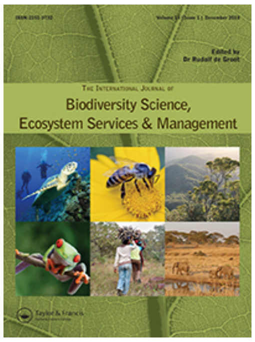

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Restoration planning for climate change mitigation and adaptation in the city of Durban, South Africa

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ABSTRACT
Effective planning of a large-scale restoration project is challenging, because of the range of factors that need to be considered (e.g. restoration of multiple habitats with varying degradation levels, multiple restoration goals and limited conservation resources). Ecological restoration planning studies typically focus on biodiversity and ecosystem services, rather than employment and other co-benefits. Robust Offsetting (RobOff), a restoration planning tool, was used in a forest restoration project in Durban, South Africa, to plan forest restoration considering a mosaic of habitats with varying levels of degradation, diverse restoration actions, a limited budget and multiple (biodiversity, carbon stock and employment) goals. To achieve this, the restoration action currently being implemented (= *current action*) was compared to three restoration alternatives. The three restoration alternatives included (1) *natural regeneration action*; (2) *carbon action*; and (3) *biodiversity action*. The results supported *biodiversity action* as most beneficial in terms of maximizing biodiversity, carbon storage and job creation. Results showed that investing in *biodiversity action* is preferable to the status quo. RobOff ensured optimal allocation of limited resources to actions and habitats that have a potential to achieve higher biodiversity, carbon storage and job creation.

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Biodiversity prioritization; carbon stock; conservation resource allocation; decision-making tool; creating employment; RobOff software; tree planting

Introduction

Many cities around the world are highly vulnerable to the adverse impacts of climate change (UN-Habitat 2011). The likely impacts include but not limited to species extinctions (Chapin III et al. 2000), a decrease in human health quality due to heat waves, poor air and water quality (Patz et al. 2005), an increase in frequency and intensity of floods, and an increase in erosion of coastal areas leading to infrastructure damage (Chapin III et al. 2000). These impacts will be exacerbated by poor governance, limited service delivery and existing socio-economic challenges. This will result in a growing dependence upon ecosystem services, thus leading to degradation and fragmentation of functional ecosystems, and loss of ecosystem services critical for human well-being (United Nations-Habitat 2011; Oldfield et al. 2013; Elmqvist et al. 2015). By 2030, the world rural and urban population is predicted to increase to 3.4 and 5.1 billion, respectively (United Nations 2015), with approximately 60% of urban land predicted to be under built infrastructure (Elmqvist et al. 2013). Environmental managers and city planners are faced with increasing pressure to protect ecosystems inside and outside of cities to ensure a continued supply of ecosystem services. This will ensure that the needs of the current and future generations are met (Schewenius et al. 2014), thus achieving more liveable and healthy cities that are prepared for the impacts of climate change (Elmqvist et al. 2015). Ecosystem-based adaptation (EBA) is increasingly recognized as one of a toolbox of solutions for challenges faced by cities (Roberts and O'Donoghue 2013; Elmqvist et al. 2015). The EBA can be defined as 'the use of biodiversity and ecosystem services as part of an overall adaptation strategy' (CBD 2009). It includes sustainable management, conservation and restoration of degraded ecosystems to provide services that help society adapt to the adverse impacts of climate change (CBD 2009; Colls et al. 2009; Munang et al. 2013; Doswald et al. 2014). For example, mangrove

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Supplemental data for this article can be accessed here.

forest and coastal wetlands can help protect coastal communities from tropical storm surges which are predicted to increase in frequency, intensity, size and duration (Alongi 2008).

Cities such as Auckland, Bangalore, Durban, London, Mombasa, New York, and São Paulo have embarked on large-scale tree planting (active restoration) projects in degraded forests, abandoned industrial mine and agricultural lands (Engel and Parrotta 2001; Kitha and Lyth 2011; Rees and Everett 2012; Oldfield et al. 2013; Douwes et al. 2015). These projects seek to enhance biodiversity conservation (through planting of native flora) and contribute a range of critical ecosystem services. The critical ecosystem services include provisioning services (e.g. water, food and medicine), regulation services (e.g. carbon sequestration, water purification, storm-water regulation and microclimate regulation), cultural services (e.g. aesthetic, recreation, spiritual fulfilment and education) and supporting services (e.g. soil stabilization and habitat provision) (Saxena et al. 2001; Dudley and Stolton 2005; Thompson et al. 2009; Elmqvist et al. 2015; Negi et al. 2015; Oldfield et al. 2015). Tree planting can also provide employment opportunities to impoverished urban communities with limited access to other employment and government services (Douwes et al. 2015; Perring et al. 2015).

Although tree planting offers a wide range of benefits, funding for restoration is often limited, which constrains restoration actions and the extent of land that can be restored (Adame et al. 2015; Mazziotta et al. 2016). The limited restoration resources necessitate the identification of cost effective actions and selection of restoration areas which provide multiple restoration benefits (Crossman and Bryan 2009). Planning of a large-scale restoration project can be a challenging undertaking given multiple habitats with varying degrees of degradation, multiple restoration activity choices and (often competing) priorities for ecological and socio-economic goals to be achieved within limited restoration budgets (Maron and Cockfield 2008; Turpie et al. 2008; Brancalion et al. 2014; Vogler et al. 2015). Socio-economic co-benefits are increasingly recognized in restoration projects, because they influence restoration success (Perring et al. 2015). For example, depriving local communities' access to forest services (e.g. food, medicine and fuelwood collection) that support their livelihoods without providing viable alternatives can lead to restoration project failure (Saxena et al. 2001; Orsi et al. 2011; Barr and Sayer 2012; Le et al. 2012).

Many restoration funding agencies, especially state agencies, are now funding restoration projects that aim to achieve stated ecological and socio-economic goals simultaneously (Maron and Cockfield 2008; Pendleton 2010). Deciding where to carry out restoration to achieve all target goals is a key challenge in large-scale restoration (Torrubia et al. 2014). Without prioritization planning, resource allocation is likely to be made in an *ad hoc* manner and this might affect the restoration success (Wilson et al. 2011). Managers of large-scale restoration projects are now incorporating systematic planning tools such as Marxan, Integer Linear-programming, and Zonation (Crossman and Bryan 2006; Egoh et al. 2014; Moilanen et al. 2014) in large-scale restoration planning (e.g. Thomson et al. 2009; Wilson et al. 2011; Perring et al. 2015). Systematic planning tools also ensure the efficient allocation of available resources through prioritization of restoration actions. This can ensure improved ecological and socio-economic benefits, and long-term sustainability of restoration projects (Maron and Cockfield 2008; Adame et al. 2015; Rappaport et al. 2015).

A recently-released open-source software platform (https://www.helsinki.fi/en/researchgroups/metapopulation-research-centre/software), Robust Offsetting (RobOff), differs from the other systematic conservation planning tools, in that it is primarily 'action' rather than spatially-based. RobOff fills the niche, because it selects the best conservation actions given a set of goals through modelling of uncertainty around alternative conservation actions (e.g. tree planting vs. invasive alien plants [IAPs] control) have on different biodiversity features (e.g. species richness) in different environments (Pouzols and Moilanen 2013).

Systematic restoration planning studies done to guide restoration plans have accounted for either biodiversity features (e.g. species richness), ecosystem services provision (e.g. climate regulation or water purification) or both (e.g. Thomson et al. 2009; Orsi et al. 2011; Wilson et al. 2011; Budiharta et al. 2014; Egoh et al. 2014; Adame et al. 2015; Rappaport et al. 2015). This is because biodiversity and ecosystem services improve human well-being, for example, by providing humans with benefits such as clean water, climate regulation, recreation (Brancalion et al. 2014), and medicinal plants mostly for peri-urban and rural communities (Douwes et al. 2015). Although some restoration programmes include financial benefits such as employment that enhances impoverished communities' adaptation capacity to adverse impacts of climate change (e.g. Roberts and O'Donoghue 2013; Brancalion et al. 2014; Wilson and Rhemtulla 2016), there is a few of studies that prioritize employment creation in their restoration planning (see Crossman et al. 2016).

In South Africa, the city of Durban (managed by eThekwini Municipality) is a leader in climate change adaptation within developing countries (Diederichs and Roberts 2015). This is because the Municipal Climate Protection Programme is addressing the challenge of climate change vulnerability within the context of widespread poverty (Roberts and O'Donoghue 2013), intensifying urbanization and ecosystem degradation (Diederichs and Roberts 2015). The Buffelsdraai Landfill Site Community Reforestation Project (BLSCRP) was initiated to offset carbon emissions and increase climate change adaptation through biodiversity and ecosystem services restoration and employment creation (Douwes et al. 2015). This study is a *post-hoc* comparison of options that were not considered during the planning of the BLSCRP in Durban, to draw lessons for future similar planning efforts. Here, we show how RobOff could be used to efficiently allocate resources in a large-scale forest restoration project with two habitats, multiple restoration alternatives and goals (biodiversity, carbon stock and employment), with a limited budget. To achieve this objective, a sequence of key research questions were addressed:

a. What is the recommended restoration action within each habitat?
b. How do different budget scenarios influence the optimal allocation of resources (hectares and budget) to alternative restoration actions?
c. Does prioritization of restoration benefits influence the division of resources to alternative restoration actions across the habitats?

This study differs from other restoration planning studies, because it prioritizes biodiversity, carbon storage and employment creation, as well as what restoration actions are appropriate to achieve these goals. Furthermore, it provides recommendations of where and how restoration should be carried out in order to maximize biodiversity, carbon storage and employment creation.

Methods

Study area

The city of Durban, South Africa, harbours remnants of scarp forest, which is described as a refuge forest that survived the last glacial maximum (≈18,000 BP) (Eeley et al. 1999). About 15–31% of this forest type has been lost due to land transformation (e.g. because of logging and clearing for agriculture) and non-sustainable harvesting of forest products by rural communities (Von Maltitz et al. 2003). The resulting fragmentation and landscape connectivity loss, between forest patches and the increased edge ecotone (Kotze and Lawes 2007), has led the eThekwini Municipality to engage in a range of land management and restoration related practices (Diederichs and Roberts 2010; Roberts and O'Donoghue 2013). One programme, namely, the Community Reforestation Programme, includes large-scale projects for carbon sequestration and climate change adaptation purposes. The Community Reforestation Programme has three projects, including the BLSCRP. In the BLSCRP, active restoration, i.e. planting of indigenous trees, was employed within this project, to restore degraded scarp forest in a buffer area around the Buffelsdraai Landfill Site (29.62961S; 30.980392E). At least 51 of the 230 indigenous tree species occurring in the region have been planted within a 580 ha (av. 1500 trees/ha) portion of the buffer zone. Aside from tree planting, control of IAPs and fire suppression (cutting fire breaks) are also implemented (Douwes et al. 2015).

Amongst the metropolitan areas in South Africa, Durban has the highest number of people living on less than US$2 per day (eThekwini Municipality 2013). The BLSCRP directly supports two of the poorest communities, namely the Buffelsdraai and Osindisweni communities. This is in the form of direct job creation as well as through supporting local community members that grow trees for the project. In terms of tree growing, the project has trained community members (known as Tree-preneurs) to collect seeds, which they grow at their homesteads. Once the trees are big enough (greater than 30 cm in height) they are supplied to the project. Tree-preneurs source indigenous tree seeds from the local forest and woodland patches. Seedlings are traded for credit notes, which can be exchanged for items such as groceries, clothes, building materials, bicycles, or to pay for school fees or for vehicle driving lessons. Land preparation, planting and maintenance are also done by community members, either permanently or temporarily employed by the project (Douwes et al. 2015).

Analytical framework

RobOff can be used to determine optimal resource allocation solutions (Pouzols and Moilanen 2013) using a resource allocation algorithm. Pouzols and Moilanen (2012) and Pouzols et al. (2012) gave a full description of RobOff tool and the structure of calculations implemented in RObOff, but below we give a brief description of RObOff. RobOff is based on environments (e.g. habitats or any other ecological entities), condition of the environment and threats, potential actions and their associated costs (e.g. protect or restore), biodiversity features (e.g. indigenous flora or carbon stock), available budget and project time span (Figure 1). Once the setup is ready, features occurrence across environment and time is converted into conservation values. Various sources of non-linearities (e.g. response of features, uncertainty envelopes, cost functions, time discounting rate and benefit function) are considered in the aggregation of

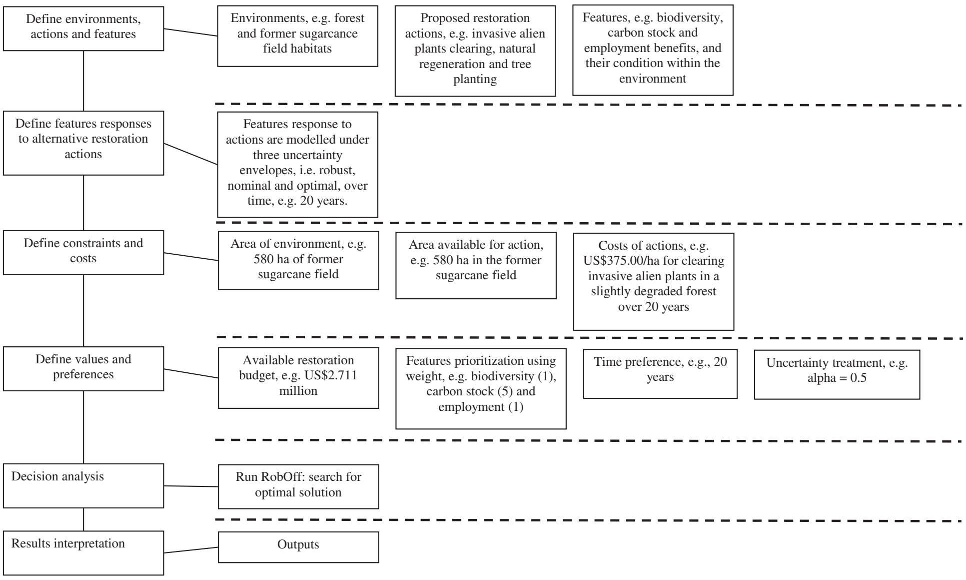


Figure 1. Flow chart of RobOff framework (modified from Pouzols and Moilanen 2013).

conservation value. Once the conservation value has been obtained, optimal allocation of resources to alternative actions can be computed. The optimization process accounts for the uncertainties within the environment and different costs of actions (Pouzols et al. 2012; Pouzols and Moilanen 2012). Five different optimization algorithms are available in RobOff. However, in this study, an Exhaustive search algorithm was used. This is because, Exhaustive search algorithm is reliable, easy to understand, deterministic and straightforward to implement (Pouzols and Moilanen 2012).

The restoration habitats used in this study included 'former sugarcane fields' and 'extant forest' with varying levels of degradation. RobOff inputs included condition of restoration habitats, external threats (e.g. IAPs), proposed alternative restoration actions (e.g. IAP control and tree planting) linked to each restoration habitat and their costs, available area to implement each action, features' occurrence in the habitat (e.g. species richness), and the features response to each action (quantified on an annual basis). The response of features over time when landscapes and environmental conditions change and when various actions are applied in different locations is uncertain. To account for uncertainty, a non-probabilistic information gap model formulation of uncertain responses is used. Information gap model contains three uncertainty envelopes (nominal, upper and lower envelopes). The uncertain development over time of the representation levels of features is given by upper and lower envelopes around the nominal envelope (Figure S1 in Supplementary Material). The uncertainty envelopes need to be specified for each discrete interval. Information gap models depend on the horizon of uncertainty using α, which indicates the degree of uncertainty. When $\alpha = 0$, the features responses will exactly match the estimated (nominal envelope) values. However, when $\alpha = 1$, features responses span the whole range between the specified envelopes (Pouzols and Moilanen 2012). In this study, the uncertainty in features responses to actions were derived using expert opinion (see Pouzols and Moilanen 2012), and α was set at 0.5. The relative weight of all biodiversity features (e.g. relative weight of 1.0 for biodiversity, 1.0 for carbon stock and 2.0 for employment) and their associated benefit functions should be defined (Pouzols and Moilanen 2012). In this study, Piecewise linear benefit function was used, because it allows one to define arbitrary shapes of the benefit function (Pouzols and Moilanen 2012). Although time discounting is an optional file in RobOff, it was included to allow comparison of future values to the present values (Pouzols and Moilanen 2012). A time discounting rate of 2.5% was used based on expert opinion.

Overall, the extent to which an action is applied to a habitat is largely determined by budget availability. Here, these inputs are used by RobOff to determine the relationship between the restoration benefits and restoration actions (e.g. what actions can achieve which benefits?), restorations actions and restoration habitats (e.g. which restoration actions can be carried out in which restoration habitats?), restoration cost and actions (e.g. what costs are associated with what actions?) and what benefits could be obtained within the budget? (Figure 1) (See Pouzols et al. 2012).

Restoration habitats

There two restoration habitats at the Buffelsdraai Landfill Site: (a) 'former sugarcane fields' where the planting of at least 51 indigenous tree species (*current action*) took place, and (b) 'extant forest' were used in this study. The 'former sugarcane fields' and 'extant forest' habitats covered 580 and 105.8 ha, respectively. The 'extant forest' was slightly degraded by invasive alien plants. Before restoration, the 'former sugarcane fields' habitat was dominated by sugarcane, IAPs and weeds (indigenous graminoids and forbs).

Restoration actions and costs

The restoration action currently being implemented (= *current action* – discontinue sugarcane farming and reforestation using at least 51 indigenous tree species to enhance biodiversity, carbon stock and provide project-linked employment for local communities) was compared to three restoration alternatives. The three restoration alternatives included (1) *natural regeneration action* – discontinue sugarcane farming and allow natural recruitment of indigenous tree species; (2) *carbon action* – discontinue sugarcane farming and undertake reforestation using 10 indigenous tree species with a higher wood density to store a higher carbon stock; and (3) *biodiversity action* – discontinue sugarcane farming and implement reforestation using 80 indigenous tree species to enhance tree species richness.

Each action was assessed in terms of tree species richness, carbon stock and employment creation and compared with the *current action* (planting of at least 51 indigenous tree species). This was done through a series of workshops with 12 local restoration ecology and biodiversity experts (academics and practitioners). Experts were chosen based on their knowledge of local biodiversity, forest restoration management and cost, and the RobOff software. The *do nothing* (default in RobOff) and *natural regeneration* actions were proposed for the 'extant forest' while *do nothing, natural regeneration action, current action, carbon action* and *biodiversity action* were proposed for the 'former sugarcane fields' by the experts (Table 1).

Restoration cost of each action within the habitats was estimated per ha, over a 20-year period (Table S1 in Supplementary Material). Cost was divided into two categories: initial reforestation and subsequent site maintenance costs. Initial costs included seedling production (buying trees from Tree-preneurs), land preparation and planting, while site maintenance cost included removal of IAPs and fire suppression. Initial and fire suppression costs were estimated using expert knowledge and the financial report from the Municipality's reforestation programme (eThekwini Municipality 2011) (Table S1 in Supplementary Material). *Natural regeneration action* cost per ha in the 'extant forest' only included the cost of clearing IAPs, because forest fires are rare at this locality, hence it was lower than the cost of the similar action per ha in the 'former sugarcane fields', which included clearing IAPs and fire suppression. In contrast, *carbon action* cost per ha was higher than the *current* and *biodiversity*

Table 1. Restoration actions and their associated costs per ha over a 20-year period in the 'extant forest' and 'former sugarcane fields' restoration habitats (see supplemental material for details).

Habitats	Actions	Aims	Intervention	Cost (US$)/ha over 20 years
Extant forest (105.8 ha)	Do nothing (default in RobOff)	Control action; indicates areas where funds do not suffice for action	No intervention	0
	Natural regeneration action	To conserve the extant forest patches.	Allow natural regeneration of indigenous plants supported by invasive alien plants (IAPs) clearing.	375
Former sugarcane fields (580 ha)	Do nothing	Same as in the extant forest	Same as in the extant forest.	0
	Natural regeneration action	To allow natural regeneration of indigenous plants.	Allow natural regeneration of indigenous plants and site maintenance (IAPS clearing and cutting fire breaks).	4260
	Current action	To restore biodiversity, sequester carbon, and to create project-related employment for the local communities.	Planting of 51 indigenous tree species at 1000 trees per hectare and site maintenance. This is the status quo plan for the site.	4352
	Carbon action	To maximize carbon sequestration.	Planting of 10 indigenous tree species with high wood density at 1000 trees per hectare and site maintenance.	4678
	Biodiversity action	To boost tree species richness and to increase ecosystem functioning.	Planting of 80 indigenous trees species from the regional pool of scarp forest trees at 1000 trees per hectare and site maintenance.	4450

actions, because it included slow growing tree species with high wood density, thus requiring more intense site maintenance than the current and biodiversity actions (Table S1 in Supplementary Material). The IAPs clearing cost was obtained from the South African National Parks' Working for Water Programme (IAPs clearing project, unpublished database) and from published scientific literature (Marais and Wannenburgh 2008). The IAPs clearing method included uprooting of saplings and cutting of shrubs and trees.

Restoration features response (referred to as restoration benefits in this study) to alternative restoration actions across habitats

Three critical co-benefits from Buffelsdraai Landfill Site were chosen, namely, biodiversity, carbon stock and employment creation. Based on published literature of biodiversity, carbon stock and reforestation costs reports and local knowledge (Tables S2–S4 in Supplementary Material), the experts estimated (annually over a period of 20 years) the response of benefits to alternative restoration actions across habitats under the lower, average and upper uncertainty envelopes (see Tables S1–S3 in Supplementary Material for a detailed description). Tree species richness was quantified in terms of no. of tree species/ha (Table S2 in Supplementary Material), carbon stock benefits in terms of above-ground carbon storage in trees (tC/ha) (Table S3 in Supplementary Material), and employment creation benefits in terms of no. of person days/ha (Table S4 in Supplementary Material). Tree species richness was chosen as a simplified measure of biodiversity, because it correlates with the diversity of the ecosystem and is a measurement that can be easily monitored (Gotelli and Colwell 2001). Employment created was calculated as the sum of people involved in seedling production, land preparation, planting and site maintenance. One person day is equivalent to eight working hours per day with a daily remuneration rate of US$7 (as of November 2015, XE Currency Converter).

A 20-year restoration period was used, because it was estimated that, after this time, the trees would have grown into a forest, and the carbon stock in the restored scarp forest would be similar to woodland in the region (Glenday 2007).

Restoration budget

The cost of restoring all the 'former sugarcane fields' (580 ha) based on the most expensive action (i.e. *carbon action*) was calculated and used as the maximum budget (estimated at ZAR 38.5 million, or US$ 2.711 million as of November 2015). Optimal resource allocations were investigated for five budget scenarios: US$ 0.271 (10%), $ 0.677 (25%), $ 1.355 (50%), $ 2.033 (75%) and $ 2.711 (100%) million to explore the influence of budget availability on the allocation of resources to alternative restoration actions.

Data analyses

The cost of each alternative restoration action per hectare was quantified. To assess the effect of budget availability on resource allocation, analyses were replicated under alternative budget levels (previous section). Effect of biodiversity, carbon stock and employment prioritization on allocation of resources to alternative restoration actions was also assessed. Seven weighting schemes (e.g. relative weight of 1.0 for biodiversity, 1.0 for carbon stock and 2.0 for employment) were used to explore this effect. Prioritization of restoration benefits was done under seven permutations (i.e. seven prioritization scenarios) (Table S5 in Supplementary Material). To assess the effects of prioritization of alternative restoration benefits, RobOff was run using the 50% and 100% budget scenarios over a 20-year period. Only the 50% and 100% budget scenarios were included, because similar restoration action to 50% and 100% was recommended under the 10% and 25% budget scenarios, although the benefits decreased with a decrease in available budget.

Results

The overall results showed when budget is limited, *biodiversity action* should be employed to restore the 'former sugarcane field' in order to maximize biodiversity, carbon stock and employment benefits. Both biodiversity and employment goals prioritization achieved higher species richness, carbon stock and employment while carbon stock goal prioritization was at the expense of biodiversity.

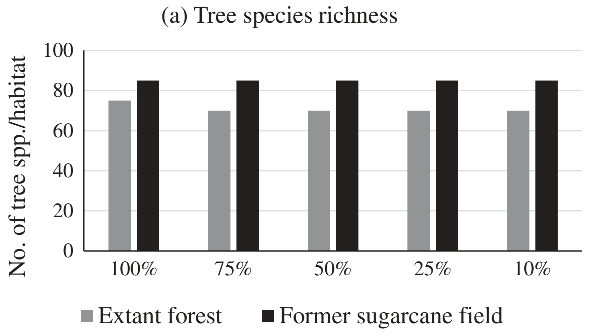
How do different budget scenarios affect the allocation of resources to alternative restoration actions and benefits across different habitats?

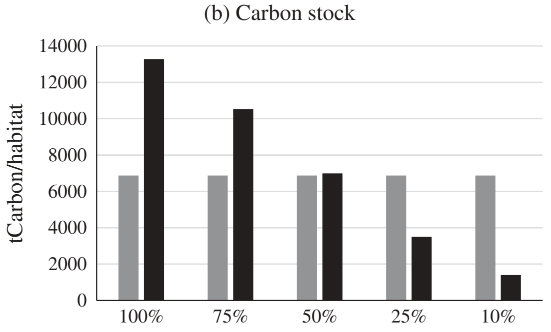
Across all budget scenarios, degraded 'former sugarcane fields' should be prioritized for restoration rather than the 'extant forest'. Only under the 100% budget scenario (US$2.711 million), some provision was made also for the slightly degraded 'extant forest'. *Natural regeneration action* was selected for the 'extant forest', while *biodiversity action* was selected for the 'former sugarcane fields'. A reduction in budget eliminated the *natural regeneration action* in the 'extant forest', and prioritized the 'former sugarcane fields' with *biodiversity action* recommended. As the allocated budget decreased by an order of magnitude, fewer hectares were allocated to restoration, but

Table 2. Allocation of resources by RobOff to alternative restoration actions under budget scenarios across habitats. *Carbon* and *current actions* were not selected under any budget scenario.

Budget scenarios (US$)	Restoration habitats	Recommended actions	Allocated area (ha)	Allocated budget (US$)
2.711 million (100%)	Extant forest	Do nothing	33.3	0
		Natural regeneration action	72.5	0.13 million
	Former sugarcane fields	Do nothing	2.6	0
		Biodiversity action	577.4	2.564 million
2.033 million (75%)	Extant forest	Do nothing	105.8	0
	Former Sugarcane fields	Do nothing	121.8	0
		Biodiversity action	458.2	2.035 million
1.355 million (50%)	Extant forest	Do nothing	105.8	0
	Former sugarcane fields	Do nothing	276	0
		Biodiversity action	304	1.35 million
0.677 million (25%)	Extant forest	Do nothing	105.8	0
	Former sugarcane fields	Do nothing	428	0
		Biodiversity action	152	0.675 million
0.271 million (10%)	Extant forest	Do nothing	105.8	0
	Former sugarcane fields	Do nothing	519.2	0
		Biodiversity action	60.8	0.27 million

biodiversity action remained the priority (Table 2); this is because *biodiversity action* offered the optimal solution.


(a) Tree species richness


(b) Carbon stock

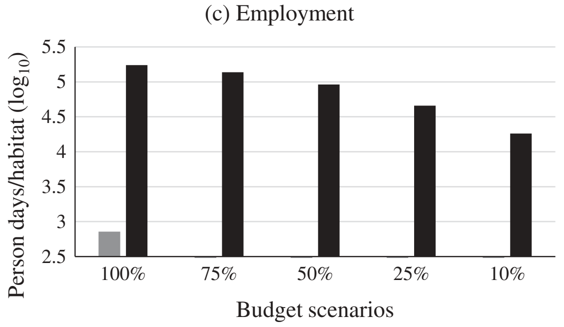

(c) Employment

Figure 2. Restoration benefits, (a) biodiversity, (b) carbon stock and (c) employment under different budget scenarios, over a 20-year period. US$2.711 million = 100%, US$2.033 million = 75%, US$1.355 million = 50%, US$0.677 million = 25% and US$0.271 million = 10%.

Under the 100% budget scenario, allocation of resources to restoring slightly degraded 'extant forest' increased tree species richness from 70 to 75 over a 20-year period. Employment increased from 0 to 720 person days over a 20-year period. Carbon stock did not change (Figure 2(a–c)) over 20 years, because, if the IAPs are not cleared, they would also store carbon. When *biodiversity action* was the chosen restoration measure in the 'former sugarcane fields', the result was an increase in biodiversity (from 2 to 85 tree species per habitat over a 20-year period), carbon stock (from 0 to 13,280 tC per habitat over 20 years) and employment (from 0 to 173,451 person days per habitat over a 20-year period) gain (Figure 2(a–c)). A decrease in budget (75% to 10% budget scenarios) did not affect biodiversity (Figure 2(a)), because 80 tree species would be planted at an average density of 1500 trees per hectare, and five more species are expected to recruit within the planted habitat over a 20-year period; hence, 85 tree species over 20 years. Although, a decrease in budget did not reduce tree biodiversity, it reduced tree population density and the planted area. For example, under the 100% budget, 866,100 trees would be planted in 577.4 ha whereas under a 10% budget, 91,200 trees would be planted in 60.8 ha. Therefore, it would take a long time for the city to achieve its restoration objectives under a 10% budget (e.g. high carbon stock).

Does prioritization of restoration benefits influence the allocation division of resources to alternative restoration actions and benefits across the habitats?

In the 'extant forest' under the 100% budget, giving more weight to one restoration goal (e.g. biodiversity) over the other did not affect the allocation of resources (Table 3), nor trade-offs in restoration benefits (Figure 3(a–c)). Under the 50% budget, a similar trend to the 100% budget was observed in terms of

Table 3. The influence of budget scenarios on the allocation of resources to alternative restoration actions under restoration benefits prioritization scenarios (see Table S5 in Supplementary Material) across habitats. Scenarios that yielded similar results were lumped.

Budget scenarios	Prioritization scenarios	Restoration habitats	Recommended actions	Allocated area (ha)	Allocated budget (million US$)
100%	1, 2, 3, 6 and 7	Forest	Do nothing	33.3	0
			Natural regeneration action	72.5	0.013
	1, 2, 3, 6 and 7	Former sugarcane fields	Do nothing	2.6	0
			Biodiversity action	577.4	2.564
	4 and 5	Forest	Do nothing	33.3	0
			Natural regeneration action	72.5	0.013
	4 and 5	Former sugarcane fields	Do nothing	1	0
			Carbon action	579	2.7
50%	1, 2, 3, 6 and 7	Forest	Do nothing	105.8	0
	1, 2, 3, 6 and 7	Former sugarcane fields	Do nothing	276	0
			Biodiversity action	304	1.3
	4 and 5	Forest	Do nothing	105.8	0
	4 and 5	Former sugarcane fields	Do nothing	290.5	0
			Carbon action	289.5	1.3

Natural regeneration action cost per ha in the forest habitat only included clearing of fewer IAPs infestations, hence is lower than the cost of the similar action per ha in the 'former sugarcane fields', which included IAPs clearing and fire suppression. On the other hand, carbon action cost per ha was higher than the current and biodiversity actions, because it included slow growing tree species with high wood density, thus requiring more intense site maintenance than the current and biodiversity actions (Table S4 in Supplementary Material).

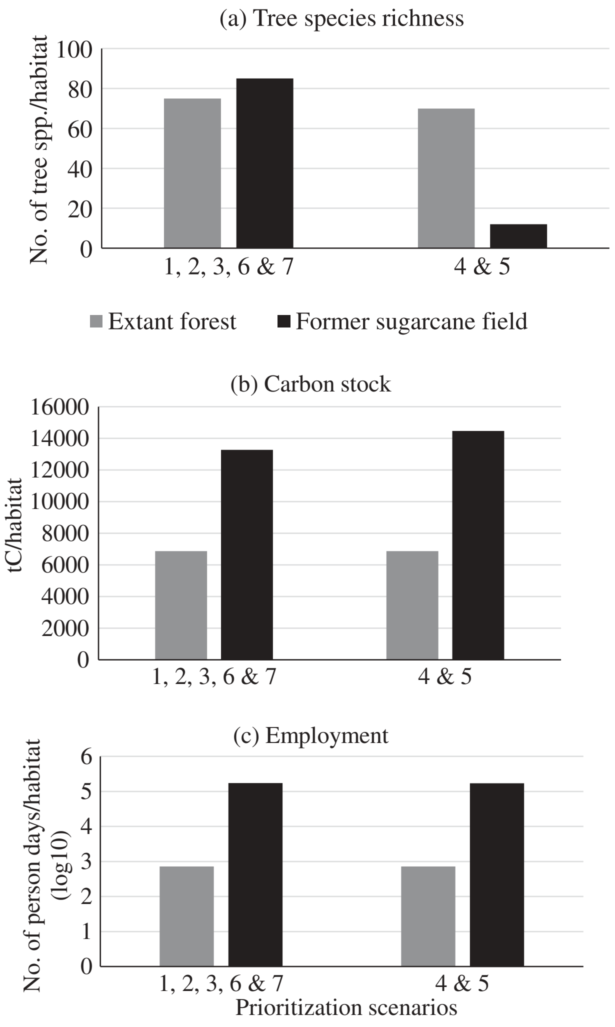


Figure 3. Restoration benefits, (a) biodiversity, (b) carbon stock and (c) employment under different restoration benefits prioritization scenarios (see Table S5 in Supplementary Material) under 100% budget scenario, over a 20-year period. Lumped scenarios yielded similar results.

resource allocation (Table 3), although restoration benefits decreased (Figure S3a–c in Supplementary Material).

In the 'former sugarcane fields' under the 50% and 100% budget, restoration prioritization scenarios 1, 2, 3, 6 and 7 yielded similar resource allocation (Table 3). The *biodiversity action* was recommended under both the biodiversity and employment benefits prioritization scenarios, because it achieved more biodiversity and employment than the other alternative restoration actions. Carbon prioritization (scenarios 4 and 5) was at the expense of biodiversity, because this action only achieved 12 tree species over 20 years. However, when budget is not limited (US $2.711 million), carbon prioritization increased carbon stock by 8.2%, and employment decreased by 1.3% compared to the unweighted, biodiversity and employment scenarios (Figure 3(a–c)). The amount of benefits also decreased with a decrease in available budget (Figure S2a–c in Supplementary Material).

Discussion

The use of RobOff in large-scale restoration projects can be helpful to systematically and effectively plan restoration interventions to achieve multiple restoration goals simultaneously. RobOff compels the user (restoration planners) to identify objectives and intended outcomes of a restoration programme (e.g. climate change mitigation vs. social advancement benefits), and to assess the suitability of multiple restoration actions to achieve the intended outcomes. In this study, RobOff identified better restoration interventions than current restoration approaches, that could have been employed to achieve greater biodiversity (= tree species richness), carbon stock and socio-economic advancement at Buffelsdraai Landfill Site. This is an important demonstration of how systematically planning for restoration can lead to greater benefits than *ad* hoc approaches.

In our study, prioritization of the degraded 'former sugarcane fields' by RobOff shows that it is more beneficial to restore degraded land than restoring a partially degraded 'extant forest' which is still functional. This is especially so, if socio-economic benefit as job creation is targeted, as was the case at Buffelsdraai (Douwes et al. 2015). This is because restoring a partially degraded forest may typically achieve only a fraction of the potential employment benefits that could be realized when restoring 'former sugarcane fields'. Furthermore, restoration of 'former sugarcane fields' simultaneously achieves the municipality's other restoration benefits (biodiversity restoration, carbon sequestration and socio-economic advancement). Employment in the 'extant forest' only included IAPs clearing, whereas in the restoration of 'former sugarcane fields' employment opportunities included seedling production, land preparation, planting, and site maintenance, IAPs clearing and fire suppression. Similar findings were reported by Budiharta et al. (2014). In the restoration planning of moderately and highly degraded forests in Indonesia, Budiharta et al. (2014) found that, when budget is not limited, restoration of moderately degraded forest is additionally recommended to achieve restoration of threatened species habitat. However when the budget is limited, resources should always be allocated to the restoration of a highly degraded lowland forest to achieve carbon sequestration and to restore habitat of the threatened mammals (Budiharta et al. 2014).

In this study, *biodiversity action* was prioritized over alternative actions in the restoration of the 'former sugarcane fields'. *Carbon action* was recommended when the main benefit sought was increased carbon stock, but the slight increase in carbon stock compared to *Biodiversity action* does not warrant its implementation. These results support the biodiversity-ecosystem functioning approach which is increasingly adopted in ecological restoration planning, because restoration of stable multiple ecosystem functions requires diverse species (Aerts and Honnay 2011; Cunningham et al. 2015). Species-rich systems are multifunctional, more stable and more productive, because different species functional traits allow species to fully utilize their limiting resources (Cardinale et al. 2012). They are more resistant and resilient to extreme climate change related disturbances such as pest and disease outbreaks, and changing fire patterns (Biringer and Hansen 2005; Aerts and Honnay 2011).

An approach focused on improving diversity rather than tree density, is also more likely to create a resilient socio-ecological ecosystem compared to the other actions (Biggs et al. 2015). While tree planting to store carbon contributes to climate change mitigation, if diversity is not considered, the system's resilience is compromised, which could impact on climate change adaptation in the socio-ecological system. Species diversity is a key factor for the resilience of the socio-ecological system, particularly after disasters such as floods and fires (Adger et al. 2005; Leslie and McCabe 2014). Actions geared towards improving biodiversity are also important in the provision of other ecosystem services such as food and medicinal plants provision (Orsi and Geneletti 2010). Furthermore, more and more studies are showing that biodiversity underpins most ecosystem services (Harrison et al. 2014). Interestingly, the biodiversity focused action also achieves employment opportunities, to alleviate poverty and improve lives of most people (Aronson et al. 2006). Therefore, instead of focusing on reforestation to store carbon, restoration actions geared towards biodiversity as in the *biodiversity action* in this study, which achieved all three restoration benefits, is a better alternative (Crossman et al. 2016).

Our results have implication for forest restoration projects that only aim to achieve climate change mitigation through planting of a few fast growing species (= *carbon action*), especially exotic tree species (e.g. Piotto et al. 2011; Oldfield et al. 2015). This is because the *biodiversity action* in this study achieved higher biodiversity, carbon and employment. Furthermore, the *carbon action* (especially planting of fast growing exotic tree species) has been widely criticized, because it offers few ecological and socio-economic benefits compared to high species diverse indigenous forests (e.g. Smith 2002; Cao et al. 2009; Fernandes et al. 2016). Numerous studies have shown that species-rich systems outperform species-poor systems and the highly favoured fast growing exotic tree species in terms carbon storage and sequestration (Aerts and Honnay 2011; Piotto et al. 2011; Hulvey et al. 2013; Cunningham et al. 2015). Therefore, forest restoration projects that are mainly driven by climate change mitigation should also plant a higher diversity of indigenous tree species, because they can achieve their main goal and other multiple co-benefits (e.g. Crossman et al. 2016).

In our study, both biodiversity and employment prioritization showed more positive contributions to employment creation for local communities, compared to carbon benefit prioritization. Apart from on-site employment, communities trade seedlings for credit notes, which can be exchanged for items such as groceries, clothes, building materials, bicycles, or to pay for school fees or for vehicle driving lessons. Furthermore, the BLSCRP also has a significant contribution to environmental education by serving as an outdoor classroom for primary and secondary schools in the area. Therefore, the benefits that local communities derive from the BLSCRP are more likely to induce positive attitude towards the project. For example, in Kosti Province of White Nile area of Central Sudan, Kobbail (2012) found that local communities developed a positive attitude towards a reforestation project that addressed their socio-economic needs (e.g. employment creation, and food and medicinal plants privision).

The likelihood of a negative attitude is real, especially if local communities, who were employed by sugarcane farmers in the area, suddenly find themselves without jobs as a result of the removal of land from sugarcane farming for conversion to forest. Some of the past forest restoration projects have not been successful because they failed to account for the socio-economic needs of local communities in the planning phase (Saxena et al. 2001; Barr and Sayer 2012; Le et al. 2012). In developing countries, restoration projects are highly likely to receive more local support if they promote socio-economic development (Aronson et al. 2006; Le et al. 2012; Abram et al. 2014). The socio-economic benefits include income from forest products, employment opportunities, food and fibre provision and community capacity building (Chokkalingam et al. 2006; Le et al. 2012). As a result, restoration projects are now designed to address both ecological and socio-economic needs (Mansourian and Dudley 2005). For example, communities are now involved in the selection of tree species that offer them benefits such as food, medicine, fuel and fodder (Saxena et al. 2001; Mekoya et al. 2008). Local community members can be recruited as labourers to carry out land preparation, planting, and site maintenance, to avoid undesirable social impacts.

Restoration practitioners are failing to show links between ecological restoration, society and policy (Aronson et al. 2010), and also underselling the full socio-economic benefits of restoration, which influence the society to invest in restoration as a primary tool of natural resource management (Aronson et al. 2010; Wortley et al. 2013). Furthermore, restoration projects that aim to achieve a balanced outcome (biodiversity and ecosystem services restoration, and socio-economic advancement) tend to be viewed more positively by funders, because of the broader benefits to the society (Sayer et al. 2004). The BLSCRP was able to gain funding, because its objectives were to mitigate climate change through biodiversity restoration and employment creation for local impoverished communities.

This study has shown the value of using RobOff to help improve the efficiency of large-scale restoration projects planning and their benefits. The inclusion of RobOff analyses in the initial planning of BLSCRP by the municipality restoration team would have shown how resources could have been more optimally allocated to alternative restoration actions that would achieve more biodiversity, carbon stock and employment benefits. Although our study assessed resource allocation within the forest ecosystem, RobOff is capable of solving very high dimensional problems, i.e. multiple ecosystems (e.g. forest, grassland and wetland) with multiple but different restoration actions and goals (Pouzols and Moilanen 2013).

Disclosure statement

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