Biol Invasions (2012) 14:839–849
DOI 10.1007/s10530-011-0120-x

ORIGINAL PAPER

Cost-benefit analysis for intentional plant introductions under uncertainty

Hiroyuki Yokomizo · Hugh P. Possingham · Philip E. Hulme · Anthony C. Grice · Yvonne M. Buckley

Received: 3 May 2011 / Accepted: 6 October 2011 / Published online: 22 October 2011

Abstract Worldwide, we rely on introduced plants for the essentials of human life; however, intentional plant introductions for commercial benefit have resulted in invaders with negative environmental, economic or social impacts. We argue that plant species of low expected economic value should be less acceptable for introduction than species of high economic value if their other traits are similar; however, key traits such as likelihood of escape and costs of escape are often highly uncertain. Methods do not currently exist which allow decision makers to evaluate costs and benefits of introduction under uncertainty. We developed a cost-benefit analysis for determining plant introduction that incorporates probability of escape, expected economic costs after escape, expected commercial benefits, and the efficiency and cost of containment. We used a model to obtain optimal decisions for the introduction and containment of commercial plants while maximizing net benefit or avoiding losses. We also obtained conditions for robust decisions which take into account severe uncertainty in model parameters using information-gap decision theory. Optimal decisions for introduction and containment of commercial plants depended, not only on the probability of escape and subsequent costs incurred, but also on the anticipated commercial benefit, and the cost and efficiency of containment. When our objective is to maximize net benefit, increasing uncertainty in parameter values increased the likelihood of introduction; in contrast, if our objective is to avoid losses, more uncertainty decreased the likelihood of introduction.

Keywords Commercial plant · Containment · Cost-benefit analysis · Information-gap decision theory · Invasive weed · Management

H. Yokomizo (✉)
Center for Environmental Risk Research, National Institute for Environmental Studies, Onogawa 16-2, Tsukuba 305-8506, Japan
e-mail: hiroyuki.yokomizo@nies.go.jp

H. Yokomizo · Y. M. Buckley
CSIRO Ecosystem Sciences, EcoSciences Precinct, GPO Box 2583, Brisbane, QLD 4001, Australia

H. P. Possingham · Y. M. Buckley
School of Biological Sciences, The University of Queensland, Brisbane, QLD 4072, Australia

P. E. Hulme
The Bio-Protection Research Centre, Lincoln University, PO Box 84, Canterbury, New Zealand

A. C. Grice
CSIRO Ecosystem Sciences, PO, Aitkenvale, QLD 4814, Australia

Introduction

Many invasive plants were introduced deliberately because of their potential commercial benefits for land rehabilitation, as forage plants, or as ornamentals (e.g.

Lonsdale 1994, Cook and Dias 2006, Hulme 2011). In Europe the deliberate importation of commercial plants is one of the most frequent pathways by which invasive plants have been introduced (Hulme et al. 2008). Yet, the potential monetary benefits of these introductions are not always realized and escaped commercial plants can subsequently have large environmental and economic impacts (US Congress 1993; Manchester and Bullock 2000; Sinden et al. 2004; Vilà et al. 2010). While new plant species continue to be introduced around the world for land rehabilitation (Bennett and Virtue 2004), forestry, pasture (Stone et al. 2008) agriculture, horticulture (Lambdon et al. 2008), and biofuels (Raghu et al. 2006; Barney and DiTomaso 2008), we currently lack a cost-benefit analysis that weighs potential commercial benefits against the risk of escape and the costs of any negative impact as well as subsequent management of the invader.

Current weed risk assessment procedures used to screen species prior to importation do not include economic costs or benefits explicitly (e.g. Pheloung et al. 1999; but see Baker et al. 2008). Keller et al. (2007) calculate the expected net benefit associated with introduced plants by considering mean benefit and loss of all species without considering benefits and losses of each species. Given that there is at least some risk of escape from a new introduction we employ the reasonable assumption that a plant of low economic value should be a less acceptable candidate for introduction than one of high economic value, if their other traits were similar. As potential commercial pathways are important for new plant introductions that might subsequently become weeds, both economic and ecological information should be used when assessing the risks associated with plant introduction. Relying solely on ecological assessments of the probability of escape and the likely impacts of an introduced species assumes that the commercial gains from the introduction are always smaller than the costs incurred, or that species with known commercial benefit are excluded from weed risk assessment procedures and treated differently.

Even if the estimated cost of damage after escape is large, it may still be acceptable to introduce the plant if its risk of escape can be lowered (Grice 2006; Grice et al. 2008). There are a number of means of containment, such as developing sterile cultivars (Anderson et al. 2006; Li et al. 2004) and managing the landscape within which cultivation of the introduced plant takes place (Buckley et al. 2005).

Cost-benefit analysis is a useful tool for helping to decide whether or not to introduce a plant and the implementation of containment measures. Risk of escape and potential damage after escape may be predicted using an existing weed risk assessment tool and used in the cost-benefit analysis. The cost-benefit analysis also qualitatively clarifies how ecological and economic characteristics of a commercial plant affect the decision on introduction and containment.

Many theoretical models of optimal management of invasive species have had as their goal to maximize or minimize ecological and management objectives (Taylor and Hastings 2004; Regan et al. 2006; Yokomizo et al. 2007, 2009; Epanchin-Niell and Hastings 2010). Management efforts to contain an introduced plant and prevent further spread are also accompanied by a cost but these actions may increase the overall net benefit by reducing the probability of escape. Here we analyze whether or not introducing a plant, then investing in containment effort are economically reasonable strategies.

Given that prior to introduction much uncertainty will accompany our estimates of costs, benefits and probability of escape it is useful to determine the maximum level of uncertainty that still allows an acceptable result, rather than optimizing the expected outcome. An information-gap decision model was devised to obtain the decision most robust to uncertainty (Ben-Haim 2006). Info-gap decision theory is very useful when uncertainty is so severe that it is difficult to obtain probability distributions of parameters. Info-gap decision theory has been applied to decisions in conservation (Regan et al. 2005; McDonald-Madden et al. 2008), design of marine protected areas (Halpern et al. 2006), and forest management (McCarthy and Lindenmayer 2007) among other areas of environmental sciences (Ben-Haim 2006).

In this paper, we develop a new cost-benefit analysis for determining intentional plant introductions that incorporates the probability of escape, expected economic costs after escape, expected commercial benefits, and the efficiency and cost of containment. We assume that there are three possible strategies: (I) no introduction, (II) introduction without containment and (III) introduction with containment. First, we choose the optimal decision that maximizes the overall net benefit. Second, in order to avoid costly mistakes, we add the criterion that we introduce a commercial plant only if the net benefit is positive and the probability of that net benefit falling below a threshold is below an acceptable level.

Methods

We deal with four models depending on criteria of decisions and degree of uncertainties of parameter values (Fig. 1). Model I deals with the case where there is no uncertainty in parameter estimates, in models II and III we use alternative decision criteria and we assume that uncertainty in parameter values can be represented with probability distributions and in model IV we assume that the uncertainty is severe and cannot be adequately represented with a probability distribution.

Optimal decisions with no uncertainty (MODEL I)

Let us assume that the annual benefit gained from an introduced commercial plant is B. However, introduced plants have the potential to cause negative economic impacts if they escape and become invasive. We therefore, define the economic cost after escape as C_{es} which includes both the economic cost of impacts and management costs to reduce impacts. C_{es} is a monetary value in the year when the commercial plant escapes and becomes non-eradicable. We define escape of an introduced plant as its sustained reproduction and survival outside of cultivation. Most weeds are difficult to eradicate once they escape (Wadsworth et al. 2000; Panetta and Timmins 2004). We assume that eradication is impossible once escape occurs and management costs

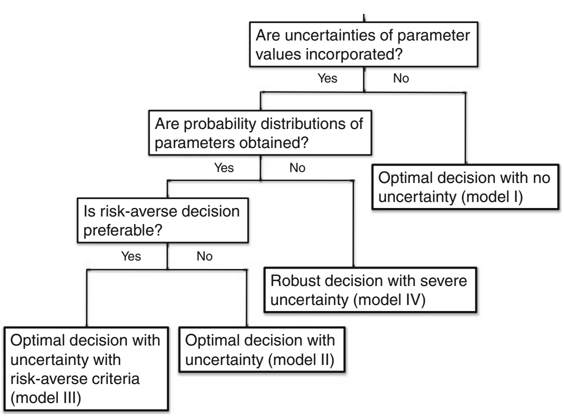

Fig. 1 Diagrammatic illustration of the four models developed

are incurred each year thereafter to reduce the impact and/or impact costs associated with escape.

We may be able to avoid incurring the costs of escape by using some containment measures, and therefore, be motivated to invest in containment to reduce the probability of escape. We define the probability with which escape occurs during a time period as P_{es} which is P_{nc} when containment activity is not implemented or is P_c otherwise. The probability of escape is reduced using containment as $P_c = (1-\beta)P_{nc}$ where β is the efficiency of containment. Containment is accompanied by a cost per year, C_c. We assume that whether or not we conduct containment does not change through time until a commercial plant escapes. Although the probability of escape probably depends on the introduction effort (propagule pressure), here we do not consider explicitly the number of individuals of a commercial plant introduced per year. We also assume, for simplicity, that the anticipated benefit, B, does not fluctuate. Hence we assume that the benefit, B, and probability of escape, P_{es}, do not change over years.

We consider that the time horizon of management is infinite. We make a decision on introducing a plant and implementing containment based on the expected net benefit of the decisions. The expected net benefit is N_{ni} for no introduction, N_i^{nc} for introduction without containment and N_i^c for introduction with containment. Each expected net benefit is:

$$N_{ni} = 0 \tag{1a}$$

$$N_i^{nc} = \sum_{t=0}^{\infty} \gamma^t (B - P_{nc} R_t C_{es}) \tag{1b}$$

$$N_i^c = \sum_{t=0}^{\infty} \gamma^t (B - P_c R_t C_{es} - C_c R_t) \tag{1c}$$

where γ is the discount factor which is obtained from the discount rate δ, $\gamma = 1/(1+\delta)$. The discount rate represents the relative importance of current benefits and costs to future benefits and costs. $R_t = (1-P_{es})^t$ is the probability that escape has not occurred at the beginning of year t. We assess whether the introduction of a commercial plant will be permitted or not and containment implemented or not based on the highest expected net benefit from the three possible decisions: N_{ni}, N_i^{nc} and N_i^c. Description of parameters used in the model is shown in Table 1.

Table 1 Description of parameters used in the models. Right column indicates the models where each parameter is used

Parameter	Definition	Model
B	Anticipated yearly benefit	All
C_{es}	Cost after escape	I
C_c	Cost per year of containment	I
P_{es}	Probability of escape	I
P_{nc}	Probability of escape without containment	I
P_c	Probability of escape with containment	I
β	Efficiency of containment	I
N_{ni}	Expected net benefit for no introduction	I
N_i^{nc}	Expected net benefit for introduction without containment	I
N_i^c	Expected net benefit for introduction with containment	I
γ	Discount factor	All
$\mu_{P_{nc}}$	Mean of probability of escape without containment	II & III
μ_β	Mean of efficiency of containment	II & III
$\mu_{C_{es}}$	Mean of cost after escape	II & III
$\sigma^2_{P_{nc}}$	Variance of probability of escape without containment	II & III
σ^2_β	Variance of efficiency of containment	II & III
$\sigma^2_{C_{es}}$	Variance of cost after escape	II & III
$\hat{N}_i^{nc}$	Expected net benefit for introduction without containment under uncertainty of parameter values	II & III
$\hat{N}_i^c$	Expected net benefit for introduction with containment under uncertainty of parameter values	II & III
N^*	Largest value between $\hat{N}_i^c$ and $\hat{N}_i^{nc}$	II & III
Θ	Threshold of net benefit in risk averse criterion	III
Ω	Prob. with which the net benefit falls below a threshold Θ	III
Ω_{accept}	Acceptable probability of Ω for introduction	III
$\tilde{P}_{nc}$	Nominal of probability of escape without containment	IV
$\tilde{\beta}$	Nominal of efficiency of containment	IV
$\tilde{C}_{es}$	Nominal of cost after escape	IV
α	Horizon of uncertainty	IV
CT	Critical threshold in Info-Gap decision theory	IV
α_{nc}	Horizon of uncertainty for no containment	IV
α_c	Horizon of uncertainty for containment	IV
α^*	Largest value between α_{nc} and α_c	IV

Optimal decisions under uncertainty of parameter values (MODELS II & III)

In general, we do not have adequate knowledge of the probability of escape P_{nc}, the efficiency of containment β, or the economic cost after escape C_{es}. We assume that distributions of P_{nc}, β and C_{es} are independent of each other and assume C_{es} follows a lognormal distribution, and P_{nc} and β follow beta distributions. The mean and variance of each distribution are μ_w and σ^2_w $(w: P_{nc}, \beta, C_{es})$, respectively. We can rewrite the expected net benefit after introduction without containment and with containment as follows,

$$\hat{N}_i^{nc} = \iint_D N_i^{nc} p(P_{nc}) p(C_{es}) dP_{nc} dC_{es} \tag{2a}$$

$$\hat{N}_i^{c} = \iiint_D N_i^{c} p(P_{nc}) p(\beta) p(C_{es}) dP_{nc} d\beta dC_{es} \tag{2b}$$

where D represents possible parameter ranges and $p(w)$ indicates probability distribution of w $(w: P_{nc}, \beta, C_{es})$. We define the larger value of the net expected benefits $\hat{N}_i^{nc}$and $\hat{N}_i^{c}$ as N^*. As in the previous case where there was no uncertainty in parameter values, we introduce a commercial plant when N^* is positive ($N^* > N_{ni} = 0$) (MODEL II).

Even when overall expected net benefit is positive, not introducing a commercial plant might be better if there is some risk of negative net benefit (i.e. a net cost) due to uncertainty. To avoid cases where we may suffer from negative net benefit, we now make the decision to introduce a commercial plant based on the following criteria (MODEL III): [1] the expected net benefit under uncertainty is positive, $N^* > 0$, and [2] the probability of that net benefit falling below a threshold Θ (≤ 0) is equal to or less than an acceptable level Ω_{accept}; the latter condition represents a risk-averse criterion. We define the probability of that net benefit falling below a threshold Θ as Ω. Meeting a condition $\Omega \leq \Omega_{accept}$ is necessary to introduce a commercial plant. When $\Omega_{accept} = 1$, we make a decision based only on the value of N^*. A small Ω_{accept} and high threshold Θ are strict standards which discourage introduction of a commercial plant unless we are very certain of incurring a positive net benefit.

Robust decisions under severe uncertainty (MODEL IV)

In some situations, we may not have sufficient knowledge of even the variance or distributional form of each parameter and the optimal strategy may not be robust to severe uncertainty (Ben-Haim 2006), i.e. the optimal strategy may change within the range of uncertainty exhibited by a parameter. There may be an alternative strategy which is robust under a wider range of values of the parameter. Here we determine the most robust containment strategy given uncertainty in the model parameters. We introduce an info-gap model of uncertainty (Ben-Haim 2006) on three parameters, β, P_{nc} and C_{es}. We define $\tilde{\beta}$, $\tilde{P}_{nc}$ and $\tilde{C}_{es}$ as the nominal values of β, P_{nc} and C_{es}, respectively. We applied an envelope bounded model (see Ben-Haim 2006) and the information-gap model for uncertainty of parameters is the family of nested intervals:

$$\frac{|w - \tilde{w}|}{\tilde{w}} \leq \alpha$$

in which w is the uncertain parameter value ($w : \beta, P_{nc}, C_{es}$) and α is the horizon of uncertainty. This equation means a parameter value deviates from a nominal value by no more than 100α %. We define the info-gap model for three uncertain parameters as follows:

$$U_{P_{nc}}\left(\alpha, \tilde{P}_{nc}\right) = \left\{P_{nc} : \max\left[0, (1-\alpha)\tilde{P}_{nc}\right] \leq P_{nc} \leq \min\left[1, (1+\alpha)\tilde{P}_{nc}\right]\right\},\ \alpha \geq 0 \tag{3a}$$

$$U_{\beta}\left(\alpha, \tilde{\beta}\right) = \left\{\beta : \max\left[0, (1-\alpha)\tilde{\beta}\right] \leq \beta \leq \min\left[1, (1+\alpha)\tilde{\beta}\right]\right\},\ \alpha \geq 0 \tag{3b}$$

$$U_{C_{es}}\left(\alpha, \tilde{C}_{es}\right) = \left\{C_{es} : \max\left[0, (1-\alpha)\tilde{C}_{es}\right] \leq C_{es} \leq (1+\alpha)\tilde{C}_{es}\right\},\ \alpha \geq 0 \tag{3c}$$

The robustness functions for implementing containment and no containment are, respectively developed as follows:

$$\alpha_c(CT) = \max\left[\alpha : \min_{\substack{\beta \in U_\beta(\alpha,\tilde{\beta}), P_{nc} \in U_{P_{nc}}(\alpha,\tilde{P}_{nc}) \\ C_{es} \in U_{C_{es}}(\alpha,\tilde{C}_{es})}} N_i^c \geq CT\right] \tag{4a}$$

$$\alpha_{nc}(CT) = \max\left[\alpha : \min_{\substack{\beta \in U_\beta(\alpha,\tilde{\beta}), P_{nc} \in U_{P_{nc}}(\alpha,\tilde{P}_{nc}) \\ C_{es} \in U_{C_{es}}(\alpha,\tilde{C}_{es})}} N_i^{nc} \geq CT\right] \tag{4b}$$

where CT is the critical threshold. The information-gap model focuses on a net benefit in the worst-case scenario so the minimum value under parameter regions shown in Eqs. 3 is calculated. We do not regard the performance as acceptable when the net benefit becomes lower than the critical threshold, CT. We set the critical threshold CT as zero. The robustness function gives us a maximum value of uncertainty that guarantees net benefit is no less than the critical threshold, CT. We should choose a strategy in which the largest uncertainty acceptable for net benefit is no less than the critical threshold, CT. Hence we implement containment only when $\alpha_c(CT) > \alpha_{nc}(CT)$. We define the largest value for the horizon of uncertainty between $\alpha_{nc}(CT)$. and $\alpha_c(CT)$ as $\alpha^*(CT)$. In this model, it is difficult to make a decision on introduction using the information-gap decision model because we are not affected by any uncertainties in the case of no introduction. We will introduce a plant if it is considered that the uncertainty $\alpha^*(CT)$ is sufficiently large based on expert opinions.

Results

Optimal decisions with no uncertainty (MODEL I)

We obtain the net benefit, N_i^{nc} and N_i^c analytically as follows:

$$N_i^{nc} = \frac{\left(1+\frac{\gamma P_{nc}}{1-\gamma}\right)B - C_{es}P_{nc}}{1-\gamma(1-P_{nc})} \tag{5a}$$

$$N_i^{c} = \frac{\left(1+\frac{\gamma P_{c}}{1-\gamma}\right)B - C_{es}P_{c} - C_c}{1-\gamma(1-P_{c})} \tag{5b}$$

The condition of investing in containment effort under the assumption that we introduce a commercial plant, $N_i^{nc} < N_i^c$, can be expressed as:

$$\frac{C_{es}P_c + C_c}{1-\gamma(1-P_c)} < \frac{C_{es}P_{nc}}{1-\gamma(1-P_{nc})} \tag{6}$$

i.e. that the discounted cost of escape where containment is implemented plus the cost of containment is less than the discounted cost of escape given no containment. The decision to implement containment is independent of the benefit from the commercial plant. When the condition in Eq. 6 is met, implementing containment is optimal. We can also derive a condition for introduction as follows:

$$C_{es} < \left(\left(1+\frac{\gamma P_c}{1-\gamma}\right)B - C_c\right)\Big/ P_c \text{ if } \frac{C_{es}P_c + C_c}{1-\gamma(1-P_c)} < \frac{C_{es}P_{nc}}{1-\gamma(1-P_{nc})} \tag{7a}$$

$$C_{es} < \left(\left(1+\frac{\gamma P_{nc}}{1-\gamma}\right)B\right)\Big/ P_{nc} \text{ if } \frac{C_{es}P_c + C_c}{1-\gamma(1-P_c)} \geq \frac{C_{es}P_{nc}}{1-\gamma(1-P_{nc})} \tag{7b}$$

when the anticipated benefit B is large with a small cost of containment (i.e. $(1+\gamma P_c/(1-\gamma))B \gg C_c$) we can rewrite Eq. 7a as follows,

$$\frac{C_{es}}{B} < \frac{1}{P_c} + \frac{\gamma}{1-\gamma} \tag{8}$$

We also can rewrite Eq. 7b as follows,

$$\frac{C_{es}}{B} < \frac{1}{P_{nc}} + \frac{\gamma}{1-\gamma} \tag{9}$$

The introduction decision is taken based on the relative value of cost after escape and the benefit of the commercial plant. The mean time to escape under the optimal containment decision $1/P_{nc}$ or $1/P_c$ is also a main factor in the introduction decision. For example, even if the cost after escape C_{es} is very large, the decision to introduce a highly profitable plant is optimal when escape probability is low (long mean time to escape).

When efficiency of containment β is large, the introduction of a commercial plant is enhanced (Fig. 2, the black region is large at large β). Even if the cost after escape C_{es} is large, we can introduce the plant when highly efficient containment measures are available. The boundary between introduction and no introduction is a straight line in this case. This means that the ratio between the anticipated commercial benefit and the cost generated by its escape is an important factor in this decision. Even if the cost after escape is large, the decision to introduce a high value commercial plant is optimal. The boundary between the black and grey regions is parallel to the horizontal axis. The decision to implement containment measures is independent of the anticipated benefit of a plant (see Eq. 6). This is because once we introduce a commercial plant, we obtain benefit from the plant regardless of whether we implement containment measures.

Optimal decisions under uncertainty of parameter values (MODELS II & III)

When the variances of probability of escape and efficiency of containment are small, no introduction is optimal for small benefit B (Fig. 3). When these variances are large, mean time to escape becomes long and the introduction of a commercial plant is favoured (see mean time to escape $1/P_{nc}$ and $1/P_c$ in Eqs. 8 and 9). When the anticipated benefit from a plant is large, introduction is optimal even at low variances of uncertain parameters. The introduction decision does not depend on the variance of cost after escape, $\sigma^2_{C_{es}}$. This is because the mean net benefit is independent of variance in cost after escape.

When we apply a risk averse high threshold Θ, introduction is optimal only in the case of a high

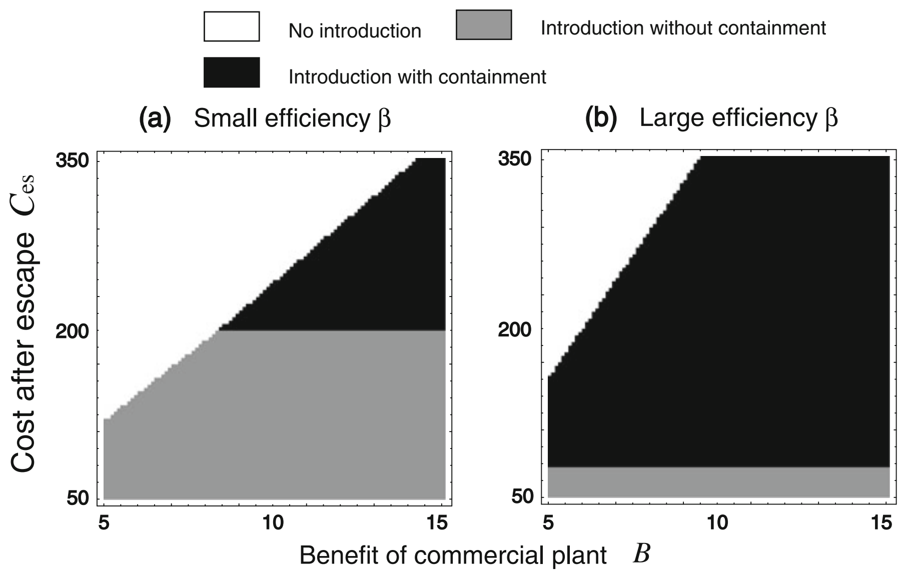

Fig. 2 Optimal decisions for introduction of commercial plants and containment. In the *black region* introduction with containment effort is optimal, in the *gray region* introduction without containment effort is optimal, in the *white region* no introduction is optimal. **a** Small efficiency of containment, $\beta = 0.3$ and **b** large efficiency of containment, $\beta = 0.8$. The other parameter values are $P_{nc} = 0.2$, $C_c = 2.5$, $\gamma = 0.95$

acceptance level Ω_{accept} (Fig. 4). When the threshold Θ is low (i.e. we are happy to accept a risk of negative net benefits if expected net benefit is positive) we accept many commercial plants regardless of whether the lenient high, or strict low, Ω_{accept} is applied.

Robust decisions under severe uncertainty (MODEL IV)

We calculated the value of the horizon of uncertainty at which the net benefit becomes zero, $\alpha_{nc}(CT = 0)$ and $\alpha_c(CT = 0)$ under two levels of containment cost (Fig. 5). When cost of containment is low, investing in containment is the most robust strategy because the line of containment with low cost crosses the x-axis in Fig. 5 at a higher value of the horizon of uncertainty, α, than the line of no containment effort ($\alpha_{nc}(CT = 0) < \alpha_c(CT = 0)$). When the cost of containment is high, not investing in containment effort is the most robust strategy because the line of no containment effort crosses the x-axis at a higher value of horizon of uncertainty, than the line of containment with high cost ($\alpha_{nc}(CT = 0) > \alpha_c(CT = 0)$). We defined the maximum horizon of uncertainty at which net benefit becomes zero at a specific cost of containment as α^*.

The maximum horizon of uncertainty (α^*) decreases with the nominal value of cost after escape C_{es} and increases with benefit of commercial plant B (Fig. 6a). The decision whether or not to introduce a species should be based on a value of α^* acceptable to policymakers and researchers, requiring discussion between these stakeholders. When α^* is sufficiently large, we could introduce the commercial plant (Fig. 6a). If not, we should not proceed with introduction When the nominal value of cost after escape, $\tilde{C}_{es}$ is large, investing in containment is better than no investment in containment effort (Fig. 6b). However, when the benefit of commercial plant is large, no investment in containment is a robust decision even when the nominal value of cost after escape $\tilde{C}_{es}$ is substantial.

Discussion

In contrast to conventional approaches to weed risk assessment, we find that whether or not to introduce a plant depends considerably on the anticipated commercial benefit of that plant. The ratio between the benefit and cost arising from its escape, and the mean time to escape are also important in our cost-benefit analysis. The mean time to escape itself depends on whether containment measures are implemented.

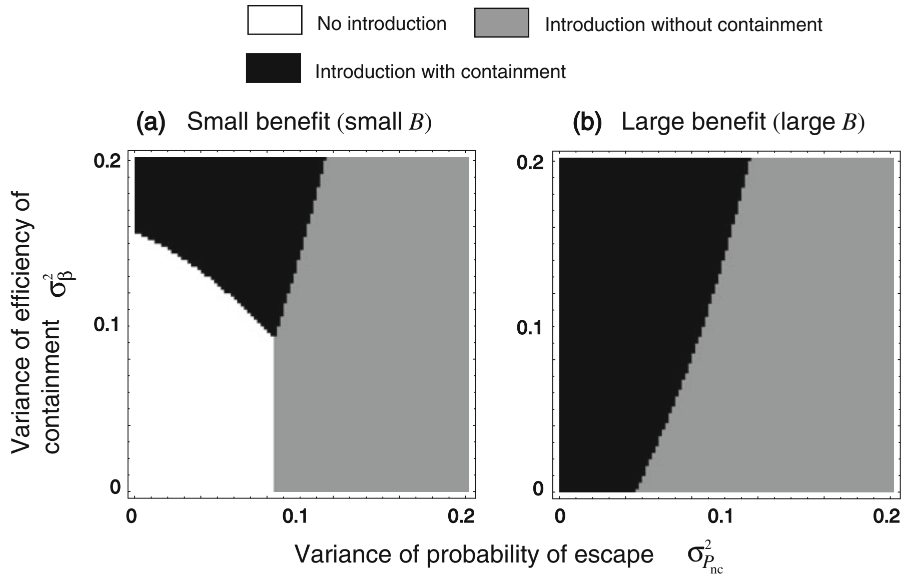

Fig. 3 Optimal decisions for introduction of commercial plants and containment under uncertainty. **a** Low benefit of commercial plant $B = 7$, **b** high benefit $B = 12$. The other parameter values are $C_c = 5$, $\gamma = 0.95$, $\mu_\beta = 0.7$, $\mu_{C_{es}} = 200$, $\mu_{P_{nc}} = 0.3$

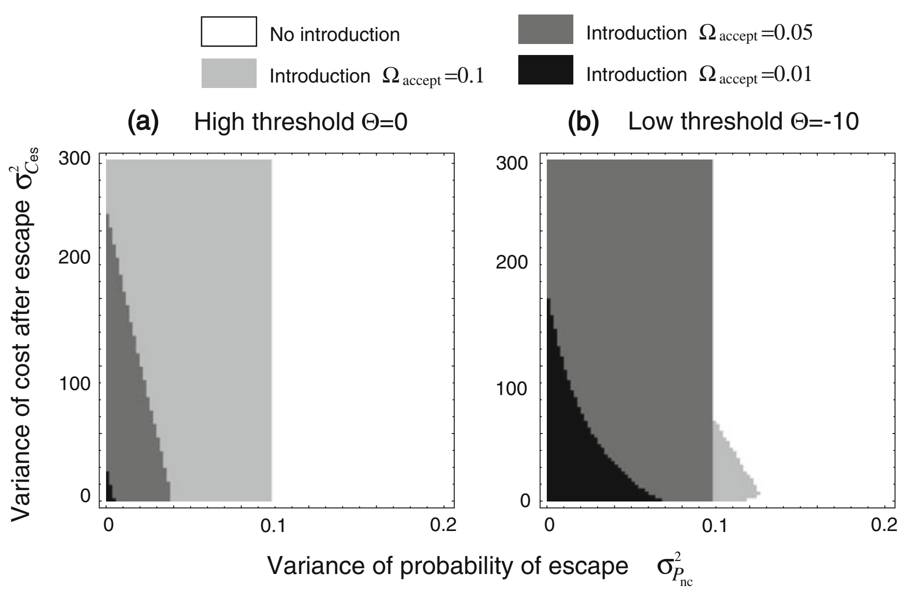

Fig. 4 Optimal decisions for introduction of commercial plants and containment to avoid negative net benefit. **a** High threshold of introduction $\Omega = 0$, **b** low threshold $\Omega = -10$. The other parameter values are $B = 12$, $C_c = 5$, $\gamma = 0.95$, $\mu_\beta = 0.7$, $\sigma^2_\beta = 0.05$, $\mu_{C_{es}} = 250$, $\mu_{P_{nc}} = 0.3$

Hence, the mean time to escape indirectly depends on the cost and efficiency of containment.

The decision to implement containment is independent of the anticipated commercial benefit (see Eq. 6 and Fig. 2). This is because once a plant has been introduced the benefit is obtained regardless of containment. The optimal strategy is not affected by variance of cost after escape, $\sigma^2_{C_{es}}$ although it is affected by the mean value of cost after escape $\mu_{C_{es}}$ (results not shown). Therefore, when deciding on an introduction, it is more important to estimate the mean cost after escape than to learn the magnitude of uncertainty in the cost after escape.

When our objective is to maximize net benefit, introduction is favoured when the variance of parameter values (probability of escape, P_{nc}, and efficiency of containment, β) is large (Fig. 3). However, we may want to avoid the chance of a large loss even if the

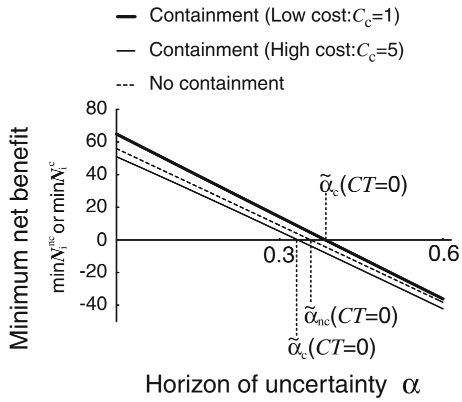

Fig. 5 Minimum net benefit with horizon of uncertainty in information-gap decision. The parameter values: $B = 10$, $\gamma = 0.95$, $\tilde{\beta} = 0.5$, $\tilde{P}_{nc} = 0.5$, and $\tilde{C}_{es} = 150$

expected net benefit is positive. As an alternative, therefore, we added a new criterion under which a plant will be introduced: that is, if the expected net benefit is positive and the probability with which the net benefit falls below a threshold Θ is smaller than an acceptable level Ω_{accept}. When this new criterion is added, large variance in the probability of escape precludes introduction (compare Fig. 4 with Fig. 3) because a large variance increases the probability of losses. Since the decision depends on the acceptable probability Ω_{accept} and the threshold level Θ, we should determine appropriate values of Ω_{accept} and Θ carefully before making a decision. Alternatively the model could be used to demonstrate explicitly the risks a stakeholder is willing to take when they are strongly in favour of a commercial plant introduction (i.e. they have already made the decision to introduce).

If we take an information-gap decision theory approach to decision-making, implementing containment is the robust decision when the benefit of a commercial plant B is small and nominal value of cost after escape, $\tilde{C}_{es}$, is large. In contrast to the case of maximizing net benefit, the decision here to implement containment does depend on the benefit of the commercial plant (compare Figs. 2, 6b). When the benefit is larger, larger uncertainty is permissible to meet the minimal requirement (positive net benefit). However, when uncertainty is large, efficiency of containment becomes small in the worst-case scenario which is the focus of the information-gap theory model. This is why no investment in containment is the robust decision for a large benefit B. The decision

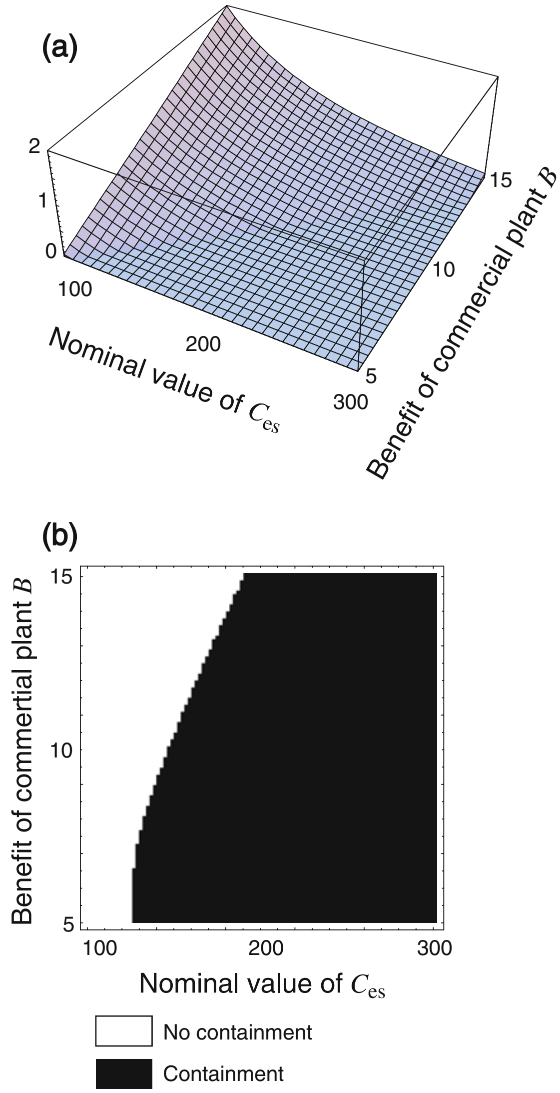

Fig. 6 **a** Maximum horizon of uncertainty to meet positive net benefit. **b** The most robust decision of containment effort. The parameter values: $C_c = 5$, $\gamma = 0.95$, $\tilde{\beta} = 0.5$, $\tilde{P}_{nc} = 0.5$

of introduction is determined based on the horizon of uncertainty which is permissible to meet a minimal requirement. This horizon of uncertainty depends on both benefit of the plant and cost after escape (Fig. 6a). Therefore, even if we apply info-gap decision theory, incorporating the benefit of a commercial plant could be a very important factor in assessing introduction.

Generally, those who bear the negative impact and those who obtain the commercial benefit of plant introductions are different (Grice 2006; Grice et al. 2008) so some means of transferring the benefit from those who receive the commercial benefit to those who bear the negative impact is needed. An adaptation of the “polluter pays” principle in which those who grow a plant must meet the cost of its escape might be useful. For example, the industry introducing the plant might be required to pay a levy, lodge a bond (Grice et al. 2008) or buy insurance (Martin 2008). However, it should be borne in mind that many invasive plants escaped and naturalized several decades after initial introductions (e.g. Aikio et al. 2010). Thus, even some of the worst invasive species may have particularly low probabilities of escape which are highly uncertain and difficult to estimate. Where future costs are discounted over time, the length of the time-lag between introduction and escape will become an important determinant of the relative costs and benefits of introduction, increasingly weighting the latter over the former. Our scheme should be considered within other ecological and policy frameworks to ensure that economic rationalism does not negate social, ethical or environmental considerations relating to the introduction.

Model parameters such as cost after escape C_{es} may vary with time. Although it is difficult to predict dynamic changes in parameter values, we can reassess decisions when our knowledge of parameter values has been updated or situations have changed. Hence even if parameter values are not constant through time, or our knowledge of parameter values or distributions improves, the cost-benefit analysis shown in this paper can be updated to contribute to adaptive decision making.

Here we considered two cases in which containment measures were either conducted or not. In some situations, however, we may also need to consider the optimal intensity of containment effort. We currently lack sufficient knowledge of the relationship between containment effort and the probability of escape, but in future work we consider it important to examine how uncertainty in this relationship affects decisions on the introduction of a plant and the relevant containment effort.

In conclusion, the theoretical model for cost-benefit analysis presented here shows that arriving at an optimal decision about introduction and containment depends not only on the cost incurred when a plant escapes and the possibility of its escape but also on the anticipated commercial benefit, and the cost and efficiency of containment. We have shown that quantitative analysis is important to determine the optimal decision in addition to qualitative analysis. Even if the cost of escape is large, we can justify introducing a plant if we can prevent its escape or if the anticipated commercial benefit is sufficiently large. We need to consider the availability of cost-effective containment measures when we make a decision, as a decision to introduce with containment is no longer supported if appropriate containment is not available or too expensive. Optimal decisions depend on whether or not we want to avoid cases where the net benefit can have a very small negative value.

Acknowledgments We are grateful to the following people for their helpful comments: Peter Baxter, Graham Bonnett, Robert Brown, Peter Caley, Alan House, Mark Lonsdale, Paul Pheloung, Andy Sheppard and two anonymous reviewers. HY is supported by a Grant-in-Aid for Scientific Research of JSPS. YMB is supported by an Australian Research Fellowship from the Australian Research Council (ARC) (DP0771387); HPP was supported by an ARC Federation Fellowship.

References

Aikio S, Duncan RP, Hulme PE (2010) Lag-phases in alien plant invasions: separating the facts from the artefacts. Oikos 119:370–378

Anderson NO, Gomez N, Galatowitsch SM (2006) A non-invasive crop ideotype to reduce invasive potential. Euphytica 148:185–202

Baker RHA, Black R, Copp GH, Haysom KA, Hulme PE, Thomas MB, Brown A, Brown M, Cannon RJC, Ellis J, Ellis E, Ferris R, Glaves P, Gozlan RE, Holt H, Howe L, Knight JD, MacLeod A, Moore NP, Mumford JD, Murphy ST, Parrott D, Sansford CE, Smith GC, St-Hilaire S, Ward NL (2008) The UK risk assessment scheme for all non-native species. In: Rabitsch W, Essl F, Klingenstein F (eds) Biological Invasions–from ecology to conservation. Neobiota 7:46–57

Barney JN, DiTomaso JM (2008) Nonnative species and bioenergy: are we cultivating the next invader? Bioscience 58:64–70

Ben-Haim Y (2006) Information-gap decision theory: decisions under severe uncertainty, 2nd edn. Academic Press, London

Bennett SJ, Virtue JG (2004) Salinity mitigation versus weed risks—can conflicts of interest in introducing new plants be resolved? Aust J Exp Agric 44:1141–1156

Buckley YM, Brockerhoff EG, Langer ER, Ledgard N, North H, Rees M (2005) Slowing down a pine invasion despite uncertainty in demography and dispersal. J Appl Ecol 42:1020–1030

Cook GD, Dias L (2006) It was no accident: deliberate plant introductions by Australian government agencies during the 20th century. Aust J Bot 54:601–625

Epanchin-Niell RS, Hastings A (2010) Controlling established invaders: integrating economics and spread dynamics to determine optimal management. Ecol Lett 13:528–541

Grice AC (2006) Commercially valuable weeds: can we eat our cake without choking on it? Ecol Manag Restor 7:40–44

Grice AC, Clarkson J, Spafford H (2008) Addressing the challenges of commercial weeds. Plant Prot Q 23:58–64

Halpern BS, Regan HM, Possingham HP, McCarthy MA (2006) Accounting for uncertainty in marine reserve design. Ecol Lett 9:2–11

Hulme PE (2011) Addressing the threat to biodiversity from botanic gardens. Trends Ecol Evol 26:168–174

Hulme PE, Bacher S, Kenis M, Klotz S, Kuhn I, Minchin D, Nentwig W, Olenin S, Panov V, Pergl J, Pyšek P, Roques A, Sol D, Solarz W, Vilà M (2008) Grasping at the routes of biological invasions: a framework for integrating pathways into policy. J Appl Ecol 45:403–414

Keller RP, Lodge DM, Finnoff DC (2007) Risk assessment for invasive species produces net bioeconomic benefits. Proc Natl Acad Sci USA 104:203–207

Lambdon PW, Lloret F, Hulme PE (2008) How do introduction characteristics influence the invasion success of Mediterranean alien plants? Perspect Plant Ecol Evol Syst 10:143–159

Li Y, Cheng Z, Smith WA, Ellis DR, Chen YQ, Zheng XL, Pei Y, Luo KM, Zhao DG, Yao QH, Duan H, Li Q (2004) Invasive ornamental plants: problems, challenges, and molecular tools to neutralize their invasiveness. Crit Rev Plant Sci 23:381–389

Lonsdale WM (1994) Inviting trouble: introduced pasture species in northern Australia. Aust J Ecol 19:345–354

Manchester SJ, Bullock JM (2000) The impacts of non-native species on UK biodiversity and the effectiveness of control. J Appl Ecol 37:845–864

Martin P (2008) Cross pollination or cross-contamination? Directions for informing the management of invasives with market-economy concepts. Keynote address. In: Van Klinken RD, Osten VA, Pancetta FD, Scanlan JC (eds) Proceedings of the 16th Australian weeds conference, May 2008, Queensland Weeds Society

McCarthy MA, Lindenmayer DB (2007) Info-gap decision theory for assessing the management of catchments for timber production and urban water supply. Environ Manag 39:553–562

McDonald-Madden E, Baxter PWJ, Possingham HP (2008) Making robust decisions for conservation with restricted money and knowledge. J Appl Ecol 45:1630–1638

Panetta FD, Timmins SM (2004) Evaluating the feasibility of eradication for terrestrial weed incursions. Plant Prot Q 19:5–11

Pheloung PC, Williams PA, Halloy SR (1999) A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. J Environ Manag 57:239–251

Raghu S, Anderson RC, Daehler CC, Davis AS, Wiedenmann RN, Simberloff D, Mack RN (2006) Adding biofuels to the invasive species fire? Science 313:1742

Regan HM, Ben-Haim Y, Langford B, Wilson WG, Lundberg P, Andelman SJ, Burgman MA (2005) Robust decision-making under severe uncertainty for conservation management. Ecol Appl 15:1471–1477

Regan TJ, McCarthy MA, Baxter PWJ, Panetta FD, Possingham HP (2006) Optimal eradication: when to stop looking for an invasive plant. Ecol Lett 9:759–766

Sinden J, Jones R, Hester S, Odom D, Kalisch C, James R, Cacho O (2004) The economic impact of weeds in Australia. CRC for Australian Weed Management, Adelaide

Stone LM, Byrne M, Virtue JG (2008) An environmental weed risk assessment model for Australian forage improvement programs. Aust J Exp Agric 48:568–574

Taylor CM, Hastings A (2004) Finding optimal control strategies for invasive species: a density-structured model for *Spartina alterniflora*. J Appl Ecol 41:1049–1057

US Congress Office of Technology Assessment (1993) Harmful non-indigenous species in the United States, OTA-F-565. US Government Printing Office, Washington, DC

Vilà M, Basnou C, Pyšek P, Josefsson M, Genovesi P, Gollasch S, Nentwig W, Olenin S, Roques A, Roy D, Hulme PE, DAISIE partners (2010) How well do we understand the impacts of alien species on ecosystem services? A pan-European cross-taxa assessment. Front Ecol Environ 8:135–144

Wadsworth RA, Collingham YC, Willis SG, Huntley B, Hulme PE (2000) Simulating the spread and management of alien riparian weeds: are they out of control? J Appl Ecol 37(Suppl. 1):28–38

Yokomizo H, Haccou P, Iwasa Y (2007) Optimal conservation strategy in fluctuating environments with species interactions: resource-enhancement of the native species versus extermination of the alien species. J Theor Biol 244:46–58

Yokomizo H, Possingham HP, Thomas MB, Buckley YM (2009) Managing the impact of invasive species: the value of knowing the density-impact curve. Ecol Appl 19:376–386