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Managing tradeoffs in landscape restoration and revegetation projects.

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Abstract:

Landscape restoration projects often have multiple and disparate conservation, resource enhancement and sometimes economic objectives, since projects that seek to meet more than one objective tend to be viewed more positively by funding agencies and the community. The degree to which there are tradeoffs among desired objectives is an important variable for decision-makers, yet this is rarely explicitly considered. In particular, the existence of ecological thresholds has important implications for decision-making at both the project level and the regional level. We develop a model of the possibilities and choices for an agency seeking to achieve two environmental objectives in a region through revegetation of a number of sites. A graphical model of the production possibilities sets for a single revegetation project is developed and different tradeoff relationships are discussed and illustrated. Then the model is used to demonstrate the possibilities for managing all such projects within a region. We show that where there are thresholds in the tradeoff relationship between two objectives, specialization (single- or dominant-objective projects) should be considered. This is illustrated using a case study in which revegetation is used to meet avian biodiversity and salinity mitigation objectives. We conclude that where there are sufficient scientific data, explicit consideration of different types of tradeoffs can assist in making decisions about the most efficient mix and type of projects to better achieve a range of objectives within a region.

Key words: *Allocasuarina;* buloke; ecological thresholds; multiple objectives; production possibilities frontier; salinity

1. Introduction

In fragmented and degraded landscapes worldwide, loss of biodiversity is of increasing concern. In many areas, particularly those in which the major land use is agriculture, the remaining native vegetation is unable to support ecologically functioning populations of all species which were present in an area (Perrings *et al.* 2006). Furthermore, in many areas, local extinctions are continuing. For example, population declines of previously common birds have been recorded in agricultural regions of Australia, Europe and North America, in many cases long after broad-scale clearing has ceased (Barrett *et al.* 1994; Fuller *et al.* 1995; Krebs *et al.* 1999). Exacerbating these problems are processes associated with land degradation such as encroaching dryland salinity and soil erosion.

Ecological restoration is the process of restoring function or health to an ecosystem that has been degraded. Restoration actions generally proceed as a series of individual projects, ranging from property to landscape to regional scale, with funding for such projects provided by governments often through regionally-based natural resource management organizations. Government agencies and/or these regional bodies approve projects that are seen to make a contribution toward the achievement of particular regional objectives, typically measured through an improvement in identified resource condition targets or at least in outputs that can be reasonably presumed to contribute to improved condition. Here we define an objective as a direction in which we should strive (Brauers 1998), progress towards which is measured by some outcome or indicator of that outcome. In a given region, the community and responsible organizations will usually have multiple objectives relating to landscape restoration derived from the need to address particular biophysical problems such as declining water quality, soil erosion and loss of biodiversity

(Qureshi & Harrison 2001; Cipollini *et al.* 2005). There is the potential for both synergy and conflict among these objectives.

2. Tradeoffs among revegetation objectives

Restoration aimed at preserving biodiversity and ecological integrity in highly fragmented regions in the long-term necessarily involves attempts to restore native vegetation and re-create large amounts of habitat in the landscape, either through active intervention or through allowing regeneration to occur (Hobbs 1993; Vesk & Mac Nally 2006). Many government, not-for-profit and community groups have embraced this concept, particularly as it refers to active re-vegetation (Elliott *et al.* 2003; Environment Australia 2001). Government-funded initiatives have encouraged the planting of components of vegetation, particularly trees and shrubs (Elliott *et al.* 2003; Sayer *et al.* 2004). This type of ecological restoration action is also generally considered an attractive option by community groups (Vitosh & Thompson 2000).

Typically, several potential objectives are considered during the planning phase of revegetation projects. These may include reducing recharge of saline water tables (Stirzaker *et al.* 1999); providing shelter for livestock or crops (Gregory 1995); improving water quality (Parkyn *et al.* 2003); improving aesthetic qualities of an area (Brack 2002); providing habitat for wildlife in general, a particular threatened species or a particular suite of species (Harley *et al.* 2005); re-establishing the original native vegetation of an area (Wilkins *et al.* 2003); producing timber (Lamb *et al.* 2005); carbon sequestration (Brack 2002) or land stabilization (Marden *et al.* 2005). Often, several of the above are implicit or explicit objectives of a given revegetation project. Determinants of project outcomes include total area of vegetation established, initial and target plant density, initial and target species mix, the relative proportions of different species, the position in the landscape and the configuration of planted areas, and the vegetation strata established.

The desire to achieve multiple objectives in a given project is understandable, since on-the-ground actions are funded through competitive schemes or through simple allocations with limited total funds. Regional or state funding agencies often have to achieve a large suite of objectives as a statutory obligation (Bryan *et al.* 2005) or to satisfy multiple stakeholders, so it may seem to both funding agencies and service providers that it is most effective to fund a project which proposes to contribute to meeting several of these objectives, rather than to invest in a project focused on a single objective (e.g. Centre for International Economics 1999; Bryan *et al.* 2005). An acceptance of the inevitability of some tradeoffs is institutionalized in, and exemplified by, the concept of sustainable development (SD), as set out in *Our Common Future* (World Commission on Environment and Development 1987) and in key policy documents and programs, such as those of the Australian Government (Hawke 1989; Commonwealth of Australia, 1996).

A number of studies have identified tradeoffs in the management of native and plantation woodlands for multiple objectives, typically focusing on the tradeoffs between economic returns and conservation values, in general or particular (Vincent and Binkley, 1993; Boscolo and Vincent, 2003; Catterall *et al*. 2005). The usual purpose of such studies is to determine whether ‘specialized management’ of woodlands yields better net outcomes than ‘uniform’ management for multiple objectives (Boscolo & Vincent 2003). Specialized management involves managing projects or activities within a portfolio with each having a sole or dominant objective. Conversely, uniform management entails managing each project or activity in the portfolio so as to achieve a similar set of objectives at all sites. For example, Green *et al.* (2005) used an approach similar to that used in this study to conclude that it may be best to more intensively crop some land leaving other areas unfarmed (specialization), rather than managing the whole of a region at a lower intensity for multiple functions (relative uniformity).

To maximise conservation benefits, decision-makers need to know what mix of specialized and uniform management to use across a portfolio of projects. Catterall *et al.* (2005) identified that the nature of the tradeoff relationship between objectives, in their case biodiversity and timber production in northern Australian rainforest timber plantations, would determine whether it was efficient to sacrifice some timber production for biodiversity benefits. Vincent and Binkley (1993) concluded that greater efficiency is achieved by ‘dominant-use’ management of forests, with different stands being managed for different dominant objectives, though Boscolo and Vincent (2003) qualify this. They concluded that uniform management is best for the joint production of timber and carbon sequestration, whereas specialized management is best if aiming for both timber and biodiversity. In particular, they showed that it may be more efficient to completely clear fell some forest patches, while leaving others for conservation purposes, rather than using a uniform management approach whereby the whole forest area is selectively logged (Boscolo and Vincent 2003).

Some of the insights and concepts from modeling trade-offs in forests (Boscolo and Vincent 2003) and production landscapes (Green *et al.* 2005; Groeneveld *et al.* 2005) are here adapted so as to develop a model of revegetation projects. Only two objectives are used to simplify the graphical representation, though multi-objective analysis is possible with more sophisticated mathematical analysis (Brauers 1998). The model illustrates how a regional decision-making body’s preferences might relate to project- and regional-level possibilities where different tradeoffs among objectives exist, following Prato's (2003) discussion of the management of protected areas and an adaptation of Baumol and Bradford's (1972) representation of production possibilities in situations where there may be detrimental externalities. In particular, we demonstrate the possibilities that arise where ecological thresholds exist in the relationship between objectives at a project level, and the solutions whereby dual objectives can still efficiently be met across a portfolio of projects at the regional level.

3. Modelling regional preferences

In this model, a regional natural resources management agency (NRMA) has the key role in synthesizing the preferences of a government and regional stakeholders (Prato 2003) and thereby expresses the utility of the expected outcomes from re-vegetation. All combinations of outcomes that are of equal utility to the NRMA are mapped on an indifference curve and each of many curves represents a different level of utility. From Figure 1a, the NRMA would be equally satisfied with, or be indifferent between, combinations C (a_3, b_1) and D (a_2, b_2). The degree to which the NRMA will 'trade' one combination for another at any point on the indifference curve is the marginal rate of substitution (MRS), so that for μ_1 in Figure 1a, moving from combination C to combination D:

$$\text{MRS} = \frac{(a_3 - a_2)}{(b_2 - b_1)}$$

In other words, the NRMA would trade off (a_3–a_2) to gain (b_2–b_1) and would still achieve the same utility (μ_1). There are, however, other combinations of outcomes that would result in greater utility. Hence, combination E (a_1, b_3) produces greater utility than either combinations C or D.

In Figure 1a, the MRS is common to all the indifference curves and constant along each curve. In practice, this could result if the NRMA applied fixed values or weights to each of the outcomes (Brauers 1998), such as a set monetary valuation for each per unit outcome or a mean weighting of aggregated expert opinion (Cippollini *et al.* 2005). If, however, attributed weights or values varied with quantities, then non-linear indifference curves would result. For example, if the NRMA used some form of multi-criteria decision analysis (MCDA) (Maguire and Boiney 1994; Cippollini *et al.* 2005; Wenstop 2005) that included stakeholder preferences (Mabin *et al.* 2001) and with conflict resolution as part of the process (Hostmann *et al.* 2005), then either implicitly or explicitly, variable weightings are likely to result. In particular, since there will be pressure to achieve some of each major outcome, resulting in aiming for some sort of balanced scorecard (Bovaird *et al.* 2003), then as an outcome decreases, its utility to the decision-makers will increase (Brauers 1998). Thus, the indifference curves for the NRMA will have a decreasing MRS, as shown in Figure 1b. Since $\Delta b_1 < \Delta b_2 < \Delta b_3$ then $\Delta a/\Delta b_1 > \Delta a/\Delta b_2 > \Delta a/\Delta b_3$ and so the MRS is decreasing. Effectively, the NRMA becomes more reluctant to substitute B for A as the quantity of A decreases and the converse holds when substituting A for B.

4. Project-scale possibilities

To develop the production side of the model, we focus first on the production possibilities for a single revegetation project. In Figure 2a, a_{max} is the maximum outcome for objective A that could be achieved if all the resources available for this project were fully utilized to that end with no outcome (zero) for objective B (following Wiggering *et al.* 2006). Conversely, if all resources were deployed to achieve objective B, then the result is b_{max} with A equal to zero. In some cases there will be an incidental benefit for one objective even where all resources are concentrated on the other (see for example Wiggering *et al.* 2006), but total exclusion is here assumed for simplicity. Full utilization in this discussion means the efficient and full use of resources allocated to this project and using known and affordable management techniques. The line a_{max}, b_{max}, known as the production possibilities frontier (PPF), is therefore all non-zero combinations of A and B that involve full utilization of resources.

The PPF is the boundary of all possible combinations of outcomes, which comprise the production possibilities set (PPS). We assume the NRMA will select combinations along the PPF to both gain a Pareto improvement and, as will be shown later, to maximize utility. Figure 2a illustrates the Pareto improvement case. If the NRMA is operating at set C outcomes, it is still possible to use the budget and resources allocated for this project to achieve a Pareto improvement. That is, an allocation of resources for set D would increase objective A outcomes without a reduction in objective B, and similarly, moving to E would increase objective B without loss of A.

Along the PPF (similar to the concept of the MRS) the rate at which the achievement of one outcome displaces another as resources are shifted is the marginal rate of transformation (MRT). Figure 2a shows a set where the MRT along the PPF is constant; there is no change in the opportunity cost along the curve when moving from one objective to the other. Such a neat tradeoff relationship, even approximate, is unlikely either in natural resource management or production economics, so Figure 2b demonstrates two scenarios where the trade-off relationships are non-linear.

In Figure 2b, PPF 2 is the boundary of a concave PPS with a decreasing MRT, as shown by measuring the tangential slopes. From G to H the MRT equals $\Delta a/\Delta b_1$ and from H to I it is $\Delta a/\Delta b_2$.

Since $\Delta b_2 > \Delta b_1$, then $\Delta a/\Delta b_1 > \Delta a/\Delta b_2$ and so on. This holds either moving down the curve or moving from B to A up the curve. This example illustrates a threshold effect, defined as a rapid 'shift in states' (Walker and Meyers 2004) for an objective occurs immediately upon any shift in resources. The thresholds, in this case, are at both a_{max} and b_{max} (Figure 2b). For the third scenario, in which the PPS is bounded by PPF3, there are no such threshold effects and the MRT is increasing (Figure 2b). In moving from J to K to L, $\Delta b_3 > \Delta b_4$ and therefore $\Delta a/\Delta b_3 < \Delta a/\Delta b_4$ and so on. In reality, however, one can envisage more complex trade-off relationships, within which there are both increasing and decreasing MRT because there are thresholds at particular non-zero combinations. Figure 3a illustrates PPF 4, whereby shifting resources from objective A to objective B has an initially increasing MRT, characteristic of convex PPS (similar to scenario 3), then a decreasing MRT as in the concave PPS (similar to scenario 2). Combination M is an approximate threshold point.

Such threshold ecological effects are being increasingly identified (Huggett 2005) at both the landscape level (Andrén 1994; With *et al.* 2002; Radford and Bennett 2004; Radford *et al.* 2005) and in species' patch-level habitat preferences (Bütler *et al.* 2004; Maron 2007). For example, in the case of arboreal marsupial gliders (*Petaurus sp.*), a gap-crossing threshold of 75 m has been reported (van der Ree *et al.* 2004). Hence, a habitat restoration project that attempts also to accommodate farm management needs by locating the revegetation site further than 75 m from a patch of native vegetation would cross the isolation threshold so that the benefits to the glider would decline rapidly with increasing distance from that point.

Such a dual threshold-type relationship could be envisaged for a project, the objectives of which included both habitat creation for a species which feeds on the fruit of a particular tree and timber production. Reducing the density of the habitat tree species in the plantation past an initial threshold value (Point O, Fig. 3b) in favor of a tree species of more value for timber production might result in a rapid decline in habitat suitability but as long as at least a small number of habitat trees are present, the habitat continues to be used at a low level. However, once no habitat trees are present, the habitat value drops to zero.

5. Regional-scale possibilities

To examine the implications of these different tradeoff relationships at a regional level, we assume there are a number of projects aimed at achieving the dual objectives across the region and these are managed as a group with costs and impacts uniform across sites. The preferences of the NRMA, illustrated by the indifference curves, are added to the production possibilities (Figure 4a). If the NRMA were to apply uniform management across all projects (i.e., all projects designed to achieve the same mix of A and B) then the regional production possibilities would have the same MRT and same shaped set as for the project scenario, only with potential outcomes multiplied by the total area (for example) of projects. Hence, in all cases, specialization to achieve objective A in all projects will result in $s{*}a_{max}$, where s is the total area of all projects across the region (Figure 4a). Conversely, the agency could also achieve $s{*}b_{max}$. The NRMA could also choose a combination of specialized projects (e.g. project combinations C–K) in Figure 4a. Combination G (a_5, b_5), results in the highest achievable utility and it is the result of devoting some of the number of available projects (n) to achieving objective A and some to achieving objective B. If the MRT for these projects were constant, exactly the same outcomes could be achieved by various combinations of uniform management but that unlikely situation is not further considered.

Applying the utility maximization principle, where there is a decreasing MRT (a concave PPS) project specialization should be preferred and where MRT is increasing, dual-objective projects should be preferred, as shown in Figure 4b. In the latter case, the NRMA would estimate possible outcomes and choose the combination of A and B on the PPF that was nearest its preferences and that would be the standard mix across all *n* projects.

The decision making becomes more complex where there are thresholds in the relationship other than immediately following combinations with one zero outcome. In Figures 5a and 5b, parts of the project PPS are above the specialization line and parts are below. In Figure 5a, if the NRMA has a preference strongly favoring Objective A, as represented by the upper indifference curve, then the option which maximizes utility is to have all dual objective projects designed to achieve a_1, b_1 and this is superior to any project specialization option (the straight line). If, however, the NRMA wants a more balanced portfolio, for example by combination R, then this would be achieved by some projects being designed to achieving a_1, b_1 and the balance aimed at achieving Objective B, with the final outcome being a_2, b_2. In this case, the regional PPF becomes $s*a_{max}$, M, $s*b_{max}$. This segmented PPF follows the approach of Baumol and Bradford's (1972) modeling of production choices where there are negative externalities. The PPF is the combination of segments that maximize outcomes where the management strategies vary.

Similarly, where there are two thresholds, the regional PPF becomes $s*a_{max}$, N, O, $s*b_{max}$ (Figure 5b), the straight line portion is achieved by selecting a combination of dual objective projects. For example, at P, some of the *n* projects would be designed to achieve the project level equivalent of a_1, b_1 and the remainder to achieve the equivalent of a_9, b_9. The key point is that when any part of a project PPS is concave, the regional level PPS includes possibilities beyond those enclosed within a straight-line PPF, which can be exploited to maximize utility through a combination of projects which include at least some dual-objective projects.

6. Case Study

We illustrate the importance of identifying tradeoff relationships between revegetation objectives with an example of dual objective revegetation projects for a region in the Wimmera region of Victoria, Australia. The local NRMA's objectives include avian biodiversity conservation and salinity mitigation. Two of the most common tree genera in the region are *Allocasuarina* (bulokes) and *Eucalyptus* (eucalypts). Eucalypts typically are deep-rooted and fast-growing, and some species are recommended for planting to reduce groundwater recharge rates in deforested areas (Schofield 1992). Bulokes, on the other hand, are small, slow-growing and leafless, and are probably of limited use for reducing groundwater recharge. Yet woodlands composed of bulokes are of exceptionally high avian conservation value (Watson *et al.* 2000; Maron & Lill 2005; Maron *et al.* 2005). Small passerines are a group of conservation concern in agricultural regions in Australia, and have suffered from habitat loss and modification (Ford *et al.* 2001). However, they occur at relatively high abundances in even degraded buloke woodlands (Maron *et al.* 2005).

In the case study discussed here, for a stand of bulokes to retain its value in supporting avian biodiversity, very few eucalypts must be present in the woodland, because as few as five eucalypts per hectare in a buloke woodland facilitates invasion by an aggressive avian competitor which excludes small passerines (Maron 2007). As a result, avian diversity declines as eucalypt density increases in buloke woodland (Maron 2007). Yet in revegetation projects in the study area, the two tree species have typically been planted in mixed plantings with bulokes usually comprising a relatively low proportion of seedlings. Such plantings are likely to contribute little to avian conservation, as the maturing woodland is expected to become dominated by species of little conservation concern which can coexist with the aggressive competitor (Maron 2007). Using data from a study of birds in mixed eucalypt/buloke woodlands and an estimation of relative transpiration rates, here used as a proxy for salinity mitigation, we construct the project and regional PPS for achieving these dual objectives.

We assume a final density of approximately 80 stems/ha of either bulokes or eucalypts. Mindful of questions about the effectiveness of broadscale planting for salinity control (Heaney *et al.* 2000; Pannell 2002) the plantations are assumed to be located on the recharge areas of a groundwater catchment and of adequate size to ensure sufficient habitat size and salinity mitigation impact (following Apan *et al.* 2004). Data on the salinity mitigation effects of trees are limited and are usually site- and species-specific, and variable with rainfall (see for example Lewis *et al.* 2003). However, for this exercise, we needed only an estimate of the relative salinity mitigation potential of bulokes compared with commonly planted eucalypts.

Leaf area correlates broadly with water use (Hatton *et al.* 1999) and so as buloke trees have small, leafless canopies, they are assumed to have lower transpiration rates, and thus lower potential to reduce recharge, than eucalypts with large, leafy canopies. In the absence of data comparing transpiration rates of these species, we use the difference in mean crown areas as a rough estimate of potential water use. 1:25,000 aerial photography from the focal catchment was used to measure the crown area of 50 randomly selected indivuduals of full-grown bulokes and eucalypts. For eucalypts (river red gum *E. camaldulensis* and yellow gum *E. leucoxylon*) mean (± 1 s.e.) canopy area was 268±20 m^2, and for bulokes was 57±4 m^2. Therefore, in the model, the transpiration rate for bulokes is set at just over 20 percent of that of eucalypts. If the net transpiration over the period to maturity were used as the indicator the difference could be even greater, given the slow growth rate of buloke. However, since no growth curve is available for these species in this region, the annual rate is used to illustrate the point.

The result of substituting eucalypts for bulokes and vice versa is shown in Figure 6. If 100 percent of a single project is devoted to improving small passerine abundance, there is still an estimated water use rate of 20 percent of the maximum achievable should only eucalypts be planted. The predicted abundance of small passerines falls rapidly with the introduction of eucalypts and when ≥ 25 percent of the trees planted are eucalypts, the avian biodiversity benefit is almost zero.

The existence of the ecological threshold results in an initially decreasing MRT and therefore, the utility-maximizing approach for the NRMA in this case would be to have specialized projects focused on either avian biodiversity or salinity mitigation. As the entire project PPS is concave, the only option for achieving an improvement in utility at the regional level is to specialize, whereas a suite of dual-objective projects would yield a sub-optimal outcome.

7. Conclusion

The conceptual model discussed here is envisaged as one of a set of regional planning tools. Catchment/watershed (or bio-regional) scale planning is increasingly the level at which natural resource management project portfolios are developed and implemented by regional NRM organizations. The PPS of project NRM outcomes was developed for a planning framework in which project objectives are derived from regional objectives which are in turn linked to national goals. Where there is sufficient evidence to identify threshold effects and estimate MRT, the development of production possibility models can be used to illustrate the outcomes of particular projects, and form that a regional NRM portfolio can be developed which maximizes utility. Data describing threshold relationships could also be an input to MCDA-type processes, so that once the optimal PPF is identified, the NRMA can select from a set of combinations on that frontier, so that utility is revealed after the production possibilities are known.

The model developed here is potentially useful for both illustrative and planning purposes. It graphically demonstrates the case for considering at least some specialized revegetation projects in cases where threshold effects between objectives are known or strongly suspected. Where more than two goals are considered, more advanced analysis is possible for 3 objectives using a production possibilities surface (see for example Groeneveld *et al.* 2005) or for more with a production possibilities manifold (Brauers 1998). For the dual objective cases, the decision rules are: 1) where there is a decreasing MRT in the relationship between two objectives, then specialization at the project level achieves optimal outcomes at the regional level; 2) where there is an increasing MRT, dual objective projects should be preferred; and 3) ecological thresholds can result in a MRT which first increases and then decreases (or vice versa), meaning that maximum outcomes will arise from a mix of dual-objective and specialized projects.

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Figure 1. Indifference curve set for regional avian biodiversity and salinity mitigation outcomes where the marginal rate of substitution is a) constant, and b) decreasing. All combinations on each curve are of equal utility to the NRMA. Utility increases from μ_1 to μ_2 and to $\mu_{3,}$ and so on.

Figure 2. Production possibilities sets for a dual objective project under different scenarios. In 2a), the marginal rate of transformation (MRT) along the PPF, or rate at which one outcome is displaced for the other, is constant. Figure 2b shows two additional scenarios for the MRT. PPF 2 has a decreasing MRT and PPF3 has an increasing MRT.

Figure 3. Production possibilities sets for dual objective projects with both increasing and decreasing MRT. In Figure 3a, point M marks a threshold after which efforts to increase outcomes for B result in a sharp decrease in A (a substantial decrease in the MRT). Some points on the PPF are above the straight line and some below. Figure 3b shows a production possibilities set for a dual objective project with two threshold effects. In this case there is a threshold in shifting from A to B at set O, similar to the case in Figure 3a, and another in moving from B to A, at set P.

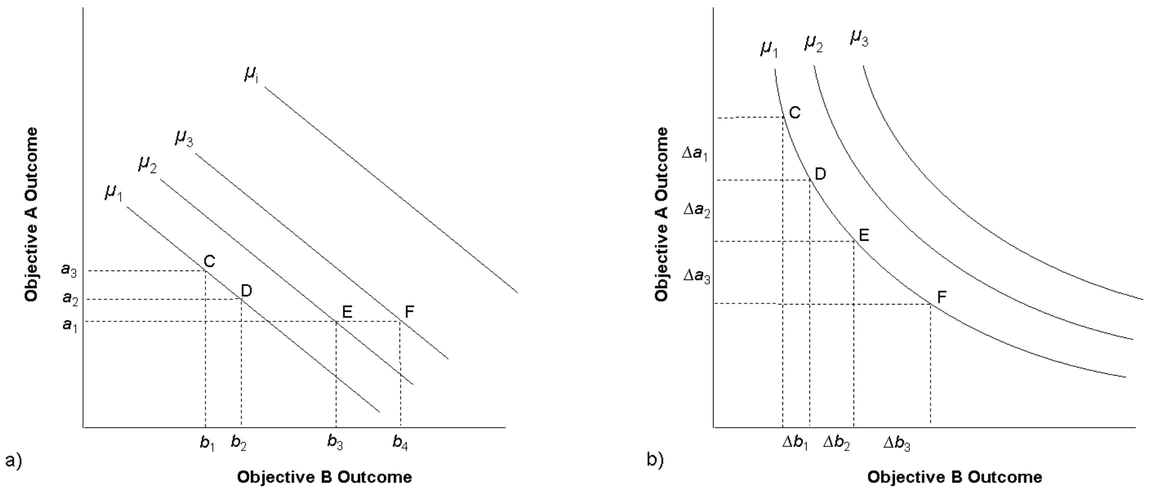
Figure 4. Regional production possibilities and utilities. In a) each point along *s**PPF1 represents a combination of specialized revegetation projects (where the number of projects = *n*). Shifting from combination C to D requires increasing the number of projects aimed at achieving Objective B and so on down the line. In b) the straight line is the combinations from 4a, compared to scenarios with projects that have, respectively, an increasing and decreasing MRT. If the MRT for all projects is consistently decreasing (*s**PPF2) then

utility will be maximized by having full specialization at the project level, since any combination on μ_3 has greater utility than any combination on μ_1. Conversely, all points on s*PPF3 are above the specialization combinations and therefore in the case of increasing MRT, dual objective projects would maximize utility, since, for example, μ_5 has greater utility than any combination on μ_3.

Figure 5. Scenarios for regional possibilities when complex threshold effects are present. 5a shows a single threshold at point M, which results in a regional PPS (bounded by the dark line) that is partially convex. From s*a_{max} to M is represents the uniform management of all projects in that project combination range. From M to s*b_{max} is achieved by some combination of dual objective projects targeted at achieving a_1, b_1 and projects specializing on Objective B. In Figure 5b there are two thresholds, at points N and O and so the straight line section of the regional PPF (N to O) represents a mix of projects aimed at either achieving a_1, b_1 or a_9, b_9. Above and below the threshold points, uniform management achieves greater outcomes.

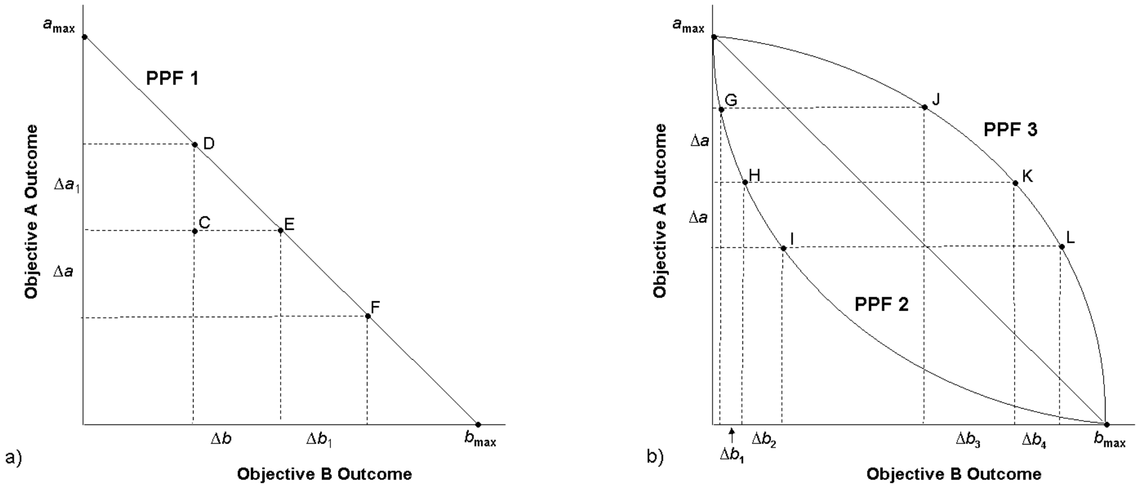
Figure 6. Water use and avian biodiversity trade-offs for revegetation projects in the study area. Although the PPS for individual projects is concave, efficiencies in meeting both objectives at the regional level can be gained through a combination of specialized projects.

1



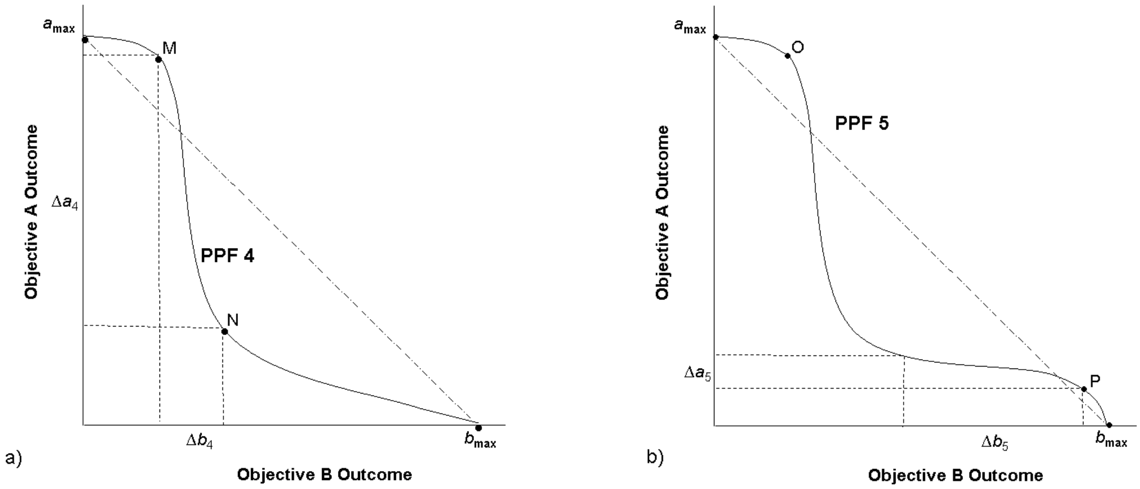
a)
Objective A Outcome
Objective B Outcome
μ_1
μ_2
μ_3
μ_i
a_3
a_2
a_1
C
D
E
F
b_1
b_2
b_3
b_4
b)
Objective A Outcome
Objective B Outcome
μ_1
μ_2
μ_3
Δa_1
Δa_2
Δa_3
C
D
E
F
Δb_1
Δb_2
Δb_3

2 Figure 1.



a)
a_{max}
PPF 1
D
C
E
F
Δa_1
Δa
Objective A Outcome
Δb
Δb_1
b_{max}
Objective B Outcome
b)
a_{max}
G
J
PPF 3
H
K
I
L
PPF 2
Δa
Δa
Objective A Outcome
Δb_1
Δb_2
Δb_3
Δb_4
b_{max}
Objective B Outcome

Figure 2.



a_{max}
M
Δa_4
PPF 4
N
Objective A Outcome
Δb_4
b_{max}
a)
Objective B Outcome
a_{max}
O
PPF 5
Objective A Outcome
Δa_5
P
Δb_5
b_{max}
b)
Objective B Outcome

Figure 3.

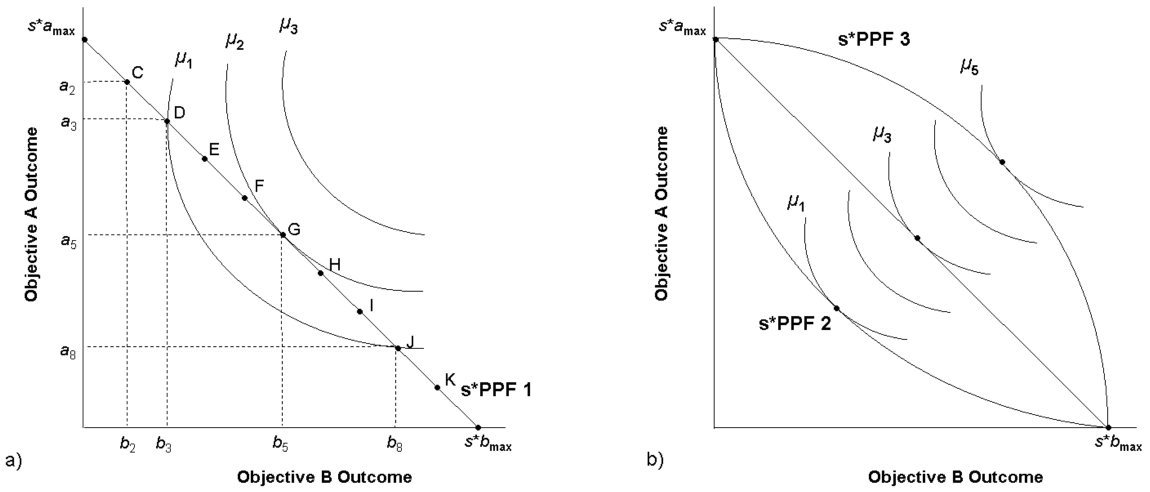
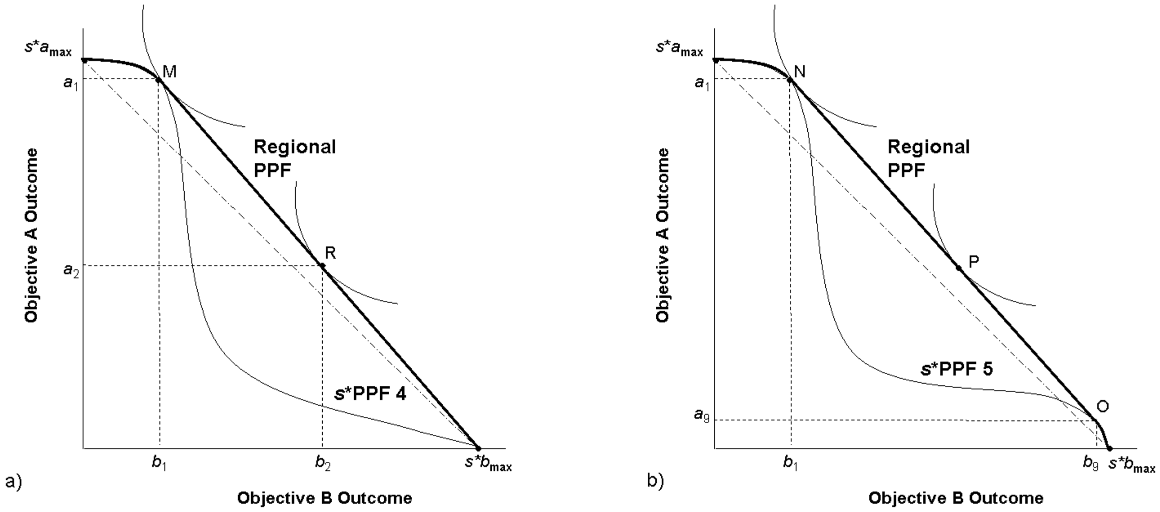

a)
s*amax
a2
a3
a5
a8
b2
b3
b5
b8
s*bmax
μ1
μ2
μ3
C
D
E
F
G
H
I
J
K
s*PPF 1
Objective A Outcome
Objective B Outcome
b)
s*amax
s*PPF 3
s*PPF 2
μ1
μ3
μ5
s*bmax
Objective A Outcome
Objective B Outcome

Figure 4.



s^*a_{max}
a_1
M
Regional PPF
R
a_2
Objective A Outcome
s^*PPF 4
b_1
b_2
s^*b_{max}
a)
Objective B Outcome
s^*a_{max}
a_1
N
Regional PPF
P
Objective A Outcome
s^*PPF 5
O
a_9
b_1
b_9
s^*b_{max}
b)
Objective B Outcome

Figure 5.

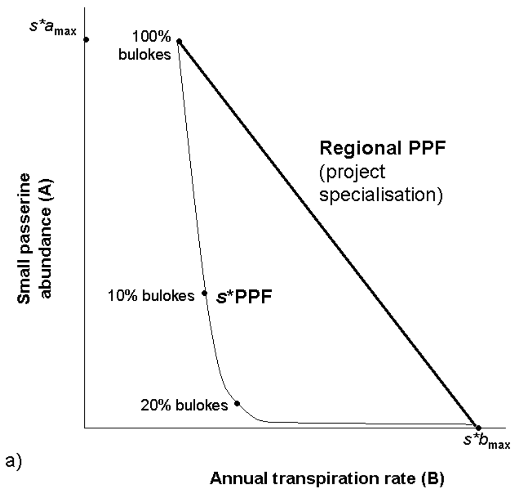

s*a max
100% bulokes
Regional PPF
(project specialisation)
Small passerine abundance (A)
10% bulokes
s*PPF
20% bulokes
s*b max
a)
Annual transpiration rate (B)

Figure 6.