Ecological Modelling 222 (2011) 2856–2866

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Suitability of short or long conservation contracts under ecological and socio-economic uncertainty

Gareth D. Lennox[a,*], Paul R. Armsworth[b]

[a] Department of Animal and Plant Sciences, University of Sheffield, Sheffield, UK
[b] Department of Ecology and Evolutionary Biology, University of Tennessee Knoxville, Knoxville, TN, USA

ARTICLE INFO

Article history:
Received 14 December 2010
Received in revised form 28 April 2011
Accepted 29 April 2011
Available online 7 June 2011

Keywords:
Conservation contract
Stochastic dynamic programming
Private land
Site selection
Agri-environment scheme
Payment for environmental services

ABSTRACT

Acquisition of land rights has become a primary tool used to protect terrestrial biodiversity. Fixed length contracts are often used when trying to secure conservation benefits on private land in agri-environment schemes and payment for environmental services schemes, but the duration of the conservation contracts used in different programmes varies. To date, very little research has been undertaken to determine the situations in which contracts of differing lengths are optimal or when conservation agencies or groups should use a portfolio of different contract lengths rather than relying on a single type. Using stochastic dynamic programming and related heuristic methods, we investigate how the choice between short or long conservation contracts is affected by uncertainty regarding the future availability of sites and their ecological condition. We also examine the benefits offered by using a portfolio of different contract lengths. Conservation agencies must pay private landowners a premium to secure longer agreements and because of this, shorter contracts are advantageous if sites are likely to remain available for conservation in the future. Long contracts are preferred when future site availability becomes more unlikely. In contrast to uncertainty over site availability, uncertainty over future ecological conditions has little effect on contract selection and only markedly influences the choice between short and long contracts when there is heterogeneity across sites in expected conservation outcomes and future availability of sites is also uncertain. Finally, when future site availability is unlikely, the use of a portfolio of short and long contracts would offer greater conservation gains than using either type in isolation, even though this option is not yet one that is commonly found in conservation practice.

1. Introduction

Acquisition of land rights has become a primary means used to protect terrestrial biodiversity (Ferraro and Kiss, 2002). Through such acquisitions, governments and conservation groups have invested billions of dollars in contracts with landowners that seek to alter land uses for the benefit of biodiversity (Cooper et al., 2009; Davies et al., 2010). Nevertheless, efforts to stem the losses of biodiversity remain grossly underfunded (James et al., 1999; Balmford et al., 2002). It is necessary, therefore, that conservation agencies wisely choose the locations on which they seek to secure land rights. From the 1980s onward, a large body of literature has grown to address this site selection problem (e.g., Cocks and Baird, 1989; Pressey et al., 1997; Ando et al., 1998; Moilanen et al., 2004; Dreschler et al., 2009). One drawback of early studies was that the solution was assumed to be static, in the sense that all desired sites could be secured instantaneously. However, the process through which land is protected is inherently dynamic. This temporal aspect of the acquisition process is caused by several factors. For instance, in any time period funding is rarely sufficient to allow the conservation agency to protect all sites of conservation concern (Costello and Polasky, 2004). Moreover, when and where sites will be available for conservation cannot be known in advance (Meir et al., 2004).

The dynamic nature of the acquisition process introduces several sources of uncertainty. Although the conservation agency may be able to determine current site availability, future availability cannot be known with certainty. Further, the conservation agency may be able to assess the current ecological value of sites but forces such as climate change or changing local land use can alter the future value of sites. Therefore, in order to make decisions that are robust to future change, conservation agencies must be aware of these sources of uncertainty and factor them into conservation planning.

Models that deal with the dynamics of the acquisition process have recently been developed. For example, Costello and Polasky (2004), Meir et al. (2004), Strange et al. (2006) and Sabbadin et al. (2007) look at the acquisition process where reserve networks are

* Corresponding author. Tel.: +44 (0)1294605737.
E-mail addresses: bop08gdl@shef.ac.uk, celtlen@gmail.com (G.D. Lennox).

0304-3800/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolmodel.2011.04.033

Table 1
Variety of contract durations employed in AES and PES around the world.

Conservation scheme	Location	Length(s) (years)
Pagos de Servicios Ambientales[a]	Costa Rica	5, 10 or 15
Environmental Stewardship Scheme[b]	UK	5 or 10
Conservation Reserve Programme[c]	USA	Between 10 and 15
Forest Carbon Sequestration[d]	Vietnam	20
Social Forestry Programme[e]	Indonesia	25 and extendable
Conservation International Forest Conservation[f]	Guyana	30

[a] ZBinden and Lee (2005).
[b] DEFRA (2008).
[c] Khanna and Ando (2009).
[d] Ha et al. (2008).
[e] Pender et al. (2008).
[f] Conservation International (2000).

created through time and where there is a risk that unreserved sites will be lost to development. In these studies, acquired sites are considered protected in perpetuity with no further loss or gain in species richness. Similarly, if development occurs on unreserved sites then it is considered irreversible with all species extirpated.

The assumptions that underlie the models developed in studies such as those cited above are particular to specific types of conservation investments or particular types of development. Firstly, the assumption of perpetual protection is applicable if sites are acquired through fee simple acquisitions or in well-monitored and defended conservation easements (Fishburn et al., 2009; Armsworth and Sanchirico, 2008; Rissman and Butsic, 2010). However, widespread use has also been made of fixed-term contracts in agri-environment schemes (AES) and payment for environmental services schemes (PES). For example, within the European Union, US$7.2 billion per year is paid to farmers to provide environmental benefits on their properties (Cooper et al., 2009). Secondly, an assumption that conservation values are lost completely and in perpetuity may be appropriate if sites become densely urbanized where this is incompatible with particular ecological functions. However, there are many situations in which conservation investment may not be possible for a temporary period only. For example, such situations arise when a landowner commits to a particular crop rotation or invests sunk costs in a particular technology that precludes conservation measures for a limited time. Furthermore, the availability status of sites will be affected by commodity prices. Such prices determine the forgone profits that would be lost if a landowner agreed to undertake particular conservation measures. Thus, at times of high prices, a conservation agency may not be willing or able to compensate for the high payment level demanded by the landowner. However, as prices fall, the site may become available to the conservation agency once again. Such factors can therefore result in sites of high biodiversity value that may be unavailable for conservation investment in one time period becoming available for investment again in some future time period.

Fixed length contracts with private landowners that are used in conservation vary in their duration. Table 1 gives examples that highlight the large variety of contract lengths employed in AES and PES around the world. This variation in contract duration (with perpetuity being the logical extreme) begs the question of what the relative advantages and disadvantages are of short versus long contracts and whether there is an optimal contract duration or optimal distribution of contract durations for a particular set of circumstances. In this paper, we examine the role that different kinds of uncertainty play in determining the relative advantages of short and long contracts. Specifically, we examine how uncertainty over future site availability and over future site ecological condition affects the choice of contract duration. Elsewhere, Ando and Shah (2010) found that the optimal length of a conservation contract depended on a trade-off between the ecological effects of the length of the contract and the number of landowners enrolled. Longer contracts lead to greater ecological benefits but diminish the incentive for landowners to accept the contract. When analysing the optimal length of an agricultural carbon contract, Gulati and Vercammen (2005) found that the greater the reduction in farming intensity demanded by the contract, the shorter the period the landowner will accept conservation. However, neither of these initial studies parses the role of different kinds of uncertainty, nor do they consider the possibility of a portfolio of contract durations.

In general, contracts that are shorter are less expensive than those that are over a longer timescale, meaning more can be secured for a given level of investment. Short-term contracts also spread the risk of wasting investments if protected sites themselves deteriorate in condition. Moreover, given that a larger number of short contracts would be available compared to longer agreements, they can increase competition among landowners for conservation investment, which can be advantageous in some programme designs (Latacz-Lohmann and Van der Hamsvoort, 1997). However, short-term contracts come with the attendant risk that landowners will decline to re-enrol on completion of the contract term. Empirical research has shown that the fate of land protected in temporary contracts is uncertain. For example, in the context of the Conservation Reserve Programme (CRP), Skaggs et al. (1994) surveyed 811 participants in New Mexico regarding their post-CRP land use plans. Of those surveyed, 21% expressed the intention to go back to farming, 40% planned to re-enrol, with the remaining 39% undecided. Long-term contracts reduce this “end of contract problem” (Whitby, 2000) and ensure priority sites stay in conservation management for longer. We look at how differing levels of uncertainty affect the trade-off between these different pros and cons of different contract lengths. In Sections 2 and 3, we address these questions optimally on a small descriptive problem using stochastic dynamic programming (SDP) (Mangel and Clark, 1988; Possingham et al., 1993; Costello and Polasky, 2004). Then, in Section 4, we address the same set of questions on a larger problem using heuristic methods.

2. Illustrative model

To formalize these ideas, we now outline a model that captures some of the structure of fixed-term contracts under uncertainty. In this first, illustrative model, the conservation agency has only $J = 3$ sites of conservation interest to choose between. Each has been assessed and given an ecological score. A stochastic process affects the ecological score, which is discretized over 2 states. These states can be thought of as the site being in a good or degraded ecological condition. Transitions between states are dependent on whether or not a site is contracted, with sites not receiving conservation investment at greater risk of degradation. There is also a stochastic process affecting site availability. Unavailable sites can become available for conservation contracting and vice versa, independent of current conservation investment.

In our models, the short contracts last one time step while the long contracts last either two or three. We therefore model a situation in which, for example, a conservation agency can use contracts of 5 years and 10 or 15 years.

To reduce the size of the state space, we assume a very simple cost structure. Specifically, we assume that the overall budget available to the conservation agency limits the investment choice to at most two concurrent short-term contracts or one long-term contract per time period. With this cost structure, the conservation agency must pay landowners a very high premium (or face much higher transaction costs) to secure a long-term agreement. We further assume that the budget is binding with no carry-over to future time periods. Variable budgets, carry-over and more realistic cost assumptions can be included by adding more state variables (Costello and Polasky, 2004).

Finally, we assume that conservation benefits accrue through time and that benefits are only derived on contracted sites. These assumptions would describe some ecosystem services such as access rights for recreation that accompany many public agency conservation contracts (e.g., in the Environmental Stewardship Scheme in the UK, landowners can receive payments for allowing public access to their land (Nature England, 2010)) or water quality improvements over baseline levels (e.g., through payments to limit the use of fertilizers on properties (Cooper et al., 2009)). We relax some of these assumptions later and also review alternative formulations in Section 5.

2.1. Markovian structure and optimal rewards

The system is assumed to have a Markovian transition structure. The observable realisations are denoted by $\mathbf{x}_t$, where $\mathbf{x}_t \in \mathbf{S}_t$, the state space, and $|\mathbf{S}_t| = 2^{2J} + 2^{2J}J/2$. Each state describes a potential configuration of contract, ecological condition and availability status of the sites at time t. Single time step transitions between states are given by

$$\mathbf{x}_{t+1} = \mathbf{T}(\mathbf{x}_t, a_t)$$

where $\mathbf{T}$ defines the transition matrix. This gives the probability of moving from one realization of $\mathbf{x}$ to another in one time step, dependent on making a particular investment decision, a_t.

The conservation agency receives the reward R for taking investment a while the system is in state $\mathbf{x}$, plus the sum of expected future rewards. Thus, starting from time t, our overall reward, V, can be defined in recursive form as

$$V(A_t|\mathbf{x}_t) = R(a_t|\mathbf{x}_t) + \sum_{\mathbf{x}_{t+1}} \mathbf{T}(\mathbf{x}_{t+1}|x_t, a_t) V(A_{t+1}|\mathbf{x}_{t+1})$$

This recursive form allows us to determine an optimal investment policy, A_t^*, that optimizes V through use of the Bellman's equation, which in this case becomes

$$V^*(\mathbf{x}_t) = \max_{a_t} \left\{ R(a_t|\mathbf{x}_t) + \sum_{\mathbf{x}_{t+1}} \mathbf{T}(\mathbf{x}_{t+1}|\mathbf{x}_t, a_t) V^*(\mathbf{x}_{t+1}) \right\} \quad (1)$$

2.2. Curse of dimensionality

In Section 3, we use SDP to determine the sequence of decisions that results in the optimal value of Eq. (1). Several studies, such as Richards et al. (1999), Westphal et al. (2003), Tenhumberg et al. (2004), Wilson et al. (2006) and McDonald-Madden et al. (2008) have applied this approach to deal with dynamics of ecological management decisions.

SDP offers vast improvements in solution times over brute force, forward solution methods. Nonetheless, the methodology suffers from what is known as the "curse of dimensionality" (Bellman, 1957), whereby the state space rises exponentially as the number of sites increases linearly. For example, given our model structure, if we had chosen $J = 5$, the state space would have had 73,728 elements compared to the 160 states with $J = 3$.

To overcome the limitation produced by this "curse", heuristic solution techniques have been developed for the site selection problem. While these methods cannot guarantee optimal results they have been shown to produce results that are close to optimal on relatively small selection sets (Costello and Polasky, 2004; Vanderkam et al., 2007) and have been used in much larger selection problems (Nalle et al., 2002; Turner and Wilcove, 2006). In Section 4, we develop an informed greedy heuristic algorithm to test the results obtained from the optimal model on a selection problem containing 20 sites. To solve this problem optimally would have meant searching a state space with approximately 1.2×10^{13} elements.

2.3. Assumptions and analyses

As noted, solving site selection problems optimally necessitates that we consider a limited number of sites. Moreover, given that we have three stochastic processes (availability, ecological conditions with investment and ecological conditions without investment), the parameter space has the capacity to be large. For example, for our initial three-site example, there are $3J = 9$ parameters. In order to manage this issue, we reduce the parameter space by making several assumptions. Firstly, we initially investigate the situation where sites have homogenous probabilities of changing availability and ecological status and then introduce heterogeneity in specific forms to test if this affects results. We assume further that conservation investment increases the probability that a site will begin the next time period in a good ecological condition by 0.2 over not contracting.

To allow the analyses to focus solely on the uncertainty of future site availability and ecological condition, the ecological value of sites in the objective function is assumed to be equal (i.e. when testing the effect of spatial ecological heterogeneity, we focus on heterogeneity in probabilities governing ecological state changes and not in human values attached to those state changes). We assume that a degraded site is worth 50% of a site in a good ecological condition and we document the rewards relative to the maximum that could be achieved through continuous investment on two good sites. This metric therefore compares the reward the conservation agency can achieve given uncertainty relative to the situation of no uncertainty. We document the optimal contract selections from the stationary part of the optimal path for differing levels of uncertainty and we calculate the optimal rewards from Eq. (1). The optimal rewards available to the conservation agency are also calculated when they are constrained to use only short contracts or only long contracts. By comparing these values to the optimal solution of the full model that allows for both long and short contracts, we can investigate if any advantage is gained by having the availability of a portfolio of different contract durations.

3. Optimal solutions of illustrative model

While we give a full exploration to the effects on the choice of conservation contracts that different types of uncertainty play, Fig. 1 gives a brief overview of our main findings. The models show that when there is a small probability that sites will be unavailable in the subsequent contracting period, short contracts are the optimal choice. As the probability that sites will become unavailable increases, we find a greater reliance on long contracts alongside a portfolio of different contract durations. Uncertainty in ecological conditions has no bearing on contract selection without the attendant risk that sites will become unavailable. When both sources of uncertainty are combined, we find that uncertainty in site availability continues to be the most influential factor in setting the choice between short and long contracts. However, heterogeneity across sites in the probability of a change in ecological condition results in an increase in the use of long contracts. We elaborate on each of these findings below.

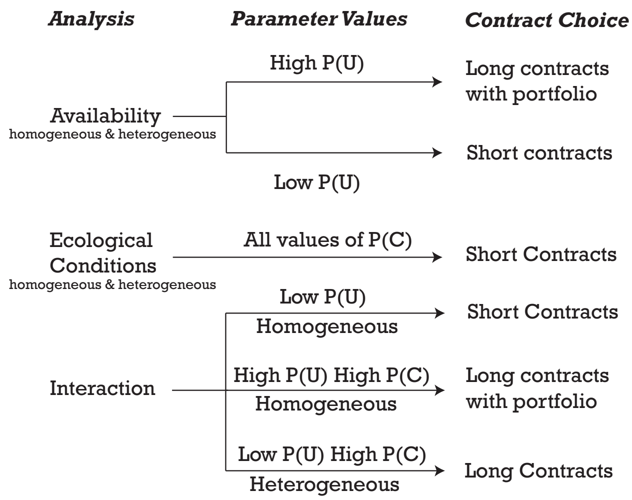

Fig. 1. Summary of the headline results presented in the paper. The analyses form three groups. Availability indicates that there is only uncertainty through time in the availability status of sites. Ecological Conditions indicates that there is only uncertainty through time in the ecological condition status of sites. Interaction indicates that there is uncertainty through time in both site availability and ecological condition. $P(\mathrm{U})$ is the probability that sites will be unavailable at the beginning of the next time period. $P(\mathrm{C})$ is the probability that sites will begin the next time period in a good ecological condition with conservation investment.

3.1. Uncertainty in site availability in isolation

In the first instance, we look at the role of uncertainty in site availability in isolation and assume that there is no uncertainty through time in the ecological condition of the sites (Fig. 1, first row). Therefore, for the optimal investment decisions, we analyse how these are affected by the initial state of the site ecological conditions as well as the probability that sites will become unavailable for conservation investment. For the rewards, we illustrate the optimal expected values with the initial conditions of all sites in good ecological condition and available.

For the first analysis, we assume that all sites have the same probability of becoming unavailable in the next time period. Fig. 2a shows the proportion of states on the stationary part of the path that result in a long contract being the optimal choice for various probabilities of the sites being unavailable in the next time period, $P(\mathrm{U})$ (see Fig. S1 in the supplementary information for the full description of state-dependent contract selections). When there is a low probability that sites will be unavailable for conservation contracting in the next time period, short contracts are the optimal choice. By assumption, in a given time period, two short contracts running concurrently offer the conservation agency twice the benefits per time step of a single long contract. This cost premium required to secure a long-term agreement is not worth paying when there is little chance that sites will become unavailable in the future. However, when the probability that sites will become unavailable is high, the balance of costs and benefits reverses and long contracts are favoured in the vast majority of states.

Turning to the optimal rewards, Fig. 2b highlights that as the probability that sites will become unavailable increases, the relative effectiveness of long contracts increases. When $P(\mathrm{U})$ is greater than 0.65 a long contracts only strategy gains more rewards than a short contracts only strategy. However, when the probability that sites will be unavailable in the future is moderate to high ($P(\mathrm{U}) \geq 0.6$), a portfolio of short and long contracts through time offers even greater rewards to the conservation agency than being limited to either type.

Finally, adding heterogeneity to the probabilities governing site availability in isolation (one site has a higher or lower likelihood of becoming unavailable next time period than the other two) does not change the overall results: long contracts are used only when all sites have a high probability of becoming unavailable.

3.2. Uncertainty in site ecological condition in isolation

We now investigate the role of uncertainty in ecological conditions in isolation (Fig. 1, second row). There is no uncertainty in availability status. Similarly to Section 3.1, we investigate the optimal investment decisions for all initial conditions of availability status, assuming that all sites are in a good ecological condition in the first time period. For the optimal expected rewards, we again illustrate the case where all sites are initially available and in a good condition.

Irrespective of the particular values of site probabilities of changing ecological conditions or whether these probabilities are homogeneous or heterogeneous over sites, short contracts are preferable in all cases where a choice over what sites to protect is available. When the likelihood that sites will begin the next time period in a good ecological condition increases, the optimal rewards from all models increase. However, the increase remains in constant proportion across the models, with the short contracts only model remaining as effective as the full model that allows for either short or long contracts, and the long contracts only model remaining half as effective as either of the other models (see Fig. S2 in the supplementary information).

3.3. Uncertainty in both site availability and ecological condition

3.3.1. Homogeneity in probabilities over sites

Next we analyse how the interaction of the uncertainty over future availability and future ecological condition affects the optimal investment decisions and the optimal expected rewards. Fig. 3 documents the state specific contract selections for various values of $P(\mathrm{U})$ and $P(\mathrm{C})$, where these values are homogeneous over sites. To simplify the presentation of the results, the figure illustrates the investment decisions taken halfway through the time path when the optimal management strategy is stationary. The horizontal axis gives the ecological conditions of the three sites and the vertical axis shows the availability status of the three sites. Should a particular configuration of site states be marked with white then short contracts should be chosen. If the site states are marked with grey then a long contract should be chosen. For example, panel d in Fig. 3 illustrates the optimal strategy on the stationary part of the path when the probability that sites will be unavailable and in a good ecological condition in the next time period are 0.8 and 0.6, respectively. The rectangle marked with GDD on the horizontal and AUU on the vertical indicates that site 1 is available and in good ecological condition whereas sites 2 and 3 are unavailable and in a degraded condition. This rectangle is shaded grey to indicate that a long contract should be chosen in this particular combination of states of the three sites.

The analysis of Section 3.1 demonstrated that long contracts become the optimal choice when the probability that sites will be unavailable in the next time period becomes high. Fig. 3 highlights that when there is uncertainty in both site availability and ecological condition, the probability that sites will become unavailable still needs to be high in order for long contracts to become the best choice. When the probability that sites will be unavailable in the next time period is less than 0.6, short contract are always selected irrespective of the availability status of sites and the likelihood that sites will begin the next time period in a good ecological condition with conservation investment ($P(\mathrm{C})$). When the probability that sites will become unavailable rises above this threshold value, long contracts are always chosen when only one site is available (Fig. 3, top row in each panel).

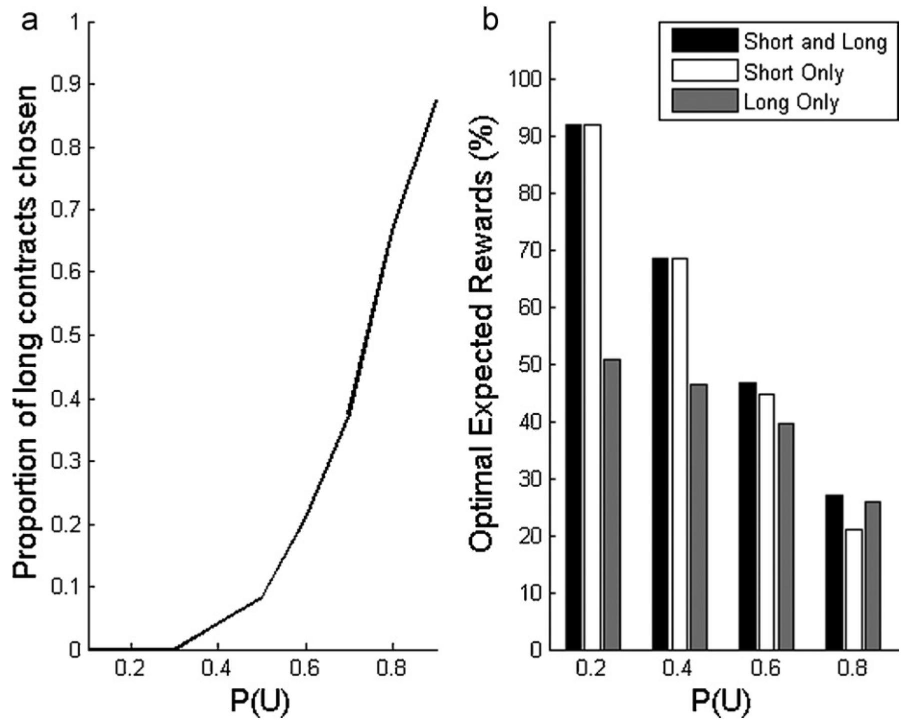

Fig. 2. Panel a: The proportion of system states that result in the selection of a long contract for differing values of the probability that sites will be unavailable in the next time period, $P(U)$, and where there is no variability in the ecological condition of sites through time. Panel b: Optimal rewards when there is only uncertainty in the availability of sites and ecological conditions are constant through time. The results of three models are presented: the optimal rewards from the full model in which the conservation agency can select short or long contracts on a given time step; and the optimal rewards when the agency is constrained to choose either short or long contracts throughout all time periods. The optimal rewards are given relative to the rewards that could be gained with continuous investment on two sites in good ecological condition.

The rationale for this is straightforward. If we can protect only one site then it is advantageous to protect it for longer when the likelihood of it becoming unavailable in the next time period is high and there is a high probability that other sites will remain unavailable. For long contracts to become widespread over site states, it is also required that the probability that sites will begin the next time period in a good ecological condition with conservation investment is high ($P(C) \geq 0.8$). In this situation, long contracts are used in almost every configuration of site state (Fig. 3b).

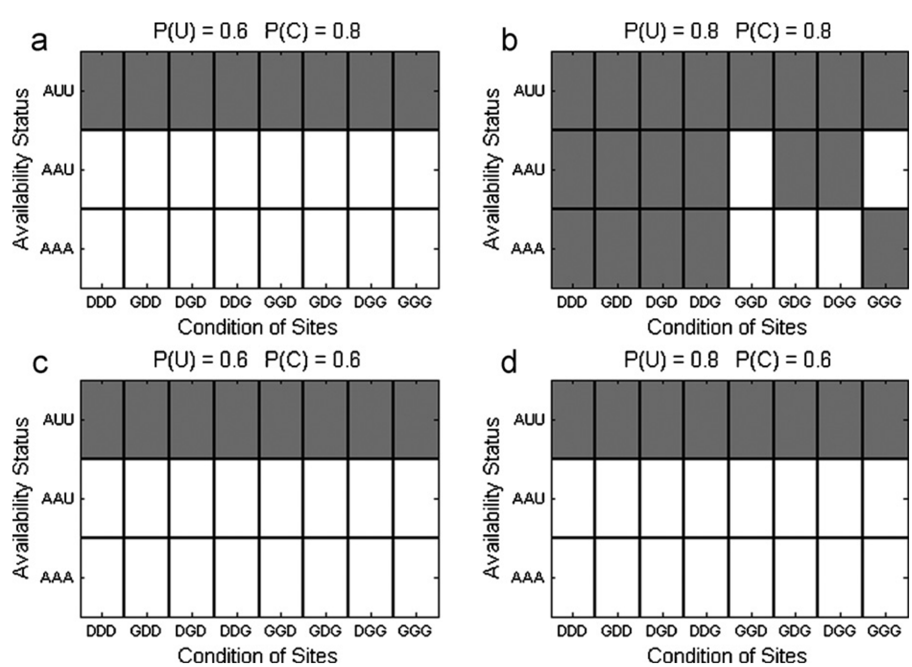

Fig. 3. Short and long contracts chosen for differing probabilities that sites will be unavailable in the future, $P(U)$, and that with conservation investment they will be in a good ecological condition, $P(C)$. We assume that the probability of beginning the next time period in a good condition decreases by 0.2 in the absence of investment. Refer to Section 3.3 for a description of the structure of the figure.

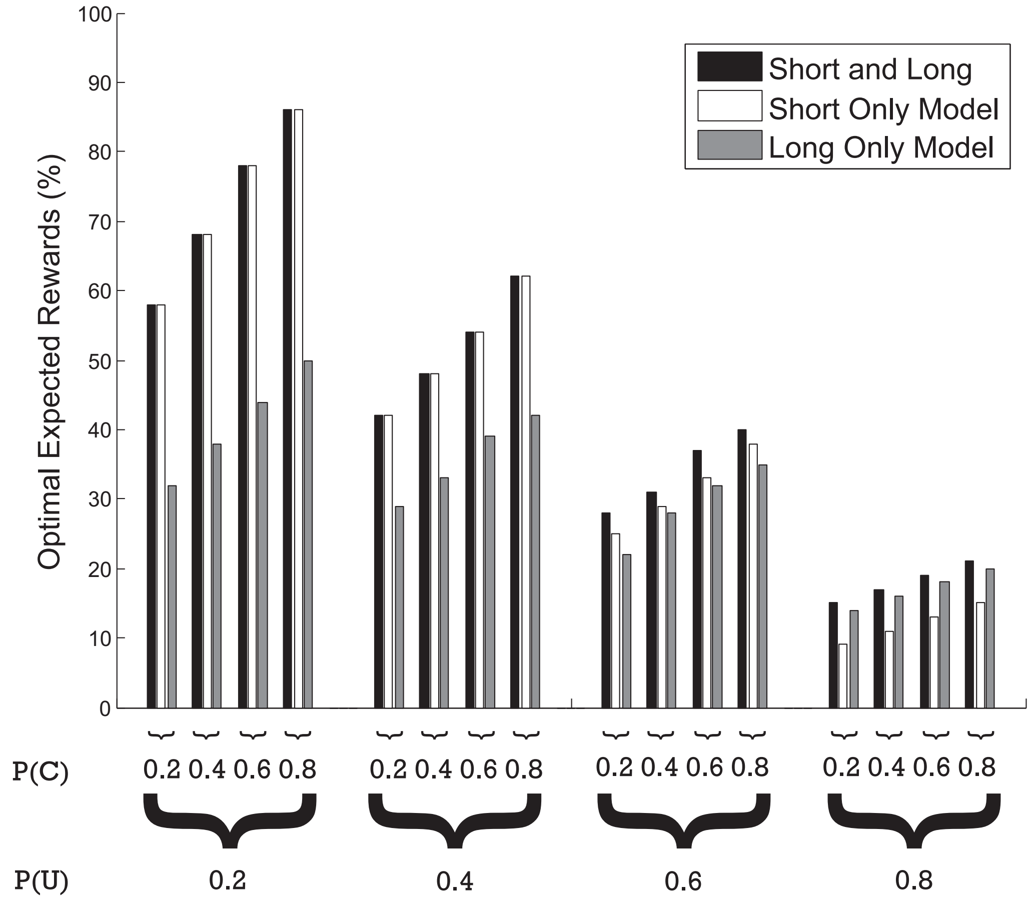

Fig. 4. Optimal rewards for various combinations of probabilities that sites will be unavailable in the future, $P(\mathrm{U})$, and that with conservation investment they will be in a good ecological condition, $P(\mathrm{C})$. We assume that the probability of beginning the next time period in a good condition decreases by 0.2 in the absence of investment. The results of three models are presented: the optimal rewards from the full model in which the conservation agency can select short or long contracts on a given time step; and the optimal rewards when the agency is constrained to choose either short or long contracts throughout all time periods. The optimal rewards are given relative to the rewards that could be gained with continuous investment on two sites in good ecological condition.

When there is uncertainty through time in both site availability and ecological condition, the expected optimal rewards from conservation investments are influenced by both sources of uncertainty. Fig. 4 demonstrates that when both these sources of uncertainty interact, the optimal expected rewards from conservation investment are affected to a greater degree than when either source acts in isolation. For example, Fig. 2b shows that when $P(\mathrm{U})$ is equal to 0.2 and there is no uncertainty in future ecological conditions, the optimal expected rewards for the short and long contracts model and the short only model equals approximately 92% of the maximum reward available for continuous investment on two good sites while the rewards for the long only model is around 51% of this maximum. Comparing this with $P(\mathrm{U})$ equal to 0.2 in Fig. 4 shows that the optimal rewards are lower and span a wide range of values when uncertainty in ecological conditions also applies. Furthermore, in Fig. 4, we see uncertainty over future site availability has a much greater impact on the rewards from conservation investment than the uncertainty regarding ecological conditions. Finally, when the probability that sites will be unavailable in the next time period is moderate to high ($P(\mathrm{U}) \geq 0.6$), greater rewards can again be gained by the conservation agency through strategically employing contracts of differing lengths depending on the current state.

3.3.2. Heterogeneity in probabilities over sites

We now introduce heterogeneity in the probability of ecological change over sites while retaining homogeneity in the site probabilities of changing availability status (Fig. 1 third row, third branch). Specifically, we assume that when in a conservation contract, site 1 has a 0.8 probability of being in a good ecological condition in the next time period. Sites 2 and 3 have a significantly lower probability of beginning the next time period in a good ecological condition. With conservation investment, this probability is 0.4. The assumption of a 0.2 decrease in the probability of being in a good ecological condition in the next time period without investment remains for all sites.

In Fig. 5a, we see that even with a small probability that sites will become unavailable ($P(\mathrm{U}) = 0.2$), taking a long contract on the site with better likely conservation outcomes (site 1) can be the optimal choice. When site 1 is the only site available, it is always optimal to secure it in a long contract (Fig. 5a, top row marked AUU), despite the low probability that sites 2 and 3 will remain unavailable in the next time period. Moreover, even when there exists the possibility of selecting two short contracts, selecting a single long contract on site 1 is the best choice for some states (Fig. 5a, middle and bottom rows marked AAU and AAA, respectively). When the likelihood that sites will be unavailable in the next time period increases to 40%, in any situation where site 1 is available, the optimal investment decision is to take this site in a long contract (Fig. 5b, top, middle and bottom rows). Thus, when any particular site offers markedly better conservation outcomes and there is any attendant risk that this site may become unavailable, the possibility of securing it for a longer period can be more beneficial to the conservation agency than accu-

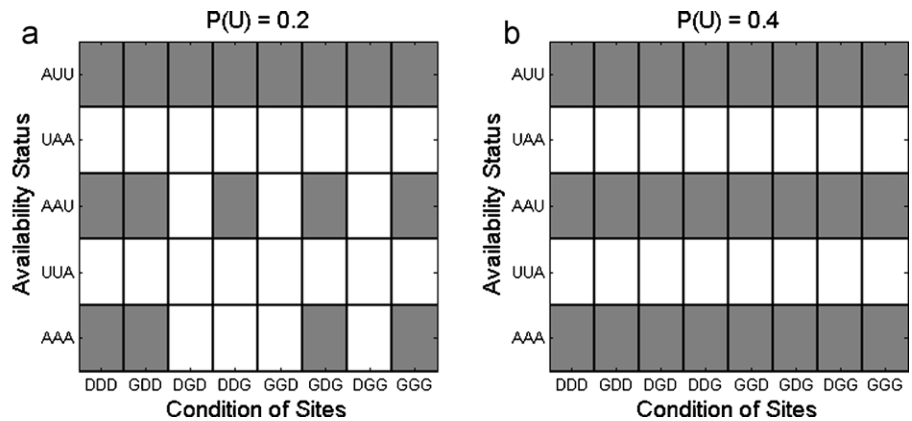

Fig. 5. Short and long contracts chosen for differing probabilities that sites will be unavailable in the future, *P*(U). Sites are now heterogeneous in the probability of beginning the next time period in a good ecological condition. With investment, this probability for site 1 is 0.8 and for sites 2 and 3 is 0.4. We again assume that the probability of beginning the next time period in a good condition decreases by 0.2 in the absence of investment. Refer to Section 3.3 for a description of the structure of the figure.

mulating greater instantaneous rewards with two concurrent short contracts.

Finally, adding heterogeneity to the probabilities governing site availability does not change the overall results: a long contract is chosen on the site with a higher probability of positive ecological outcomes even when there is a small probability that this site will become unavailable and irrespective of the probabilities that other sites will be available.

4. Contract selections on a larger set of sites

In this section, we analyses whether contract selection is affected by the number of sites of conservation interest. To achieve this, we use a heuristic algorithm to undertake similar analyses to those of Section 3 on a larger selection problem. The algorithm makes contract selection decisions by assessing the value of all possible current investments plus the expected value of potential investments in the next two time periods. The investments that give the highest expected value over the three time steps are chosen. In this way, the conservation agency is choosing the best contract in light of the immediate uncertainty regarding site availability and ecological conditions. However, unlike the optimal model, they do not consider the whole time path over which decisions are being made.

The conservation agency now has 20 sites to choose among. As with the optimal model, all sites contribute equally to the objective function when in a particular ecological state, with degraded sites 50% as valuable to the conservation agency as a site in a good ecological condition. The same budget constraint applies, allowing for two concurrent short contracts or one long contract. In each run of our simulations, we calculate the number of long contracts chosen after 50 time steps and then repeat this process for 1000 simulations.

4.1. The effect of site availability on the choice of contract duration

We undertake three analyses to investigate the effect of site availability on contract selection. We first look at the situation where there is homogeneity over sites in the probability that they will be unavailable in the next time period. Then we look at the situation where the probability is heterogeneous over sites but is constrained to lie in an interval with a range of 0.2. We examine cases where the likelihood that sites will become unavailable can be described as low, moderately low, moderate, moderately high and high. Finally, we combine homogeneity with an extended long contract to test if a greater difference in the durations of the available contracts offers any advantages.

Fig. 6 displays the results and shows that an increasing probability of sites being unavailable in the next time period leads to an increased use of long contracts. In contrast to the optimal model (Fig. 2a), however, even when this probability is very low, some long contracts are chosen. Also highlighted is the fact that homogeneity and heterogeneity over sites in the uncertainty relating to site availability results in effectively the same outcomes. When long contracts last three times steps rather than two, they may be marginally less beneficial when the probability that sites will be unavailable is low and marginally more beneficial when this probability is high, but differences are small.

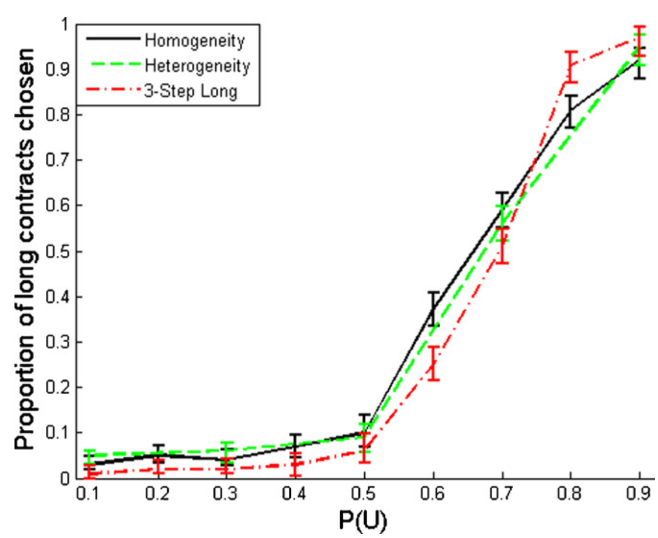

Fig. 6. The proportion of long contracts chosen as the probability of sites being unavailable in the next time period, P(U), increases for the three analyses outlined in Section 4.1. In all three, 1000 simulations were run at each probability and the proportion of long contracts chosen was calculated. Presented is the mean number with error bars set at the 5th and 95th percentiles. It should be noted that the different number of error bars between the homogeneous and heterogeneous analyses is a function of the heterogeneous analysis being over probabilities with a range of 0.2 whereas in the homogeneous analyses the probability was increased by 0.1 from 0.1 to 0.9.

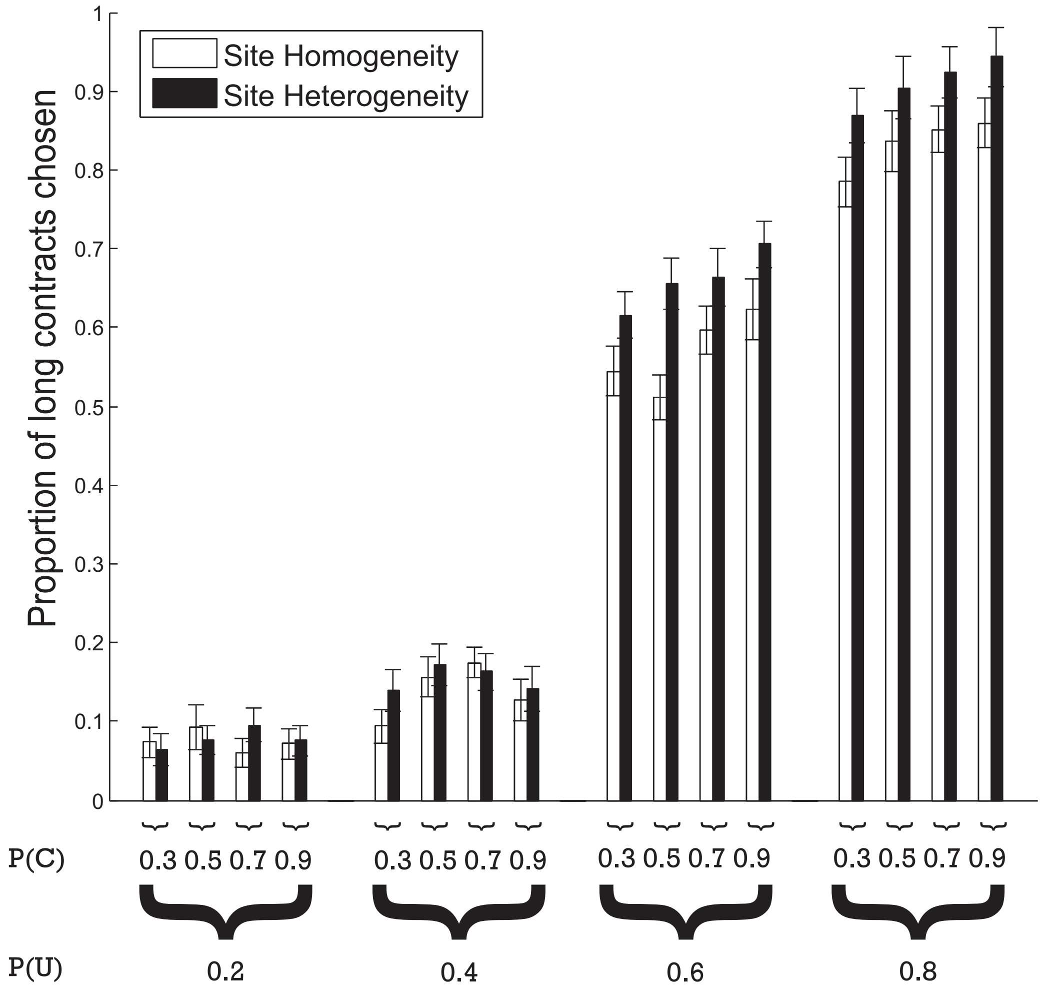

Fig. 7. Proportion of long contracts chosen for differing probabilities that sites will be unavailable in the next time period, *P*(U), and that with conservation investment they will begin the next time period in a good ecological condition, *P*(C) for the homogeneous and heterogeneous analyses outlined in Section 4.3. Presented is the mean number with error bars set at the 5th and 95th percentiles.

4.2. The effect of ecological condition on on the choice of contract duration

With the optimal model, short contracts were always chosen when there was only uncertainty in site ecological conditions. We find exactly the same result when the number of candidate sites is increased to 20. Similar analyses were undertaken to those in Section 4.1. We undertook two analyses with site homogeneity. In the first, long contracts lasted two time steps and in the second, the long contract was extended to three time steps. In both these analyses, we retained the assumption that with conservation investment there was a 0.2 increase in the probability that sites would begin the next time period in a good ecological condition compared with no investment. We also undertook an analysis where sites were heterogeneous in the probabilities of positive conservation outcomes. To introduce heterogeneity, we assigned a random number of sites to be "good" conservation sites. With conservation investment, these sites had a probability of beginning the next time period in a good ecological condition (*P*(C)) ranging from 0.3 to 0.9, again with the assumption of a 0.2 decrease in this probability in the absence of investment. The "bad" conservation sites all had the probability of beginning the next time period in a good ecological condition of 0.2 with investment and without that probability was 0.1. Irrespective of the analysis undertaken or the given probabilities, short contracts were the optimal choice as we found in Section 3.

4.3. Contract selections when there is uncertainty in both future site availability and ecological condition and the influence of site heterogeneity

In the three-site optimal model, when there was uncertainty regarding both future site availability and ecological condition, we found that contract selection was primarily set by site availability (Fig. 3). However, in Section 3.3.2, we saw that heterogeneity regarding the uncertainty of future site conditions can result in a larger impact on contract selection from this source of uncertainty. In this section, we test these results on the larger selection problem. Heterogeneity in ecological conditions was introduced as in Section 4.2 and we retain homogeneity over sites in the likelihood of future availability.

Both the homogeneity and heterogeneity analyses documented in Fig. 7 indicate that the primary driver setting contract length is the uncertainty regarding future site availability. However, when the probability that sites will be unavailable in the next time period is moderate to high ($P(\mathrm{U}) \geq 0.6$), heterogeneity over sites in the probabilities determining likely future ecological status results in an increase in the use of long contracts compared to when these probabilities are homogeneous. In contrast to the optimal model (Fig. 5), heterogeneity in ecological conditions only affects contract selection when the likelihood that sites will be unavailable in the future is moderate to high. The underlying reason for this is likely due to differing number of sites between the optimal and heuristic models. When there are 20 sites of conservation interest and the probability that they will be unavailable in the next time period is small, the conservation agency can have confidence that at least some of the "good" sites will be available in the next time period. This leads to the primary use of two short-term contracts. In the optimal model, given that we only had one good site, it made sense to secure that site in a long contract even when there was even a very small possibility that the site could become unavailable. Nonetheless, both models are consistent in the conclusion that heterogeneity over sites in the uncertainty regarding future ecological conditions produces an increase in the use of long contracts compared to when sites are homogeneous in this source of uncertainty.

5. Discussion

In this paper, we used both optimal and heuristic models to examine the suitability of either short or long conservation contracts in light of ecological and socio-economic uncertainty. Our analyses consistently pointed to several important results (Fig. 1). Firstly, the most important factor in setting the choice of conservation contract was the likely availability of sites in the next time period. Secondly, contract choice was relatively insensitive to uncertainty over future ecological conditions. Finally, when the probability that sites would be unavailable was moderate to high, a portfolio through time of short and long contracts was more advantageous than relying solely on either type.

The fact that we found that uncertainty in site availability was more influential in setting contract choice than uncertainty in ecological conditions to some extent reinforces the conclusions of other recent works that socio-economic factors can be as or more important in determining conservation priorities than ecological factors (Ando et al., 1998; Naidoo and Iwamura, 2007; Bode et al., 2008). One aspect of our model that contributes to this result is the differing ways in which the sources of uncertainty affect conservation rewards. Irrespective of the ecological condition of sites, the conservation agency can derive some benefit from contracting on sites. However, should sites be unavailable for conservation investment, no reward can be gained. Thus, availability is likely to have a larger impact on conservation rewards and contract selection. Nonetheless, both the three-site optimal and twenty-site heuristic analyses indicated that heterogeneity in the probabilities governing changes in ecological conditions can lead to a greater reliance on longer conservation contracts. Thus, conservation programmes that are highly targeted and recognise ecological heterogeneity among candidate sites, such as Higher Level Stewardship in the Environmental Stewardship Scheme (ESS) in the United Kingdom, should involve longer contracts. In contrast, schemes that are focused on conserving the overall landscape and that are less resolved in how they assess properties, such as the Entry Level Stewardship in the ESS, could rely on shorter contracts. However, our findings suggest that the imperative for using long contracts is reduced when there are a large number of sites of good ecological quality that can act as substitutes for conservation investment.

In some circumstances, a portfolio of different contract types was seen to offer better rewards than when only one type of contract was available (Figs. 2b and 4). The strategy of using a portfolio of different contract types is commonly overlooked in practice yet the ability to use contracts of differing lengths can offer advantages to conservation agencies when decisions are made to be robust to future change. However, employing a large number of different contract types could have higher implementation costs, which would limit the number of different contracts durations used. Nonetheless, some flexibility in the nature of conservation contracts might lead to better outcomes than rigidly sticking to one type irrespective of the situations faced.

This study is the first attempt to analyses how different sources of uncertainty set the choice between fixed-term conservation contracts of differing lengths. While it may be the first in the conservation planning literature, a number of studies of labour markets have sought to understand how economic uncertainty sets contract length. Theoretical works by Grey (1978), Canzeroni (1980) and Dye (1985) and later empirical studies by Vromen (1989) and Murphy (1992) found that high levels of uncertainty should lead to shorter contracts. The proposition that underlies this phenomenon is simple. An increase in economic uncertainty increases the probability that unforeseen contingencies will arise during the course of the contract. This leads to the negotiating parties favouring a short contract. In our model, the conservation agency is least able to predict future availability when $P(\mathrm{U}) = 0.5$. In these conditions, we find that there is general indifference between long and short conservation contracts, in contrast to these studies in labour economics. Instead, the advantages of either short or long contracts are most pronounced for low or high values of $P(\mathrm{U})$, when the conservation agency can predict future availability of sites with more confidence.

5.1. Assumptions and extensions

In our model, the manner in which the conservation agency derives benefits from the sites on which it invests rests on several assumptions. Firstly, we assumed that conservation benefits accumulate through time in the objective function. This assumption will be appropriate for describing some conservation programmes, such as those seeking to sustain a regular supply of some ecosystem service (e.g., public access to the land on contracted sites or site specific measures to improve water quality). However, other conservation programmes may be better represented by objectives based on the condition of the system at the terminal time only, such as those focused on ensuring long-term persistence of a rare species. Furthermore, we assumed that benefits accumulate additively in space, or in other words that the benefit derived from contracting on multiple sites is simply the sum of the benefits on the individual sites. However, should there be a non-linear spatial accumulation of benefits, the imperative for different contract durations would be affected. If benefits were to accrue super- or subadditively in space, the desirability of more short contracts versus fewer longer agreements would increase or decrease respectively. Also, we incorporated spatial heterogeneity in sites only through the probabilities regarding future status. An extension of the model would be to incorporate spatial heterogeneity in the ecological value of sites in the objective function. Finally, we assumed that no benefit was derived from non-contracted sites. This assumption is consistent with many conservation studies and programmes. Nonetheless, a number of conservation planning studies have shown that assuming that non-contracted sites can support some ecological functions can have an impact on planning decisions and conservation outcomes (e.g., Polasky et al., 2005; Armsworth et al., 2006).

The cost structure of the model determines the number of contracts of differing durations that the conservation agency can apply. The central assumption that defined our cost structure was that the annual rental rate on a two time period contract (10 years) was twice that of a one time period contract (5 years). This is clearly a gross simplification and was made to reduce the size of the state space, while also recognizing that longer contracts are likely to be more costly than shorter ones. However, with this assumption, the conservation agency must pay a very high price premium and/or face much higher transaction costs to secure long-term agreements. An obvious alternative assumption would have been to assume an equal annual rental payment and small transaction costs making annual costs of short and long-term agreements similar. Overall, this would make longer agreements more desirable than predicted by our model. However, both assumptions seem somewhat exaggerated and we anticipate the real world would fall somewhere in between. With either cost structure, we are also assuming that annual monitoring and enforcement costs do not vary greatly between short versus long-term contracts. More complex cost structure could be included in the model through, for example, contract re-enrolment bonuses and increasing payments schedules for time spent contracted. Both of these cost structures incentivize landowners to keep their land under conservation management for longer and have been shown to lead to better conservation outcomes and increased economic efficiency (Gulati and Vercammen, 2006).

Other important model assumptions concern the transition probabilities governing changes of ecological condition. We assumed these probabilities were constant through time and adopted a Markovian structure that assumes that only the current condition of a site and the transition probability that specifies the likely change in site condition influence the future condition of the site. However, other aspects of the model reflect the gradual improvements of ecological condition on sites through time with conservation investment. For example, for $P(C) \geq 0.5$, the difference in the likelihood of a site remaining in a good ecological condition with conservation investment compared to the likelihood of a site remaining in a good ecological condition without conservation investment has a unimodal relationship with the number of consecutive periods for which it is enrolled (Fig. S3).

Finally, we focused throughout on fixed-term contracts that last 1 and 2 or 3 time periods. This situation conforms to one in which the conservation agency uses contracts of 5 or 10/15 years. However, many conservation contracts with private landowners in the USA and elsewhere are made in perpetuity through conservation easements. The model could easily be extended to capture these alternative forms of investment. Moreover, by including the use of permanent acquisitions alongside fixed-term agreements, the model could be used to determine if a portfolio of these different contract structures can result in higher conservation benefits than the uniform application of one type or another.

5.2. Conclusions

The use of conservation contracts of different lengths should be in part determined by both socio-economic and ecological factors. We have shown that uncertainty in the configuration of tomorrow's landscape should influence the length of contract that a conservation agency chooses to employ. The future availability of sites must be considered carefully when making conservation plans as this factor can have a dramatic effect on the benefit of contracts with different durations. Uncertainty in ecological conditions has a smaller effect. But uncertainty over future ecological conditions can influence contract duration when acting alongside uncertainty in availability and with heterogeneity over sites. Conservation agencies should also consider the merit of flexibility in contracting arrangements through a portfolio of different contract types so that they can shape their investments to maximize conservation outcomes. Given the paucity of conservation resources, it is essential that the large sums spent on fixed-term contracts are used in the most efficient ways. This efficiency can only be achieved through an appreciation of an uncertain future.

Acknowledgements

This research was funded by a Natural Environment Research Council (NERC) Studentship to G.D.L. with further assistance provided at the National Institute for Mathematical and Biological Synthesis, an Institute sponsored by the National Science Foundation, the U.S. Department of Homeland Security, and the U.S. Department of Agriculture through NSF Award # EF-0832858, with additional support from The University of Tennessee, Knoxville. We also thank the two anonymous reviewers for their suggestions and Carl Toews, Michael Bode and Gwen Iacona for helpful discussions.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2011.04.033.

References

Ando, A., Camm, J., Polasky, S., Solow, A., 1998. Species distributions, land values, and efficient conservation. Science 278, 2126–2128.

Ando, A.W., Shah, P., 2010. Demand-side factors in optimal land conservation choice. Resource and Energy Economics 32, 203–221.

Armsworth, P.R, Daily, G.C., Kareiva, P., Sanchirico, J.N., 2006. Land market feedbacks can undermine biodiversity conservation. Proceedings of the National Academy of Sciences of the United States of America 103, 5403–5408.

Armsworth, P.R., Sanchirico, J.N., 2008. The effectiveness of buying easements as a conservation strategy. Conservation Letters 1, 182–189.

Balmford, A., Bruner, A., Cooper, P., Costanza, R., Faber, S., Green, R.E., et al., 2002. Economic reasons for conserving wild nature. Science 297, 950–953.

Bellman, R., 1957. Dynamic Programming. Princeton University Press, Princeton, NJ.

Bode, M., Wilson, K.A., Brooks, T., Turner, W., Mittermeier, R., et al., 2008. Cost-effective global conservation spending is robust to taxonomic group. Proceedings of the National Academy of Sciences of the United States of America 105, 6498–6501.

Canzeroni, B., 1980. Labor contracts and monetary policy. Journal of Monetary Economics 6, 241–255.

Cocks, K.D., Baird, I.A., 1989. Using mathematical programming to address the multiple reserve selection problem – an example from the Eyre Peninsula, South-Australia. Biological Conservation 49, 113–130.

Conservation International, 2000. Conservation international creates new market mechanism to conserve global forests. Press release.

Cooper, T., Hart, H., Baldock, D., 2009. The provision of public goods through agriculture in the European Union, report prepared for DG Agriculture and Rural Development. Technical Report Contract No 30-CE-0233091/00-28. Institute for European Environmental Policy: London.

Costello, C., Polasky, S., 2004. Dynamic reserve site selection. Resource Energy Economics 26, 157–174.

Davies, Z.G., Kareiva, P., Armsworth, P.R., 2010. Temporal patterns in the size of conservation land transactions. Conservation Letters 3, 765–775.

DEFRA, 2008. Environmental Stewardship: Review of Progress. Department for Environment, Food and Rural Affairs and Natural England.

Dreschler, M., Lourival, R., Possingham, H.P., 2009. Conservation planning for successional landscapes. Ecological Modelling 220, 438–450.

Dye, A., 1985. Optimal length of labor contracts. International Economic Review 26, 251–270.

Ferraro, P.J., Kiss, A., 2002. Ecology – direct payments to conserve biodiversity. Science 298, 1718–1719.

Fishburn, I., Kareiva, P., Gaston, K.J., Armsworth, P.R., 2009. The growth of easements as a conservation tool. PLoS ONE 4, e4996.

Grey, J.A., 1978. On indexation and contract length. Journal of Political Economy 89, 1–18.

Gulati, S., Vercammen, J., 2005. The optimal length of an agricultural carbon contract. Canadian Journal of Agricultural Economics 53, 359–373.

Gulati, S., Vercammen, J., 2006. Time inconsistent resource conservation contract. Journal of Environmental Economics and Management 52, 454–468.

Ha, H.M., Noordwijk, M.V., Thuy, P.T., 2008. Payment for Environmental Services: Experiences and Lessons in Vietnam. World Agroforestry Centre (ICRAF), Hanoi, Vietnam.

James, A.N., Gaston, K.J., Balmford, A., 1999. Balancing the earth's accounts. Nature 401, 323–324.

Khanna, M., Ando, A.W., 2009. Science, economics and the design of agriculture programmes in the US. Journal of Environmental Planning and Management 52, 575–592.

Latacz-Lohmann, U, Van der Hamsvoort, C., 1997. Conservation contracts: a theoretical analysis and an application. American Journal of Agricultural Economics 79, 407–418.

Mangel, M., Clark, C., 1988. Dynamic Modeling in Behaviorial Ecology. Princeton University Press, Princeton, New Jersey.

McDonald-Madden, E., Bode, M., Game, E.T., Grantham, H., Possingham, H.P., 2008. The need for speed: informed land acquisitions for conservation in a dynamic property market. Ecology Letters 11, 1169–1177.

Meir, E., Andelman, S., Possingham, H.P., 2004. Does conservation planning matter in a dynamic and uncertain world? Ecology Letters 7, 615–622.

Moilanen, A., Runge, M., Elith, J., Tyre, A., Carmel, Y., et al., 2004. Planning for robust reserve networks using uncertainty analysis. Ecological Modelling 199, 115–124.
Murphy, K., 1992. Determinants of contract duration in collective bargaining agreements. Industrial and Labor Relations Review 45, 352–365.
Naidoo, R, Iwamura, T., 2007. Global-scale mapping of economic benefits from agricultural lands: implications for conservation priorities. Biological Conservation 40, 40–49.
Nalle, D.J., Arthur, J.L., Sessions, J., 2002. Designing compact and contiguous reserve networks with a hybrid heuristic algorithm. Forest Science 48, 59–68.
Nature England, 2010. Higher level Stewardship.
Pender, J., Suyanto, Kerr, J., Kato, E., 2008. Impacts of the Hutan Kamasyarakatan Social Forestry Program in the Sumberjaya Watershed, West Lampung District of Sumatra, Indonesia. The International Food Policy Research Institute.
Polasky, S., Neilson, E., Lonsdorf, E., Fackler, P., Starfield, A., 2005. Conserving species in a working landscape: land use with biological and economic objectives. Ecological Applications 15, 1387–1401.
Possingham, H., Day, J., Goldfinch, M., Salzborn, F., 1993. The mathematics of designing a network of protected areas for conservation, in: Decision Sciences: Tools for Today. In: Proceedings of the 12th National Australian Society for Operations Research Conference, Australian Society for Operations Research , Canberra, pp. 536–545.
Pressey, R.L., Possingham, H.P., Day, J.R., 1997. Effectiveness of alternative heuristic algorithms for identifying indicative minimum requirements for conservation reserves. Biological Conservation 80, 207–219.
Richards, S.A., Possingham, H.P., Tizard, J., 1999. Optimal fire management for maintaining community diversity. Ecological Applications 9, 880–892.
Rissman, A.R., Butsic, V., 2010. Land trust defense and enforcement of conserved areas. Conservation Letters 4, 31–37.
Sabbadin, R., Spring, D., Rabier, C., 2007. Dynamic reserve site selection under contagion of risk of deforestation. Ecological Modelling 201, 75–81.
Skaggs, R.K., Sirksey, R.E., Harper, W.M., 1994. Determinants and implications of post-CRP land-use decisions. Journal of Agricultural and Resource Economics 19, 299–312.
Strange, N., Thorsen, B.J., Bladt, J., 2006. Optimal reserve selection in a dynamic world. Biological Conservation 131, 33–41.
Tenhumberg, B., Tyre, A.J., Shea, K., Possingham, H.P., 2004. Linking wild and captive populations to maximize species persistence: optimal translocation strategies. Conservation Biology 18, 1304–1314.
Turner, W.R., Wilcove, D.S., 2006. Adaptive decision rules for the acquisition of nature reserves. Conservation Biology 20, 527–537.
Vanderkam, R.P.D., Wiersma, Y.F., King, D.J., 2007. Heuristic algorithms vs. linear programs for designing efficient conservation reserve networks: evaluation of solution optimality and processing time. Biological Conservation 137, 349–358.
Vromen, S., 1989. Inflation uncertainty and contract duration. Review of Economics and Statistics 71, 677–681.
Westphal, M.I., Pickett, M., Getz, W.M., Possingham, H.P., 2003. The use of stochastic dynamic programming in optimal landscape reconstruction for metapopulations. Ecological Applications 13, 543–555.
Whitby, M., 2000. Challenges and options for the agri-environment: presidential address. Journal of Agricultural Economics 51, 317–332.
Wilson, K, McBride, M.F., Bode, M., Possingham, H., 2006. Prioritizing global conservation efforts. Nature 440, 337–340.
ZBinden, S., Lee, D.R., 2005. Paying for environmental services: an analysis of participation in Costa Rica's PSA program. World Development 33, 255–272.