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Title: Eliciting and integrating expert knowledge to assess the viability of the critically endangered golden sun-moth *Synemon plana*

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Running title: Golden sun-moth population viability

Abstract

The critically endangered golden sun-moth *Synemon plana* occurs in urban fringe areas of southeastern Australia that are currently experiencing rapid and extensive development. The urban fringe is a complex and uncertain environment in which to manage threatened species with the intersection of fragmented natural habitats, built environments and human populations generating novel, poorly-understood interactions. In this context, management frameworks must incorporate ecological processes as well as social considerations. Here we explore how biodiversity sensitive urban design might improve the fate of the golden sun-moth, and threatened species generally, in urban fringe environments. We: (1) developed an expert-informed Bayesian Belief Network model that synthesises the current understanding of key determinants of golden sun-moth population viability at sites experiencing urbanising pressure; (2) quantified the nature and strength of cause-effect relationships between these factors using expert knowledge; and (3) used the model to assess expectations of moth population viability in response to different combinations of management actions.

We predict that adult survival, bare ground cover and cover of resource plants are the most important variables affecting the viability of golden sun-moth populations. We also demonstrate the potential for biodiversity sensitive urban design as a complementary measure to conventional management for this species. Our findings highlight how expert knowledge may be a valuable component of conservation management, especially in addressing uncertainty around conservation decisions

when empirical data are lacking, and how structured expert judgements become critical in supporting decisions that may help ameliorate extinction risks faced by threatened species in urban environments.

Key words: Bayesian Belief Networks, Biodiversity sensitive urban design, Grassland management, Insect conservation, Threatened species management, Urban ecology

INTRODUCTION

The golden sun-moth *Synemon plana* Walker, 1854 (Lepidoptera, Castniidae) is a listed ‘critically endangered’ endemic species occurring in the native grassland ecosystems of southeastern mainland Australia (western and northern Melbourne, and parts of the Australian Capital Territory). It is a flagship species for grassland conservation, and is threatened by the severe and on-going reduction in extent of native grassland habitat and the conversion of remaining grassland into degraded and exotic plant dominated ecosystems (Kutt *et al.* 2015). A large proportion of the moth’s known distribution overlaps with urban growth areas and many populations of high conservation significance now occur within a matrix of housing and industrial development (Gilmore *et al.* 2008).

The occurrence of golden sun-moth populations adjacent to urban housing presents particular challenges for habitat management, including conflicts between different management actions that may be scientifically grounded but socially impractical or unacceptable (Whitehead *et al.* 2014). For example, the golden sun-moth prefers grasslands of low biomass that are dominated by native *Austrostipa* and *Rytidosperma* that were historically maintained by native herbivore grazing and periodic intense fire (Dorrough *et al.* 2004). In degraded sites, managed grazing by domestic stock and controlled burning can potentially assist the species persistence through the control of exotic pasture species and maintenance of low biomass (O'Dwyer & Attiwill 2000). However, management by stock and fire in locations adjacent to human populations is contentious because of real and perceived risks to human health, lives and property (Gibbons *et al.* 2012). There is some evidence that the physical structure and design of dwellings may provide habitat for known non-native predators of the golden sun-moth (e.g. the common mynah *Acridotheres* *tristis*) and increased predation may adversely affect golden sun-moth population persistence in urban environments (Australian Government 2009).

Conventional management actions include measures to improve golden sun-moth habitat quality through reestablishment of native grasses, weed and biomass removal, and measures to reduce the mortality of golden sun-moth adults through predation control. However, these ‘conventional actions’ may not be sufficient on their own in a landscape where remnant habitats co-occur with the urban matrix. Biodiversity sensitive urban design proposes a series of key principles aimed at enhancing biodiversity at the site level, by improving the viability of native species and ecosystems (Garrard *et al.* in review). These may involve design measures to improve remnant native habitat through sympathetic management of private gardens, installations that mitigate adverse impacts such as buffer zones, management techniques that reduce human disturbance at important times such as sanctuary periods, and initiatives to enhance human-nature interactions with community engagement and education.

Active management is therefore an important component of sustaining golden sun-moth population viability. However, there are few empirical data on cause-effect linkages between the species demographic variables and conventional and biodiversity sensitive urban design management actions. We therefore turn to expert knowledge and knowledge engineering (Korb & Nicholson 2011) to (1) synthesise in a formal model, current understanding of key determinants of golden sun-moth population viability at sites experiencing urbanising pressure; (2) quantify the nature and strength of cause-effect relationships between these factors using expert knowledge; and (3) use the resultant model to assess expectations of golden sun-moth site-level population viability, in response to different combinations of management actions.

Our approach was driven by the need to deliver conservation-orientated management solutions for a listed ‘critically endangered’ data-deficient Australian insect species that coincides with human populations. Management actions aimed at preserving the golden sun-moth in southeastern Australian peri-urban grassland ecosystems may synergistically contribute to the protection of other threatened grassland species (e.g. striped legless lizard *Delma impar*, matted flax-lily *Dianella* *amoena*, spiny rice-flower *Pimelea spinescens spinescens*) as well as the Natural Temperate Grasslands of the Victorian Volcanic Plain, which are themselves critically endangered (Australian Government 2011). We are also motivated to improve threatened species evaluation and policy processes by incorporating structured expert opinion and exploring uncertainty, as urban landscapes are undervalued and highly significant locations for such species (Ives *et al.* 2016).

METHODS

Modelling framework

We used a Bayesian Belief Network modelling framework to represent the viability of golden sun-moth under different management scenarios. Bayesian Belief Networks (Pearl 1988; Korb & Nicholson 2011) are graphical probabilistic models for reasoning under uncertainty. Bayesian Belief Networks consist of a set of nodes that represent the salient variables in the system of interest. Uncertainty is represented by specifying probability distributions for the node variables (which can be continuous or discrete). Arcs (or arrows) indicate where conditional dependencies exist between 'parent' (denoted $pa(X)$) and 'child' (denoted $P(X)$) nodes. For each variable, all relevant (and mutually exclusive states) are defined. Each child node has a conditional probability table that quantifies the probabilistic effects that parent nodes have on it, that is, $P(X|pa(X))$.

The graphical network of nodes and arcs expresses the chain of logic or causal argument that links variables to outcomes. When the graphical structure is fully specified, the conditional probability tables parameterised, and the Bayesian Belief Network is compiled, it can be used for predictive reasoning about the system. Users can set the values of any combination of nodes in the network. This 'evidence', e, propagates through the network producing a new posterior probability distribution ($P(X|e)$) for each node in the network. In the Bayesian Belief Network modelling software that we use (Netica, version 5.18, Norsys Software Corporation), a number of efficient exact and approximate inference algorithms are available for performing this belief updating. A particular benefit of Bayesian Belief Networks is that knowledge and data from multiple sources such as theoretical insight, empirical data, output from statistical or process models and expert judgements can be used to construct the graphical structure and parameterise the conditional probability tables (Cain 2001).

Model development

The goal was to capture the key factors that influence the population viability of golden sun-moth at sites experiencing urbanising pressure. The three main tasks are selection and definition of variables, specification of the Bayesian Belief Network graphical structure (i.e. network of nodes and arcs) and construction of conditional probability tables for each node. We developed a first-cut Bayesian Belief Network using a review of the literature. We then used an expert workshop to revise the model and parameterise the conditional probability tables for each node.

We searched for ‘golden sun-moth’ and ‘golden sun moth’ in the Web of Knowledge, Scopus and Google Scholar (April 2014). From this literature, we identified key variables that influence the population viability of golden sun-moth and their putative cause-and-effect relationships. We also incorporated five biodiversity sensitive urban design features, namely ‘Ecological buffer zone’, ‘Fire buffer zone’, ‘Clean construction’, ‘Viewing platforms’ and ‘Sanctuary periods’, as we wanted to investigate their influence on golden sun-moth population viability. These features were chosen as they adhere to the key principles for biodiversity sensitive urban design (i.e. maintain or introduce habitat, facilitate dispersal, minimise threats and anthropogenic disturbances, facilitate natural ecological processes, and facilitate positive human-nature interactions). Some of these have also been previously assessed by Garrard *et al.* (in review) in a study involving the persistence of the native temperate grasslands of the Victorian Volcanic Plain. The first-cut Bayesian Belief Network and the literature used to develop it are given in Figure A1 (Supporting Information). In developing this literature-based Bayesian Belief Network, we took care to apply the following recommendations given in Marcot *et al.* (2006), Korb & Nicholson (2011) and Chen & Pollino (2012): (1) the number of parent nodes to any given child node was kept to three or less; (2) a balance between parsimony and precision was sought when deciding on the number of necessary discrete states within each node; and (3) continuous correlates were discretised as appropriate. As the joint probabilistic effects of parents on child nodes were to be assessed by experts, these guidelines help to ensure that the structure did not impose a heavy cognitive burden on the assessment task.

We refined the literature-based Bayesian Belief Network and populated the conditional probability tables in a one-day workshop involving five specialists with expertise in golden sun-moth ecology and conservation, in July 2014. The experts included an academic with decades of entomological research experience, a research entomologist at a leading government agency and environmental consultants with extensive field experience in golden sun-moth survey protocols. All experts had authored one or more peer-reviewed publications and/or reports in which the main focus of research had been the golden sun-moth. Prior to the workshop, the experts received a training document, in which they were provided with information on the facilitators, the workshop's goals, biodiversity sensitive urban design principles and expert elicitation methodologies.

During the workshop, the five experts (ASK, ALY, BB, JU & TRN), supported by three facilitators (BCW, GEG & LM), established the spatial and temporal context for the Bayesian Belief Network model that would be built. It was agreed that the model would focus on grassland patches of 10-20 hectares, located in areas about to be disturbed by urban development. The model timeframe was set to 1-3 years, since it is presently unclear whether the golden sun-moth life cycle takes one, two or three years to complete (New 2012). An agreement was also reached to work exclusively with input variables that could be modified through management. Consequently, environmental variables such as temperature, though important, were excluded. Instead, we assumed 'average' temperature conditions for the modelling exercise.

After agreeing on the modelling context, the experts were given a detailed model walkthrough of the literature-based Bayesian Belief Network. This formed the starting point for discussions about candidate output, intermediate and input variables; exactly what each represented, how they ought to be described and defined, and how they related to any parent or child variables. Using the Bayesian Belief Network modelling software, Netica (version 5.18, Norsys Software Corporation), modifications to the model's structure were incorporated and removed dynamically by the facilitators as the discussion proceeded. After multiple rounds of discussions, experts and facilitators agreed on a consensus Bayesian Belief Network that they felt was a good representation of current knowledge about key influences on the population viability of the golden sun-moth.

Parameterisation of the peer-reviewed Bayesian Belief Network using expert knowledge

The strength of the relationships between conditionally dependent variables in the graphical model was assessed and parameterised using expert elicitation. We followed the guidelines provided in Kuhnert *et al.* (2010), Martin *et al.* (2012) and McBride & Burgman (2012) to design the process by which knowledge was elicited from the experts. Prior to running the elicitation to parameterise the golden sun-moth model, the experts completed a practice run to familiarise themselves with the task of conditional probability table assessment. We also used a percentage scale (0-100) rather than a probability scale (0-1), as research suggests that people find probabilities difficult to understand and reason with (Gigerenzer & Hoffrage 1995). Each expert completed all the conditional probability tables in the model independently and privately, resulting in five parameterised Bayesian Belief Networks. We also created a combined consensus model by pooling individual node conditional probability table judgements through simple averaging.

Model evaluation

The individual expert models as well as the final combined model were evaluated using two types of sensitivity analysis: sensitivity to evidence and sensitivity to changes in parameters. Sensitivity to evidence tells us how much a finding at one node will likely change the beliefs at another (the so-called ‘query’ node). We used this to identify which variables have the greatest influence on the output node ‘Change in golden sun-moth population’. In Netica, the ‘sensitivity to findings’ function uses entropy reduction (measured in bits) to measure the effect of one variable on another. The greater the entropy reduction value associated with a findings node, the greater its influence on the query node.

In this study, the outcome of greatest concern was when the ‘Change in golden sun-moth population’ variable, was in the state ‘Decline’. We therefore conducted our sensitivity to changes in parameters analysis with specific reference to this outcome. This involved noting the posterior probability of this outcome, as the state of each node in the Bayesian Belief Network was altered between its minimum and maximum range (Pollino *et al.* 2007, Korb & Nicholson 2011). This analysis can tell us for which variables, greater precision in estimation would be useful.

Finally we also undertook scenario-based evaluation to examine the expected ‘Change in golden sun-moth population’ associated with a series of scenarios of management interest.

The .neta extension ‘Netica Bayesian Belief Network’ files containing the necessary expert-parameterised conditional probability tables to re-run the analyses are provided in the online Supporting Information.

External review

As a means of further evaluating the consensus model, we sought external peer-review (Marcot *et al.* 2006). We asked the experts who had participated in the workshop to recommend other suitably qualified golden sun-moth experts. Of the recommended experts who were contacted, three agreed to assist with the external peer-review. Either in person or via videoconference, we stepped each expert individually through the process that led to the consensus model. We asked the experts for specific feedback on whether: (1) the model variable names and states were appropriately and adequately defined with respect to the spatial and temporal scale and specific problem context; (2) the overall graphical structure of the model was based on sound ecological reasoning; and (3) all important variables had been included in the model and whether any omissions were justifiable/defensible. The external reviewers were further requested to provide a ‘reasonableness’ check on node relationships encoded in the conditional probability tables. The external reviewers were provided with all workshop outputs, including the ‘Netica Bayesian Belief Network’ (.neta) files necessary to re-run the analyses. Of the three experts who were briefed to conduct the external review, two provided feedback (ADT & GWB).

RESULTS

The consensus Bayesian Belief Network model is composed of 14 nodes and 16 arcs (Fig. 1), and the names, states, descriptions and explanations of all model variables are summarised in Table 1. The graphical model is structured according to the main conceptual ideas as follows:

1. The viability of golden sun-moth at urban fringe sites is believed to be strongly linked to the magnitude of ‘Change in golden sun-moth population’ over a 1-3 year timeframe.
2. The golden sun-moth population includes short-lived adults and larval stages of variable longevity. In the model therefore, ‘Change in golden sun-moth population’ depends explicitly on ‘Adult survival’, while the contribution of larval golden sun-moth stages is represented indirectly by ‘Cover of resource plants’ and ‘Bare ground cover’ which both influence the survival of the larval stages.
3. ‘Adult survival’ is affected by whether ‘Predation management’ is implemented or not. ‘Cover of resource plants’ depends on whether native grasses are re-established and how much weed cover there is in the grassland patch. ‘Bare ground cover’ which is important for the larval stages is determined by ‘Weed cover’ and ‘Biomass management type’.
4. ‘Weed cover’ in turn, is driven by the strength of the ‘Weed propagule pressure’, the amount of nitrogen and phosphorus reaching the grassland patch (‘Soil inputs’), and whether ‘Weed management’ follows standard practice or is absent.
5. Construction practices during development (‘Clean construction’) have an impact on ‘Weed propagule pressure’, as does the type of ‘Buffer zone’. In addition, the type of ‘Buffer zone’ influences nitrogen and phosphorous inputs to the site and constrains the ‘Biomass management type’ that can be applied (e.g. burning to remove excess biomass is infeasible in the absence of a buffer zone between built environments and a grassland patch).
6. ‘Community engagement’ based around informed discussion of benefits and risks of biomass management options is expected to increase the acceptability of burning as a tool.

Entropy reduction values calculated in the sensitivity to evidence analysis allowed us to produce a ranking of the network variables, in order of influence on the ‘Change in golden sun-moth population’ query node (Table 2, Table A1 in the online Supporting Information).

Though there were slight differences in the variables ranked from 2 to 13, experts were largely and consistently in agreement about the relative importance of variables. In the combined model, as well as for each expert-parameterised model, ‘Adult survival’ was the variable that most influenced golden sun-moth viability. The sensitivity analysis indicated that changes to the golden sun-moth population were most influenced by its parent nodes ‘Adult survival’, ‘Cover of resource plants’ and ‘Bare ground cover’, and least sensitive to the most distal nodes such as the biodiversity sensitive urban design input nodes ‘Community engagement’, ‘Clean construction’, and type of ‘Buffer zone’ (Fig. 2). This is not surprising and these results reflect the logic represented by the graphical structure of the network.

Using the combined Bayesian Belief Network, we examined multiple scenarios to probe the expected response of golden sun-moth to different sets of management actions. As a basic check, we corroborated that setting the three most influential network variables of ‘Adult survival’, ‘Bare ground cover’ and ‘Cover of resource plants’ to their lowest value shifted the probability mass of ‘Change in golden sun-moth population’ strongly to the ‘Decline’ state. By contrast, a shift in the opposite direction occurred when these variables were set to their highest values (Table 3 and Fig. 3).

When the full suite of conventional management options of ‘Predation management’, ‘Weed management’ and ‘Reestablishment of native grasses’ were all set to their highest values, the most likely state of ‘Change in golden sun-moth population’ was ‘Stable’ (Conventional Management *best-case scenario* in Table 3). In contrast, when these options were at their lowest values, the most likely state of ‘Change in golden sun-moth population’ was ‘Decline’ (Conventional management *worst-case scenario* in Table 3).

There is a small difference in the expected outcome when the biodiversity sensitive urban design variables (i.e. ‘Clean construction’, ‘Buffer zone’ and ‘Community engagement’) were set to their highest or lowest values (Biodiversity sensitive urban design *best-case scenario* and biodiversity sensitive urban design *worst-case scenario* in Table 3). In both scenarios, the most likely state is ‘Stable’, and the difference in probabilities for each of the states ‘Decline’ and ‘Increase’ (between the two scenarios) was approximately 3%. Enacting all biodiversity sensitive urban design options in addition to conventional options (i.e. Conventional management + Biodiversity sensitive urban design *best-case scenario*) demonstrated some support for this management approach, with the probability of the ‘Increase’ state of ‘Change in golden sun-moth population’ increasing from 31.7 to 33.0% (Table 3).

DISCUSSION

The results of our study suggest that adult survival, bare ground cover and cover of resource plants are the most important variables affecting the viability of golden sun-moth populations, and this corresponds to field evidence for the species collected across its range (O’Dwyer and Attiwill 1999; Brown *et al*. 2012; Richter *et al*. 2013a). In addition, outputs from the scenario-based evaluations further suggest that a best-case scenario in which all three variables are simultaneously tested at their higher states has the potential to improve golden sun-moth populations from a stable to increasing state (i.e. change in population size greater than 25%). By contrast, a worst-case scenario in which these variables are tested at their lowest states is predicted to change the state of golden sun-moth populations from stable to declining (i.e. change in population size greater than -25%). Taken together, these findings highlight the interacting and pivotal role that management of adult survivorship, ground cover and food resources have for the conservation of this species. Actions that are designed to optimise the state of these key population and habitat variables are predicted to enhance the persistence of golden sun-moth populations into the future.

When the model variables were assessed individually, our results show adult survival to be the most influential variable affecting golden sun-moth population viability. Our model further identified predation management as the single-most important controllable variable influencing adult survival. Management of introduced predators is particular important given that naturally co-occurring species, such as the striped legless lizard *Delma impar* (Kutt *et al.* 1998), also prey on golden sun-moths. These findings suggest that management and urban design that a) minimises the degradation of native vegetation and b) reduces human-made structures that could facilitate species predation on the golden sun-moth, are key. The Australian Government impact assessment guidelines for the golden sun-moth, for example, indicate that moth predation by insectivorous birds (e.g. willie wagtail *Rhipidura leucophrys*) may be avoided or mitigated by limiting the availability of nesting and breeding structures and by designing fences that allow passage of adult golden sun-moth while simultaneously limiting perching surfaces (Australian Government 2009).

The cover of resource plants was the second most influential variable affecting the population viability of the golden sun-moth. This variable in turn was most strongly affected by the extent of weed cover and the implementation of management actions aimed at the re-establishment of native grasses. Understanding of the full range of consumable plants for larval golden sun-moth, and of the optimal density, condition and species of these, is still very incomplete – but the critical importance of larval food plants in site restoration to support and enhance golden sun-moth populations underpins practical conservation management for the moth. Threshold density of a key host plant, *Rytidosperma erianthum*, was assessed experimentally at Mt. Piper (Broadford, Victoria) by combining weeding with the planting of seedlings (O'Dwyer & Attiwill 2000). The elimination of competition from weeds provided significant benefit, and sites with golden sun-moth had *Rytidosperma* cover of >40 %, a level subsequently cited as a target threshold for site quality.

A major alien invader of grassland sites, Chilean needle grass *Nassella neesiana*, is a declared noxious weed – with an obligation to eradicate it wherever it is found. It occurs on many grasslands occupied by golden sun-moth, and large moth populations have been found on grassland patches comprised entirely of *Nassella* (Richter *et al.* 2013a). Pupal case surveys implied a close association with the weed, endorsing earlier suppositions (Gilmore *et al.* 2008; Brown *et al.* 2012) that *Nassella* may be a supplementary or primary food for golden sun-moth larvae in Victoria, where the native grass species have been reduced or eliminated. This presents a clear conservation dilemma, the conflict between the legal requirement to eliminate or prevent the spread of a declared noxious weed and its potential role as a key food source for a critically endangered moth species in degraded grassland patches in which alternative, native, food plants are sparse. The relative priority of weed control versus golden sun-moth population management should be context-specific for each individual grassland patch.

Bare ground cover was found to be the third most important variable influencing golden sun-moth population viability, and this variable was directly affected by weed cover and biomass management type. The golden sun-moth prefers an open tussock structure with sparse inter-tussock spaces (O'Dwyer & Attiwill 2000; Gilmore *et al.* 2008; Australian Government 2009), and patches of bare ground may be important during various stages of their lifecycle, especially reproduction. Females are semi-flightless and, after emerging from the pupa, they tend to remain on the ground, flashing their brightly-coloured hindwings from a conspicuous location to attract low-flying patrolling males (Australian Government 2009). Areas of bare ground, often covered by bryophytes, may also be an indication of native grasslands in good condition (Australian Government 2011). For example, *Themeda*-dominated grasslands without appropriate biomass control may form a thick thatch of vegetation that chokes out other native species (Morgan & Lunt 1999). With biomass reduction, competitive exclusion may be prevented, allowing the growth of grasses preferred by golden sun-moth, such as *Austrostipa* and *Rytidosperma*. Grasslands of low biomass and dominated by golden sun-moth preferred grasses were historically maintained by grazing by native herbivores and periodic fire (Dorrough *et al.* 2004), and such 'natural' disturbance would be considered optimal for controlling biomass. In degraded sites, controlled grazing by domestic stock has assisted in the control of exotic pasture species (O'Dwyer & Attiwill 2000). However, grazing by heavy stock can lead to increased soil compaction and decreased water infiltration, and soils in pastures that are even lightly grazed may eventually reach the same compacted state as heavily-grazed pastures (Greenwood & McKenzie 2001).

The contentious and difficult social problems created by grazing and fire management actions in locations adjacent to human populations, including the potential for loss of property (Gibbons *et al.* 2012), has led to suggestions that other management solutions such as slashing, mowing and weed spraying to control grass biomass and weed species might be more appropriate in an urban setting (Australian Government 2009). However, land managers need to recognise the potential impacts of these alternative solutions. For example, compressive and sliding/shearing forces by the wheels of agricultural vehicles, particularly when soils are damp, are principal causes of soil compaction (Batey 2009). Much also remains to be learnt about the effects of herbicides in natural ecosystems, particularly their impacts on insects and other invertebrates (Pratt *et al*. 1997).

Our results suggest that amongst the variables included in our model, those representing biodiversity sensitive urban design (i.e. clean construction, an appropriate buffer zone and community engagement) were individually and collectively unlikely to exert a large influence over the viability of golden sun-moth populations. This was anticipated, as these variables are indirect actions, located furthest from the output node in the model. However, we recommend a cautious approach to interpreting these findings. Biodiversity sensitive urban design aims to mitigate the severe impacts of urbanisation on biodiversity by improving the *in situ* viability of native species and ecosystems (Garrard *et al.* in review). This is in contrast to common approaches to compensate for biodiversity and habitat losses in urban areas via off-site offsets. Offsetting is unlikely to achieve net positive outcomes for biodiversity (Bekessy et al. 2010), particularly in the case of critically endangered ecosystems where available offset sites are limited (Gordon *et al.* 2011). The assessment of the influence of biodiversity sensitive urban design on species viability requires the integration of social and ecological variables, for example, to determine in this case the extent to which engagement with the community may indirectly influence bare ground cover by improving understanding of and support for specific biomass control measures such as fuel reduction burns. Existing research and evidence for these relationships is scarce, even when compared to the paucity of ecological information for data-deficient species like the golden sun-moth. Perhaps either our model or the domain experts that parameterised it was/were overly cautious about the potential benefits of biodiversity sensitive urban design. The potential of biodiversity sensitive urban design actions to mitigate *in situ* the detrimental impacts of poorly-planned urban development remains to be fully empirically tested.

The results from our study highlight how expert knowledge may be a valuable component of conservation management, especially in addressing uncertainty around conservation decisions when empirical data are lacking. However, it is important to acknowledge that our model is a literature-based, expert-judged approximation of the causal web of key correlates affecting the population viability of the golden sun-moth, and expert judgements are not without their biases. While a group of experts is likely to be less biased than any given individual (Burgman et al. 2011), experts within a narrow domain are not wholly independent from each other, because they tend to source knowledge from a similar literature, and often share similar beliefs. Arguably, a more accurate representation could be achieved by generating the model using data derived from empirical studies; however, in our case, few empirical data exists. Therefore, when pressing conservation actions are warranted and empirical data are lacking, structured expert judgements become critical in supporting decisions that may help ameliorate extinction risks faced by threatened species. When experts make judgements within their domain of expertise, and when those judgements are elicited and aggregated in a transparent and repeatable way using approaches that mitigate common biases such as group think and halo effects, their judgements are almost certainly better than the alternative: i.e. relying on no evidence or opaque and unstructured lay estimates to make decisions (Aspinall 2010, Burgman et al. 2011). If poorly formulated, those decisions could have strong detrimental impacts on the focal species.

There were several important limitations of the study including issues raised by the external experts who reviewed the model. We examined the causal web of key correlates affecting the viability of golden sun-moth populations in city fringe grasslands prior to hypothetical disturbance by urban development, and hence our results do not necessarily extend beyond this particular context. For example, our modelling approach does not incorporate variables that are beyond our control, notably abiotic environmental variables such as temperature and precipitation. Focusing exclusively on drivers of golden sun-moth viability for which there are potential management solutions might be an issue, most notably when the golden sun-moth is expected to do poorly as a consequence of the strong influence of an abiotic environmental factor (e.g. extreme temperatures). The challenge remaining, then, will be to incorporate the interactive effects of abiotic environmental and management variables to better understand the effect of the former on the efficacy of the latter.

Bayesian Belief Networks can also be extended to explicitly aid decision-making by including decision nodes to represent specific choices and utility nodes to measure the cost of particular choices as well as the value of predicted outcomes. Future investigations could benefit from addressing other important issues relevant to golden sun-moth conservation such as habitat contraction and degradation outside urban environments, habitat heterogeneity and its influence on population fluctuation and survivorship (Kutt *et al.* 2015) and the potential impacts of climate change. Although we strived to elucidate and include all relevant variables and links (given the constraints to minimise probability elicitation and unnecessary uncertainty propagation), the external experts considered that the model may have been more informative if it had included further management impacts such as compaction and spraying. Other variables, such as ‘commercial or government investment’ or ‘land acquisition’, would also be good to include in future iterations of the model. The external reviewers indicated that ‘biomass management’ (i.e. slashing, grazing and burning) may warrant separation into distinct actions, since the effect of each approach on structure and floristics may vary, and all three methods would not be used together in one location, or at least not simultaneously.

CONCLUSIONS

The golden sun-moth is a critically endangered species that occurs in urban fringe areas that will experience substantial future development. Management of this species requires tools to help make sound conservation management and planning decisions in the face of complex socio-ecological processes and substantial uncertainty. Our findings are relevant at multiple levels. First, our results may be applied to the management of the golden sun-moth in urban environments as they indicate the important role of adult survival, bare soil cover and cover of resource plants for the population viability of the species. Second, we investigated the potential of biodiversity sensitive urban design as a complementary measure to conventional management for this species, and demonstrate some support for this approach; the *in-situ* nature of this approach contrasts with typical urban design scenarios that seek to offset biodiversity from areas to be developed and forgo onsite values. Finally, our study provides a good example of structured elicitation and aggregation of expert knowledge to address uncertainty around conservation decisions when ecological data are lacking.

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Table 1 Nodes of the final peer-reviewed Bayesian Belief Network representing the causal web of key correlates affecting the population viability of the golden sun-moth *Synemon plana* in southeastern Australian peri-urban grassland ecosystems.

Node	**Type**	**States**	**Description**	**Importance**
Output node				
Change in golden sun-moth population	C	Decline (> -25%) Stable (-25% – 25%) Increase (> 25%)	Percentage inter-annual variation in population size.	A strong indicator of the viability of the population.
Intermediate nodes				
Adult survival	D	Below average Average Above average	Probability that adult individuals will survive at least into reproductive stage.	Linked to higher rates of female oviposition.
Bare ground cover	C	Low (< 15%) Average (15 – 25%) High (> 25%)	Percentage of grassland not covered by vegetation.	The species immature stages develop in the ground.
Biomass management type	D	Absent Slashing Grazing Burning	Method used to manage the grassland's excess biomass.	Removal of excess biomass prevents sprouting of non-resource plant species.
Cover of resource plants	C	Low (< 10%) Average (10 – 30%) High (> 30%)	Percentage of grassland covered by resource plant species.	Resource plants are critical for the species to feed and reproduce.
Soil inputs	D	Low Average High	Amount of external nitrogen and phosphorous	Higher rates of nitrogen and phosphorous will favour weed

			reaching the grassland.	establishment.
Weed cover	C	Low (< 15%) Average (15 – 75%) High (> 75%)	Percentage of grassland covered by weed plant species.	Weeds compete directly with resource plants whilst reducing bare ground cover.
Weed propagule pressure	D	Low Average High	Amount of weed seeds reaching the grassland from adjacent areas.	Linked to higher rates of weed establishment.
Input nodes				
Conventional management actions				
Predation management	D	Not implemented Implemented	Actions taken to prevent adult mortality by non-native predators.	Preventing predation is associated with higher rates of adult survival.
Reestablishment of native grasses	D	Not implemented Implemented	Actions taken to increase the amount of native grasses present in the grassland.	Reestablishing native grasses is associated with higher densities of resource plants.
Weed management	D	Absent Standard	Actions taken to remove weeds from the grassland.	Weed removal is linked to a decrease in weed cover.
Biodiversity sensitive urban design actions				
Buffer zone	D	Absent Impervious	Establishment of either	A buffer zone may reduce the

		Pervious	impervious (e.g., street) or pervious (e.g., vegetated) surface buffering the grassland from the development.	likelihood of nutrient runoff spilling from the developed area into the grassland.
Clean construction	D	Not implemented Implemented	Actions taken to minimise the introductions of weed seeds during development.	Linked to a decrease in weed propagule pressure.
Community engagement	D	Absent Present	Actions taken to educate the community on the pros and contras of conventional biomass management actions.	Associated with an increase likelihood of accepting burning as a safe option to managed the grassland's excess biomass.
C: Continuous; D: Discrete				

Table 2 Network variables ranked in order of influence on 'Change on golden sun-moth population' for each expert-parameterisised Bayesian Belief Network and the combined, expert averaged model.

Rank	**Combined model**	**Expert A**	**Expert B**	**Expert C**	**Expert D**	**Expert E**
1	Adult survival	Adult survival	Adult survival	Adult survival	Adult survival	Adult survival
2	Cover of resource plants	Cover of resource plants	Bare ground cover	Bare ground cover	Cover of resource plants	Cover of resource plants
3	Bare ground cover	Predation management	Predation management	Predation management	Weed cover	Predation management
4	Weed cover	Bare ground cover	Cover of resource plants	Cover of resource plants	Bare ground cover	Weed cover
5	Predation management	Weed cover	Biomass management type	Biomass management type	Predation management	Bare ground cover
6	Reestablishment of native grasses	Weed propagule pressure	Reestablishment of native grasses	Reestablishment of native grasses	Reestablishment of native grasses	Reestablishment of native grasses
7	Soil inputs	Soil inputs	Weed cover	Weed cover	Weed propagule pressure	Soil inputs
8	Weed propagule pressure	Buffer zone	Weed management	Weed management	Weed management	Biomass management type
9	Weed management	Reestablishment of native grasses	Weed propagule pressure	Weed propagule pressure	Biomass management type	Weed management
10	Biomass management type	Biomass management type	Soil inputs	Soil inputs	Buffer zone	Weed propagule pressure

11	Buffer zone	Clean construction	Buffer zone	Buffer zone	Soil inputs	Buffer zone
12	Clean construction	Weed management	Community engagement	Community engagement	Clean construction	Clean construction
13	Community engagement	Community engagement	Clean construction	Clean construction	Community engagement	Community engagement

Table 3 Scenario-based evaluation of the expected ‘Change in golden sun-moth population’ using the combined Bayesian Belief Network. Cells show the evidence entered for each network variable (columns) for each of the eight scenarios (rows). The last three columns give the predicted probability distribution of ‘Change in golden sun-moth population’ associated with each scenario.

	Variable									**Predicted probability**		
Scenario	Adult survival	Bare ground cover	Cover of resource plants	Reestablishment of native grasses	Weed management	Predation management	Clean construction	Buffer zone	Community engagement	Decline	Stable	Increase
Adult survival + Bare ground cover + Cover of resource plants worst-case scenario	Below average	Low	Low							84.0	13.6	2.4
Adult survival + Bare ground cover + Cover of resource plants best-case scenario	Above average	High	High							7.0	28.0	65.0
Conventional management worst-case scenario				Not imp.	Absent	Not imp.				40.9	38.3	20.3
Conventional management best-case scenario				Imp.	Standard	Imp				29.3	39.0	31.7
Biodiversity sensitive urban design worst-case scenario							Not imp.	Absent	Absent	33.2	39.8	27.1
Biodiversity sensitive urban design best-case scenario							I	Pervious	Present	30.9	39.3	29.8
Conventional management + Biodiversity sensitive urban design worst-case scenario				Not imp.	Absent	Not imp.	Not imp.	Absent	Absent	42.2	38.6	19.1

Conventional management + Biodiversity sensitive urban design best-case scenario				Imp.	Standard	Imp.	Imp.	Pervious	Present	28.3	38.7	33.0

Imp: Implemented; Not imp: Not implemented. See Table 1 for a full description of the variables and their states.

Figures

Figure 1

Conceptual model depicting the causal web of key variables affecting change in golden sun-moth population. Dark grey nodes indicate ‘Conventional management’ input nodes. Light grey indicate ‘Biodiversity sensitive urban design’ input nodes.

Figure 2

A wizard’s hat diagram showing the sensitivity of each node in the model to the probability that state of the output node ‘Change in golden sun-moth population’ equals ‘Decline’. For ease of interpretability, the most sensitive node is plotted at the bottom (i.e. constituting the hat’s rim), and all other nodes, ordered from most to least sensitive, stacked on top (forming the hat’s cone). Black lines indicate the range of the change as the parameter is varied from its lowest to its highest values.

Figure 3

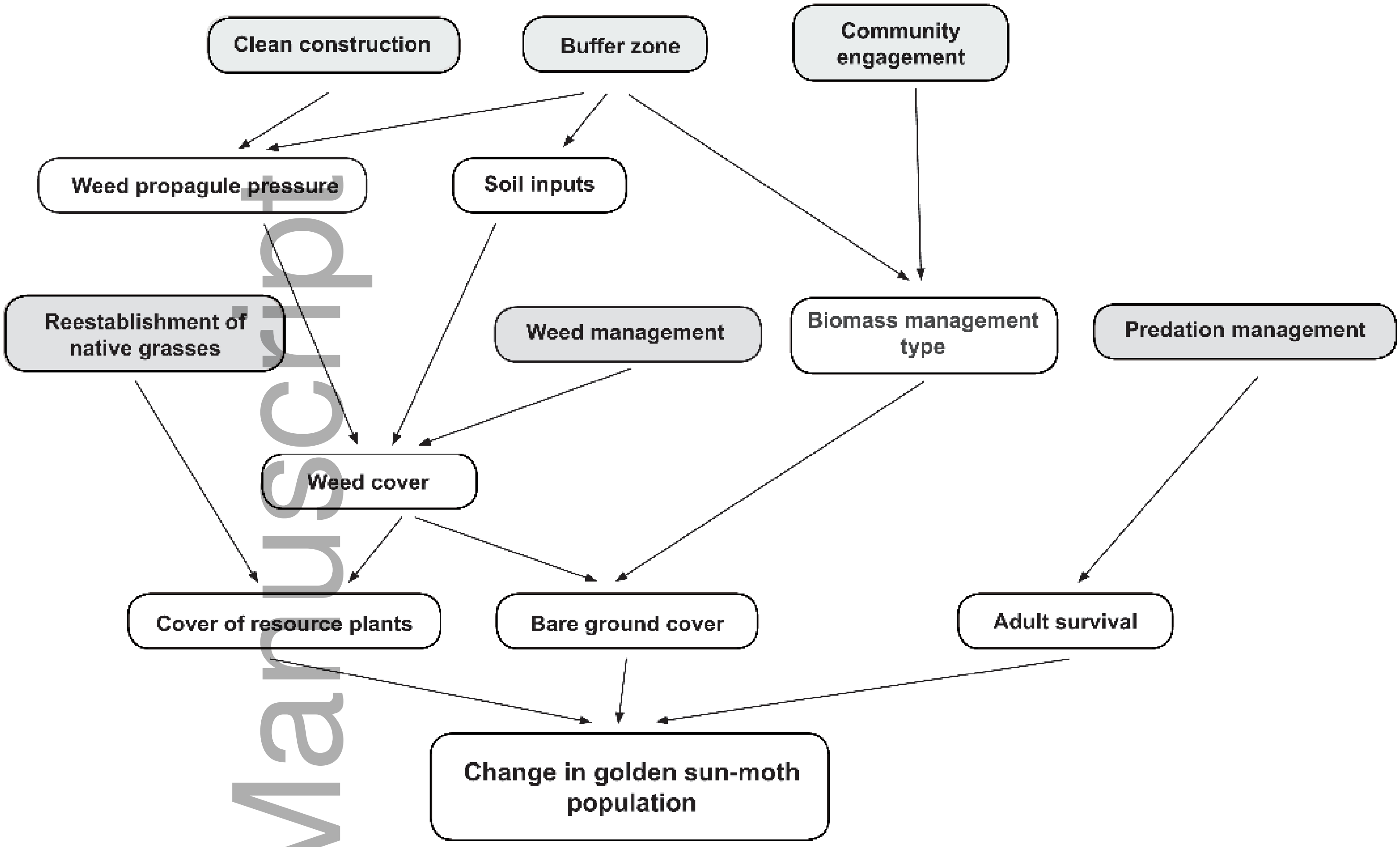
Effects of simultaneously placing ‘Adult survival’, ‘Bare ground cover’ and ‘Cover of resource plants’ (i.e. the nodes directly linked to the output node) in their lowest (A: worst-case scenario) and highest (B: best-case scenario) states. Grey shaded areas represent the posterior probability density function of the combined Bayesian Belief Network.

Supporting Information

Figure A1.pdf Literature-based Bayesian Belief Network

Table A1.pdf Sensitivity to evidence

NeticaFiles.zip



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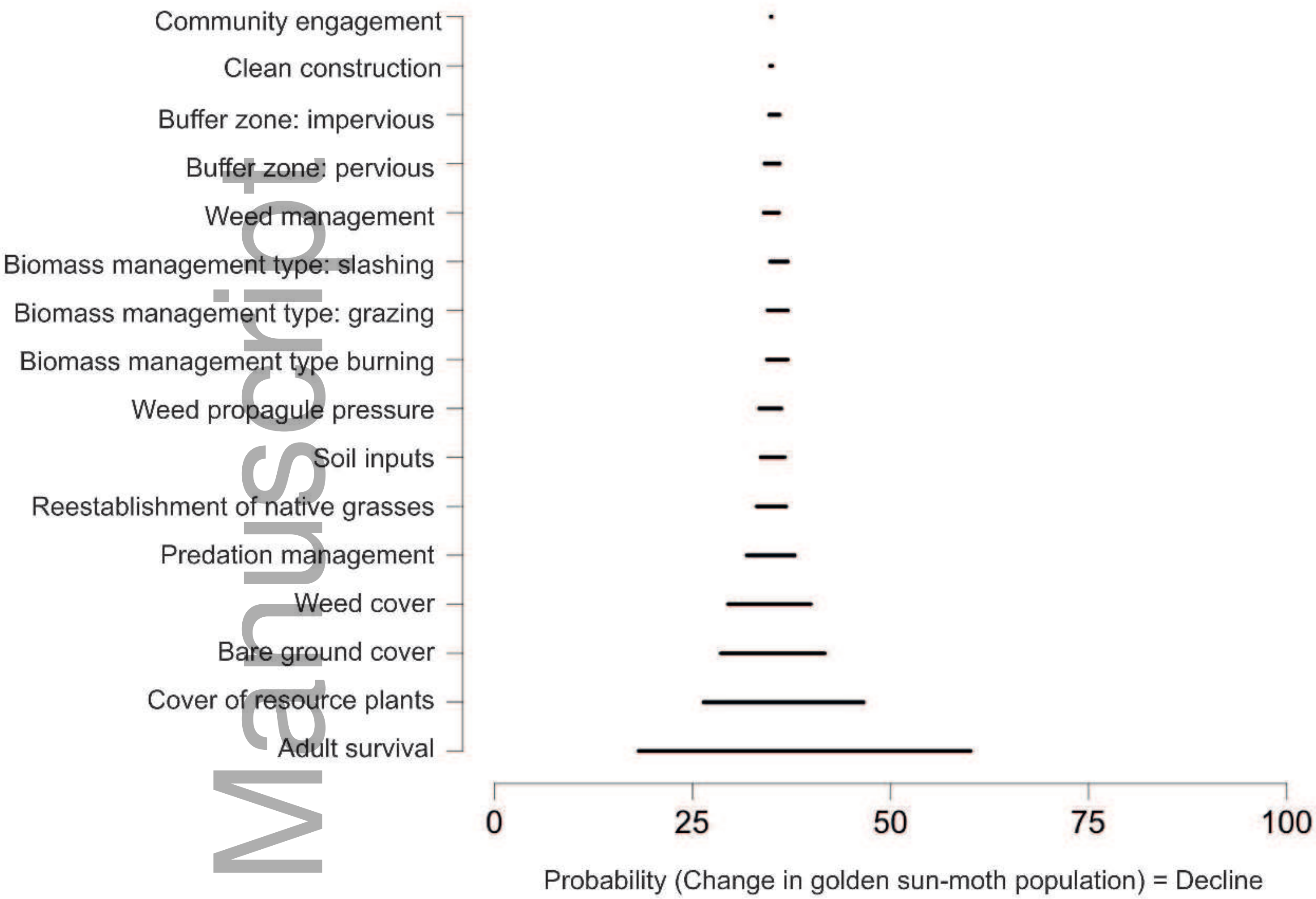

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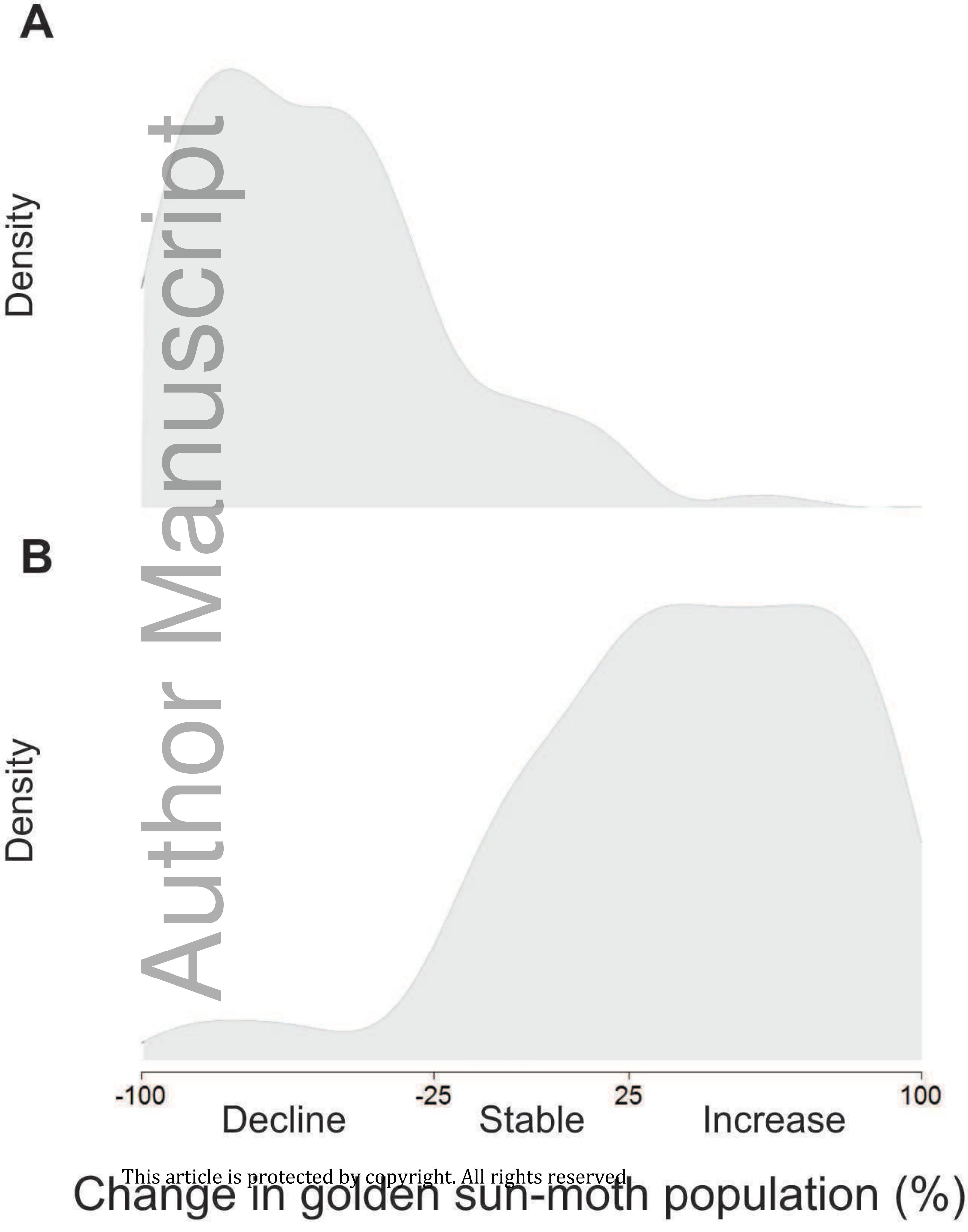
A
Density
B
Density
-100
-25
25
100
Decline
Stable
Increase
Change in golden sun-moth population (%)