et al. 2000; Vécrin and Muller 2003; Jaunatre et al. 2012), this technique does not appear to be effective for the conservation of Cu-Co communities. After two years, topsoil spreading communities did not tend to become similar to the reference ecosystem. Success of this technique relies mainly on seed bank expression (Cobbaert et al. 2004; Bossuyt and Honnay 2008) or seed immigration and is expected to be efficient when species in the reference communities create large seed bank and/or when restoration sites areas are surrounded by native ecosystems that represent an external seed source. Low emergence from seed bank due to large proportions of dormant seeds or the absence of a seed bank has been reported in tropical grassland communities (Medina and Fernandes 2007; Le Stradic 2012). Cu-Co communities are dominated by perennial species which have evolved to resprout after fire and have a low tendency for seed production and seed bank accumulation (Overbeck and Pfadenhauer 2007a; Fidelis et al. 2010; Veldman et al. 2015). Moreover, it has been shown that resprouting species generally have low fecundity in comparison to non-sprouting species (Lamont and Wiens 2003; Lamont et al. 2011). In both communities, we observed uneven emergence from seed bank which significantly contributed to the lack of similarity of spreading topsoil to reference ecosystems after two years as illustrated by both HAI and CSII. A large proportion of common and endemic species did not emerge from the seed bank, whereas others such as *Eragrostis racemosa, Bulbostylis cupricola or Haumaniastrum robertii*, show overabundances on topsoil spreading areas compared to the reference ecosystem. These specific species are known to occur on secondary habitats (Faucon et al. 2011), which is likely due to their high capacity for seed production and accumulation in the seed bank.

Colonization of large area of topsoil by ruderal species that were not present in the reference ecosystem, such as *Celosia trigyna, Bidens oligoflora* and *Setaria sphacelata*, was observed in the steppic savanna topsoil despite the metal content of the soils. These species compete strongly with Cu-Co species and likely limited the establishment of target native species. Ruderal species were less common in the recreated steppe communities, likely as a result of the higher soil mineralization levels in those areas.

Whole-turf translocation appeared to be the better technique for *ex-situ* conservation of endemic Cu-Co species. Not only did whole-turf successfully translocate numerous target species (i.e. species present on the reference ecosystem) that were not present in the topsoil areas, but it also resulted in fewer ruderal and non-target species compared to topsoil spreading. This was likely due to a higher competition with already established vegetation (Bullock 1998). Whole-turf translocation success varied by vegetation type, with steppe community presenting better results than steppic savanna. In a restoration perspective, the translocated steppe community structure was close to the reference ecosystem and most of the structuring species were successfully translocated, with only one SoC missing: *Ocimum vanderystii*. Xeric communities, such as the steppe, seem to transfer most successfully (Bullock 1998; Trueman et al. 2007; Pywell et al. 2011), as the shallower soils improve the ability to salvage intact underground root systems. Steppe contains shallow soils, commonly around 40cm in depth (unpublished data), which limits root breakage and increases survival translocation. In addition, higher Cu and Co concentrations in steppe soils (Saad et al. 2012; Séleck et al. 2013) reduce colonization and competition by invasive species that are not adapted to harsh edaphic conditions (Bullock 1998). Population reinforcement should be planned to prevent the decline of some particular species which might be observed (i.e. for species of concern missing or in low abundances). Fitness of translocated and pristine populations should be studied to assess potential differences between these populations.

Whole-turf translocation was less successful for the steppic savanna as the translocated communities differed from the reference ecosystem. This may be due to several factors including the inefficient translocation of species, mechanical fragmentation and disturbance of mats, gaps between mats, inadequate mat depth, preparation of the receptor site, and environmental/edaphic differences between donor and receptor sites (Bullock 1998; Box 2003). Inefficient translocation of some dominant and structuring species, including *Cryptosepalum maraviense*, *Droogmansia pteropus*, *Ocimum vanderystii* and *Triumfetta likasiensis* in our case, likely contributed to divergence in species composition compared to reference ecosystem (Tischew et al. 2014). *Cryptosepalum maraviense* (Fabaceae) which represented close to 80% of the vegetation cover in the reference ecosystem, is a xylopod species with a large woody underground root system that strongly competes with grass. In translocated communities, the absence of this dominant species allowed an overabundance of grass species such as *Diheteropogon grandiflorus*, *Rhytachne rottboellioides*, *Trachypogon spicatus* or *Monocymbium ceresiiforme*. This is also true for other xylopod species; the process of removing vegetation mats breaks up the deep rooting systems of these structuring species which did not establish in the translocated communities. In addition, several opportunist and non-target species colonized gaps between mats in the less mineralized soils further increasing the divergence from reference communities. In this case, the introduction/translocation of some nursery seedlings of key species could maybe limit the grass competition and allow the steppic savanna community to tend to the reference state.

The study results also revealed that whole-turf translocation communities tended to diverge from the reference communities over time, particularly for the steppic savanna community. While resulting in the successful translocation of a high proportion SoC, the whole-turf translocation method did not exactly duplicate the reference Cu-Co communities due to disturbance during translocation and changes in vegetation cover and dominant species, particularly an increase in grasses and decrease in forbs. This was already noticed for numerous community translocation studies (Conlin and Ebersole 2001; Bruelheide 2003; Bay and Ebersole 2006; Fahselt 2007; Trueman et al. 2007; Klimes et al. 2010; Box et al. 2011; Pywell et al. 2011).

This study was realized based on 2 years monitoring and offer an excellent view of the short term results of translocation. However, long term monitoring (i.e. up to 20 years, Pywell et al. 2011) **is required to conclude on successful outcomes of these translocations, which is why translocation monitoring is continuing. In addition,** it should be noted that this study assessed success of one project, and, based on these short-term results, TFM has made modifications to the translocation program based on the results of this study including development of a layer of highly mineralized subgrade at translocation sites and improving quality and efficiency of topsoil and mat transfer. There are several additional recommendations based on the results of this study that could improve translocation success. First, active management is a critical factor to ensure the sustainability of translocated communities (Box 2003; SER 2004; Box et al. 2011). Removal of invasive species, reduction of the density of overabundant species, and control of weeds and invasive species are required to promote long-term success of the translocated communities. Second, ,focus should be set on finding new effective techniques to translocate tropical ecosystems that are dominated by perennial, resprouting species with limited seed production and deep, complex root systems. TFM is currently experimenting with equipment such as tree spades which are able to salvage deeper soils and obtain more root systems, and thereby increase translocation of the important structuring species. Vegetative reproduction techniques, such as tissue culture used in Bauxite Mines in Western Australia (Koch 2007), may also provide another mechanism for conserving these species. Third, supplemental planting could be used to translocate target species which are not successfully transferred through topsoil spreading or whole turf translocation. TFM is currently experimenting with hand transplanting several target species from reference ecosystems in an effort to increase species diversity and establish important structuring Cu-Co species at the translocation sites.

Conclusion

The results of this study stress the fact that tropical old-growth grassland communities require several centuries to assemble (Veldman et al. 2015) and are difficult to restore or translocate. It appears that large underground root systems common among plant species in savanna and tropical grasslands (Overbeck and Pfadenhauer 2007b; Fidelis et al. 2010; Veldman et al. 2015) are limiting the success of translocation techniques (topsoil spreading or whole-turf translocations) that have been successful in temperate ecosystems. In this study, whole-turf translocation was better than topsoil spreading in the successful translocation and conservation of a high proportion of endemic species from the reference ecosystem. However, neither translocation technique was able to replicate the reference communities largely due to the loss of community structure. While whole-turf translocation appears to be a better technique than topsoil spreading in Cu-Co communities, the high cost may limit its implementation at large scale and would require significant economic commitment to be included in restoration programs (Kirmer et al. 2009; Box et al. 2011; Török et al. 2011).

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Table 1: Presence of Species of Concern (SoC) (i.e. strict endemic, broad endemic, threatened and metallophytes species, see Faucon et al. 2010) in both whole-turf translocation and topsoil spreading for both vegetation type, the steppe and the steppic savanna.

	SoC present in the Kavifwafwaulu reference outcrop	SoC in whole-turf translocation	SoC in topsoil spreading
Species of Concern in the steppe	*Sporobolus congoensis*	X	X (low abundance)
	Eragrostis racemosa	X	X
	Crotalaria cobalticola	X	X (low abundance)
	Bulbostylis cupricola	X	X
	Ascolepis metallorum	X	
	Haumaniastrum robertii	X	X
	Bulbostylis pseudoperennis	X (low abundance)	X
	Ocimum vanderystii		
	Gladiolius ledoctei	X	X
	Sopubia neptunii	X	
	Anisopappus davyi	X	
Species of Concern in the steppic savanna	*Ocimum vanderystii*	X (low abundance)	
	Diplolophium marthozianum	X (low abundance)	
	Triumfetta welwitschii var. *rogersii*	X (low abundance)	X
	Triumfetta likasiensis		
	Eragrostis racemosa	X	
	Haumaniastrum rosulatum	X	
	Basananthe kisimbae		
	Lopholaena deltombei	X	
	Ascolepis metallorum	X	
	Acalypha cupricola		
	Sporobolus congoensis		

Fig.1 Effect of translocation technique on a) plant species richness.m^{-2} and b) the percentage of vegetation cover in march 2013 compared to the reference ecosystem surveyed in 2009 . For both vegetation type, Ref is the reference community, WWT represent the whole-turf translocation and TS is the topsoil spreading. Data represent mean ± SE, two bars with no letter in common are significantly different according to the glm procedures ($p<0.05$).

Fig.2 Correspondence Analysis run on the matrix of plant percent cover in 1m² quadrats in 2013 according to the both vegetation-type: steppe and steppic savanna and according to the reference and the two different translocation techniques: whole-turf translocation and topsoil spreading [109 points x 158 species]. Projection of the two first axes, axis 1 (42.8 %) and axis 2 (25 %).

Fig.3 a) Correspondence Analysis run on the matrix of plant percent cover in 1m² quadrats in the references and in whole turf translocation in 2011, 2012 and 2013 according to the two vegetation-type: steppe and steppic savanna [205 points x 136 species]. Projection of the two first axes, axis 1 (50%) and axis 2 (26%), only plot barycenters are shown. WWT represent the whole-turf translocation. b) Correspondence Analysis run on the matrix of plant percent cover in 1m² quadrats in the references and in topsoil spreading in 2012 and 2013 according to the two vegetation-type: steppe and steppic savanna [71 points x 1113 species]. Projection of the two first axes, axis 1 (49.5 %) and axis 2 (20.5 %), only plot barycenters are shown. TS is the topsoil spreading.

Fig.4 Higher Abundance Index (HAI), Community Structure Integrity Index (CSII) and Normalized Community Structure Integrity Index (Normalized CSII) for the reference (Ref), whole-turf translocation (WTT) and topsoil spreading (TS) communities according to the two kinds of communities: steppe and steppic savanna. Data are mean ± SE, two bars with no letter in common are significantly different according to the Tukey Honestly Significant Differences comparisons ($p<0.05$).

Fig.5 Mean abundance (± standard error) of reference steppe community at Kaviwafwaulu hill and translocated steppe communities (whole-turf translocation and topsoil spreading). In order to have an easy reading graph, log of mean abundance are represented. White bars represent mean abundances in the reference communities. Light grey bars represent less or same mean abundances in the translocated communities than in the reference whereas dark grey bars represent higher mean abundances in the translocated communities than in the reference. * indicates Species of Concern (i.e. strict endemic and broad endemic of Cu-Co-rich soil (Faucon et al. 2010) and hyperaccumuator species (Faucon et al. 2007)).

Fig.6 Mean abundance (± standard error) of reference steppic savanna community at Kaviwafwaulu hill and translocated steppic savanna communities (whole-turf translocation and topsoil spreading). In order to have an easy reading graph, log of mean abundance are represented. White bars represent mean abundances in the reference communities. Light grey bars represent less mean abundances in the translocated communities than in the reference whereas dark grey bars represent higher mean abundances in the translocated communities than in the reference. For clearness purposes, only species which occur in more than 3 quadrats are represented (83 on 121 species). * indicates Species of Concern (i.e. strict endemic and broad endemic of Cu-Co-rich soil (Faucon et al. 2010) and hyperaccumulator species (Faucon et al. 2007)).

Electronic Supplementary Material

Appendix 1: a) Global view of the original Kavifwafwaulu Cu-Co outcrop with details on b) the steppe and c) the steppic savanna.

Appendix 2: Design of topsoil spreading experimentation. On top, depths of subsoil and topsoil layers are represented on a transversal section schema. At the bottom, aerial view of the two topsoil stripes spread on the waste dump.

Appendix 3: Pictures of the different steps of the topsoil spreading experimentation, a) delimitation of the area where topsoil was collected; b) the first 20cm of topsoil layer was stripped with a bulldozer and c) stored at the edge of the area for a short time, d) around 50 cm of subsoil was also stripped with a bulldozer; e) topsoil and subsoil were loaded and transferred to the waste dump and spread (first the subsoil and then the topsoil); f) topsoils from the steppe and the steppic savanna were spread on strips of 10m x 75m and 13m x 75m respectively in August 2011, g) topsoil spreading in February 2012 and h) topsoil spreading in May 2014.

Appendix 4: Design of whole-turf translocation experimentation. On top, depth of subsoil and topsoil layers are represented on a transversal section scheme. At the bottom, aerial view of the area where whole vegetation turves were established.

Appendix 5: Pictures of the different steps of the whole-turf translocation, a) delimitation of the area where vegetation mats were collected; b) the receptor site consisted in a fallow where the local upper soil layer was excavated and a layer of subsoil from the donor site, Kavifwafwaulu, was spread; c) and d) vegetation turfs were extracted at the donor site using a backhoe; e) vegetation turfs were brought to the receptor site by truck, f) unloaded and set in place manually; g) vegetation mats from steppe were set in a strip of 40m x 6m and a strip of 40m x 34m for the steppic savanna vegetation mats between September 2010 to January 2011, h) whole-turf translocation in March 2013.