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TITLE: MONITORING OF COMPLIANCE IN WESTERN AUSTRALIAN CONSERVATION CONTRACTS

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ABSTRACT:

Contracting with private landholders for labor towards production of environmental services (payment for actions) or the environmental services themselves (payment for outcomes) is reliant on the environmental organization's ability to monitor and assess the environmental outcomes provided. Inaccurate and costly assessment reduces the cost effectiveness of the contract. Different assessment technologies will have different impacts on the cost effectiveness and optimal contracting choice of the environmental organization. The paper compares the influence of field assessment by a local expert, and remote assessment via satellite imagery, on the optimal contracting decision for the Western Australian wheat belt.

INTRODUCTION

In Australia, government and non-government environmental organizations have begun incorporating private lands into conservation programs primarily due to the high cost of establishing national parks and reserves (Figgis 2004). Private ownership and leasehold controls 77% of Australia's land (DEHA and DAFF 2008). The land available to enter national parks and reserves will be insufficient for reserves alone to achieve the environmental organization's goals and objectives of biodiversity and environmental service provision into the future. The goals and objectives of government and non-government environmental organizations are diverse, but consistently include broad environmental aims which require long-term investment. For example, the *Australian Government Department of the Environment and Water Resources develops and implements national policy, programmes and legislation to ensure the protection, conservation and sustainable use of Australia's natural environment, water resources and cultural heritage* (DEWR 2007). The World Wide Fund for Nature state their mission is *to stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature by: conserving the world's biological diversity; ensuring that the use of renewable natural resources is sustainable; and promoting the reduction of pollution and wasteful consumption* (WWF 2007). The broad, long-term nature of the goals and objectives of environmental organizations require them to make long-term investments in diverse conservation work.

Government and non-government environmental organizations have introduced a number of conservation schemes and programs designed to provide biodiversity and environmental services on private land through market-based instruments (Figgis 2004). Development of new conservation programs in Australia has progresses rapidly, with 19 pilot programs within the National Action Plan for Salinity and Water Quality alone (NAPSWQ 2008). In 2009, a dedicated Environmental

Stewardship program was launched as part of the national Caring for Our Country scheme. In Western Australia, private landholders can receive a wide range of support for providing environmental services, including financial or labor assistance for conservation works, assistance entering into a covenant, as well as technical advice and training (Government of Western Australia 2004). Internationally, conservation programs have existed for much longer than Australian. Most well known are the USA Conservation Reserve Program and the Wetlands Reserve Program (Hanrahan and Zinn 2005), and the UK Countryside Stewardship Scheme and Environmental Stewardship (NE 2006). Typically conservation schemes have contract landholders to undertake actions which increase the probability of establishing or conserving a target vegetation community. Programs are now focusing on the contracts for the environmental outcomes of actions, rather than the actions themselves.

The assessment of environmental contract compliance by landholders with conservation contracts by organizations have received limited attention in the literature. Internationally, reviews of agri-environmental policy monitoring in the UK and elsewhere conclude that monitoring to assess ecosystem change incurs significant costs and is prone to inaccuracy in the form of mis-classifications of vegetation types (Hooper 1992; National Audit Office 1997; World Bank 1998). A wide variety of monitoring techniques are available to the organization, each with a unique combination of accuracy, cost and ease of use. The most popular method is on-ground field surveys by trained experts, but remote satellite imagery also has potential. The USA Conservation Security Program takes the unusual approach of providing funds directly to farmers for undertaking recordkeeping, monitoring, and evaluation themselves (Farm Policy Team 2006).

Markov-chain decision process analysis is a usefully technique for the environmental organization to value collecting information about the landholder or their land to overcome the issue of adverse selection, as well as to value accurate assessment and enforcement at the completion of the contract to avoid moral hazard. Markov-chain decision processes determine the optimal decision when the outcome is based on a stochastic process. The stochastic process is represented as a matrix of the probability of transition from the present to the next or final state, with each decision option or action is represented by a unique matrix. The product of the various combinations of alternative decisions over time is then calculated and the optimal sequence of decisions determined (Bellman 1957). The impact of adverse selection and moral hazard is incorporated into the probability matrix and decision options. Markov-chain decision processes are particularly popular in medical science (Briggs and Sculpher 1998) and forest management (Taylor *et al.* 2009).

The basic model of decision making based on Markov-chains has been developed into one where the decision makers do not know the current state but can engage in potentially costly and imperfect monitoring, known as partially observable Markov-chain decision processes (POMDP) (Smallwood and Sondik 1973; Puterman 1994; Cassandra 1998; Kaelbling *et al.* 1998). Summaries of early POMDP analysis (Monahan 1982) , as well as more recent summaries (Cassandra 1998) highlight its growing popularity. POMDP is now being promoted to in behavioral sciences, expanding from its traditional artificial intelligence base (Littman 2009). Currently POMDP is receiving attention in analyzing environmental issues as it models the environmental as a set of states and transitions, as well as incorporating the use of costly and imperfect monitoring.

Markov-chains have been used to estimate and model ecosystems as they represent a stochastic process that is defined on a discrete state space (Barber 1978; Usher 1979). Recently ecologists have developed Markov chains to represent the stability of a heterogeneity ecosystem over time as well as space (Li 1995). Techniques Markov chain model has been further developed, including model calibration (Logofet and Korotkov 2002), hidden Markov models (Tucker and Anand 2005), combination with Monte Carlo simulation analysis (Roberts and Rosenthal 1998), and observability and uncertainty (Williams 2009). These advances have enabled the analysis of succession within various ecosystem types, from grasslands (Balzter 2000; Somodi *et al.* 2004), heath (White 2005) and forests (Korotkov *et al.* 2001; Yemshanov and Perera 2002; Benabdellah *et al.* 2003) to marine communities (Liu *et al.* 2006).

The analysis of ecosystems using Markov-chains are based on various types of field and remotely sensed data sources, often combining the two to improve accuracy of the work (Neeff *et al.* 2005). Aerial photographs have previously been used as the basis for estimating transition probabilities in Markov chain analysis (Li 1995; Hill *et al.* 2002). Aerial photographs give historical perspective and can be combined with secondary information such as ground surveys or maps (Martin *et al.* 2006). Current GIS data can also be successfully matched with aerial photography (Hathout 2002; Weng 2002). GIS analysis has developed with the input of data and access to data becoming easier (Logsdon *et al.* 1996), improvements in matching land use to land cover (Brown *et al.* 2000) and scaling effects (Li 2000). The NEWROC study draws on the methods of the studies mentioned here, as well as similar work using state-and-transition models of Australian woodlands (Hill *et al.* 2005; Spooner and Allcock 2006) to assess the changes in land use and land cover in the Western Australian intense agricultural zone.

The monitoring problem described here differs from most previous contributions to the literature in two fundamental respects. First the variable monitored is a categorical variable classifying the state of the vegetation community into a finite number of classes. Most previous economic studies describe monitoring an emission variable where standards are in terms of quantities or concentrations. Secondly, the monitoring problem here is dynamic and extends from 2 periods up to potentially an infinite time horizon. Given this added complexity the strategic interaction between the landholder and the organization is not modeled explicitly, instead in the model it is characterized as 'nature' which determines if whether an environmental scheme succeeds or fails.

Australian environmental stewardship contract schemes are on a small scale stage and will require further development to meet the long-term and large scale goals of environmental organizations. In particular, the assessment of the legal contract between the organization and the landholder to ensure the environmental objectives of the scheme are achieved requires further attention. At present, assessment of compliance and environmental outcomes of these schemes is primarily focused on prediction for efficient allocation mechanisms such as auctions. The success of environmental schemes has generally measure by the quantity of inputs contracted to be supplied, rather than the quantity of inputs achieved or environmental services provided.

The aim of this paper is to use POMDP to explore the organization's decision to enter into conservation contracts with landholders, whether to assess the contract or not, and if so the type of assessment technology to employ. The case study investigates the organization's decision to contract landholders to revegetate or maintain native vegetation for five years, and the use of assessment of the vegetation succession to change the contract type or to withdraw from contract. The unit of analysis is an area of land which either had or has the potential to establish the target vegetation community. This analysis draws upon the ecology literature on how vegetation successions are modeled, the economic analysis of monitoring and irreversible environmental change and the operations research analysis of dynamic monitoring and control problems.

METHODOLOGY

The methodology of POMDP is described following the notation of (White 2005). A regulator/environmental organization has an objective of maximising the public value of a piece of private land where vegetation types are described by N discrete states $s_i = 1, \dots, N$. The vegetation type or state changes through time according to a Markov process and the (NxN) matrix of transition probabilities, for instance for two vegetation states we have:

$$P(e_t) = \begin{bmatrix} p_{11}(e_t) & p_{12}(e_t) \\ p_{21}(e_t) & p_{22}(e_t) \end{bmatrix} \qquad (1).$$

The elements $p_{ij}(e_t)$ give the probability of the land in state i being in state j after a single period t. Conservation effort, e_t, is a measure of resources allocated to maintaining or improving the quality of the vegetation. In the conservation contracts the resources would be defined as labor effort by the landholder. The organization offers a contract that stipulates conservation effort e_t, and both parties know the resulting probability of vegetation change. Landholder labor effort increases the probability of a transition to the target vegetation community.

The environmental organization has a prior probability of the current vegetation type given by the $(1xN)$ vector π known as the *belief state*. This is a realistic many ecosystems as vegetation classifications are uncertain or the vegetation may be a mosaic of different vegetation classes. Often the high cost of a definitive vegetation survey means that conservation schemes are initialised with incomplete knowledge of the current vegetation type across the whole area. The observation matrix, which is a function of monitoring effort u_t determines the accuracy of monitoring. For two states the *(NxN)* observation matrix is given by:

$$R(u_t) = \begin{bmatrix} r_{11}(u_t) & r_{12}(u_t) \\ r_{21}(u_t) & r_{22}(u_t) \end{bmatrix} \qquad (2)$$

where the element $r_{j\theta}(u_t)$ is the probability that if state θ is observed the vegetation at the end of period t is j. If $R(u_t)$ is an identity matrix then monitoring is perfectly accurate, if it is uniform it is uninformative. Increased monitoring effort raises the probability of a correct observation. Monitoring reduces the uncertainty about which state the land is in and updates the prior probability to a posterior probability by Bayes rule:

$$\pi_{jt} = \frac{\sum_i \pi_{it-1} p_{ij}(e_t) r_{j\theta}(u_t)}{\sum_{i,j} \pi_{it-1} p_{ij}(e_t) r_{j\theta}(u_t)} \qquad (3)$$

The new belief state is a $1 - N$vector of probabilities. In vector form, (3) can be rewritten as:

$$\pi_t = T(\pi_{t-1} | e_t, u_t, \theta) \qquad (4)$$

where $T(.)$ is the belief transformation function. The belief state captures the history of all past observations and actions.

MONITORING COSTS

Observation can give an environmental audit which is definitive or inspect an environmental variable with a noisy signal Heyes (2002) Methods for monitoring vegetation change range from low cost remote sensing methods such as satellite images, to relatively high cost field surveys (World Bank 1998). We assume that from past audits or 'ground truthing', these methods have established observation matrices. We assume that the cost of monitoring depends on the observation matrix thus the quasi-convex monitoring cost function $c^v(u_t)$ is at a maximum when $R(u_t)$ is an identity matrix, that is the state is observed with perfect accuracy, and $c^v(u_t) = 0$ when $u_t = 0$ and $R(u_t)$ is a uniform matrix with all elements equal to $1/N$.

THE ENVIRONMENTAL ORGANIZATION'S PROBLEM

The organization maximizes the expected present-value of the welfare function in relation to abandoning, maintaining or improving an area of land by specifying landholder labor effort and their monitoring effort. The organization's problem can be represented by the following POMDP mathematical programming problem:

$$V[\pi_t] = \max_{wrt\ e_t u_t} \sum_t \sum_i \pi_{it} [g_i(e_t) - c_i(e_t) - c^v(u_t)] \delta^t \qquad (5a)$$

Subject to:

$$\pi_t = T(\pi_{t-1} | e_t, u_t, \theta) \qquad (5b)$$

$$\pi_0 = \tilde{\pi} \qquad (5c)$$

The first term $g_i(e_t)$ in (5a) gives the net benefits of the vegetation being in state i, it is given as a function of e_t as landholder labor effort is partly determines the vegetation state. The term $c_i(e_t)$ gives the cost to the organization for procuring landholder labor effort e_t. Monitoring costs given by $c^v(u_t)$ depend upon the monitoring effort u_t. The term $\delta^t = 1/(1+g)^t$ is the discount factor which converts net benefits generated at time t to their present-value at $t = 0$, g is the discount rate. High discount rates reduce the value of the vegetation state improving, and indirectly labor effort and the value of monitoring. To simplify the notation in later sections net-benefit is defined as:

$$w_i(e_t, u_t) = g_i(e_t) - c_i(e_t) - c^v(u_t) \qquad (6)$$

DYNAMIC OPTIMIZATION

Unlike a Markov Decision Problem (MDP) which has a standard dynamic programming solution (Puterman 1994), the solution to a POMDP problem is more difficult because the probability of the system being in a particular state depends upon past monitoring and the resulting observations. The original solution by Smallwood and Sondik (1973) introduces the notion of a *belief state* where the conventional states of MDP, namely s_i, are replaced by a *belief state* π_t which is the vector of probabilities of being in the states. The solution entails finding a set of actions which are optimal across the belief state (Cassandra 1995). In a simplified form the optimization problem is to solve the following version of Bellman's equation:

$$V_t(\pi_t) = \max_{wrt\ e_t u_t} \sum_i \pi_{it} \{ w_i(e_t, u_t) + \sum_j \sum_\theta p_{ij}(e_t) r_{j\theta}(u_t) V_{t+1} [T(\pi_t | e_t, u_t, \theta)] \} \qquad (7)$$

where $V_t(\pi_t)$ is the optimal value from optimizing across the time horizon from t to T starting in belief state π_t. The optimal value comprises two components, the first term is the expected immediate reward and the second term is the expected reward for the remaining periods, the term $p_{ij}(e_t) r_{j\theta}(u_t)$ gives the joint probability of observing state θ when the previous state is i and the current state j. Equation 7 is similar in construction to a standard stochastic dynamic programming model except for the presence of the belief state. For instance if the initial state was known with certainty and there was no monitoring, optimization would proceed by maximizing the current net-benefit whilst accounting for the effect the action has on the expected value across the remaining periods. This principle of optimality still holds in POMDP except it has to solve the problem across all possible belief states. This involves defining the optimal solution as a set of action vectors which are optimal in some belief state.

Solving the dynamic optimization presented in Equation 7 is complex due to the difficulty of determining $V_t(\pi_t)$. However, if we restrict $e_t$and u_t to a discrete set of values we can make use of the result that $V_t(\pi_t)$ is always piecewise linear and convex (Smallwood and Sondik, 1973), thus a modified dynamic programming algorithm can determine $V_t(\pi_t)$ as a set of vectors generated from different actions. This allows us to rewrite Equation 7 as:

$$V_t(\pi_t) = \max_{wrt\ e_t u_t} \sum_i \pi_{it} \left\{ w_i(e_t, u_t) + \sum_j \sum_\theta p_{ij}(e_t) r_{j\theta}(u_t) \alpha_j^{t(\pi_t, e_t, u_t, \theta)}(t+1) \right\} \qquad (8)$$

where $\alpha_j^k(t)$ is a $(1xN)$ policy vector which gives the expected payoff from an action across all the states. The superscript on the policy vector gives the optimal vector for a particular belief state and is formally defined as follows:

$$t(\pi_t, e_t, u_t, \theta) = \arg\max_k \sum_i \sum_j \pi_{it} p_{ij}(e_t) r_{j\theta}(u_t) \alpha_j^k(t+1) \qquad (9)$$

that is it selects the vector, by the superscript k, which gives the highest expected value for the belief state resulting from the prior probability, action and observation.

CASE STUDY

BACKGROUND

The Western Australian wheatbelt, has received attention recently due to its agricultural and environmental importance. The area is of high biodiversity significance but is under threat from salinity, grazing, and large scale clearing (Hancock *et al.* 1996). The NEWROC comprises the shires of Koorda, Mount Marshall, Mukinbudin, Nungarin, Trayning, Westonia and Wyalkatchem (Figure 1). The area was 75% zoned for clearing and intensive agricultural use, with 12% of the cleared area remaining or remnant native vegetation. In 2002, the area of remnant vegetation in cleared areas within each shire ranged from 5% in the south west shire of Wyalkatchem to 21% in the eastern most shire of Westonia (Shepherd *et al.* 2002) (Figure 2).

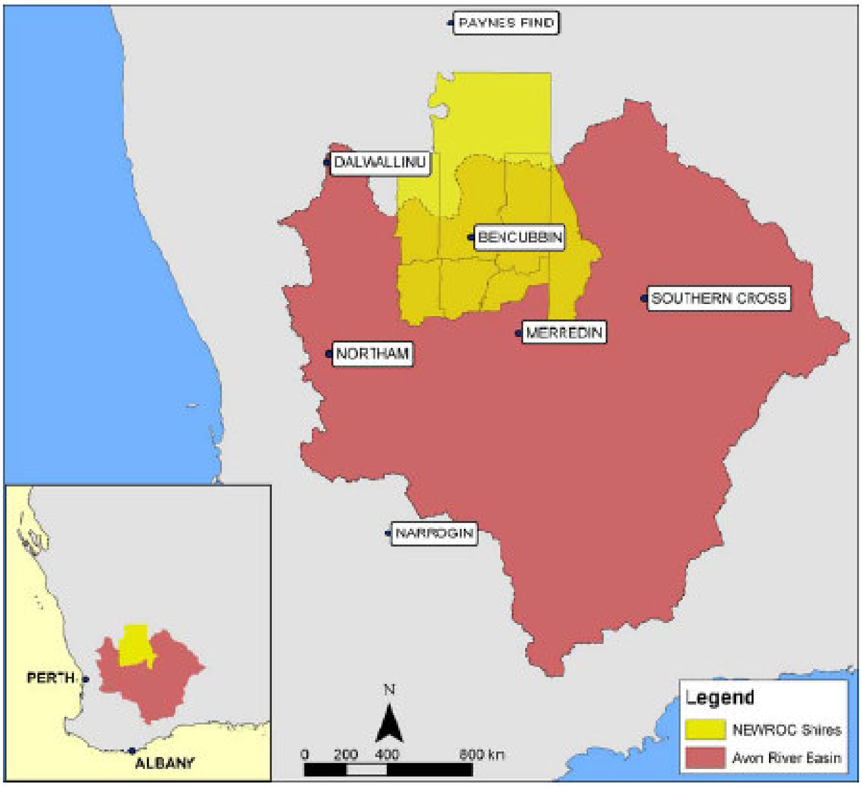

FIGURE 1 LOCATION OF NEWROC WITHIN WESTERN AUSTRALIA.

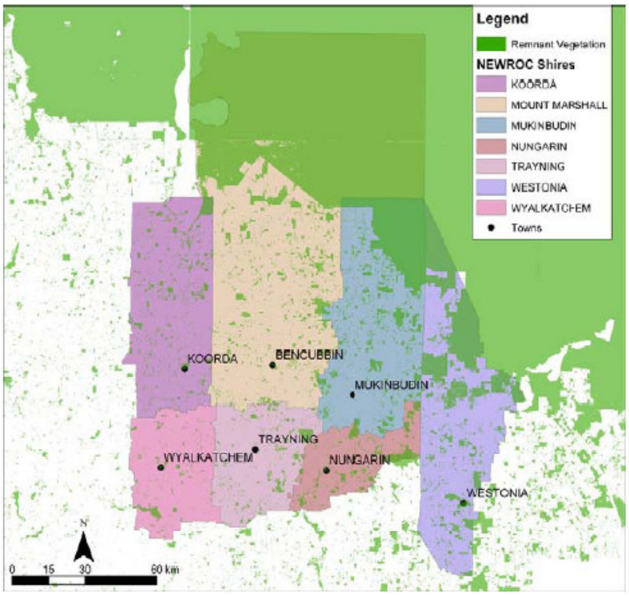

FIGURE 2 EXTENT OF NATIVE OR REMNANT VEGETATION IN NORTH-EASTERN WHEATBELT REGIONAL ORGANIZATION OF COUNCILS (GOLE *ET AL.* 2005).

Yates and Hobbs (1997) detail the state of *Eucalyptus* woodlands in southeast and southwest Australia. Woodlands have been extensively cleared and are often badly degraded due to livestock grazing. Currently it is estimated only 10% of *Eucalyptus loxophleba* (York gum) and 20% of *Eucalyptus salmonophloia/Eucalyptus salubris* (salmon gum/gimlet) woodlands remain. A similar situation exists on the east coast of Australia, where 0.01% of *eucalyptus albens* (white box) woodland remains relatively unmodified. Woodland in the south-east of Australia has declined to 5% in 2000, with a quarter of these being less than 5 hectares and frequently grazed (Duncan and Dorrough 2009).

The removal of degrading factors such as grazing and weeds may be insufficient to restore the woodland, with revegetation action required. Yates and Hobbs (1997) go on to identify the spectrum of stable woodland states that exist in *Eucalyptus salmonophloia* woodlands currently and the actions required to shift the woodland areas from one state to another. Remnant vegetation in the NEWROC area is highly fragmented due to agricultural clearing, and degraded due to weeds, livestock grazing and firewood collection. Together with the impact of dryland salinity this means high levels of habitat loss, with the remaining vegetation severely degraded. The actions required and probability of their success in restoring the vegetation quality is largely determined by the current state of the woodland and its ability to shift to another state. The fencing of remnant vegetation to remove livestock and feral grazing may be insufficient to return degraded woodland to an undegraded state. Extensive revegetation and weed control would likely be required to achieve this shift. The interaction of states and land use actions for NEWROC salmon gum woodland for this case study are shown in the diagram given in Figure 3. Photos of degraded and undegraded are presented in Figure 4 and Figure 5 respectively.

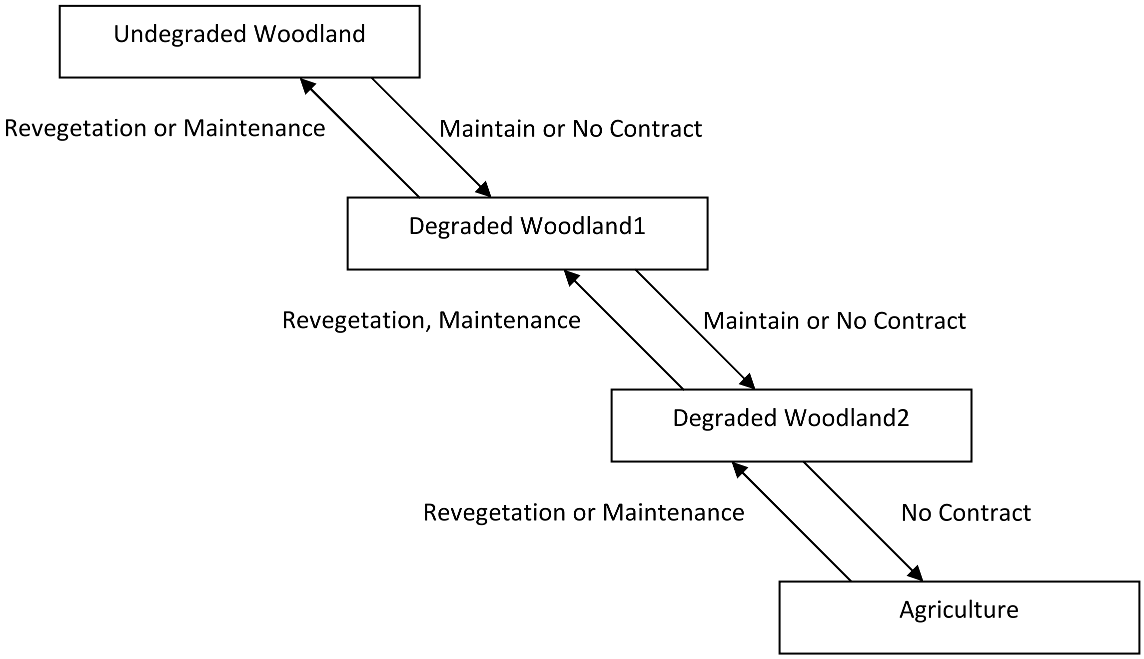

FIGURE 3 TRANSITIONS AND STABLE STATES OF SALMON GUM WOODLAND (BASED ON YATES AND HOBBS, 1997)

FIGURE 4 AN EXAMPLE OF DEGRADED REMNANT EUCALYPTUS WOODLAND IN WESTERN AUSTRALIA.

FIGURE 5 AN EXAMPLE OF REVEGETATED EUCALYPTUS WOODLAND IN WESTERN AUSTRALIA, TEN YEARS AFTER REVEGETATION WORK TOOK PLACE.

This paper uses POMDP to investigate a hypothetical conservation organization's optimal investment in payment for actions and payment for outcomes in the NEWROC region. The contracting process of a payment-for-actions and payment-for-outcomes contract is outlined in Figure 6**Error! Reference source not found.**. Payment for actions pays the landholder b_1 for undertaking agreed actions l regardless of the woodland state of the land at the end of the contract. Payment for outcomes ties the payment amount to the woodland state observed at the end of the contract $s_T b_2$ based on society's valuation of this woodland type. The study investigates two possible levels of action by the landholder within a payment-for-actions or payment-for-outcomes contract. One is for a small improvement or maintenance of the current woodland quality, and the second to significantly improve it through revegetation. The use of independent monitoring of the site, either by an on-ground expert or remote imagery, is also examined. Monitoring has a cost c.

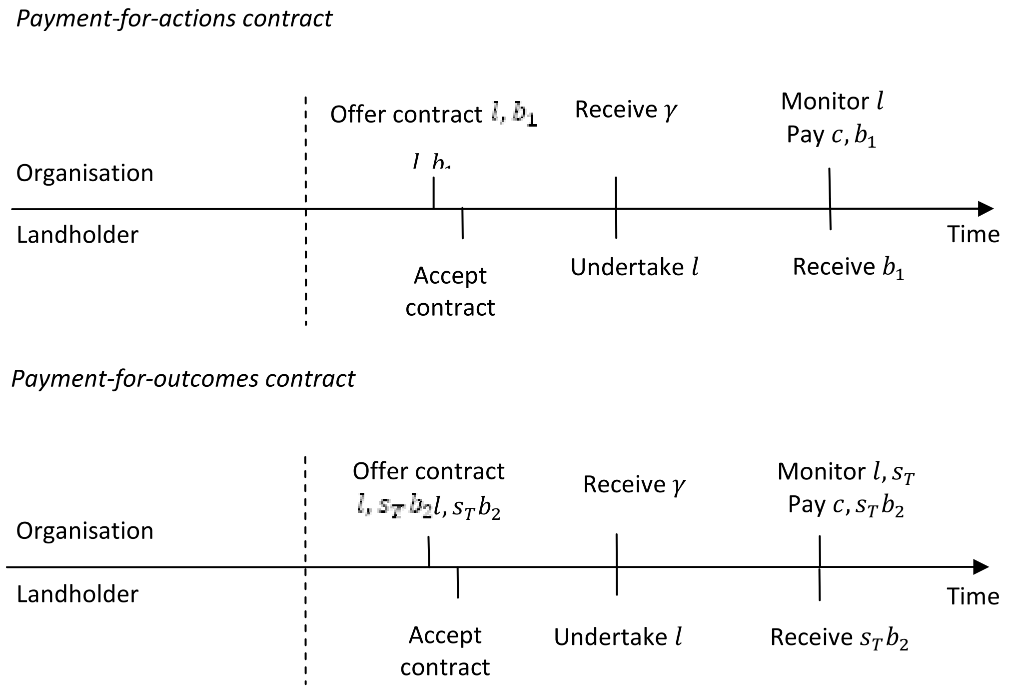

FIGURE 6 TIMELINE OF CONTRACTING PROCESS FOR PAYMENT-FOR-ACTIONS AND PAYMENT-FOR-OUTCOMES CONTRACTS BETWEEN CONSERVATION ORGANISATION AND LANDHOLDER.

MARKOV CHAIN ESTIMATION

Time-series aerial photographs were used to identify attributes of native woodland in a section of NEWROC. The area selected included approximately 209 fragmented blocks of woodland on private land, varying in size and management regimes. Changes in the state of the woodland and management were estimated by combining the time-series aerial photographs with on-ground calibration. Photographs were captured in 1962, 1972, 1984, 1996 and 2007. Aerial photography was purchased from the Western Australia Land Information Authority (Landgate). Imagery was 1:25000, orthorectified using ERDAS ER MAPPER to state road maps provided by the Department of Agriculture and Food Western Australia. The specific steps in converting aerial photographs data into Markov transition probabilities were: (1) entering the images, (2) classifying image attributes, (3) converting attributes to states using principle components analysis, (4) using regression analysis to link these state attributes with the woodland model states indentified in Figure 7, and (5) converting transitions over time into annual Markov-chain transition probabilities for unmanaged land. Figure 7gives an example of the final classification of remnants in NEWROC into Undeg, Degw1, Degw2 and

Agric. These techniques could equally be applied to other forms of remote imagery (Sadler *et al.* 2010). The principle components analysis, regression and Eigen value matrix manipulations were performed using the software package 'R'.

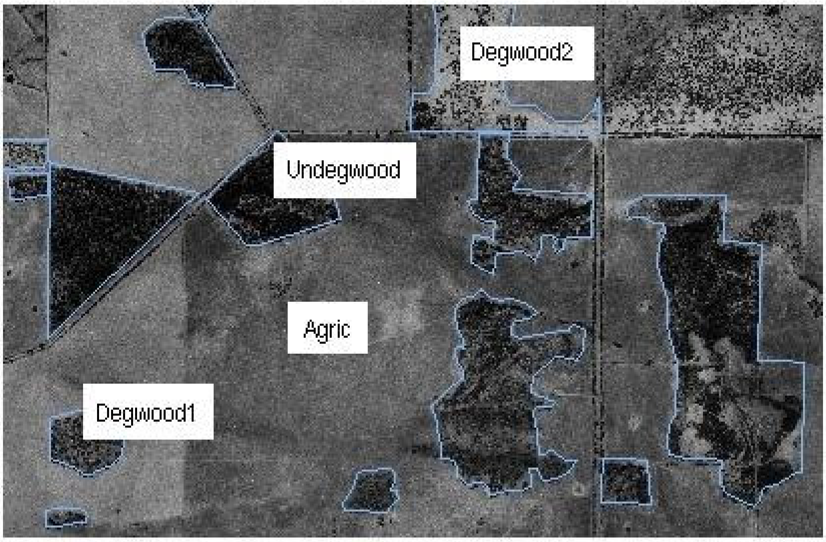

FIGURE 7 EXAMPLE OF CLASSIFICATION OF WOODLAND STATES IN THE NEWROC AREA.

ECOLOGICAL STATES

Markov chain analysis represents vegetation types as N discrete states $s_i = 1, \dots, N$. The predominant vegetation type in the NEWROC area, prior to European settlement and clearing was Eucalyptus woodland. The vegetation communities or states of the salmon gum (*Eucalyptus salmonophloia*) woodland of southeast and southwest Western Australia as classified by Yates and Hobbs (1997) have been grouped into 4 states for this study;

1. Undegraded woodland: Woodland with a generally intact shrubby understorey, a heterogeneous litter layer, and friable, porous soil with possibly some annual weeds (Undeg).
2. Degraded woodland 1: Woodland lacking perennial understorey, except for a few unpalatable species. Ground layer comprised entirely of annual weeds. Litter absent and soil compacted (Degw1).
3. Degraded woodland 2: Mixture of endemic perennial grasses and annual weeds with a few trees (Degw2).
4. Agricultural land: Rotations of annual crop and/or pasture species (Agric).

The benefit and costs society gain from the different vegetation states are based on valuations from similar vegetation communities in eastern Australia. The community willingness to pay for management of remnant native woodland in the Murray catchment of New South Wales was $75 and in the North-east region of Victoria $72 (Lockwood *et al.* 2000). Management of remnant native woodland was for 40 years and included fencing large remnant vegetation blocks, prohibitions on clearing, and restrictions on grazing and collecting timber. Management would provide a benefit of $75.6 million on aggregate to the New South Wales population for management in the Murray catchment's 203,429 ha of remnant vegetation, a benefit of approximately $30/ha/year. Management of the 113,313 ha of remnant vegetation North-east of Victoria would benefit Victorians by $60.7 million, approximately $40/ha/year. Transposing these estimates to NEWROC, the environmental organization is assumed to benefits of $40/ha/year from Undegraded woodland, and $30 from Degwood1. Degw2 and Agric vegetation states are assumed to not provide any benefits to society or the environmental organization.

Private landholders frequently identify the ecological, aesthetic and recreation benefits they receive from managing remnant vegetation, as well as the agricultural production advantages (Lockwood, Walpole et al. 2000; Moore and Renton 2002). Research to date has not quantified these non-agricultural benefits, rather estimating opportunity costs from not clearing and livestock advantages. In this study, the landholders' value of the improvement in vegetation is assumed to be incorporated into the estimated cost to the environmental organization of engaging private landholders to undertake environmental work. Any discrepancy between the direct cost of the work to the landholder and the payment required from the environmental organization to undertake the work, is assumed to be the agricultural and non-agricultural benefits of the improvement in remnant vegetation to the landholder.

ENVIRONMENTAL ORGANIZATION ACTIONS

Action choices are defined as the states were, a set of M discrete actions $a_i = 1, \dots, M$. Yates and Hobbs (1997) identify 16 transitions between the 8 states due to various actions taken by land holders and/or regulators. These 16 transitions have been simplified into 3 actions available to the environmental organization when contracting with a private landholder:

1. Revegetation: a contract with the landholder for intensive revegetation work and maintenance to improve the biodiversity condition of existing remnants of native woodland or establishment of new sites (*Reveg*);
2. Maintenance: a contract to maintain the existing biodiversity condition of remnant native woodland (*Maintain*); or
3. No Contract: not entering into any contract, i.e. the status quo of voluntary revegetation works, grazing, etc. at the landholder's discretion (*No Contract*).

The Revegetation (Reveg) contract requires the landholder to undertake actions including; fencing remnant vegetation blocks, planting of woodland species, controlling weeds and prohibition of grazing and collecting timber. These actions are typical of intensive revegetation schemes such as the Auctions for Landscape Recovery in WA (Gole, Burton et al. 2005). Maintenance (Maintain) requires the landholder to fence remnant native vegetation, but they are allowed limited grazing and collection of firewood or fence post timber (Lockwood, Walpole et al. 2000). Each action has an associated benefits and cost, and expected impact on the transition between vegetation states. The action choice by the environmental organization changes the net benefit ($w_i(e_t, u_t)$) by altering the cost of the action choice ($c_i(e_t)$) and the benefits of the vegetation state as stated above ($g_i(e_t)$). The cost of contracting land for Reveg is \$350 per hectare per year (Gole, Burton et al. 2005), and Maintain is \$30 per hectare per year (Lockwood, Walpole et al. 2000).

An action leads to a change in the state according to a Markov process and an (NxN) matrix of transition probabilities. Each element $p_{ij}(e_t)$ gives the probability of the land in state i being in state j after a single period t. The transition probability matrix in Table 1 gives the predicted end state of the vegetation given the start state for each action over 5 years. The *No Contract* matrix is estimated from aerial photography of the NEWROC as described above. The transition probabilities are an average for the NEWROC, incorporating differences in topography, climate, and landholder skill and landholder compliance across the region.

Estimates for *Maintain* and *Reveg* are calculated based on the *No Contract* matrix (Table 1). The *Maintain* contract is assumed to prevent the land from being used for agricultural production and becoming the state Agric at the end of the period. With a *Maintain* contract, the probability of the land being Agric at the end of the period for *No Contract* is reallocated to Undeg, Degw1 and Degw2 based on the probability of these states occurring. For example, with *No Contract* there is a 7% probability of Degw2 land being Agric at completion of the period. With a *Maintain* contract the probability of Degw2 becoming Agric at the end of the period is zero. The 7% probability previously assigned to Agric is distributed across Undeg, Degw1 and Degw2 according to their probability of occurring with *No Contract*. In this case, it is an additional 1% to Undeg, 1% to Degw1 and 5% to Degw2. Leading to the probability of Degw2 being Undeg at completion of the *Maintain* contract being 10%, Degw1 10% and Degw2 80%. A *Reveg* contract is assumed to prevent the woodland remaining or becoming Agric or Degw2 at the end of the period. The probably of Agric and Degw2 is then reallocated as in the *Maintain* example.

TABLE 1 FIVE YEAR PROBABILITY OF TRANSITION MATRIX BETWEEN VEGETATION STATES FOR EACH ACTION.

No Contract

	Undeg	Degw1	Degw2	Agric
Undeg	0.83	0.03	0.04	0.1
Degw1	0.15	0.17	0.32	0.36
Degw2	0.09	0.09	0.75	0.07
Agric	0.07	0.01	0.09	0.83

Maintenance Contract

	Undeg	Degw1	Degw2	Agric
Undeg	0.92	0.04	0.04	0
Degw1	0.23	0.26	0.6	0
Degw2	0.1	0.1	0.8	0
Agric	0.42	0.04	0.54	0

Revegetation Contract

	Undeg	Degw1	Degw2	Agric
Undeg	0.96	0.04	0	0
Degw1	0.47	0.53	0	0
Degw2	0.49	0.51	0	0
Agric	0.91	0.09	0	0

The state of the land and choice of action and monitoring determine the net benefit to the regulator of the land for each period of the analysis. The cost of contracting land ($c_i(e_t)$) for revegetation (*Reveg*) is \$86 per hectare per year (Gole, Burton et al. 2005), and maintenance of current vegetation (Maintain) is \$42 per hectare per year (Lockwood, Walpole et al. 2000). While not entering a contract (*No Contract*) does not incur a cost or provide a benefit to the regulator. Land being in the state of Undegw or Degw1 provides a benefit to wider society and the regulator, or non-market value. The community willingness to pay for remnant native woodland vegetation in the Murray catchment of New South Wales is used as an estimate of the benefit to wider society and regulator of salmon gum woodland in NEWROC ($g_i(e_t)$); \$91 per hectare per year for Undeg and \$46 per hectare per year for Degw1 (Lockwood, Walpole et al. 2000). Monitoring the land to determine its current vegetation state requires engaging a local expert and is estimated to cost (c^m) \$8 per hectare per year (Gole, Burton et al. 2005).

“Monitoring” refers to the environmental organization observing the state of the vegetation at the end of the contract period. The observation recorded is used to determine future contracted actions and the payment amount for the contract. For a *Reveg* contract, if Undeg is observed, the landholder receives the full payment amount, \$350/ha/year. However, if Degw1 is observed, the payment is reduced by 25% to \$260/ha/year, and if Degw2 or Agric is observed the payment is zero. A *Maintain* contract pays the landholder the full \$30/ha/year if Undeg is observed at completion of the contract, \$22/ha/year if Degw1 and zero if Degw2 or Agric are observed. The discount to the landholder payment is the same proportion as the discount for society’s valuation of Degw1, Degw2 and Agric compared with Undeg.

The combinations of conservation contract type and monitoring effort give six different action options for the regulator to choose from:

1. *No Contract-Monitor*
2. *Maintain-Monitor*
3. *Reveg-Monitor*
4. *No Contract-No Monitor*
5. *Maintain-No Monitor*
6. *Reveg-No Monitor*.

Undertaking monitoring is costly and does not necessarily provide perfect information about the woodland state. This study investigates the optimal monitoring decision (whether to monitor or not), with a choice between on-ground monitoring by an expert with knowledge of the local ecosystem, or monitoring by remote sensing using satellite imagery. Monitoring is estimated to cost (c^m) \$8 per hectare per period when using field visits by a local expert (Gole, Burton et al. 2005), and \$1 per hectare per period for remote sensing. The (NxN) observation matrix, which is a function of monitoring effort u_t, specifies the accuracy of monitoring. Each element $r_{j\theta}(u_t)$ is the probability that if state θ is observed, the woodland at the end of period t is j, i.e. how accurately the end woodland state is observed. Reviews of agri-environmental policy monitoring conclude that monitoring to assess ecosystem change incurs significant costs and is prone to inaccuracy in the form of misclassifications of woodland types (Hooper 1992; National Audit Office 1997; World Bank 1998). Remote sensing is seen to accurately identifying grassland types of 64% of the time (Peterson *et al.* 2002) and accurately map grass cover density 89% of the time (Zha *et al.* 2003). The observation matrix of all actions for field monitoring is given in Table 0-2 and for remote sensing monitoring in Table 0-3.

TABLE 0-2 ACCURACY OF OBSERVATION FOR FIELD MONITORING.

		Observed state			
		Undeg	**Degw1**	**Degw2**	**Agric**
	Undeg	0.95	0.05	0	0
	Degw1	0.05	0.9	0.05	0
Actual state	**Degw2**	0	0.05	0.9	0.05
	Agric	0	0	0.05	0.95

Table 0-3 Accuracy of observation for field monitoring.

		Observed state			
		Undeg	**Degw1**	**Degw2**	**Agric**
	Undeg	0.75	0.25	0	0
	Degw1	0.15	0.7	0.15	0
Actual state	**Degw2**	0	0.15	0.7	0.15
	Agric	0	0	0.25	0.75

An annual discount factor of $\delta^t = 0.93$ (discount rate of seven percent) is assumed for all analysis. This discount rate was applied for consistency with the valuation of NEWROC woodland based on the valuation of native remnant woodland in NSW and Victoria that applied a discount factor of 0.93 (Lockwood, Walpole et al. 2000).

RESULTS AND DISCUSSION

There is a positive return to the environmental organization for contracting with the landholder with a payment-for-outcomes contract in some circumstances. The optimal decision for the organization considering offering a 5-year payment-for-outcomes contract to the landholders is determined by the decision timeframe and their initial belief about the state of the woodland. The organization can contract the landholder for *Maintain-Monitor* or *Reveg-Monitor* and the payment amount will be determined by the observed woodland state (payment for outcomes). Alternatively the environmental organization can contract *Maintain-No Monitor* or *Reveg-No Monitor* and the payment amount is not based on the woodland state observed (payment for actions). The analysis then highlights the environmental organization's preference between a payment-for-actions and payment-for-outcomes contracts, as well as their preference between field and remote monitoring.

The various optimal sequences of actions for the environmental organization over different timeframes are shown in policy graphs, such as Figure 8 for perfect monitoring. The level of the diagram marked '5 years' gives the optimal decision choice of the environmental organization when they have a five-year decision timeframe. The level marked 10 years gives the optimal decision initial action for the first 5-year period, and their decision in the following five-year period is given in the level below. For example, to read the policy graph for the environmental organization taking a decision timeframe of 15 years, firstly select one of the actions list at '15 years' as the action for the first five years of the decision timeframe. Second, follow the arrow to the subsequent action for a 10 year timeframe. The second decision of the conservation agency with a 15-year timeframe is an action of the 10-year timeframe. When *Monitor* occurs the arrow choice in the following period is notated by U, D1, D2 or A depending on the woodland state observed being Undeg, Degw1, Degw2 or Agric respectively. Lastly, in the final five year period the environmental organization would always do the action given at '5 years'. In this way, the optimal sequence of actions (the action vector) for a decision timeframe builds on the optimal action vector of the shorter timeframes it incorporates.

PERFECT AND COSTLESS MONITORING

The environmental organization with a 25-year timeframe and perfect, costless monitoring should commence with *Maintain-Monitor* (vector 0), or *No Contract-Monitor* (vector 1). *No Contract-Monitor* is used to identify Agric land so the environmental organization can then contract *Maintain-Monitor* in the following five-year period to improve the woodland state. If Undeg, Degw1 or Degw2 is observed at the end of 10 years, the environmental organization should undertake *No Contract-No Monitor*. Monitoring also enables the environmental organization to reduce the payment to the landholder depending on the woodland state observed at the end of the contract. As outlined above, the payment if Undeg is observed is the full payment amount for the contract type ($350/ha/year), or 75% of the payment if Degw1 is observed ($260/ha/year), or $0/ha/year if Degw2 or Agric is observed. The next action in the sequence following *Maintain-Monitor* or *No Contract-No Monitor* is *No Contract-No Monitor*, unless Agric is observed. Agric is always contracted *Maintain-Monitor*.

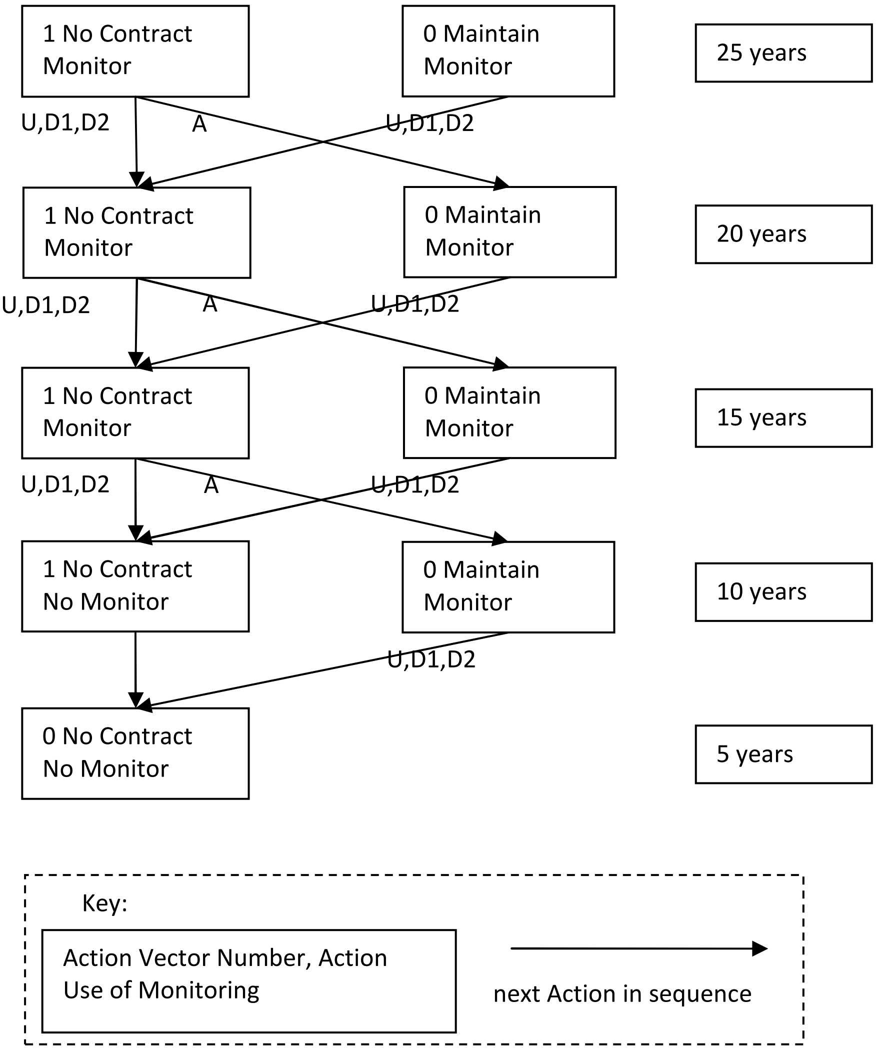

FIGURE 8 POLICY GRAPH OF OPTIMAL ACTION SEQUENCES FOR THE ENVIRONMENTAL ORGANIZATION OFFERING A 5-YEAR PAYMENT-FOR-OUTCOMES CONTRACT, WITH PERFECT AND COSTLESS MONITORING (NOTE: U=UNDEG, D1=DEGW1, D2=DEGW2, A=AGRIC).

Table 4 gives the net present value of the optimal actions for a sample of prior probabilities relating to the state. When monitoring is perfect and costless, it is optimal for the environmental organization to enter a payment-for-outcomes contract when the woodland state is likely to be Agric. Monitoring is employed to identify when other land types degrade to Agric to then offer a contract and improve this Agric land. Monitoring is also employed to determine the payment amount at completion of the contract, reducing the cost of the program to the environmental organization (by avoiding payment in some cases). Compared with a payment-for-actions contract, payment for outcomes with perfect monitoring increases the net present value of the optimal decision by between 2% (if Undeg) and 107% (if Agric).

TABLE 4 OPTIMAL ACTION VECTOR FOR A ENVIRONMENTAL ORGANIZATION OFFERING A 5-YEAR PAYMENT-FOR-OUTCOMES CONTRACT WITH PERFECT AND COSTLESS MONITORING, FOR A SAMPLE OF DIFFERENT PROBABILITIES OF THE INITIAL WOODLAND STATE.

Probability of initial state				Optimal Initial Action	Net present value
Undeg	**Degw1**	**Degw2**	**Agric**		
0.5	0.5			*No Contract-Monitor (1)*	269
0.5		0.5		*No Contract-Monitor (1)*	223
0.5			0.5	*No Contract-Monitor (1)*	221
1				*No Contract-Monitor (1)*	359
	0.5	0.5		*No Contract-Monitor (1)*	133
	0.5		0.5	*Maintain-Monitor (0)*	133
	1			*No Contract-Monitor (1)*	180
		0.5	0.5	*Maintain-Monitor (0)*	90
		1		*No Contract-Monitor (1)*	87
			1	*Maintain-Monitor (0)*	112

FIELD MONITORING

Figure 9 shows the optimal sequences of payment-for-outcome contracting and not contracting by the environmental organization over different timeframes when field monitoring is possible. Comparing Figure 9 and Figure 8 shows the change in the optimal action choices of the environmental organization using inaccurate field monitoring rather than perfect monitoring. When using field monitoring, the organization with a 25-year decision timeframe should commence with *Maintain-Monitor* (action vector 0), *No Contract-Monitor* (vector 1), or *No Contract-No Monitor* (vector 2). The inaccuracy and cost of field monitoring means *No Monitor* is optimal in some circumstances.

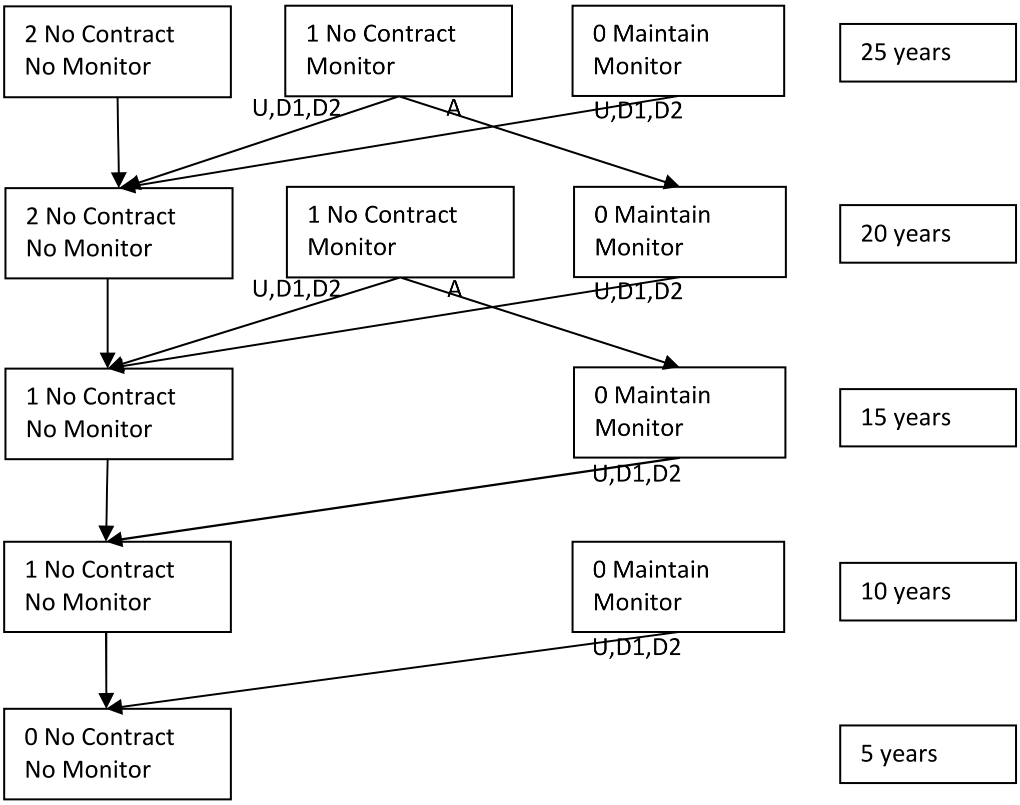

FIGURE 9 POLICY GRAPH OF OPTIMAL ACTION SEQUENCES FOR THE ENVIRONMENTAL ORGANIZATION OFFERING A 5-YEAR PAYMENT-FOR-OUTCOMES CONTRACT WITH FIELD MONITORING (NOTE: U=UNDEG, D1=DEGW1, D2=DEGW2, A=AGRIC).

From Table 1-7, field monitoring reduces the net present value by between approximately 2% and 13%, depending on the initial state of the woodland, relative to perfect information. When the woodland is Agric, the optimal initial action is *Maintain-Monitor*, followed by *No Contract-No Monitor* (vector 0). Monitoring of *Maintain* enables the environmental organization to reduce the payment to the landholder if Degw1 is observed, and pay $0/ha/year if Degw2 or Agric is observed. When the state is Agric, the optimal action sequence of a *Maintain-Monitor* payment-for-outcomes contract, followed by *No Contract-No Monitor* (vector 0), has a net present value of $100/ha. This compares to the maximum net present value of $112/ha achieved by a payment-for-outcomes contract with perfect and costless monitoring.

On Degw1 land, the environmental organization should *No Contract-Monitor* for the initial period (vector 1). This is followed by *Maintain-Monitor* if Agric is observed at the end of the period, or *No Contract-No Monitor* if Undeg, Degw1 or Degw2 is observed. *No Contract-Monitor* is used to identify Agric land, and strategically invest in *Maintain-Monitor* where it has a positive return. When the woodland is Degw1 and vector 1 is undertaken, the net present value is $166/ha. The net present value for this sequence when monitoring is perfect and costless is $180/ha.

If the initial woodland state is likely or known to be Undeg or Degw2, the optimal action for the entire 25-year decision timeframe is *No Contract-No Monitor* (vector 2). *No Contract-No Monitor* when the woodland state is Undeg or Degw2 for 25 years (vector 2), has a net present value of $353 or $83/ha. This is identical to the return of the payment-for-actions as contracting does not occur. However, it is lower than a payment-for-outcomes contract with perfect monitoring, which achieved $359 and $87/ha for Undeg and Degw2 respectively by continuously monitoring and contracting to improve Agric land that appeared.

TABLE 5 OPTIMAL ACTION VECTOR FOR A ENVIRONMENTAL ORGANIZATION OFFERING A 5-YEAR PAYMENT-FOR-OUTCOMES CONTRACT WITH FIELD MONITORING, FOR DIFFERENT PROBABILITIES OF THE INITIAL WOODLAND STATE.

Probability of initial state				Initial action	Net present
Undeg	**Degw1**	**Degw2**	**Agric**	**(action vector number)**	**value**
0.5	0.5			*No Contract-No Monitor (2)*	259
0.5		0.5		*No Contract-No Monitor (2)*	218
0.5			0.5	*No Contract-Monitor (1)*	208
1				*No Contract-No Monitor (2)*	353
	0.5	0.5		*No Contract-No Monitor (2)*	124
	0.5		0.5	*Maintain-Monitor (0)*	121
	1			*No Contract-Monitor (1)*	166
		0.5	0.5	*Maintain-Monitor (0)*	78
		1		*No Contract-No Monitor (2)*	83
			1	*Maintain-Monitor (0)*	100

Field monitoring reduces the net present value of the optimal action vector for all possible initial woodland types compared with perfect and costless monitoring. The reduction is only 2% when the environmental organization is confident of the initial state of the woodland being Undeg, but increases to 11% when they are uncertain if it is Dewg2 or Agric. The reduction is due to the environmental organization not monitoring constantly with field monitoring compared with perfect monitoring. Constant monitoring when it is perfect and costless allows the organization to identify any land that becomes Agric for contracting in the following period. The inaccuracy and cost of field monitoring reduce its use in some circumstances and the overall return to the environmental organization.

REMOTE MONITORING

In this model, when offering a payment-for-outcomes contract, it is preferable for the environmental organization to use remote monitoring rather than field monitoring. Figure 10 shows the optimal action vectors for a environmental organization using remote monitoring. Contrasting this with Figure 8 and Figure 9 shows the impact that remote monitoring has on the optimal action sequence for the environmental organization compared with perfect or field monitoring respectively. A environmental organization considering remote monitoring with a 25-year decision timeframe has 5 optimal action vectors, one beginning with *Maintain-Monitor* (vector 0), two *No Contract-No Monitor* (vector 1,2) and three *No Contract-Monitor* (vector 3,4,5). Each vector differs in how the environmental organization responds to the information gained through monitoring.

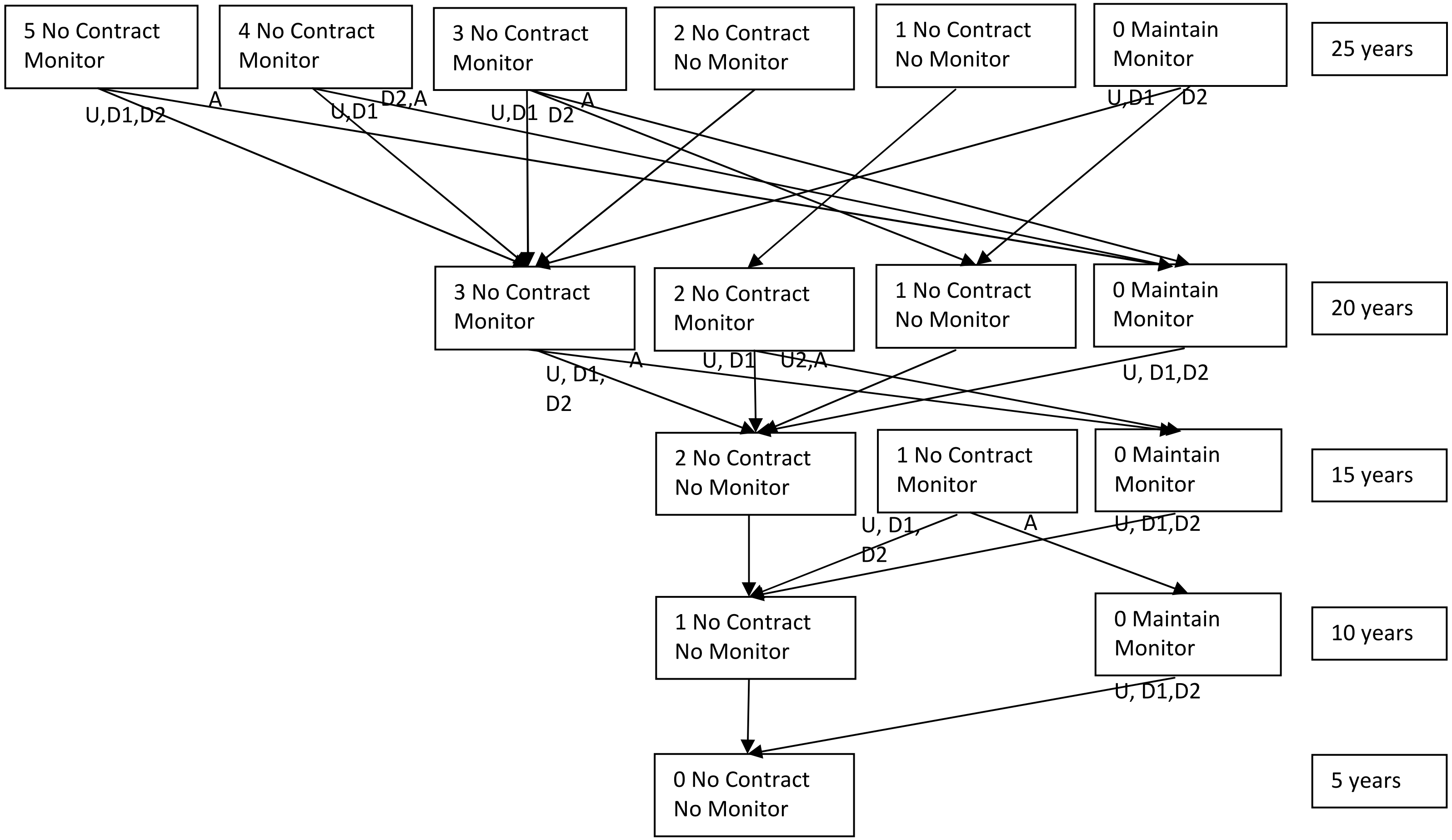

FIGURE 10 POLICY GRAPH OF OPTIMAL ACTION SEQUENCES FOR THE ENVIRONMENTAL ORGANIZATION OFFERING A 5-YEAR PAYMENT-FOR-OUTCOMES CONTRACT, WITH REMOTE MONITORING (NOTE: U=UNDEG, D1=DEGW1, D2=DEGW2, A=AGRIC).

The net present value of the optimal action vector using remote monitoring for different probabilities of the initial woodland state is given in Table 6. Comparing this with the net present value of the optimal sequence with perfect monitoring in Table 4 and field monitoring in Table 5 shows the impact remote monitoring has on the outcome for the environmental organization. Both remote monitoring and field monitoring reduce the net present value compared with perfect monitoring, but the reduction is larger for field monitoring. Remote monitoring reduces the return on the optimal action by 1% when the land is Undeg, 4% when Degw1, 5% when Degw and 6% when Agric, compared with perfect monitoring. Field monitoring reduces the return on the optimal action by 2% when the land is Undeg, 8% when Degw1, 5% when Degw and 11% when Agric.

If the land is known or likely to be Agric it is optimal to contract *Maintain-Monitor* in the initial period, then *No Contract-No Monitor* until the end of the decision timeframe (vector 0). When the land is Agric the net present value of the optimal *Maintain-Monitor* then *No Contract-No Monitor* sequence is \$105/ha. This compares to \$105/ha with field monitoring and \$112/ha with perfect and costless monitoring.

The environmental organization should undertake *No Contract-Monitor* if the woodland is likely to initially be Undeg or Degw1 in order to identify any land which becomes Agric (vector 5). When Agric land is observed it is then contracted *Maintain-Monitor*. If Undeg, Degw1 or Degw2 is observed at the end of the period it is left to *No Contract-No Monitor.* The net present value of this optimal action vector is \$355/ha for Undeg and \$172/ha for Degw1. With field monitoring the net present value of the optimal action vector for Undeg was \$353/ha and Degw1 \$166/ha. A payment-for-outcomes contract with perfect monitoring would achieve a net present value of \$359/ha if Undeg and \$180/ha if Degw1.

If the land is Degw2 it is optimal to *No Contract-No Monitor* for the entire 25 year decision timeframe. The net present value of this sequence is \$83/ha, which is identical to a payment-for-outcomes contract with field monitoring but lower than the \$87/ha achieved with perfect and costless monitoring.

TABLE 6 OPTIMAL ACTION VECTOR FOR A ENVIRONMENTAL ORGANIZATION OFFERING A 5-YEAR PAYMENT-FOR-OUTCOMES CONTRACT WITH REMOTE MONITORING, FOR DIFFERENT PROBABILITIES OF THE INITIAL WOODLAND STATE.

Probability of initial state				Initial action	Net present
Undeg	**Degw1**	**Degw2**	**Agric**	**(action vector number)**	**value**
0.5	0.5			*No Contract-Monitor (5)*	263
0.5		0.5		*No Contract-No Mon (2)*	218
0.5			0.5	*No Contract-Monitor (4)*	216
1				*No Contract-Monitor (5)*	355
	0.5	0.5		*No Contract-Monitor (5)*	127
	0.5		0.5	*Maintain-Monitor (0)*	127
	1			*No Contract-Monitor (5)*	172
		0.5	0.5	*Maintain-Monitor (0)*	81
		1		*No Contract-No Mon (1)*	83
			1	*Maintain-Monitor (0)*	105

In NEWROC, the conservation organization should only contract a landholder with a payment-for-outcomes contract to improve the woodland when the current state of the woodland is likely to be Agric and the decision timeframe is at least 10 years. When the woodland is currently Degw2, Degw1 or Undeg it is optimal not to institute a payment-for-outcomes contract with the landholder, and the woodland is left to decline at its natural rate. A payment-for-actions contract is not offered with any woodland type. A preference for a payment-for-outcomes contract over a payment-for-actions contract is observed across all assessment types, including perfect assessment. Payment for outcomes increases the net present value of the optimal action vector undertaken by the environmental organization compared with payment for actions as it eliminates the cost of payment when the outcome is unfavorable.

In the base-case runs for this model, monitoring of a payment-for-outcomes contract can reduce the cost of achieving environmental outcomes in two ways. Firstly by reducing the payment amount when low-quality woodland is observed, and secondly by identifying land where contracting has a positive return on investment. Comparing field and remote monitoring to perfect and costless monitoring shows that low-cost remote monitoring gives a higher return to the environmental organization than field monitoring. Remote monitoring is used over a wider range of prior probabilities relating to the initial woodland state.

CONCLUSIONS

In the base-case analysis presented in this paper, contracting landholders in the NEWROC region to improve the woodland state is only optimal for an environmental organization when the following combination of circumstances is present: the environmental organization bases the contract payment amount on the observed woodland state at the completion of the contract, the woodland state is probably Agric and the decision timeframe is at least 10 years. For other states (i.e. Undeg, Degw1, and Degw2), would only be optimal to offer contracts if the cost of the contract is reduced or the woodland is of high value relative to the base-case scenario. In this model, a contract with payment based on the woodland state at the contract’s completion is generally superior to payment without monitoring . This is reflected in the results showing that, monitoring almost always selected when contracting is optimal.

In this case study, if monitoring is employed by the environmental organization solely to improve decision making, then it should be used when the environmental organization is uncertain about the woodland state, the decision timeframe is sufficiently long, and a payment-for-outcomes contract is applied. The environmental organization's decision timeframe must be at least 20 years if field monitoring is used and 15 years if perfect or remote monitoring is used. A longer decision timeframe means the environmental organization has a longer time to accrue benefits from the improved decision making.

In most circumstances examined, actions with remote monitoring had a higher net present value than did actions with field monitoring. Also it is optimal for the environmental organization to employ remote monitoring over more belief states for the initial woodland state than field monitoring. Overall, the lower cost of remote monitoring is usually sufficient to outweigh the slight diminution of benefits from better decision making.

The POMDP model does not link monitoring to the landholder's behavior. Rather, monitoring in this model has value only from improving the environmental organization's decision making prior to investment in a contract or to determine the payment amount at completion the contract. The landholder receives their payment based on the woodland state of the land at the end of the contract, but this outcome is not related to their behavior, as the POMDP model describes the conservation organization's optimal decision when faced with a compliant landholder. The impact of the landholder's behavioral response to inaccurate monitoring is investigated in further research.

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