Received: 14 April 2023 | Revised: 18 December 2023 | Accepted: 3 January 2024

DOI: 10.1002/sres.2999

RESEARCH PAPER

SYSTEMS and BEHAVIORAL RESEARCH SCIENCE

WILEY

Archetypal representations of dilemmas concerning invasive alien species management—A case of invasive *Lantana camara* in the protected areas of Nilgiri Biosphere Reserve, India

Thangatur Sukumar Hariharan[1] | **Lakshmanasamudram Sriramamurthi Ganesh**[2] | **Venkatraman Vijayalakshmi**[3] | **Piyush Sharma**[4] | **Vidyasagar Potdar**[4]

[1]T A Pai Management Institute, Manipal Academy of Higher Education, Manipal, India

[2]ICFAI Foundation for Higher Education, Hyderabad, India

[3]Department of Management Studies, Indian Institute of Technology, Chennai, India

[4]School of Management and Marketing, Curtin University, Bentley, Perth, Australia

Correspondence
Thangatur Sukumar Hariharan, T A Pai Management Institute, Manipal Academy of Higher Education, Manipal, India.
Email: hariharan.t.sukumar@gmail.com

Abstract

This multi-site case study on the invasive alien plant *Lantana camara* in protected areas of Nilgiri Biosphere Reserve, India, addresses the reasons for inadequate institutional responses from stakeholders in managing the species despite the seriousness. The study uses thematic analysis and qualitative systems approach. The themes are converted into a qualitative-system-dynamics model and are then abstracted into system archetypes. The study identified three major themes: the dilemma involving stakeholders, the dilemma of alternative and commercial use of *Lantana*, and the *Lantana* management conundrum. The study translated these dilemmas into four generalisable archetypes: 'drifting goals', 'modified-shifting-the-burden', 'fixes-that-fail' and 'substitution rebound'. The latest is a novel contribution to the systems literature. Practically, the study helps understand the recurring undesired behavioural patterns in invasive species management and suggests policy and governance changes to tackle them. The study also points towards building stakeholder relationship protocols, focussing on fundamental solutions and having clear *Lantana* management targets.

KEYWORDS

causal loop diagrams, invasive species management, *Lantana camara*, Nilgiri Biosphere Reserve, system archetypes

1 | INTRODUCTION

Invasive alien species (IAS) are one of the greatest threats to biodiversity and ecological well-being (Bellard et al., 2016; Panlasigui et al., 2018; Roberts et al., 2013; Simberloff et al., 2013; Tilman et al., 2017). IAS are non-native species introduced in an ecosystem for commercial/aesthetic purposes or accidentally (Kannan et al., 2013). Losses because of IAS, on their cost of management and negative impacts, run into billions of dollars annually (Alvarez & Solís, 2018; Paini et al., 2016; Pimentel, 2009; Pimentel et al., 2005). IAS management includes a wide range of activities, including prevention, early detection, rapid response and control of IAS (Auld & Johnson, 2014). IAS management may involve methods such as (i) manual removal of IAS, (ii) machinery-based removal, (iii) chemical control, (iv) biological control and (v) fire treatments. These activities are guided by environmental governance paradigms, policies and practices (Simberloff et al., 2013). However, the practice of IAS management is easier said than done because of various factors and conflicts affecting the efficacy and efficiency of the management programme (Bennett & van Sittert, 2019; Shackleton et al., 2017).

IAS management is not only an ecological problem but also an administrative, legal, and interpersonal problem. For instance, conflicts of interest among the stakeholders can deter IAS management efforts (Crowley et al., 2017). The differing priorities and variations in stakeholders' perceptions towards an IAS exacerbate the conflicts on the ground. The efficacy of IAS management is primarily affected by the interest shown by the officer-in-charge (Fleischman, 2014; Fleischman, 2016) in countries such as India. These ambiguities and differing priorities make the problem difficult to solve. For instance, evidence suggests that about a century of *Lantana* management efforts in the protected areas (PAs) of Nilgiri Biosphere Reserve (NBR) has not yielded any apparent result for reasons not known; the lack of success concerning management interventions may lead to the abandonment of any efforts to control *Lantana* (Peters, 2017; Termeer et al., 2015). However, abandonment may not be a solution for the park managers as they are forced to act on invasions because of the nudging of various stakeholders, so they resort to ad hoc management. This paper is a multi-site case study of IAS (specifically *L. camara*, hereafter referred to as *Lantana*) management (or the lack of it) in the PAs of the NBR ecosystem. The paper focuses on human-related aspects of IAS management, such as administration and stakeholder involvement, by answering the following research question: Despite the seriousness of the issue of *Lantana* invasion in the region, why are there no concerted efforts taken by the park managers to manage *Lantana*?

1.1 | Research problem and context

Lantana, one of the 100 worst IAS listed in the Global Invasive Species Database (GISD) maintained by the International Union for Conservation of Nature (IUCN), poses multiple negative impacts on the invaded protected area ecosystem and its stakeholders (Jhala, 1992; Kannan et al., 2013; Negi et al., 2019; Richardson & Rejmánek, 2011). Environmental impacts of *Lantana* invasion are the loss of biodiversity and fire regime change (Bhagwat et al., 2012; Negi et al., 2019), forage pressure on herbivores (Prasad, 2010; Ticktin et al., 2012), and possibly reduced wildlife density in the PAs (Sharma & Raghubanshi, 2009). Studies concerning the negative socio-economic implications of *Lantana* invasions are also found in the literature (Kannan et al., 2014; Kent & Dorward, 2015). Stakeholders spatially proximal to the *Lantana* invasion consider it a severe threat to their livelihood (Kannan et al., 2014). Human–animal conflicts in the fringe areas of PAs (Sundaram et al., 2012), reduction in the non-timber forest produces yield (Sundaram et al., 2012; Ticktin et al., 2012), difficulty in accessing places of cultural and religious significance (Kent & Dorward, 2015), and very high cost of conservation (Day et al., 2003; Mungi et al., 2020) are other socio-economic impacts of *Lantana* invasion.

Lantana invasion is typically observed in government lands, including the PAs (managed by the forest department), than in private lands in India. Ubiquitous *Lantana*-specific studies are conducted on the negative impacts, invasion ecology, methods of removal and alternative uses (Negi et al., 2019; Prasad, 2010; Prasad et al., 2018; Sundaram et al., 2012). Many articles are available on invasion ecology, such as dispersion dynamics, climate niche, and control mechanisms of IAS and on the triple bottom line impacts of *Lantana*. However, the equally important softer aspects of *Lantana* management in India concerning administration, bureaucracy, and stakeholder involvement are sparsely studied in an integrated manner. This article focusses on and attempts to theorise the anthropocentric activities surrounding the *Lantana* invasion in the PAs of NBR.

The NBR (11°59′38″N; 77°8′26″E), established in 1986, is the first biosphere reserve in India. The reserve comprises contiguous patches of forests (552,000 ha) across the Indian states of Tamil Nadu, Kerala and Karnataka. The vegetation types in the region are diverse, with different ecosystems such as tropical wet evergreen forests, dry deciduous forests, scrub forests and shola montane (Shylesh Chandran et al., 2012). The NBR contains about 3500 plants, 550 birds and 100 mammal species (UNESCO, 2019). One of the primary threats to the NBR region's biodiversity is IAS, such as *Lantana, Chromolaena odorata, Senna spectabilis, and Parthenium hysterophorus*. The PAs of the NBR, especially the dry deciduous forest ecosystems within the region, are among the worst affected in India (Taylor et al., 2012; Thekaekara, 2015, 2016). For instance, 36,000 ha of area in Bandipur Tiger Reserve of the NBR region is heavily invaded by *Lantana* (Thekaekara, 2016).

Lantana management in India, especially what is now the NBR region, began in the 1910s by using manual methods of removal, fire-based controls, biological agents, and their combinations (Bhagwat et al., 2012; Kannan et al., 2013; Troup, 1921). However, little is known about the previous efforts towards managing *Lantana*. Chemical control of *Lantana* in India was temporarily tried in the early 20th century, but the results are unknown (Iyengar, 1933). Biocontrol agents used for *Lantana* management were unsuccessful in India (Bhagwat et al., 2012; Muniappan & Viraktamath, 1986). Post the 1940s, the *Lantana* management efforts gradually decreased to zero in the 1980s in the PAs of India (Bhagwat et al., 2012), corroborating with the prohibition of manipulations (that include *Lantana* management) in the PAs decreed by the Wildlife Protection Act (WPA) of 1972.[1] It is observed that *Lantana* management efforts were revived in the late 2000s because rampant *Lantana* proliferation in many PAs of the NBR.

However, the efforts are not commensurate with the seriousness of the issue. For instance, the National Tiger Conservation Authority (NTCA), through the Project Tiger programme, is the only funding source for habitat management activities (including *Lantana* management) in some tiger reserves in the NBR. Even Project Tiger funds are predominantly used in tiger protection activities, staff welfare, and civil development projects inside tiger reserves. There are other funding sources for habitat management, such as (a) state budget, (b) Compensatory Afforestation Fund Management and Planning Authority (CAMPA), and (c) corporate social responsibility and non-governmental organisations' funding. However, no evidence exists that these funds were used for *Lantana* management in India (Mungi et al., 2020). For instance, 15,000 million in Indian Rupees (200 million in United States Dollars) was released by the CAMPA to Karnataka (DHNS, 2019), an amount sufficient to manage *Lantana* on a landscape-scale for many years but was not used for *Lantana* management. The insufficient funds allocated for *Lantana* management indicate the low priority of habitat management activities.

Despite being a signatory of the Convention of Biological Diversity (CBD), which mandates the conservation of biodiversity and sustainable use of resources, India has not shown adequate importance to habitat management activities, evidenced by a lack of appropriate control actions on IAS. For instance, *Lantana* management activities in the PAs of the NBR are carried out in 3000 to 4000 ha (app ~ 4%), calling for a thorough understanding of the lacklustre and woefully inadequate response to invasion. The Karnataka Forest Department clears[2] about 700–1000 ha of *Lantana* annually (estimated based on the tiger reserves of Karnataka's annual plan of operations for 2020). NGO bodies in the NBR region manage about 1000–2000 ha annually. No formal reports are published by the forest departments about the status of IAS management, especially *Lantana* management, indicating low priority. One possible explanation for this phenomenon is the futility of solving a wicked problem (Termeer et al., 2015), such as *Lantana* management.

1.1.1 | Wicked problems

Rittel and Webber (1974) first defined and discussed 'wicked problems' in social and public policy planning contexts. Later, Conklin (2006) generalised the wicked problem concept for all planning areas. Wicked problems are identified and defined by six characteristics presented in Table 1, LM qualifies as a wicked problem as it involves multiple stakeholders with conflicting interests, and solutions require trade-offs between competing goals.

1.2 | Systemic approaches to tackling wicked problems

Wicked problems are ill-defined, ill-structured, complex and difficult to solve (Conklin, 2006; Rittel & Webber, 1974). Wicked problems need a bigger window of perception of the park managers and the policymakers to be solved. They cannot be solved by classical management approaches involving serial procedures from data gathering to solution implementation (Nelson & Stroink, 2014). Holistic and analytic thinking must be operated in tandem to tackle the interdependencies among the entities and their corresponding complexities observed in wicked problems (Pan et al., 2013). The systems approach combines these two thinking approaches, where the park managers (Forest Department officials) have a global picture of the problem but act locally on entities and sub-systems. Systems approaches are better suited to tackle unstructured problems like *Lantana* management (Hirschheim, 1983).

An optimal solution to the *Lantana* invasion problem would be completely eradicating the *Lantana* from the PAs. However, it is difficult to manage *Lantana* because of factors such as faster growth and spread rate, and abundant seed production. Given constraints such as financial resources availability and knowledge of

[1]It is a legal instrument enacted by the parliament of India to protect flora and fauna in the year 1972. The provisions in the act restrict access to PAs, involvement of direct and indirect stakeholders, and commercial activities in the proximity of PAs.

[2]Not much is known about the subsequent management after the initial clearing *Lantana* invaded patches.

TABLE 1 Characteristics of wicked problems with illustrative examples from *Lantana* management context.

Characteristics of wicked problem (Conklin, 2006)	Explanations	Parallel in *Lantana* management in PAs
'The problem is not understood until after the formulation of a solution.'	Problems are concomitant to solutions to wicked problems. Unless total solutions, both possible and impossible, are available and exhausted, the problem's root cause cannot be achieved.	Biodiversity loss in the PAs is caused by *Lantana* invasion and is also driven by various anthropogenic and ecosystem factors. These factors are influenced by global factors such as climate change and extreme weather events. These events affect the *Lantana* invasion and management. Unless the causes of each connected problem are understood, LM cannot be wholly formulated.
'Wicked problems have no stopping rule.'	The problem owner (PO) knows when an operations research problem is solved. However, in wicked problems, the problem owner cannot conclude whether to terminate an intervention based on specific criteria.	Problem owners cannot know if the *Lantana* invasion will recur even after thoroughly removing *Lantana* from the PAs. The boundary-agnostic nature of *Lantana* and its dispersers force the park managers to continue the *Lantana* removal effort for a long time.
'Solutions to wicked problems are not right or wrong.'	Solutions to the wicked problem do not have conventionalised criteria to be verified with repeatable accuracy and objectivity by independent third parties and relevant stakeholders to qualify them as right or wrong.	The use of large machinery for removing *Lantana* may not be considered right by all stakeholders in LM. Some stakeholders may agree with this method because of the operational difficulty of other methods, and some may disagree because of the consequent disturbance to soil and canopy (Bhutia et al., 2021).
'Every wicked problem is essentially novel and unique.'	A solution applied and thriving in one context may not work in another similar context.	A solution to the *Lantana* invasion in one context may not be successful in another. For instance, the use of biological control agents such as *Teleonemia scrupulosa* was successful in South Africa but was not so in India (Bhagwat et al., 2012)
'Every solution to a wicked problem is a one-shot operation.'	Every solution attempt is a significant and irreversible change in the problem field.	Using biological agents to control *Lantana* on a large scale may lead to agents feeding on the native species.
'Wicked problems have no given alternative solutions.'	"There may be no solutions, or there may be a host of potential solutions devised, and another host may not have even [been] thought [of]. Thus, it is a matter of creativity to devise potential solutions and a matter of judgement to determine which are valid and should be pursued and implemented." - (Conklin, 2006, pp.9)	The park managers have various methods for removing *Lantana*, but the effectiveness of each method cannot be ascertained, and; therefore, they have to use their judgement to manage *Lantana*.

Lantana management, achieving an optimal solution may not be possible. Hence, a 'satisficing solution' (Simon & Kadane, 1975) that is agreeable to stakeholders and at the same time keeps the *Lantana* in check in the PAs has to be attempted. While the extent of the *Lantana* invasion can be represented with hard empirical data, the dynamics of interrelationships are not described with data. Hence, this study has used an exploratory and qualitative system dynamics approach to understanding the interrelationships of factors influencing *Lantana* management. This paper endeavours to investigate the difficulties associated with managing *Lantana*, one of the world's most destructive IAS, and suggests solutions that consider the complex and wicked nature of the problem.

2 | METHOD

A qualitative system dynamics approach has been used to study the factors influencing *Lantana* management represented by means of causal loop diagrams. The qualitative approach is used when the data for quantitative

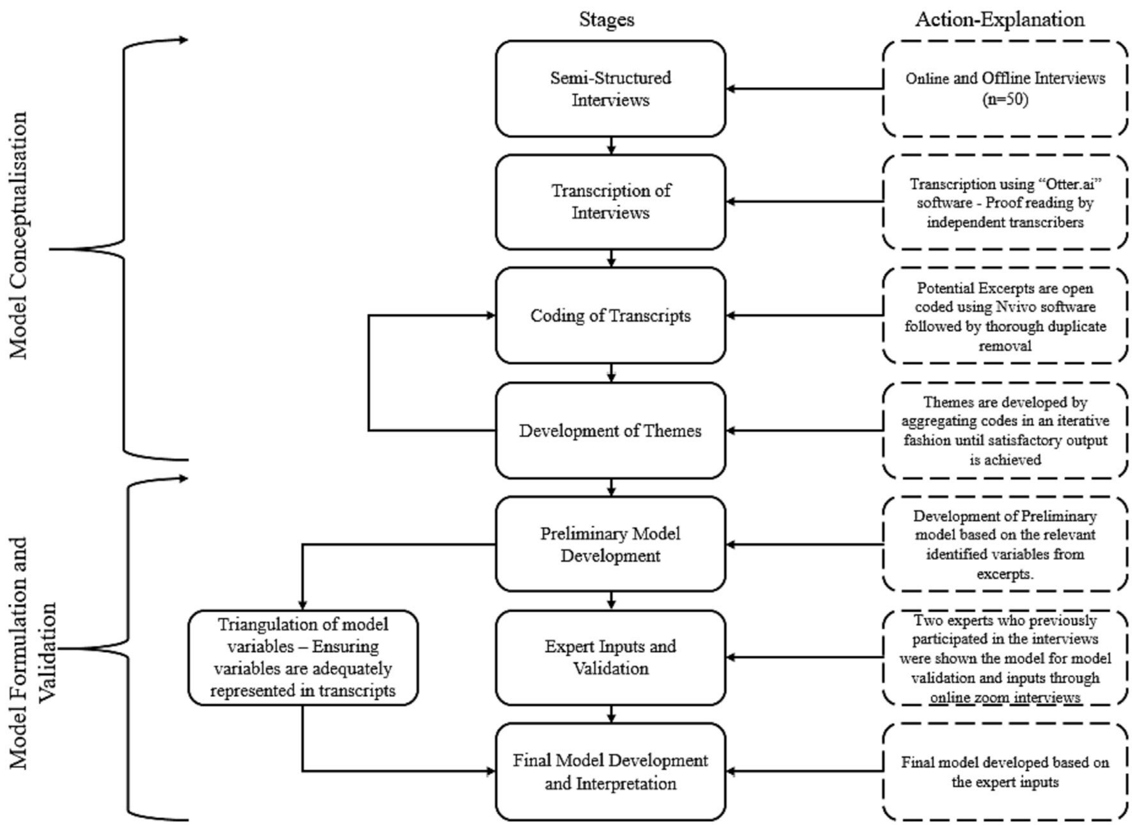

FIGURE 1 Qualitative systems modelling approach.

simulations are unavailable or cannot be assumed and when understanding the system is paramount for decision-making (Wolstenholme, 1993; Wolstenholme & Coyle, 1983). One of the primary concerns of this approach is that the model validation with empirical data may not be feasible, and therefore, the degree of accuracy with which the model corresponds to real-world conditions cannot be ascertained (Sterman, 2000). However, researchers and scientists have developed various methods to validate the models that are discussed in detail in the Model Validation Section. The qualitative system dynamics approach follows the typical 'conceptualisation–formulation–validation' phases in arriving at the requisite model representing the ground conditions of *Lantana* management in the NBR's PAs (Figure 1).

2.1 | Model conceptualisation

Conceptualisation is how the researcher understands the problem and identifies relevant parameters (variables) for subsequent model building. The variables of the model can be arrived at based on various methods such as (a) literature review (Laurenti et al., 2016), (b) interviews, (c) focus group discussions, and (d) the Delphi technique[3] (Luna-Reyes & Andersen, 2003). The authors collected primary and secondary data to identify relevant variables in this phase. Because the authors wanted to represent various stakeholders' perspectives across geographically dispersed locations, methods such as focus group discussions and Delphi techniques were not used during the primary data collection of the conceptualisation stage. Primary data were collected through 50 semi-structured interviews with 97 respondents belonging to various stakeholder groups, such as the park managers, NGOs, indigenous communities and research institutions (refer to Table 2 for more details) after obtaining informed consent. The respondents were contacted through purposive sampling. The authors conducted interviews for dual purposes (i) to identify themes related to *Lantana* management and (ii) to identify variables that influence or are influenced by *Lantana* management (Pineo et al., 2020; Ullah et al., 2021). Themes were developed using the thematic analysis processes prescribed by Braun and Clarke (2006).

The interviews were recorded and later transcribed with 'otter.ai' software to develop open codes (Braun &

[3]'Delphi technique' is a structured qualitative technique used to gather and distil the insights of experts on a subject matter to reach a consensus or forecast outcomes.

TABLE 2 Demographic details of interview respondents.

Stakeholder groups (notation)[1]	Selection criteria	No. of interviews	No. of respondents
Lantana experts (LE_XXX)	A senior PhD with several years of on-field/ research experience with solid publications related to *Lantana*	5	5
Indigenous Communities[2] (IC_XXX)	Adult residents of the tribal hamlet inside or on the fringes of protected areas of NBR	13	53
Non-governmental organisations (NGO_XXX) and research institutions (RI_XXX)[3]	NGOs or research institutions with direct or indirect work experience in *Lantana*-based projects in NBR region.	14	17
Park managers (PO_XXX)[4]	Senior officers with several years of experience in ecosystem management in the NBR region	14	18
Tourism industry reps (TI_XXX)	NBR presence of a minimum of 10 years	4	4
Total		**50**	**97**

[1]The notations such LE_XXX refer to the respondent codes.
[2]Wherever possible group interviews were conducted with indigenous communities. While we wanted to include women's participation, except in a few villages (V1, V5, V9, and V11), women respondents did not come forward. Some of them were present but stayed silent throughout the interview. This is a sampling limitation of the study.
[3]Of the nine interviews with various NGOs, only one was not involved in the research. However, the research institutions have little or no role in direct *Lantana* management.
[4]Two respondents in one of the interviews did not consent to the audio recording. The interviewer prepared field notes immediately after the interview.

Clarke, 2006). These codes were reviewed thoroughly to remove duplicates and merge codes with similar meanings. Following this, the researchers excluded variables that were not relevant to *Lantana* management based on their assessment of the topic (Luna-Reyes & Andersen, 2003). Nvivo software has been used to conduct these processes. The codes are then grouped into major themes. The code book is provided as a supporting information (Table S1).

2.2 | Model formulation

In this stage, the researcher developed a preliminary causal loop diagram based on the analysis and synthesis of the transcribed interviews, major themes identified through the thematic process, and the scientific literature (Pineo et al., 2020; Ullah et al., 2021). The relationship between pairs of variables is identified from the existing literature. Figure 2a depicts the notations used to develop causal loop diagrams based on the broad themes generated by grouping the open codes. The coding schema for the generation of themes includes (i) the relationship of variables to *Lantana* management and (ii) the exogenous influencers (variables) of the *Lantana* management processes (environmental factors). Themes related to the dilemma in managing *Lantana* are adopted for model formulation. The model formulation has also included developing system archetypes (discussed in Section 2.2.2).

2.2.1 | Causal loop diagram

A system is a set of interrelated entities with a purpose (Hariharan et al., 2022). A system/model is defined by the observer, based on the purpose of the endeavour. In this study, the system under consideration is protected areas of the NBR. This system and its interaction are represented using causal loop diagrams. They are pictorial representations used in the systems approach to illustrate the interconnectedness of various factors in the system (Sterman, 2000). In causal loop diagrams, the variables are linked through arrows that carry the 'positive (+ve)' or 'negative (−ve)' sign. The diagram captures the recurring behaviour of the system as feedback loops (dynamic hypothesis): balancing and reinforcing loops. A balancing loop creates a balancing effect, by countering the change in one variable to stabilise the system. A reinforcing loop amplifies the effect of the change in one variable by propagating through the loop to reinforce the initial deviation (Sterman, 2000). A causal loop diagram captures the causal dynamic hypothesis and effectively represents the feedback through balancing and reinforcing loops (Sterman, 2000).

2.2.2 | System archetypes

Archetypes are the combinations of dynamic hypotheses whose interactions result in recurring behaviour patterns in a system. However, it must be noted that all

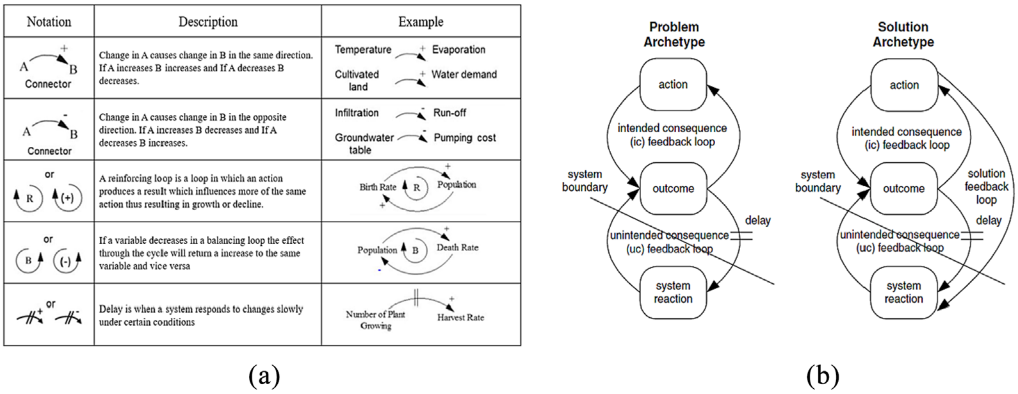

FIGURE 2 (a) Elements of causal loop diagram; *Source: Purwanto, A., Sušnik, J., Suryadi, F.X. and de Fraiture, C., (2019). Using group model building to develop a causal loop mapping of the water-energy-food security nexus in Karawang Regency, Indonesia. Journal of Cleaner Production*. (b) Generic problem and solution archetype. *Source: Wolstenholme, E.F. (2003), Towards the definition and use of a core set of archetypal structures in system dynamics. System dynamics review.*

combinations of dynamic hypotheses cannot be considered system archetypes. 'A good way to recognise true archetypes is that each must be driven by an intended policy (choice) link' (Wolstenholme, 2004). Each two-loop archetype contains one intended consequence loop and one unintended consequence loop (Banson et al., 2016; Kim & Burchill, 1992). In this study, the researchers have attempted to understand and represent the systemic behaviour of the variables concerning *Lantana* management as two-loop archetypes. Archetypes can also be classified as problem archetypes and solution archetypes. As the name suggests, a problem archetype represents specific problematic system behaviour patterns. The solution archetype provides a solution to each problem archetype.

'For every problem archetype, there exists a closed-loop solution archetype' (Wolstenholme, 2003, pp.7). Wolstenholme also argues that the key to finding solution archetypes lies in (a) understanding the delays and (b) demarking the system boundary. The intervenor of the system must make the boundary explicit. In this case, the policymakers and the park managers should list boundary conditions and understand the delays in systemic reactions of *Lantana* management, such as creating dependency on *Lantana* by stakeholders. The solution archetype operates by countering the effects of unintended consequence loops and activating the intended consequences loop through closed-loop interactions and the introduction of exogenous variables. The structure of the problem and solution archetypes is represented in Figure 2b.

2.3 | Model validation

Without empirical quantitative data to perform simulations, qualitative 'structural adequacy tests' are performed (Sterman, 2000). These tests include accessing boundary adequacy.[4] Expert interviews were conducted to validate the developed model on (i) boundary parameters, (ii) the relationship between two variables, and (iii) the correctness of the representation of balancing and reinforcing loops and the overall model (Luna-Reyes & Andersen, 2003). The experts were shown the preliminary models and asked to challenge the correctness of the model with justifications. Each challenge by the experts is recorded, and the researchers evaluate the rationale provided to accept the change. These challenges were accepted if the explanations were logically acceptable or empirically validated. Using Nvivo software, the researcher also validated the variables used in the model by coding the transcripts retrospectively to identify excerpts related to the variable. All the variables are coded, and their excerpts are linked to the respective variable (see Table S2). This method triangulates that the variables are indeed developed from the primary data. The researcher also used the existing literature to triangulate and validate the balancing and reinforcing loops developed through interviews.

3 | ANALYSIS AND RESULTS

In ecosystem management problems, the ecosystem's behaviour or the ecosystem itself is influenced by the ecological and anthropogenic environment, such as park authorities and relevant stakeholders (Mungi et al., 2018; Paul et al., 2021). Even in the *Lantana* management context in the NBR, anthropogenic influences are inevitable,

[4]Boundary adequacy ensures whether the model has included relevant variables and their relationships that are necessary and sufficient for the model to emulate the actual system (Sterman, 2000).

given the stage of *Lantana invasion*. The research question concerning the problem of inaction can be understood through the dilemmas concerning *Lantana* management that are arrived at using thematic analysis and depicted as causal loop diagrams.

The causal loop diagram models consider the dynamics of *Lantana* invasion and its management only in the PAs, although *Lantana*'s growth and spread are observed even in the non-PAs. The justification for restricting the model boundary to the PAs is that they are legally mandated biodiversity conservation hotspots (Le Saout et al., 2013; Naughton-Treves et al., 2005). Also, the PAs are owned by and belong to the Government, making it easy for any official management activity. This section depicts and discusses the current state of *Lantana* management, dilemmas faced in *Lantana* management, their underlying system archetypes, and potential solutions to the dilemmas.

3.1 | *Lantana* management—current state

The park managers predominantly carry out *Lantana* management in various NBR's PAs. These management efforts are largely ineffective because of efforts being taken only on a smaller scale and discontinuities in *Lantana* management. While other stakeholders can help mitigate the problem, their involvement is minimal because of multiple issues such as legitimacy, interest, power and proximity. Park managers follow what we call a 'protectionist paradigm' or the fortress model (Rai et al., 2021), in which their mental model is such that (a) forests are pristine, (b) forests are sources of timber and other resources and therefore must be protected against all forms of exploitation, and (c) other stakeholders are a threat to the forests and therefore must be involved only sparsely (Guha, 2001; Rangarajan, 1994).

3.2 | Fire and *Lantana* invasion—A system dynamic hypothesis

Rooted in colonial forestry management thinking, park managers negatively perceive fire in the NBR region. This thinking leads to the non-application of litter fire[5] to manage the NBR ecosystem. This practice of litter fire indirectly benefitted the ecosystem as these fires prevented bush encroachment, reduced high-intensity fires, killed buried *Lantana* seeds in the soil and prevented hemiparasitic attacks on adult trees (Thekaekara et al., 2017). The practice of litter fire gradually stopped resulting in fuel load build-up leading to high-intensity fires, denoted by the reinforcing loop Ra (Figure 3). Hiremath and Sundaram (2005) proposed a *Lantana* and fire relationship in dry deciduous forests. Frequent fires in the forests are less severe than infrequent fires (Hiremath & Sundaram, 2005; Reddy et al., 2020) as these fires substantially reduce the fuel load build-up preventing large-scale canopy fires.

The opened canopy from high-intensity fires is conducive to the growth and spread of otherwise shade-intolerant *Lantana*, which thrives in burnt and degraded ecosystems (Mamba & Singwane, 2019). The *Lantana* stocks are highly flammable, with a calorific value of about 18,900 KJ/Kg (Sahoo et al., 2021), and perpetrate high-intensity fires. These fires degrade soils, burn hotter and destroy canopies setting a vicious reinforcing cycle. The loop Rb (Figure 3) denotes the vicious cycle of *Lantana* invasion limited by indigenous burning practices or anthropogenic litter fire.[6]

3.3 | Perverse consequences of the *Lantana* invasion

The invasion of *Lantana* in the NBR region has a detrimental effect on the region's biodiversity and potentially results in human–animal conflicts (Sundaram et al., 2012; Ticktin et al., 2012). Secondly, in the long run, the forage area availability for the wild herbivores may reduce in the NBR region. Currently, the existing native vegetation can be assumed to support the herbivores in the region sufficiently. Harihar et al. (2018) observed that the current prey density could help twice as many tigers as the PAs currently have. This observation points to the abundance of the herbivores and their corresponding herbages. However, the foraging pressure on these herbages is bound to increase with the *Lantana* invasion.

Reduced poaching because of stricter laws and regulations, such as the Wildlife Protection Act of 1972, increased large-herbivore[7] density (Baskaran et al., 2011). A higher large-herbivore density leads to higher foraging pressure, which has delayed but direct implications on

[5]Litter fires are low-intensity early summer fires practised by indigenous Soliga communities of the NBR region (Thekaekara et al., 2017). The introduction of the Wildlife Protection Act of 1972 has restricted the use of litter fire in the PAs.

[6]The loop does not depict variables such as changes in species composition and degradation of soil to maintain the parsimony of the model.

[7]Large herbivores are animals whose adult body weight is greater than 5 kg (Fritz & Loison, 2006).

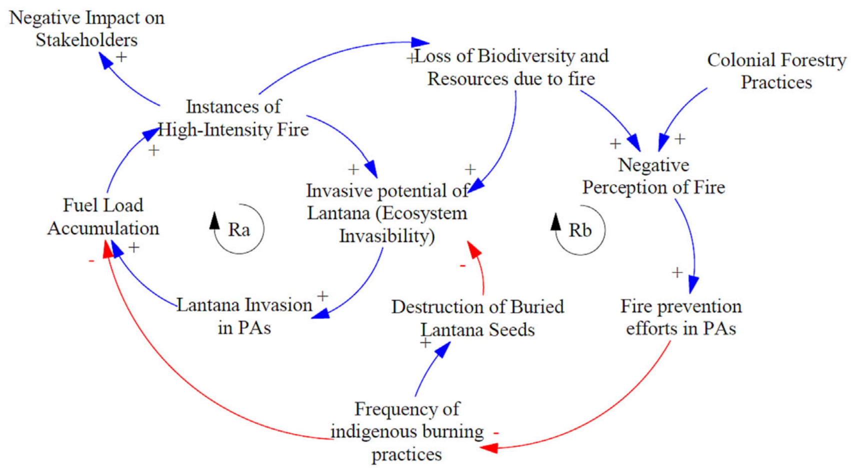

FIGURE 3 *Lantana* invasion and fire—a dynamic hypothesis. [Colour figure can be viewed at wileyonlinelibrary.com]

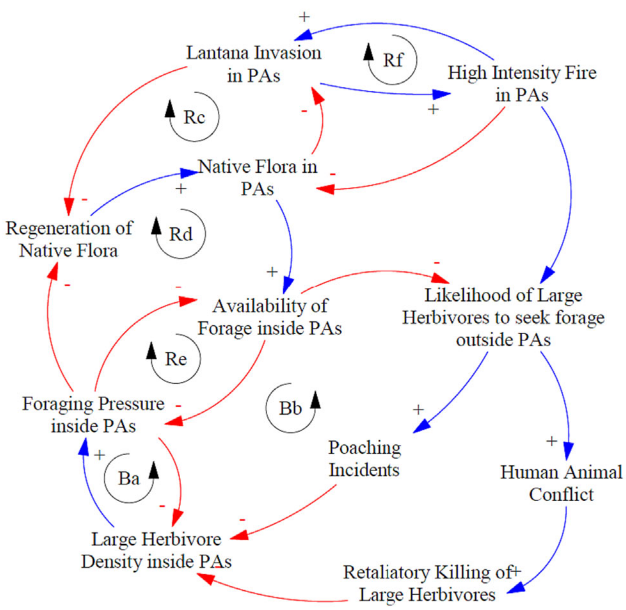

FIGURE 4 Relationship between *Lantana* invasion and human–animal conflicts. [Colour figure can be viewed at wileyonlinelibrary.com]

the population of herbivores and eventually on the carnivores (Figure 4). Also, one of the respondents opined that the dense growth of *Lantana* deters the herbivores from foraging in the invaded area, and thickets of *Lantana* restrict their mobility inside the PAs, affecting the tendency of large-herbivores to stay inside the PAs. Therefore, these large-herbivores prefer to raid the nearby farmlands despite vegetation availability in PAs, resulting in human–animal conflicts.[8] Various stakeholders note that the *Lantana* invasion led to wild herbivores, such as elephants foraging into the fringe farmlands, but no scientific evidence is available. However, the observation cannot be discounted as many respondents opined the same. These conflicts lead to the retaliatory killing of large herbivores observed in the fringe areas of the PAs. This movement of the large herbivores outside the PAs increases the likelihood of poaching incidents.

> *I worked on a human-wildlife conflict project. In many of our farmer interviews, they said that the conflict had increased because elephants do not have enough food inside the forest and come out to the farm fields. –*
> A *Lantana* Research Expert

These human-animal conflicts, coupled with biodiversity loss,[9] induce urgency in the park managers to address the problem of the *Lantana* invasion (Ranjan, 2019). However, the response to the problem is limited by resources such as funds, labour and knowledge. Legal provisions such as the Wildlife Protection Act deter park managers from taking necessary action. Therefore, they resort to ad hoc management efforts such as clearing densely invaded areas using large machinery to appease the stakeholders. Evidence from literature and observation suggests that these efforts are not fruitful as the *Lantana* invasion continues to date in the NBR region (Thekaekara, 2015, 2016).

The following sections discuss the system dynamics variables considering the *Lantana* management dilemmas the park managers face. The discussion revolves around three significant dilemmas identified in the study, viz., (i) dilemma of involving stakeholders, (ii) dilemma around alternate and commercial use of

[8]This is stated as a proposition based on anecdotal evidence from the observations made by the respondents.

[9]Other detrimental effects of *Lantana* such as degradation of soil and change in the forest structure are not discussed as the park managers currently do not consider these factors in taking a decision on *Lantana* management.

Lantana, and (iii) '*Lantana* management conundrum'. Apart from these dilemmas represented through causal loop diagrams, the section also discusses the underlying system archetypes.

3.4 | The dilemma of involving stakeholders in *Lantana* management

Literature in ecosystem management suggests that the involvement of stakeholders, such as indigenous community members, researchers and NGOs, in the early stages of invasion is fruitful in mitigating the problem of IAS (Shackleton et al., 2019). Formally involving stakeholders increases the accountability of the park managers, and therefore, the utilisation of resources becomes effective and efficient (Hahn, 2011), as depicted in the balancing loop Bc of Figure 5. The involvement of stakeholders also deters the corrupt and nepotistic practices of some of the Forest Department officials. Stakeholders can play various roles in *Lantana* management, such as watchdogs to monitor resource utilisation, provide support in technical know-how, and help organise funds (Jericó-Daminello et al., 2021).

It is to be noted that the influence and interests of the stakeholders in the problem of *Lantana* invasion are not the same. For instance, the influence of Forest Department officials in *Lantana* management in PAs of NBR will be greater than other stakeholders because of the legitimate responsibility. Likewise, the interest of NGOs, researchers and indigenous communities in matters concerning *Lantana* invasion is higher than other stakeholders, especially the indigenous communities whose livelihood is related to *Lantana* invasion. Tourism operators in the region may not be concerned about the presence of *Lantana* in the short run as more *Lantana* in the PAs means more wild animals on the road, resulting in good wildlife safari income. However, even the tourism operators in the region are also aware of the negative impacts of *Lantana* and want it to be controlled in the long run. The dilemma of involving stakeholders tries to explain the reason for low stakeholder engagement, despite the high interest among many stakeholders in managing *Lantana* invasions.

Interview data suggest stakeholders such as indigenous communities, local NGOs, local industries (who could potentially utilise *Lantana*) and research communities seem interested in contributing towards *Lantana* management in the PAs of the NBR. Stakeholders can play various roles in *Lantana* management, such as (a) indigenous communities can be a source of labour for *Lantana* management, (b) the local industries can consume *Lantana* removed from PAs for firing their boilers, (c) the researchers and NGOs can help in research and long-term monitoring, and (d) NGOs can also augment financial resources available for *Lantana* management.

However, there is a strong hesitancy among the park managers in the NBR region to involve stakeholders (Bhattacharya et al., 2010). The problem of the involvement of stakeholders is multi-dimensional. Involving stakeholders results in conflicts because of their varied interests in the issue of *Lantana*. For instance, tourism operators may want higher levels of *Lantana* invasion in the PAs of NBR so that the likelihood of wild-animal sightings increases on the accessible roads (Ranjan, 2019). However, local NGOs and research institutions may want *Lantana* removed from PAs.

Another cause of stakeholder conflicts could be the opportunistic behaviour of one or many stakeholders (Fleischman, 2014; Fleischman, 2016). These conflicts feed into the hesitancy of stakeholders' involvement. The

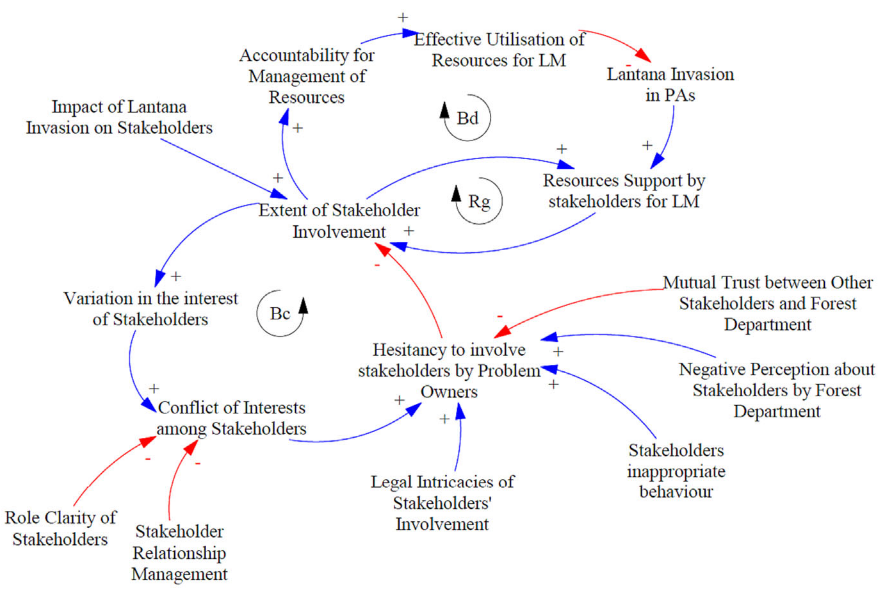

FIGURE 5 Causal loop diagram of stakeholder dynamics concerning *Lantana* management. [Colour figure can be viewed at wileyonlinelibrary.com]

conflict resolution theory suggests that the more conflicts in pursuing a task, the lesser the incentive for the owners to continue (Deutsch et al., 2011). Extending the argument to IAS management, the more conflicts in the context, approach and outcome of the IAS management efforts, the lesser the IAS management efforts will be.

The Wildlife Protection Act of 1972 restricts access to the forest by various stakeholders (Niraj et al., 2012); however, it does not outrightly oppose the involvement of stakeholders. Despite the willingness of the stakeholders proximal to PAs of the NBR to contribute to *Lantana* management, the risk-averse managers interpret ambiguity in the law against stakeholder involvement.

Park managers referred to isolated incidents where the members of indigenous communities (who legitimately access the forests enabled by the Forest Rights Act of 2006) are involved in poaching. Experts and other stakeholders opined that the trust between the park managers and other stakeholders is lacking, which is a deterrent to stakeholder involvement. The relationship between the stakeholder involvement and (accountability in *Lantana* management) intended consequence and conflict of interests and, thereby, hesitancy to involve stakeholders (unintended consequence) is reflected by the problem archetype, namely, the 'drifting the goal' archetype in Figure 6. In this archetypal depiction of system behaviour, the action to achieve the desired outcome is countered by the unintended system's reaction. In the context of *Lantana* management, the more the stakeholders are involved, the more accountability will be; however, the conflict of interest because of stakeholders' varied interests and influence will result in a hesitancy to include stakeholders.

A solution to the drifting goals archetypes is to have an absolute target of the desired outcome and constantly monitor the actual result. In the case of *Lantana* management, the policymakers must determine the stakeholders' target accountability level, and the actual accountability levels should be constantly monitored. The accountability levels are measured based on the process efficiency and effectiveness of the *Lantana* management. The accountability can also be calculated based on principles such as (a) transparency of resource utilisation, (b) fairness in the treatment of low-influence and impact stakeholders, (c) integrity in *Lantana* management decision-making, and (d) stakeholders' mutual trust. Apart from the target setting, the policymakers and the park managers can mitigate the conflicts by another closed-loop solution, viz., clarifying the role of all concerned stakeholders through implementing stakeholder relationship management practices, as depicted in Figure 6. Stakeholder relationship practices also improve trust, transparency and fairness among stakeholders. Adopting appropriate environmental governance paradigms and models is essential for enhancing stakeholder involvement (Rai et al., 2021).

3.5 | The dilemma of alternate and commercial use of *Lantana*

Lantana can be used for many purposes, such as a substitute for firewood, raw material for the furniture industry, and particleboard manufacturing, and it also has medicinal properties (Negi et al., 2019). The scale of *Lantana* use varies in different ventures such as the ones mentioned above. Expert interview respondents opined that the prospect of *Lantana* as firewood for the local tea, tobacco and textile industries is both scalable and continuous in demand. Cement-bonded *Lantana* particle boards seem to have better mechanical and chemical properties suitable for commercial usage (M. Ranjan et al., 2017). Furniture-making from *Lantana* has been successful in certain pockets of the NBR region. While the uses of *Lantana* for alternate and commercial

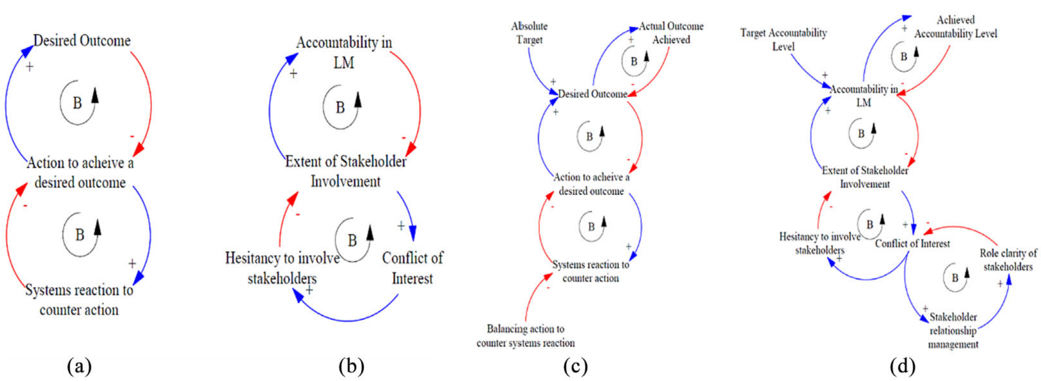

FIGURE 6 Drifting goals—problem and solution archetypes. (a) *Typical structure of drifting goals problem archetype;* (b) *Special case of drifting goals archetypes in Lantana management context;* (c) *Typical structure of drifting goals solution archetype;* (d) *Solution to drifting goals archetypes in Lantana management context.* [Colour figure can be viewed at wileyonlinelibrary.com]

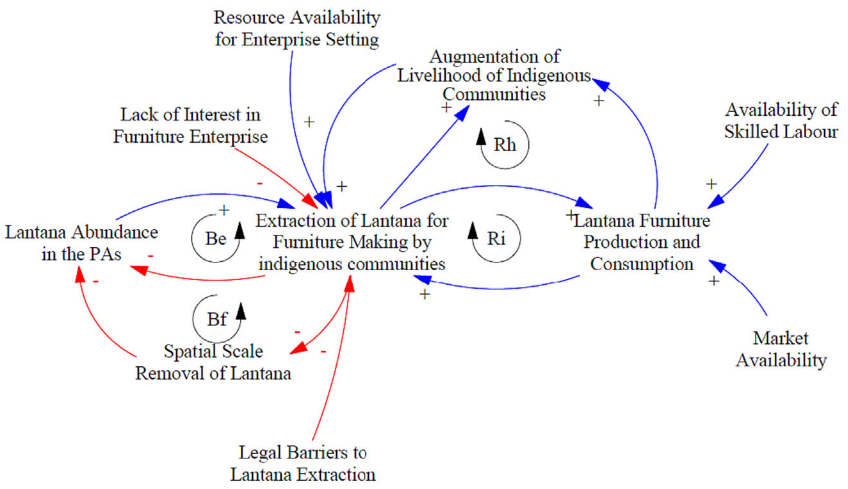

FIGURE 7 Causal loop diagram of Small scale *Lantana* furniture making and its dynamics. [Colour figure can be viewed at wileyonlinelibrary.com]

purposes are multifold, we have focussed only on using *Lantana* as firewood and raw material for furniture making. Other benefits of *Lantana* are yet to be established in the market, and their market potential is also unknown. It is underscored that we discuss the valorisation potential of *Lantana* harvested only from PAs.

3.5.1 | Alternate use of *Lantana*—*Lantana* furniture making

Lantana wood can substitute bamboo in furniture making (Kannan et al., 2014; Negi et al., 2019). ATREE, a research cum non-governmental organisation, along with the indigenous communities of Male Mahadeshwara Hills (MM Hills) in Karnataka, pioneered the hand-made furniture industry based on *Lantana* (Bawa et al., 2007). The industry has improved the livelihood of the indigenous communities in that area (Bawa et al., 2007). Copying the scheme's success, various Forest Departments, including Mudumalai Tiger Reserve and Sathyamangalam Tiger Reserve, have proposed these initiatives in their working plans.

The indigenous communities residing inside forests or on the fringes are encouraged to carry out *Lantana*-based enterprises through village forest committees or eco-development committees. This observation is also corroborated during the interview; the park managers revealed that their department intends to initiate/already initiated furniture making using *Lantana* in their respective PAs. In some PAs, this is the only initiative proposed apart from the ad hoc removal of *Lantana*. Various media outlets and articles have covered this initiative by various forest departments of the NBR region (Balasubramanian, 2018; Negi et al., 2019).

While this solution seems versatile and can solve the dual purpose of *Lantana* removal and provide livelihood benefits to the indigenous communities, the scalability and continuity of these initiatives are still a concern (Figure 7). Kannan et al. (2016) observed that *Lantana* availability in the PAs is far too much that the local furniture production may not check *Lantana* invasion at a landscape scale. Also, the roots of *Lantana* are not a valuable raw material source for furniture making (although they could be used as a source for heating water that treats *Lantana* wood); hence, the communities may resort to coppicing of *Lantana* rather than killing the plant.

However, it is observed that coppicing of the primary stem of the *Lantana* plant in wet seasons kills the plant (Kannan et al., 2016). The scale of the *Lantana* invasion in the NBR region is so high that involving more members of indigenous communities may become inevitable. Involving more members of indigenous communities may also lead to the problem of dependency on *Lantana* for their livelihood (this phenomenon is discussed in detail in the next section under substitution rebound archetype), and members may not have the incentive to kill *Lantana* plants.

On the contrary, interview respondents observed challenges in the availability of skilled labourers in the indigenous communities and the (lack of) interest of indigenous community people to start and own an enterprise.[10] Given such a scenario, the likelihood of *Lantana* furniture-making enterprises creating dependency among the members of indigenous communities is less. Hence, the problem with *Lantana* furniture making is the scalability and continuity.

[10]Multiple explanations are possible for such an observation such as cultural upbringing and disbelief in the scheme. However, it requires a separate social study to understand the behaviour exhibited by the members of the indigenous communities.

> *Adivasis [indigenous communities] are incapable [to be read as uninterested] of running an enterprise at scale themselves.* –
> An anonymous respondent

Also, the support provided by the forest department and other NGOs is not sustainable enough to consolidate the industry, opined a respondent. On the demand side, the penetration of *Lantana* furniture in the open market is a concern.

> *[On why the lantana furniture industry is not continued] They cannot find a market for many reasons, but the product was good. However, they cannot find a market. So I think it just went off.* –
> A Coordinator of an NGO

Despite efforts by various community and conservation NGOs in the area, the *Lantana* furniture is not yet widespread. One of the reasons for the non-adoption is that *Lantana* furniture is costlier than machine-manufactured wood and bamboo products if the indigenous communities were paid fair wages,[11] resulting in poor demand. Given such a scenario, the proposition of such a solution will only delay the 'actual solution' needed to mitigate the problem of *Lantana*. This situation is typically depicted as a 'shifting the burden' archetype. In this archetype, the policymaker attempts a symptomatic solution that will only delay the fundamental solution, aggravating the problem (Kim & Burchill, 1992; Wolstenholme, 2003). The study proposes a slightly modified variant of the 'shifting the burden archetype' (Figure 8), where a low-hanging, beneficial solution is pursued. This pursuit will delay effective action, resulting in aggravation of the problem. While the furniture-making industry can operate as a source of livelihood for the indigenous communities, it may not be a winning strategy for the park managers against the problem of the *Lantana* invasion in PAs.

A solution to the 'modified shifting the burden' archetype emphasises the relationship between landscape-scale *Lantana* removal and invasion in the PAs (Wolstenholme, 2003). The 'solution link' connecting the problem system and the fundamental solution, as depicted in Figure 8, is the closed-loop solution that creates awareness among the stakeholders.

However, it is to be understood that awareness about the relationship already exists in the context of *Lantana* management. The interview respondents were aware that furniture making might augment the livelihood of indigenous communities but not reduce the impact of *Lantana* invasions in the PA. The literature also corroborates this observation (Kannan et al., 2016). The utilisation of IAS need not always result in control of IAS. However, utilisation can be part of an integrative management strategy. Park managers and other stakeholders (such as NGOs) may have to constantly monitor the process of valorisation to keep a check on the corrupt and other opportunistic practices of individuals.

An intervention that propels a fundamental solution is needed in such scenarios. In this context, the primary solution is 'landscape-scale *Lantana* removal or targeted control in priority sites', which can be augmented by providing more resources to *Lantana* management, opined the respondents. However, landscape-scale removal of *Lantana* as a fundamental solution is also debatable. Given the likelihood of recurrent invasions, the resources required for landscape-scale removal may be too high even to attempt landscape-scale removal but not impossible. Financial resources for *Lantana* removal can be arranged through (a) commercialisation of *Lantana* as a resource and (b) budgetary allocations, whereas non-monetary resources are obtained through stakeholder involvement. This brings out the significance of the previously discussed drifting goals archetype.

3.5.2 | Commercial use of *Lantana*—Large-scale industrial use

Many respondents suggested that heavy funding would be required to check the substantial growth and spread of *Lantana* in the PAs, as substantiated in the literature (Mungi et al., 2020). The Government of India alone cannot provide the required financial resources. The fund availability and disbursal for *Lantana* management may not be sufficient for landscape-scale removal unless the PA managers decide to do only targeted control of *Lantana*, where the biodiversity of the PAs is protected only in specific priority sites. *Lantana* has large-scale commercial uses such as fuel wood, briquettes and medicinal uses (Negi et al., 2019).

Given such a situation, many stakeholders, including the park managers, propose commercialising and using *Lantana* from protected areas. *'If you cannot eliminate it, why cannot you use it'* argued a *Lantana* researcher. Given the scale of the *Lantana* invasion in the PAs and the difficulty of managers in organising resources because of multiple priorities, the need for involvement of private–public partnerships may be warranted for a few years. It should be noted that the private player involved in *Lantana* harvesting may not be interested in

[11]Wages may range anywhere between INR 400 and INR 600 (US$7–$9) per day.

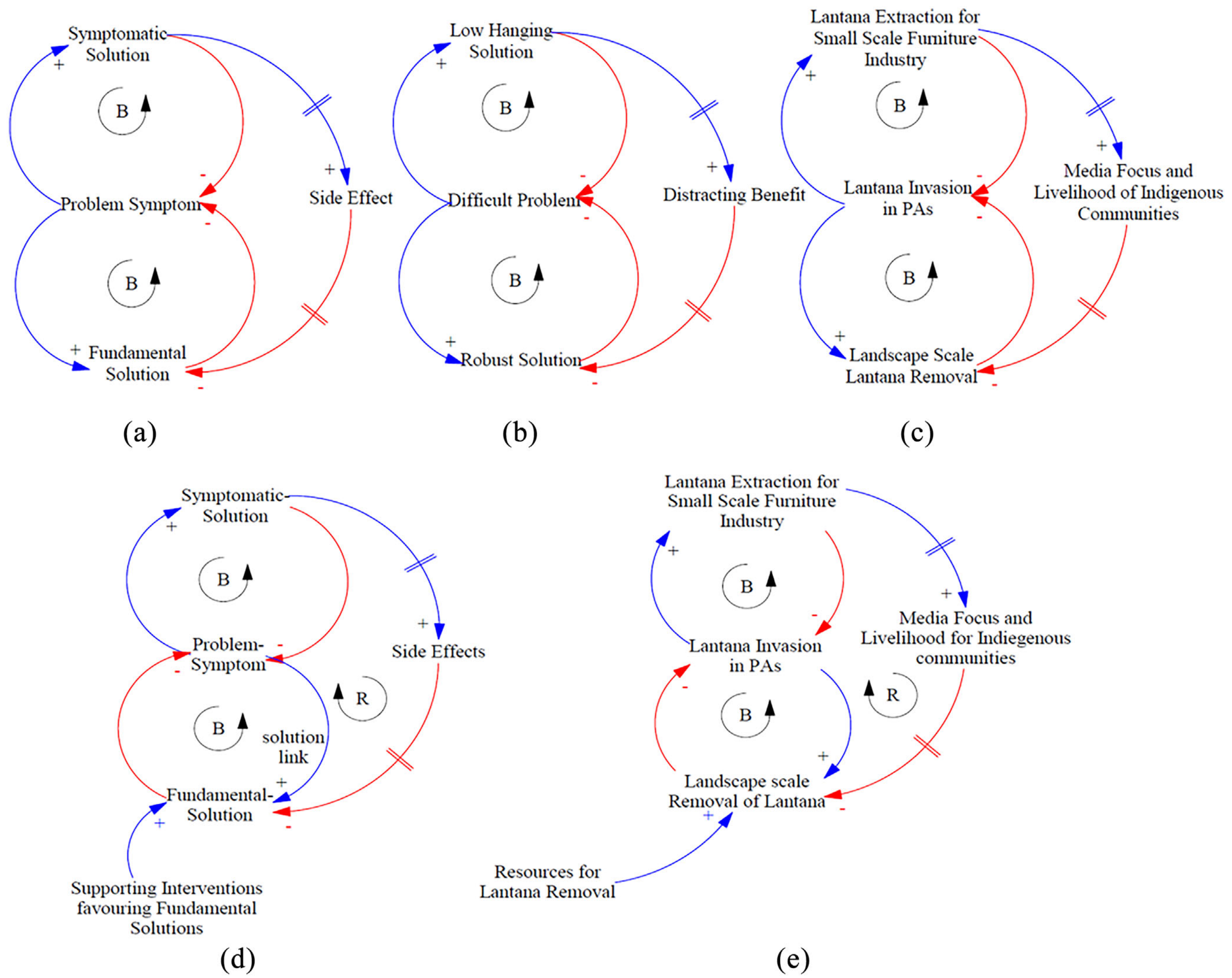

FIGURE 8 Shifting the burden—problem and solution archetypes. (a)*Typical structure of shifting the burden problem archetype;* (b) *Modified shifting the burden problem archetype;* (c) *Special case of shifting the burden archetype in Lantana management context;* (d) *Typical structure of shifting the burden solution archetype;* (e) *Solution to shifting the burden archetype in Lantana management context.* [Colour figure can be viewed at wileyonlinelibrary.com]

controlling the growth and spread of *Lantana*. Hence, the park managers may have to take the additional role of monitoring the harvesting process. Monitoring prevents the native plants from being damaged and also prevents mere coppicing of *Lantana* plants. Unless the park managers and policymakers decide on clear-cut policies, plans and performance metrics, involving private players is more detrimental than beneficial. The dynamics of commercialisation are represented in Figure 9.

However, in the current legal environment surrounding *Lantana* management in India, it is unclear whether the commercialisation of *Lantana* and the involvement of private enterprises are possible. The NBR's PAs can be classified into wildlife sanctuaries, tiger reserves, national parks and reserve forests. Each of the PAs has different legal mandates, jurisdictional consensus and barriers to overcome that may impact the possibility of commercialisation. For instance, the laws in national parks and tiger reserves regarding the commercial consumption of forest resources are stricter. A clear policy directive on the employment of stakeholders and private partnerships in *Lantana* management supported by an appropriate amendment in the legislation, such as the Wildlife Protection Act, may be needed to move in this direction.

Furthermore, the policy framework must be incentive-cum-regulation based rather than just regulatory, as it is currently. Even if the policies and laws favouring commercialisation are developed, many factors affect the adoption of *Lantana* as firewood, such as a (a) the need for change in the boiler/kiln design, (b) the bulk density of *Lantana* is low, and, therefore, the

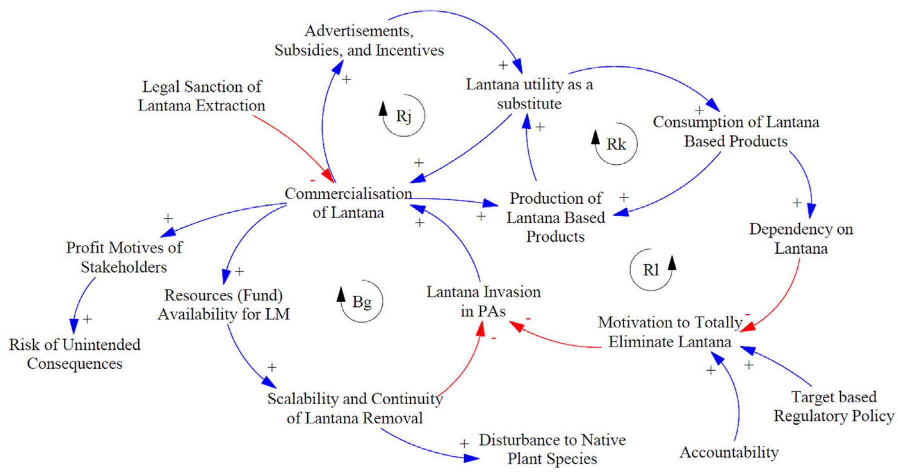

FIGURE 9 Dynamics of Commercialisation of *Lantana* from PAs. [Colour figure can be viewed at wileyonlinelibrary.com]

transportation is costlier, (c) the attractiveness of the substitute (e.g. *Prosopis juliflora*), (d) fire hazard of dry *Lantana* in the PAs before being transported, and (e) the commercial and technical feasibility of *Lantana* use.

One of the respondents from the NGO suggested that *Lantana* firewood would be around 20% costlier because of its lower bulk density and resulting higher transportation cost than its alternative despite the geographical proximity of the *Lantana* vis-à-vis the *Prosopis*. In such a scenario, the market adoption of *Lantana* as a source of firewood may not be encouraging. Another option proposed for the transportation problem of *Lantana* is to mulch it before being transported; however, the mulching process may create unnecessary commercial activity near the eco-sensitive zone and result in undesirable consequences. Some respondents called for initial subsidies and incentives to encourage *Lantana* from PAs as firewood.

> *Lantana is not competitive from a cost perspective; it has to be only subsidised fuel, which is good [to be read as desirable], right? There is no risk of people growing lantana to provide energy for textile mills and other industries.* –
> *A senior manager of an NGO operating in the region.*

Subsidies and incentives may encourage more takers to offset the excess movement cost from the substitute to *Lantana* firewood. They were also optimistic that *Lantana*'s large-scale use might eliminate the need for subsidy in the long run because of economies of scale. This is also the case with the *Lantana* furniture industry, which may become economical if operated on a larger scale. The economic viability, in turn, will attract more private interests.

> *Because there is no cost to the lantana itself, it is only the cost of extraction. So the higher the scale of extraction, the cheaper you can make it … if you are going to do it on a large, larger scale, it is possible to bring down [the cost]* –
> *A manager from an NGO operating in the region.*

Some researchers argue that the neoliberal environmentality paradigm of commercialising natural resources such as *Lantana* dissuades community participation (Anand & Mulyani, 2020), except for certain influential NGOs and private players. This decentralisation approach, albeit effective, gives more control to corporations, which may prioritise profit over local stakeholder interests (Barnes et al., 2017). Some respondents are also apprehensive about the large-scale commercialisation of *Lantana* as it would create dependency on it in the long run, and, therefore, the profit-making interest may dominate the will to eliminate *Lantana*. They suggested that *Lantana* must be made as useless as possible to prevent it from creating dependency.

> *Do not allow lantana or any invasive species to threaten the landscape; do not use it. Make it completely useless. Only then will people not grow it or see it completely eradicated.* –
> A Co-founder of a Local NGO (NGO_008)

History is replete with examples where commercialising any resource without regulatory support has been exploited for profit. The respondents discussed the instance of *P. juliflora* becoming invasive in the arid regions of western and southern India. Now, *P. juliflora* consumers are not interested in eliminating it despite knowing the detrimental effects. The commercialisation of *Acacia mearnsii* is another example that resulted in the establishment of companies that harvested tannin barks from Indian forests to reduce reliance on the import of tannin barks from South Africa because of trade suspension. But once the trade suspension was revoked, the demand for the Indian tannin barks dwindled, and as a result, the invasion of *A. mearnsii* aggravated in Nilgiri Hills and Palni Hills of India (Kull et al., 2011; Tassin et al., 2012). The apprehension of the respondents concerning the commercialisation of *Lantana* is, therefore, not unfounded.

This apprehension can be explained by a special case of the 'out of control' archetype, which the study calls the 'substitution rebound archetype' (Figure 10). The archetype signifies that 'when the problem becomes a solution, the solution rebounds to become a problem after a delay'. However, in *Lantana*'s case, the likelihood that its substitution with the existing option may rebound or not is determined by *Lantana*'s attractiveness. Given the availability of cheaper alternatives such as *P. juliflora* and other hydrocarbon-based fuels, the *Lantana* may not be attractive. There may be market acceptance of *Lantana* with a subsidy, but how long can the subsidy be offered? Will *Lantana* products become attractive to the market in terms of cost vis-a-vis *P. juliflora* when operated on a large scale? Will the *Lantana* industry be attractive for private investments? These questions determine whether *Lantana* substitution may rebound to create dependency.

Even if using *Lantana* creates dependency, respondents also opine that *Lantana* invasion is a concern in the PAs; it can be so that the *Lantana* be eliminated from PAs, and if the industry wishes to cultivate *Lantana*, it can do so in non-PAs. While this argument is accepted, the park managers may have to manage *Lantana* in the PAs longer (maybe perpetually) because of boundary permeability problems, as dispersers are boundary agnostic and may carry *Lantana* seeds back into the PAs from non-PAs.

The solution for the special case of the 'substitution rebound archetype' is to uncover the relationship between excess availability and the production of the problematic resource. However, in the context of *Lantana* management, it is already known that the commercialisation of *Lantana* on a large scale may create dependency, and therefore, willingness to eliminate *Lantana* in the PAs may be lower. The respondents proposed a multi-pronged approach to *Lantana* management given the condition of commercialisation (large-scale commercial use) of *Lantana*, namely, (a) legislative and policy support controlling the use of *Lantana* as a commercial

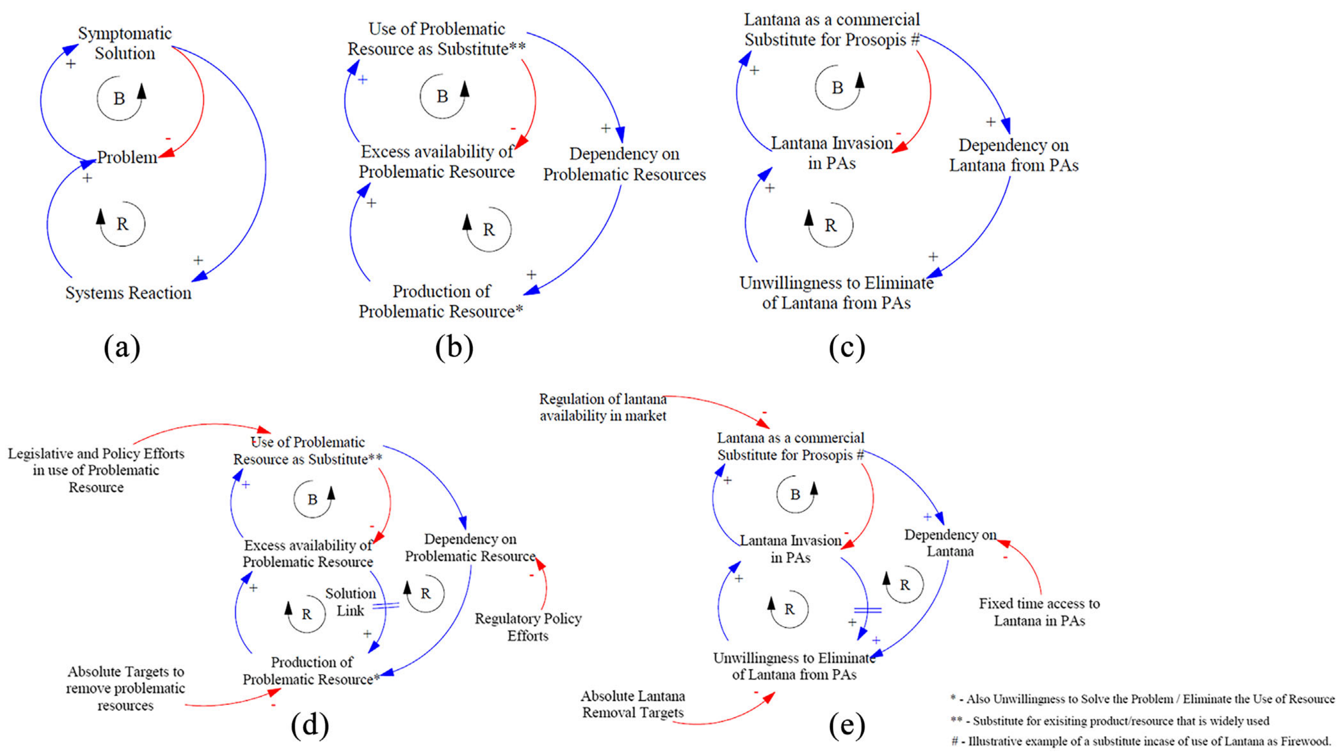

FIGURE 10 Substitution rebound—problem and solution archetypes. (a) *Typical structure of out of control problem archetype;* (b) *Substitution rebound problem archetype;* (c) *Special case of substitution rebound archetypes in Lantana management context;* (d) *Typical structure of out of control solution archetype;* (e) *Solution to substitution rebound archetype in lantana management context.* [Colour figure can be viewed at wileyonlinelibrary.com]

substitute to *P. juliflora*,[12] (b) regulatory policy support and (c) fixation of absolute *Lantana* removal target to manage *Lantana*. Figure 10 represents the solution to the substitution rebound archetype.

Firstly, to control the widespread use of *Lantana* in the commercial market, restrictions on openly selling *Lantana* in the market may be introduced as and when required. A restriction shall be placed on the commercial use of *Lantana* only from the PAs authorised by the policymakers and park managers. This restriction can stop the cultivation of *Lantana* even outside the PAs, addressing the dispersion problems. Secondly, to control the dependency on *Lantana*, the managers can restrict the commercial availability of the *Lantana* only for a few years (hard stop), irrespective of the success or failure of the *Lantana* removal efforts. Thirdly, having an absolute target to remove *Lantana*, such as '40% of the stipulated area to be *Lantana* free within the next 5 years', can be useful in mitigating the unwillingness to eliminate *Lantana* from the PAs.

3.6 | The *Lantana* management conundrum

The forest department officials face three dilemmas linked to each other. First, given the limited availability of resources, should they focus on protecting species such as tigers and elephants or managing the habitat? This observation may look contradictory because conserving the habitat is vital to conserve the species inside it. However, the current dispensation of the Forest Department in India is a protectionist paradigm where poaching of species or illegal lumbering is a primary concern than habitat management. Given the heavy workload of the officials and the scarcity of monetary and non-monetary resources, they tend to focus more on protectionism than on habitat management. The lack of a dedicated division for research and habitat conservation activities in each PA indicates a lower priority.

Many interview respondents opined that a species protection focus would be one of the deterrents to comprehensive *Lantana* management. While the park managers know that a species protection focus is ineffective and can be counter-intuitive in the long run, they are forced to carry it out because of pressures from the ministry and media. 'A tiger dying is a more important problem than a lantana invasion in the forest, which will eventually kill (endanger) the tiger', expressed a respondent.

> *The politicians … are more interested in poaching; a tiger was killed, Elephant was electrocuted, and a tiger attacked a local farmer. It is all related to direct conflict. Nothing has to do with habitat.* –
>
> A lantana Research Expert

Similarly, the media and ministry pressure to remove *Lantana* in large-scale fires will propel the park managers to make ad hoc management efforts. While the ministry and the media pressure is a constant on the managers, the underlying dynamics are not generally visible to the stakeholders. No clear-cut policies and directives guide the managers in general *Lantana* management. The constant pressure on the workforce and the highly bureaucratic and restrictive legal environment deters park managers from taking *Lantana* management initiatives (Torugsa & Arundel, 2017).

Park managers are typically posted in a location for three years, and their answerability is only up to when they are posted there, whereas *Lantana* management activities may have to run for more extended periods. Therefore, the officers tend to maintain the status quo and not take any new initiatives. In certain PAs of the NBR, the continuity of habitat management efforts is ensured, at least on paper, through site-specific plans. However, given the complex nature of the *Lantana* problem, the park managers need more structured solutions, which are currently not evident.

Secondly, park managers face the scale dilemma; should they eradicate *Lantana* from PAs or do targeted control? While complete eradication of *Lantana* is the most desirable option, it may not be feasible because of resource constraints. Targeted management may involve the protection of priority sites identified based on a scientific understanding of the utility of such sites. For instance, the purpose of targeted control has to be clearly defined, such as *Lantana* control to provide (i) access to water holes for wild animals and (ii) suitable niches for certain keystone/flagship species.

Ecosystem management is complex, and the interactions of the entities are almost inconceivable; therefore, one wrong move may be detrimental to the entire ecosystem (DeFries & Nagendra, 2017; Dronova, 2019). Thus, robust scientific inputs are required to perform targeted control. However, no such strategies have been adopted in controlling *Lantana* in the PAs of NBR. Park managers perceive the nature of the problem of *Lantana* as a catch-22 problem with high risk and low return, demotivating

[12]It is to be noted that *Lantana* as a substitute for *Prosopis* spp. is one of its many commercial uses such as particle boards and briquettes. The causal loop diagram model considers the example of *Prosopis* spp. to explain the dynamics of commercialisation and does not comprehensively represent all potential commercial use of *Lantana*.

any potential actions. However, inaction is not a solution for them because of the pressure from the media and ministry pushing them towards the next easiest option, ad hoc management.

Thirdly, park managers face a methodological quandary. The beginning of the *Lantana* invasion in the NBR region dates almost a century ago; however, there still exists confusion in managing the problem of *Lantana* in terms of methods, procedures and stakeholder involvement in India. There are uncertainties around the outcome of *Lantana* management. There is exhaustive literature detailing various control measures of *Lantana*, such as (i) classical biological control (Katembo et al., 2020; Simelane et al., 2021), (ii) chemical control (Erasmus & Clayton, 1992; Graaff, 1986; Swarbrick et al., 1995), (iii) mechanical control, (iv) manual labour, (v) working animal and (vi) indigenous burning practices (Sundaram et al., 2012; Thekaekara et al., 2017).[13]

However, the respondents opined that biological and chemical control of *Lantana* in the PAs is generally dissuaded in the NBR's PAs because of the perceived risk of such interventions. Evidence from the literature corroborates this observation (Bhagwat et al., 2012). Traditional knowledge that includes indigenous burning practices is also not entirely recognised by the park managers, complicating the problem. Park managers in NBR PAs either use the manual (machete and gudali, an indigenous short-hand tool) or machinery (excavators and bulldozers) mode of *Lantana* removal. From the author's observation working in NBR PAs, the cost of manually clearing 1 ha of *Lantana* could be around INR 20,000 (USD 240)–INR 60,000 (USD 720),[14] depending on the density of the *Lantana*. The machinery mode would cost about INR 15,000 (USD 180) per hectare (Mungi et al., 2020).

The manual method of *Lantana* removal is time-consuming and may not be a suitable choice for landscape-scale removal. Given limited resources, park managers use large machinery to clear *Lantana*. The respondents of the interview, especially the experts and the researchers, opined that the large machinery usage for *Lantana* management is detrimental to the ecosystem. Large machinery use results in the systemic reaction of 'disturbance of canopy and soil', exposing buried *Lantana* seeds and, eventually, *Lantana* invasions in the PAs (Bhutia et al., 2021).

> *You want to get rid of lantana, that is right, but you cannot use big machines, and these are all biodiversity hotspots; that will have [do] much damage to the forest. I do not recommend that at all. –*
>
> An lantana research expert working in the NBR region

The relationship or interconnectedness of these three dilemmas discussed in this section is captured in the causal loop diagram represented in Figure 11. The figure explains the interconnectedness of the problem of choice of methods, choice of strategies (scalability), and resource allocation dilemma.

While it is understandable that using large machinery in certain terrains is unavoidable, it can be avoided in other landscapes considering their undesired consequences. The special case of the 'out-of-control' archetype, the 'fixes that fail archetype', captures large machinery use and its corresponding systemic reaction. Figure 12 represents the generic 'fixes-that-fail' archetype[15] and the contextual application in *Lantana* management.

The fixes that fail archetype, a special case of the 'out-of-control' archetype, depicts the scenario where the intervention to a problem does not solve it but aggravates it. In the context of *Lantana* management, the issue of *Lantana* invasion can be mitigated by (a) awareness of the detrimental effects of large machinery use and (b) regulatory and policy efforts that control the use of large machinery and provision of resources support for *Lantana* management. Figure 12 represents the solution archetype for the problem archetype.

4 | DISCUSSION

'All models are wrong, but some are useful' (Box & Draper, 1987, p.424). The models depicting the interactions of *Lantana* within the PA ecosystem in the NBR, and the corresponding anthropogenic interventions, are not comprehensive but can meaningfully represent the dynamics of the problem. Models capturing all details of real-world phenomena will be far too complex to be valid. Qualitative causal loop diagrams are advantageous in identifying dynamic hypotheses depicted through balancing and reinforcing loops. Table S3 consolidates the dynamic hypotheses identified in the study. The

[13]These are not discussed in detail in this paper as the scope is restricted to administrative, legal and political issues concerning *Lantana* management.

[14]INR – Indian Rupee; USD – United States Dollar.

[15]The authors intend to use this archetypal representation only for machinery-based *Lantana* removal and not other modes of control such as biological or chemical controls because of lack of evidence of unintended consequences of these control measures in Indian context.

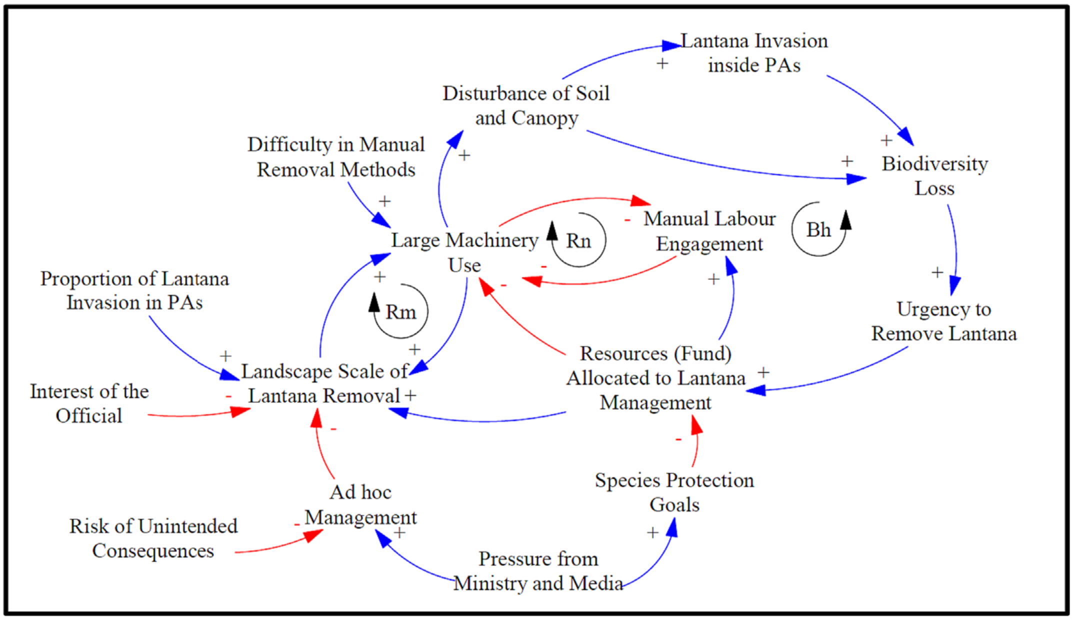

FIGURE 11 The *Lantana* management conundrum. [Colour figure can be viewed at wileyonlinelibrary.com]

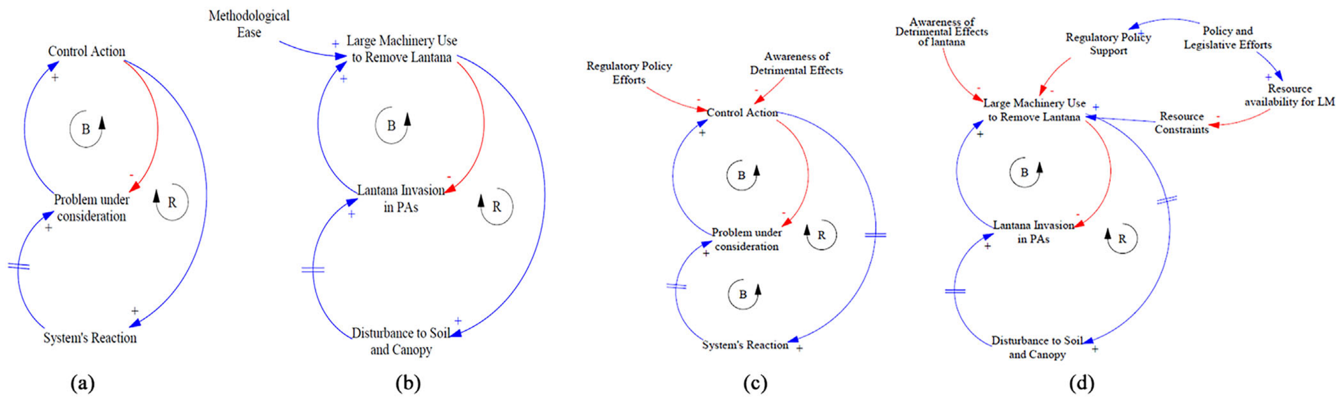

FIGURE 12 Substitution rebound—Problem and solution archetypes. (a) *Typical structure of fixes that fail problem archetype;* (b) *Special case of fixes that fail archetype in Lantana management context;* (c) *Typical structure of fixes that fail solution archetype;* (d) *Solution to fixes that fail archetype in Lantana management context.* [Colour figure can be viewed at wileyonlinelibrary.com]

qualitative causal loop diagrams can be used (a) as a base for quantitative simulations (stock and flow models) and (b) to devise strategies based on dynamic hypotheses as depicted in the problem archetypes.

The dilemmas surrounding the *Lantana* management are captured by the causal loop diagrams, although represented in silos, and are interconnected. For instance, the dilemma of involving stakeholders connects to the dilemma of commercial use; without stakeholders being involved, the consumption of *Lantana* harvested from PAs shall not be possible. However, given the legal ambiguities, the involvement of stakeholders is arbitrary in the PAs of the NBR. Currently, only the indigenous communities are involved on an ad hoc basis as labourers in *Lantana* removal. One of the primary reasons for such poor stakeholder involvement and relationship is the protectionist paradigm or the sovereign environmentality paradigm followed by the policymakers and the park managers (Anand & Mulyani, 2020).

The park managers are forced to take a myopic view, in which forests are reduced to resource tanks and need to be protected from everybody else. This view discounts all relationships between forest ecosystems and human beings. Recent literature suggests that the fortress model based on the sovereign environmentality paradigm is not yielding favourable results (Fletcher et al., 2021). A separate study is warranted to understand an appropriate environmental governance paradigm for managing *Lantana* and other invasive alien species. Unless a suitable change in the governance paradigm is adopted, stakeholder involvement may not be possible. The governance paradigm is also crucial as it guides policy and plan development, the lack of which is another point of concern in managing *Lantana*.

The lack of policies impacts not only stakeholder involvement but also the development of the IAS management strategy. Unfortunately, no other policies are available except for the policy on *Lantana* by the Himachal Pradesh Forest Department, especially in the NBR. A policy document could be site-specific, species-specific, or both. A good start would be focussing on the high-concern-invasive species (HiCIS), which also enlists *Lantana* (Mungi et al., 2019). Policy documents shall guide the park managers in developing specific IAS management strategies by providing guidance (not limited to) on the role of stakeholders, valorisation schemes, method of IAS management, management approach and nature of monitoring. These policies could translate into decadal National Invasive Species Strategies and Action Plans (NISSAP), which the Convention on Biological Diversity (CBD) encourages.

The stakeholder involvement need not be ad hoc and limited to 'labour and knowledge support' but 'continuous and strategic'. For instance, the limited human resources of the park managers can be supplemented with support from indigenous community members. They can be a part of the regular monitoring of IASs in the PAs, which must be an integral part of the early detection and rapid response (EDRR) strategy. Other stakeholders, such as NGOs and research institutions, can also be involved in the monitoring programme. Unfortunately, EDRR protocols are not strictly followed in the NBR PAs for unknown reasons. EDRR monitoring shall be effective if employed in the least invaded and uninvaded parts of the PAs of the NBR, as it could save monetary resources.

Another problem with IAS management is the uncertainty of the outcomes of any intervention. These uncertainties are more pronounced in the *Lantana* management problem in the PAs of the NBR because of its wickedness. There are also uncertainties concerning the appropriate method of *Lantana* removal. Section 3.1.6 discusses the quandary surrounding *Lantana* management. Each intervention is a one-shot operation, and the outcome may become irreversible. Under such uncertainties, a fixed plan to manage *Lantana* may not be fruitful. Researchers argue that the adaptive management approach, which encourages 'learning by doing', is best suited in cases such as *Lantana* management that involve complex dynamics (Bhagwat et al., 2012; DeFries & Nagendra, 2017). However, inflexible policies and plans and bureaucratic environments may hinder the implementation of an adaptive management approach. Centralised decision-making approaches typically followed in India's PAs may not be conducive to adaptive management, which calls for quick decentralised decision-making.

Landscape-scale removal requires (a) extensive resources, (b) native species seed banks to restore the removed area, (c) commitment to *Lantana* management for at least a decade and (d) an unintended consequences management plan. Landscape-scale removal using large machinery may harm the ecosystem, as discussed in Section 3.1.6. Hence, to cater to the monetary requirements of manual *Lantana* removal methods, the valorisation of *Lantana* biomass in the PAs can be introduced strictly temporarily as an 'integrative management strategy', Care should be taken that the valorisation of *Lantana* cannot be independent of *Lantana* management. A conservation network model involving other stakeholders, such as NGOs, media, and research institutions, could improve the accountability of *Lantana* management activities (Anand & Mulyani, 2020).

Despite landscape-scale removal of *Lantana*, park managers may still have to grapple with boundary permeability problems as the movement of dispersers of *Lantana* between PAs and non-PAs cannot be controlled. Expert respondents opined that the total eradication of *Lantana* from peninsular India (including the PAs of the NBR) in the near future might not be possible because of the scale of the invasion. Therefore, it may be prudent to do targeted control of priority sites using a phased management plan (Ramaswami et al., 2014).

A phased management plan involves (i) identifying and prioritising habitats requiring management of IAS, (ii) long-term monitoring and managing of the identified site scaled to ecological processes timeframe (a minimum of 5–10 years) and (iii) enlarging the priority site in a phased manner over time such that the likelihood of dispersals of IAS seeds from the surrounding invaded areas is lesser (Ramaswami et al., 2014). However, the political boundaries of the forests (Tamil Nadu, Kerala and Karnataka) may interfere with identifying appropriate priority sites. Hence, a federal-level policy facilitating the interactions is necessary. More success of targeted *Lantana* control (phased management plans), in terms of regeneration of native species in the previously invaded area, may motivate policymakers and other stakeholders to clear larger areas.

5 | CONCLUSION

This study has been performed to address the research question: Despite the seriousness of the issue of *Lantana* invasion in the region, why are there no concerted efforts taken by the park managers to manage *Lantana*? This study used 'wicked problems' and 'systems theory' as theoretical underpinnings to understand the phenomenon. The study has used the primary interview data from the field and thematic analysis that identified the dilemmas inhibiting the stakeholders, especially the Forest Department officials and Conservation NGOs, from acting on invasion. These dilemmas are used to develop qualitative system dynamics models to represent interrelationships among relevant variables concerning *Lantana* management visually.

The study's importance lies in identifying recurring system behavioural patterns depicted as system archetypes with theoretical and practical implications. Theoretically, archetypal patterns explain and predict system behaviours and are generalisable in other contexts and problems. For instance, 'the substitution rebound archetype', a novel archetype we proposed in this study, can be extended to other applications such as the 'use of plastics for laying roads', which will demotivate efforts to reduce plastic production. Other archetypes found in this study support the explanations of existing theoretical system archetypes. These archetypes could point to similar problem behaviours in different ecosystem management contexts.

The study also points to the need for a policy for IAS management (including *Lantana* management) and a shift in the environmental governance models that allow the valorisation of IAS. The causal loop diagrams identified in the study give practitioners an overview of the interrelationship of factors concerning *Lantana* management. The proposed solutions, such as (see Sections 3 and 4) in this study, guide policymakers and park managers to manage IAS better. In future, the archetypal patterns identified in the study can be quantitatively validated using system dynamics simulation. The effectiveness and efficiency of phased management plans, and adaptive management approaches can be studied using action research methodology. In essence, the complexity of *Lantana* management within PAs necessitates a nuanced approach, urging for a paradigm shift in governance model, adaptive management strategies, strategic stakeholder involvement, clear IAS management policies, and phased management plans to address dilemmas and the intricate challenges posed by IAS.

ORCID

Thangatur Sukumar Hariharan https://orcid.org/0000-0001-8361-3352
Piyush Sharma https://orcid.org/0000-0002-6953-3652
Vidyasagar Potdar https://orcid.org/0000-0002-7292-5462

REFERENCES

Alvarez, S., & Solís, D. (2018). Rapid response lowers eradication costs of invasive species: Evidence from Florida. *Choices*, *33*(4), 1–9.

Anand, M., & Mulyani, M. (2020). Advancing 'environmental subjectivity' in the realm of neoliberal forest governance: Conservation subject creation in the Lokkere Reserve Forest, India. *Geoforum*, *110*(March), 106–115. https://doi.org/10.1016/j.geoforum.2020.01.025

Auld, B. A., & Johnson, S. B. (2014). Invasive alien plant management. *CABI Reviews*, 1–12. https://doi.org/10.1079/PAVSNNR20149037

Balasubramanian, S. (2018, May 31). Tribal people in TN are making furniture out of an invasive plant which threatens environment. *The News Minute*. https://www.thenewsminute.com/article/tribal-people-tn-are-making-furniture-out-invasive-plant-which-threatens-environment-82277

Banson, K. E., Nguyen, N. C., & Bosch, O. J. H. (2016). Using system archetypes to identify drivers and barriers for sustainable agriculture in Africa: A case study in Ghana. *Systems Research and Behavioral Science*, *33*(1), 79–99. https://doi.org/10.1002/sres.2300

Barnes, C., Claus, R., Driessen, P., Santos, M. F. D., George, M. A., & Van Laerhoven, F. (2017). Uniting forest and livelihood outcomes? Analysing external actor interventions in sustainable livelihoods in a community forest management context. *Int J Commons*, *11*(1), 532–571. https://doi.org/10.18352/ijc.750

Baskaran, N., Varma, S., Sar, C. K., & Sukumar, R. (2011). Current status of Asian elephants in India. *Gajah*, *35*(1–2), 47–54.

Bawa, K. S., Joseph, G., & Setty, S. (2007). Poverty, biodiversity and institutions in forest-agriculture ecotones in the Western Ghats and Eastern Himalaya Ranges of India. *Agriculture, Ecosystems & Environment, Biodiversity in Agricultural Landscapes: Investing without Losing Interest*, *121*(3), 287–295. https://doi.org/10.1016/j.agee.2006.12.023

Bellard, C., Cassey, P., & Blackburn, T. M. (2016). Alien species as a driver of recent extinctions. *Biol Lett*, *12*(2), 20150623. https://doi.org/10.1098/rsbl.2015.0623

Bennett, B. M., & van Sittert, L. (2019). Historicising perceptions and the National Management Framework for invasive alien plants in South Africa. *J Environ Manage*, *229*(January), 174–181. https://doi.org/10.1016/j.jenvman.2018.07.029

Bhagwat, S. A., Breman, E., Thekaekara, T., Thornton, T. F., & Willis, K. J. (2012). A battle lost? Report on two centuries of invasion and management of *Lantana camara L.* in Australia, India and South Africa. *PLoS ONE*, *7*(3), e32407. https://doi.org/10.1371/journal.pone.0032407

Bhattacharya, P., Pradhan, L., & Yadav, G. (2010). Joint Forest Management in India: Experiences of two decades. *Resources, Conservation and Recycling*, *54*(8), 469–480. https://doi.org/10.1016/j.resconrec.2009.10.003

Bhutia, P., Kumar, M., & Khola, O. P. S. (2021). Control of lantana invasion in rangeland. *Agricultre & Food: E- Newsletter*, *3*(5), 362–364.

Box, G. E. P., & Draper, N. R. (1987). *Empirical model-building and response surfaces*. John Wiley & Sons.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qual Res Psychol*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Conklin, J. (2006). *Wicked problems & social complexity*. CogNexus Institute San Francisco.

Crowley, S. L., Hinchliffe, S., & McDonald, R. A. (2017). Conflict in invasive species management. *Front Ecol Environ*, *15*(3), 133–141. https://doi.org/10.1002/fee.1471

Day, Michael D., Wiley, Chris J., Playford, Julia, and Zalucki, Myron P. 2003. *Lantana: Current management status and future prospects*. Australian Centre for International Agricultural Research.

DeFries, R., & Nagendra, H. (2017). Ecosystem management as a wicked problem. *Science*, *356*(6335), 265–270. https://doi.org/10.1126/science.aal1950

Deutsch, M., Coleman, P. T., & Marcus, E. C. (2011). *The Handbook of Conflict Resolution: Theory and Practice*. John Wiley & Sons.

DHNS. (2019). Karnataka gets Rs 1,350 Cr green fund from centre. *Deccan Herald*. August 30, 2019. Retrieved May 3, 2022, from https://www.deccanherald.com/state/top-karnataka-stories/karnataka-gets-rs-1350-cr-green-fund-from-centre-758155.html

Dronova, I. (2019). Landscape beauty: A wicked problem in sustainable ecosystem management? *Sci Total Environ*, *688*(October), 584–591. https://doi.org/10.1016/j.scitotenv.2019.06.248

Erasmus, D. J., & Clayton, J. N. G. (1992). Towards costing chemical control of *Lantana camara L. South African Journal of Plant and Soil*, *9*(4), 206–210. https://doi.org/10.1080/02571862.1992.10634630

Fleischman, F. D. (2014). Why do foresters plant trees? Testing theories of bureaucratic decision-making in Central India. *World Dev*, *62*(October), 62–74. https://doi.org/10.1016/j.worlddev.2014.05.008

Fleischman, F. D. (2016). Understanding India's forest bureaucracy: A review. *Regional Environmental Change*, *16*(1), 153–165. https://doi.org/10.1007/s10113-015-0844-8

Fletcher, M. S., Hamilton, R., Dressler, W., & Palmer, L. (2021). Indigenous knowledge and the shackles of wilderness. *Proceedings of the National Academy of Sciences*, *118*(40), e2022218118. https://doi.org/10.1073/pnas.2022218118

Fritz, H., & Loison, A. (2006). Large herbivores across biomes. In J. Pastor, K. Danell, P. Duncan, & R. Bergström (Eds.), *Large herbivore ecology, ecosystem dynamics and conservation* (pp. 19–49). Cambridge University Press. https://doi.org/10.1017/CBO9780511617461.003

Graaff, J. L. (1986). *Lantana camara*, the plant and some methods for its control. *South African Forestry Journal*, *136*(1), 26–30. https://doi.org/10.1080/00382167.1986.9629625

Guha, R. (2001). The prehistory of community forestry in India. *Environmental History*, *6*(2), 213–238. https://doi.org/10.2307/3985085

Hahn, T. (2011). Self-organized governance networks for ecosystem management: Who is accountable? *Ecology and Society*, *16*(2), 1–19. https://www.jstor.org/stable/26268891

Harihar, A., Chanchani, P., Borah, J., Crouthers, R. J., Darman, Y., Gray, T. N. E., Mohamad, S., Rawson, B. M., Rayan, M. D., Roberts, J. L., Steinmetz, R., Sunarto, S., Widodo, F. A., Anwar, M., Bhatta, S. R., Chakravarthi, J. P. P., Chang, Y., Congdon, G., Dave, C., … Vattakaven, J. (2018). Recovery planning towards doubling wild Tiger Panthera Tigris numbers: Detailing 18 recovery sites from across the range. *PLoS ONE*, *13*(11), e0207114. https://doi.org/10.1371/journal.pone.0207114

Hariharan, T. S., Ganesh, L. S., Venkatraman, V., Sharma, P., & Potdar, V. (2022). Morphological analysis of general system–environment complexes: Representation and application. *Systems Research and Behavioral Science*, *39*(2), 218–240. https://doi.org/10.1002/sres.2794

Hiremath, A. J., & Sundaram, B. (2005). The fire-lantana cycle hypothesis in Indian forests. *Conservation and Society*, *3*(1), 26–42. https://www.jstor.org/stable/26396598

Hirschheim, R. A. (1983). Systems in OR: Reflections and analysis. *Journal of the Operational Research Society*, *34*(8), 813–818. https://doi.org/10.1057/jors.1983.175

Iyengar, A. V. V. (1933). The problem of the lantana. *Curr Sci*, *1*(9), 266–269.

Jericó-Daminello, C., Schröter, B., Mancilla Garcia, M., & Albert, C. (2021). Exploring perceptions of stakeholder roles in ecosystem services coproduction. *Ecosyst Serv*, *51*(October), 101353. https://doi.org/10.1016/j.ecoser.2021.101353

Jhala, Y. V. (1992). Biological invasion in the tropics. *Ecology*, *73*(4), 1522–1523. https://doi.org/10.2307/1940698

Kannan, R., Shackleton, C. M., Krishnan, S., & Uma Shaanker, R. (2016). Can local use assist in controlling invasive alien species in tropical forests? The case of *Lantana camara* in southern India. *For Ecol Manage*, *376*(September), 166–173. https://doi.org/10.1016/j.foreco.2016.06.016

Kannan, R., Shackleton, C. M., & Uma Shaanker, R. (2013). Reconstructing the history of introduction and spread of the invasive species, lantana, at three spatial scales in India. *Biol Invasions*, *15*(6), 1287–1302. https://doi.org/10.1007/s10530-012-0365-z

Kannan, R., Shackleton, C. M., & Uma Shaanker, R. (2014). Invasive alien species as drivers in socio-ecological systems: Local adaptations towards use of lantana in southern India. *Environment, Development and Sustainability*, *16*(3), 649–669. https://doi.org/10.1007/s10668-013-9500-y

Katembo, N., Witkowski, E. T. F., Simelane, D. O., Urban, A. J., & Byrne, M. J. (2020). Impact of biocontrol agents on *Lantana camara* in an inland area of South Africa. *BioControl*, *65*(2), 143–154. https://doi.org/10.1007/s10526-019-09991-9

Kent, R., & Dorward, A. (2015). Livelihood responses to *Lantana camara* invasion and biodiversity change in southern India: Application of an asset function framework. *Regional Environmental Change*, *15*(2), 353–364. https://doi.org/10.1007/s10113-014-0654-4

Kim, D. H., & Burchill, G. (1992). System archetypes as a diagnostic tool: A field-based study of TQM implementations. In *Proceedings of the 10th international conference of the system dynamics society* (pp. 14–17).

Kull, C. A., Shackleton, C. M., Cunningham, P. J., Ducatillon, C., Dufour-Dror, J.-M., Esler, K. J., Friday, J. B., Gouveia, A. C., Griffin, A. R., & Marchante, E. (2011). Adoption, use and perception of Australian acacias around the world. *Diversity and Distributions*, *17*(5), 822–836. https://doi.org/10.1111/j.1472-4642.2011.00783.x

Laurenti, R., Singh, J., Sinha, R., Potting, J., & Frostell, B. (2016). Unintended environmental consequences of improvement actions: A qualitative analysis of systems' structure and behavior. *Systems Research and Behavioral Science*, *33*(3), 381–399. https://doi.org/10.1002/sres.2330

Luna-Reyes, L. F., & Andersen, D. L. (2003). Collecting and analysing qualitative data for system dynamics: Methods and models. *System Dynamics Review: the Journal of the System Dynamics Society*, *19*(4), 271–296. https://doi.org/10.1002/sdr.280

Mamba, H. S., & Singwane, S. S. (2019). Effects of *Lantana camara* and *Psidium guajava* on the chemical properties of the soil in Eswatini—A case of Ngudzeni area. *1*(1), 1–16. https://scirange.com/pdf/irjas.2019.1.16.pdf

Mungi, N. A., Coops, N. C., Ramesh, K., & Rawat, G. S. (2018). How global climate change and regional disturbance can expand the invasion risk? Case study of *Lantana camara* invasion in the Himalaya. *Biol Invasions*, *20*(7), 1849–1863. https://doi.org/10.1007/s10530-018-1666-7

Mungi, N. A., Kaushik, M., Mohanty, N. P., Rajat Rastogi, J., Johnson, A., & Qureshi, Q. (2019). Identifying knowledge gaps in the research and Management of Invasive Species in India. *Biologia*, *74*(6), 623–629. https://doi.org/10.2478/s11756-018-00186-8

Mungi, N. A., Qureshi, Q., & Jhala, Y. V. (2020). Expanding niche and degrading forests: Key to the successful global invasion of *Lantana camara* (Sensu Lato). *Global Ecology and Conservation*, *23*(September), e01080. https://doi.org/10.1016/j.gecco.2020.e01080

Muniappan, R., & Viraktamath, C. A. (1986). Status of biological control of the weed, *Lantana camara* in India. *Tropical Pest Management*, *32*(1), 40–42. https://doi.org/10.1080/09670878609371025

Naughton-Treves, L., Holland, M. B., & Brandon, K. (2005). The role of protected areas in conserving biodiversity and sustaining local livelihoods. *Annu Rev Env Resour*, *30*(1), 219–252. https://doi.org/10.1146/annurev.energy.30.050504.164507

Negi, G. C. S., Sharma, S., Vishvakarma, S. C. R., Samant, S. S., Maikhuri, R. K., Prasad, R. C., & Palni, L. M. S. (2019). Ecology and use of *Lantana camara* in India. *The Botanical Review*, *85*(2), 109–130. https://doi.org/10.1007/s12229-019-09209-8

Nelson, C. H., & Stroink, M. L. (2014). Accessibility and viability: A complex adaptive systems approach to a wicked problem for the local food movement. *Journal of Agriculture, Food Systems, and Community Development*, *4*(4), 191–206. https://doi.org/10.5304/jafscd.2014.044.016

Niraj, S. K., Krausman, P. R., & Dayal, V. (2012). A stakeholder perspective into wildlife policy in India. *The Journal of Wildlife Management*, *76*(1), 10–18. https://doi.org/10.1002/jwmg.263

Paini, D. R., Sheppard, A. W., Cook, D. C., De Barro, P. J., Worner, S. P., & Thomas, M. B. (2016). Global threat to agriculture from invasive species. *Proc Natl Acad Sci*, *113*(27), 7575–7579. https://doi.org/10.1073/pnas.1602205113

Pan, X., Valerdi, R., & Kang, R. (2013). Systems thinking: A comparison between Chinese and Western approaches. *Procedia Computer Science, 2013 Conference on Systems Engineering Research*, *16*(January), 1027–1035. https://doi.org/10.1016/j.procs.2013.01.108

Panlasigui, S., Davis, A. J. S., Mangiante, M. J., & Darling, J. A. (2018). Assessing threats of non-native species to native freshwater biodiversity: Conservation priorities for the United States. *Biol Conserv*, *224*(August), 199–208. https://doi.org/10.1016/j.biocon.2018.05.019

Paul, R., Subudhi, D. K., Sahoo, C. K., & Banerjee, K. (2021). Invasion of *Lantana camara L.* and its response to climate change in the mountains of eastern Ghats. *Biologia*, *76*(5), 1391–1408. https://doi.org/10.1007/s11756-021-00735-8

Peters, B. G. (2017). What is so wicked about wicked problems? A conceptual analysis and a research program. *Policy and Society*, *36*(3), 385–396. https://doi.org/10.1080/14494035.2017.1361633

Pimentel, D. (2009). Invasive plants: Their role in species extinctions and economic losses to agriculture in the USA. In *In Management of Invasive Weeds, edited by Inderjit, 1–7. Invading nature – Springer series in invasion ecology*. Springer Netherlands. https://doi.org/10.1007/978-1-4020-9202-2_1

Pimentel, D., Zuniga, R., & Morrison, D. (2005). Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecological Economics, Integrating Ecology and Economics in Control Bioinvasions*, *52*(3), 273–288. https://doi.org/10.1016/j.ecolecon.2004.10.002

Pineo, H., Zimmermann, N., & Davies, M. (2020). Integrating health into the complex urban planning policy and decision-making context: A systems thinking analysis. *Palgrave Communications*, *6*(1), 21. https://doi.org/10.1057/s41599-020-0398-3

Prasad, A. E. (2010). Effects of an exotic plant invasion on native understory plants in a tropical dry Forest. *Conserv Biol*, *24*(3), 747–757. https://doi.org/10.1111/j.1523-1739.2009.01420.x

Prasad, A., Ratnam, J., & Sankaran, M. (2018). Rainfall and removal method influence eradication success for *Lantana camara*. *Biol Invasions*, *20*(12), 3399–3407. https://doi.org/10.1007/s10530-018-1785-1

Rai, N. D., Soubadra Devy, M., Ganesh, T., Ganesan, R., Setty, S. R., Hiremath, A. J., Khaling, S., & Rajan, P. D. (2021). Beyond fortress conservation: The long-term integration of natural and social science research for an inclusive conservation practice in India. *Biol Conserv*, *254*(February), 108888. https://doi.org/10.1016/j.biocon.2020.108888

Ramaswami, G., Prasad, S., Westcott, D., Subuddhi, S. P., & Sukumar, R. (2014). Addressing the management of a long-established invasive shrub: The case of *Lantana camara* in Indian forests. *Indian Forester*, *140*(2), 129–136.

Rangarajan, M. (1994). Imperial agendas and India's forests: The early history of Indian forestry, 1800-1878. *The Indian Economic & Social History Review*, *31*(2), 147–167. https://doi.org/10.1177/001946469403100202

Ranjan, M., Khali, D. P., & Bhatt, S. (2017). Effect of cement: Wood particle ratio on physical and mechanical properties of cement bonded particle board using *Lantana camara*. *Indian Forester*, *143*(4), 360–363. https://doi.org/10.36808/if/2017/v143i4/113690

Ranjan, R. (2019). Deriving double dividends through linking payments for ecosystem services to environmental entrepreneurship: The case of the invasive weed *Lantana camara*. *Ecol Econ*, *164*(October), 106380. https://doi.org/10.1016/j.ecolecon.2019.106380

Reddy, C. S., Bird, N. G., Sreelakshmi, S., Maya Manikandan, T., Mahbooba Asra, P., Krishna, H., Jha, C. S., Rao, P. V. N., & Diwakar, P. G. (2020). Identification and characterisation of spatio-temporal hotspots of forest fires in South Asia. *Environ Monit Assess*, *191*(3), 791. https://doi.org/10.1007/s10661-019-7695-6

Richardson, D. M., & Rejmánek, M. (2011). Trees and shrubs as invasive alien species—A global review. *Diversity and Distributions*, *17*(5), 788–809. https://doi.org/10.1111/j.1472-4642.2011.00782.x

Rittel, H. W. J., & Webber, M. M. (1974). Wicked problems. *Man-Made Futures*, *26*(1), 272–280.

Roberts, P. D., Diaz-Soltero, H., Hemming, D. J., Parr, M. J., Wakefield, N. H., & Wright, H. J. (2013). What is the evidence that invasive species are a significant contributor to the decline or loss of threatened species? A systematic review map. *Environmental Evidence*, *2*(1), 5. https://doi.org/10.1186/2047-2382-2-5

Sahoo, A., Kumar, S., Kumar, J., & Bhaskar, T. (2021). A detailed assessment of pyrolysis kinetics of invasive lignocellulosic biomasses (*Prosopis juliflora* and *Lantana camara*) by thermogravimetric analysis. *Bioresour Technol*, *319*(January), 124060. https://doi.org/10.1016/j.biortech.2020.124060

Saout, L., Soizic, M. H., Shi, Y., Hughes, A., Bernard, C., Brooks, T. M., Bertzky, B., et al. (2013). Protected areas and effective biodiversity conservation. *Science*, *342*(6160), 803–805. https://doi.org/10.1126/science.1239268

Shackleton, R. T., Adriaens, T., Brundu, G., Dehnen-Schmutz, K., Estévez, R. A., Fried, J., Larson, B. M. H., Liu, S., Marchante, E., Marchante, H., Moshobane, M. C., Novoa, A., Reed, M., & Richardson, D. M. (2019). Stakeholder engagement in the study and management of invasive alien species. *Journal of Environmental Management, the Human and Social Dimensions of Invasion Science and Management*, *229*(January), 88–101. https://doi.org/10.1016/j.jenvman.2018.04.044

Shackleton, R. T., Le Maitre, D. C., van Wilgen, B. W., & Richardson, D. M. (2017). Towards a national strategy to optimise the management of a widespread invasive tree (*Prosopis species; Mesquite*) in South Africa. *Ecosystem Services, Investing in Ecological Infrastructure in South Africa*, *27*(October), 242–252. https://doi.org/10.1016/j.ecoser.2016.11.022

Sharma, G. P., & Raghubanshi, A. S. (2009). Plant invasions along roads: A case study from central highlands, India. *Environ Monit Assess*, *157*(1–4), 191–198. https://doi.org/10.1007/s10661-008-0527-8

Shylesh Chandran, M. S., Sujatha, S., Mohan, M., Julka, J. M., & Ramasamy, E. V. (2012). Earthworm diversity at Nilgiri biosphere reserve, Western Ghats, India. *Biodivers Conserv*, *21*(13), 3343–3353. https://doi.org/10.1007/s10531-012-0365-4

Simberloff, D., Martin, J.-L., Genovesi, P., Maris, V., Wardle, D. A., Aronson, J., Courchamp, F., Galil, B., García-Berthou, E., Pascal, M., Pyšek, P., Sousa, R., Tabacchi, E., & Vilà, M. (2013). Impacts of biological invasions: What's what and the way forward. *Trends Ecol Evol*, *28*(1), 58–66. https://doi.org/10.1016/j.tree.2012.07.013

Simelane, D. O., Katembo, N., & Mawela, K. V. (2021). Current status of biological control of *Lantana camara L.* (Sensu Lato) in South Africa. *Afr Entomol*, *29*(3), 775–783. https://doi.org/10.4001/003.029.0775

Simon, H. A., & Kadane, J. B. (1975). Optimal problem-solving search: All-or-none solutions. *Artificial Intelligence*, *6*(3), 235–247. https://doi.org/10.1016/0004-3702(75)90002-8

Sterman, John D. 2000. *Business dynamics: Systems thinking and modeling for a complex world*. McGraw-Hill Higher Education. HD30. 2 S7835 2000.

Sundaram, B., Krishnan, S., Hiremath, A. J., & Joseph, G. (2012). Ecology and impacts of the invasive species, *Lantana camara*, in a social-ecological system in South India: Perspectives from local knowledge. *Hum Ecol*, *40*(6), 931–942. https://doi.org/10.1007/s10745-012-9532-1

Swarbrick, J. T., Willson, B. W., & Hannan-Jones, M. A. (1995). The biology of Australian weeds 25. *Lantana camara L. Plant Protection Quarterly*, *10*, 82–82.

Tassin, J., Rangan, H., & Kull, C. A. (2012). Hybrid improved tree fallows: Harnessing invasive woody legumes for agroforestry. *Agr Syst*, *84*(3), 417–428. https://doi.org/10.1007/s10457-012-9493-9

Taylor, S., Kumar, L., Reid, N., & Kriticos, D. J. (2012). Climate change and the potential distribution of an invasive shrub, *Lantana camara L. PLoS ONE*, *7*(4), e35565. https://doi.org/10.1371/journal.pone.0035565

Termeer, C. J. A. M., Dewulf, A., Breeman, G., & Stiller, S. J. (2015). Governance capabilities for dealing wisely with wicked problems. *Administration & Society*, *47*(6), 680–710. https://doi.org/10.1177/0095399712469195

Thekaekara, T. (2015). Mapping the distribution of *Lantana camara* in the Hasanur division, Sathyamangalam Tiger Reserve Tamilnadu: Report submitted to WWF-India and the Tamilnadu Forest Department. *The Shola Trust*. http://www.thesholatrust.org/wp-content/uploads/2019/05/STR_LantanaReport_Final_Feb2016.pdf

Thekaekara, T. (2016). Mapping the distribution of *Lantana camara* in the Bandipur Tiger Reserve, Karnataka: Draft report submitted to the Karnataka Forest Department. *The Shola Trust*. https://ruffordorg.s3.amazonaws.com/media/project_reports/16098-2%20Detailed%20Final%20Report.pdf

Thekaekara, T., Vanak, A. T., Ankila Hiremath, J., Rai, N. D., Ratnam, J., & Raman, S. (2017). Notes from the other side of a forest fire. *Econ Polit Wkly*, *52*(25–26), 22–25.

Ticktin, T., Ganesan, R., Paramesha, M., & Setty, S. (2012). Disentangling the effects of multiple anthropogenic drivers on the decline of two tropical dry forest trees. *J Appl Ecol*, *49*(4), 774–784. https://doi.org/10.1111/j.1365-2664.2012.02156.x

Tilman, D., Clark, M., Williams, D. R., Kimmel, K., Polasky, S., & Packer, C. (2017). Future threats to biodiversity and pathways to their prevention. *Nature*, *546*(7656), 73–81. https://doi.org/10.1038/nature22900

Torugsa, N., & Arundel, A. (2017). Rethinking the effect of risk aversion on the benefits of service innovations in public administration agencies. *Research Policy*, *46*(5), 900–910. https://doi.org/10.1016/j.respol.2017.03.009

Troup, R. S. (1921). *The silviculture of Indian trees: Dilleniaccae to Leguminosae (Papilionaceae)* (Vol. 1). Clarendon Press.

Ullah, M. A., Urquhart, C., Arthanari, T., & Ahmed, E. (2021). Dimensions of corruption in Pakistan: A systems thinking approach and qualitative analysis. *Systems Research and Behavioral Science N/a (N/a)*, *39*, 324–338. https://doi.org/10.1002/sres.2775

UNESCO. (2019). *Nilgiri biosphere reserve*. UNESCO. January 11, 2019. https://en.unesco.org/biosphere/aspac/nilgiri

Wolstenholme, E. F., & Coyle, R. G. (1983). The development of system dynamics as a methodology for system description and qualitative analysis. *J Oper Res Soc*, *34*(7), 569–581. https://doi.org/10.2307/2581770

Wolstenholme, E. (2004). E. Wolstenholme: Using generic system archetypes 341 using generic system archetypes to support thinking and modelling. *System Dynamics Review*, *20*(4), 341–356. https://doi.org/10.1002/sdr.302

Wolstenholme, E. F. (1993). The changing role of system dynamics. In F. A. Stowell, D. West, & J. G. Howell (Eds.), *Systems science: Addressing global issues* (pp. 617–621). Springer US. https://doi.org/10.1007/978-1-4615-2862-3_109

Wolstenholme, E. F. (2003). Towards the definition and use of a core set of archetypal structures in system dynamics. *System Dynamics Review*, *19*(1), 7–26. https://doi.org/10.1002/sdr.259

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Hariharan, T. S., Ganesh, L. S., Vijayalakshmi, V., Sharma, P., & Potdar, V. (2024). Archetypal representations of dilemmas concerning invasive alien species management—A case of invasive *Lantana camara* in the protected areas of Nilgiri Biosphere Reserve, India. *Systems Research and Behavioral Science*, 1–25. https://doi.org/10.1002/sres.2999