Which Perspective of Institutional Change Best Fits Empirical Data? An Agent-Based Model Comparison of Rational Choice and Cultural Diffusion in Invasive Plant Management

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Abstract: There are multiple theories regarding how institutions change over time, but institutional change is often difficult to study and understand in practice. Agent-based modeling is known as a technique to explore emergent phenomena resulting from the micro level activities and interactions between heterogeneous agents and between agents and the environment. Such models allow researchers to investigate theories which may otherwise be difficult to examine. We present a theoretically driven agent-based model to explore two perspectives on institutional change, rational choice and cultural diffusion, in the context of invasive plant management in Chitwan, Nepal. The Chitwan region is grappling with the spread of the invasive mile-a-minute weed, *Mikania micrantha* (*Mikania*). We focus on understanding which perspective of institutional change better fits empirical survey data on *Mikania* management. We find that rational choice is an unlikely candidate for institutional change in Chitwan and that the social learning and imitation mechanism modeled in the cultural diffusion perspective better replicates empirical patterns. Additionally, the model reveals that the percentage of agents adopting the best practice removal method is not as influential in reducing *Mikania* as the initial amount of *Mikania* removed. This result indicates that it may be useful to conduct an empirical assessment varying the initial amount of *Mikania* removed to understand the management implications for successful removal of *Mikania* in Chitwan and elsewhere.

Keywords: Agent-Based Model, Institutions, Invasive Pest, Collective Action

Introduction

- 1.1 Institutional scholars have widely documented that institutions, as the shared rules, norms, strategies, and values that shape human decision making (North 1990), influence natural resource management. The institutions in a given system can shape whether resource management will be successful or not (Ostrom et al. 1994). In cases where natural resource management is deemed unsuccessful, people often seek to change the institutions governing that system (Burger 2001; Ostrom 1990). Understanding how institutions change is a topic rife with difficulties, including observing change over long time scales, different theories about the mechanism of change, and analysis and measurement (Campbell 2004). In this paper, we present a theoretically driven agent-based model (ABM) examining institutional change in a social-ecological system grappling with management of an invasive plant, comparing theoretical perspectives of institutional change with empirical data on management efforts. A better understanding of which theories of institutional change are consistent with empirical data can lead to new theoretical insights just as when empirical studies of cooperative resource management confronted the tragedy of the commons (Janssen & Ostrom 2006).

- 1.2** Many institutional studies of common pool and natural resources have focused on operationalizing the role of rules in management decisions (Helmke & Levitsky 2004; Raiser 1997), but here we examine strategies and norms associated with the management of an invasive plant. We differentiate rules, norms, and strategies in terms of the institutional grammar, using the ADICO syntax (Crawford & Ostrom 1995). In this syntax, A represents the *attributes* of an actor to which an institution applies (e.g. gender, education, experience); D represents the *deontic* logic operators may/must/must not; I represents the *aim* or actions to which the deontic applies; C represents the *conditions* under which the aim is permitted; and O is the “*or else*” representing sanctions for deviating from a rule. Strategies contain the elements AIC, norms include ADIC, and rules are the most precise, written as ADICO. In practice, the boundaries between strategies and norms or norms and rules may be blurred (Crawford & Ostrom 1995). In the background section, we explain why we categorize institutions related to invasive plant management in our model as strategies and norms using the ADICO syntax. Examining shared strategies and norms for natural resource management is relevant to understanding management outcomes, especially in decentralized situations. In decentralized cases, where local communities are responsible for natural resource management, there may be less emphasis on rules (including laws and policies) and more emphasis on social norms (Ostrom 2005).
- 1.3** Studies of successful common pool resource management are often case-study based and rely upon analysis of rich qualitative data. More recently, the field has focused on incorporating complementary quantitative data and computational analysis with qualitative data. Advances in the area of computational social science have made agent-based (also known as individual-based in ecology) models increasingly appealing to study natural resources and social-ecological systems (SES) (Bonabeau 2002; Heard et al. 2015). Such computational models provide researchers the opportunity to manipulate a wide variety of system characteristics to construct counterfactual situations, reevaluate past conditions, or explore the impact of added factors that cannot be or are difficult to directly observe. In this sense, agent-based models have been described as virtual laboratories for exploring social-ecological systems (Magliocca et al. 2015). Our agent-based model explores two theoretical perspectives of institutional change (rational choice and cultural diffusion) to understand which perspective better explains empirical data on strategies and norms used to manage an invasive plant in locally governed forests, known as community forests, in Chitwan, Nepal.
- 1.4** Invasive species represent one type of challenge facing social-ecological systems and are often interconnected with or exacerbated by other issues such as urbanization, climate change, and environmental pollution (Keller et al. 2014). Invasive species are most frequently studied in the context of their ecological or economic, but not social, impacts (Rai & Scarborough 2015; Schüttler et al. 2011). Yet it is recognized that it is important to understand invasive species’ social and ecological effects (Atlan & Darrot 2012). Without an understanding of how invasive plants impact both the social and ecological subsystems, management attempts may be contentious among social groups with different interests and values (Epanchin-Niell et al. 2010; Estévez et al. 2015) or ineffective due to poor understanding of the institutions that interact with management efforts. Murphy et al. (2013) find that future Mikania management efforts in Chitwan should incorporate plans to reduce burning and to introduce information about best practices. Successful implementation of these recommendations requires a detailed understanding of the social context, including institutions.
- 1.5** The primary objective of this study is to compare two theories of institutional change, rational choice and cultural diffusion, to understand which better fits empirical observations of Mikania management strategies and norms in Chitwan. Two secondary aims are: to test the hypothesis that higher initial percentages of agents adopting the best practice removal method will reduce Mikania (even with burning occurring) and to analyze the effect of the initial percentage of Mikania present. Our agent-based modeling approach adds value to this human-environment research, including acting as a platform to address uncertainty (for example, our analysis of different scenarios of strategy and norm adoption). The ABM allows us to perform theory-based experiments (what-if tests) to understand which parameters influence model outcomes and provides interesting insights into future research avenues.
- 1.6** Next, we present the details of the study site and literature related to institutional change that inform our model. We then provide the model conceptualization and overview, and results from the rational choice and cultural diffusion sub-models. The subsequent discussion identifies areas for further research based on the results, including empirical studies of the initial amount of Mikania removal and comparison of additional theories of institutional change.

Background

Study site

- 2.1 Chitwan, Nepal is a district located in southern Nepal, in the sub-tropical Terai region. The Terai is one of Nepal's five physiographic regions and was historically densely forested. However, much deforestation has occurred in the nineteenth century and forested areas continue to decline at an annual rate of approximately 1.7 percent (Bhuju et al. 2007). Forests cover approximately 30 percent of the region, with other areas composed of wetlands, tall grasslands, and scrub savannah (Bhuju et al. 2007). Chitwan has been home to community forest user groups since the program was formalized in the 1990s by the national Forest Management Act (Gilmour 2003).
- 2.2 Community forestry programs give local users some degree of autonomous resource management, and include the forest ecosystem and the group of people that actively contribute to the management of the forest resources. Globally, they have encountered differing levels of success (Charnley & Poe 2007). Some are entirely managed by local organizations, while others are formally owned by the national, state, or regional governments with management rights held by locally established community forest management committees (White & Martin 2002). The complex human-environment dynamics and the heterogeneity in management and decision processes in community forestry situations make them an excellent candidate for agent-based modeling (Janssen & Ostrom 2006).
- 2.3 Chitwan community forest user groups have faced a variety of challenges, such as increasing urbanization, but more recently a rapidly growing invasive plant (*Mikania micrantha*, referred to as *Mikania*) has disturbed the system. *Mikania* is a vine-like plant that is difficult to successfully remove partially due to its sexual and asexual reproduction. If not properly contained after removal efforts during the flowering season, the seeds can further spread the plant (Barreto & Evans 1995) and pieces of dropped stem can result in unintended regrowth (Murphy et al. 2013). *Mikania* grows on the forest floor and climbs small trees, meaning it is often tangled in fodder and grasses that community forest users collect. Thus, commonplace resource collection and management efforts have resulted in aiding *Mikania* dispersal (Sullivan et al. 2017b).
- 2.4 To manage *Mikania*, people in Chitwan engage in a variety of removal strategies and/or follow management norms. These include doing nothing; mechanical removal (pulling/uprooting and cutting/slashing the plant); burning; use of herbicides; pulling the plant and burying it in a deep hole; and a best practice method that involves uprooting, bagging, burying, and burning the plant. These practices are considered strategies in terms of the institutional grammar (AIC), as they include *attributes* (e.g. households that are members of a community forest), an *aim* (e.g. to remove *Mikania* by pulling), and *conditions* (such as the time of year removal will be performed). These strategies can sometimes also be classified as norms (ADIC), as *deontic* elements are occasionally present. For example, households may be forbidden (must not) to use herbicides in some areas of their community forest, subject to their community's rules, and typically at least one member of each household should participate in removal efforts. Additionally, there is a norm associated with burning, as burning in the forest is forbidden or permitted according to a given community forest's rules (in most cases burning is forbidden). This burning norm does not become a rule in most cases, as there are not consistent sanctions (or *else*) associated with the practice.

How do institutions change?

- 2.5 There are several theories of institutional change (Table 1). These theories are at times competing, but often elements of separate theories are compatible. Here, we describe two main categories of institutional change, while acknowledging there are others.

Type	Description	Examples	Problems	Citations
Centralized	Deliberate/purposeful; not usually accidental (but can have unintended consequences); often occurs via a political process or collective choice mechanism	Origin of property rights via 'contracting'; Cost-benefit analysis embedded in Ostrom's constitutional-collective choice-operational rule hierarchy	Difficulty explaining when/why 'formal' rules are ineffective/ignored and addressing "informal" institutions, such as social norms	Libecap (1994), Ostrom (2005), Alston (1996), Kantor (1998)
Decentralized	Described as evolutionary (where institutions emerge via a decentralized selection process), incremental; new institutions can emerge at random and sometimes through design	Transaction cost literature where most efficient institutions are assumed to survive; habits that cause emergent actions; punctuated equilibrium	Often neglects roles of collective action/political processes in institutional change	Williamson (2000), Veblen (1899), Hayek (1978), Young (1996)

Table 1: Common categories of theories of institutional change (summarized from Kingston & Caballero 2009 and Mahoney & Thelen 2009).

- 2.6** The primary distinction we draw between theories of institutional change is deliberate change that occurs via a centralized mechanism (like collective-choice situations) versus evolutionary change that occurs via a decentralized mechanism (Kingston & Caballero 2009). Institutional change that occurs in a deliberate manner in a centralized process (such as through legislation) tends to occur more quickly than institutional changes that occur via a decentralized process. It has been noted that 'formal' institutions, often defined as written rules (such as laws) and rules using the institutional grammar tool, are more frequently changed deliberately, whereas 'informal' institutions (strategies and norms using the institutional grammar tool) are slower to change and shift in a decentralized process resulting from uncoordinated micro-level behaviors.
- 2.7** Informal institutions include unwritten agreements, moral or ethical norms, and social norms. Institutional change may also occur, via both centralized and decentralized processes, in a punctuated manner with periods of stability interrupted by points of rapid transition. Understanding rates of institutional change is important to policy makers and stakeholders attempting to deliberately change either formal or informal institutions (Mahoney & Thelen 2009). The two perspectives in our model, rational choice and cultural diffusion, explore decentralized processes of institutional change, with individuals interacting on the micro-level potentially leading to changes in the composition of strategies and norms on the macro-level over time.
- 2.8** Rational choice is explored in the first sub-model. Considering the rational choice perspective, under a bounded rationality framework, individuals seek to maximize their own utility under cognitive, information, and time constraints (Bohensky 2014; Ostrom 2005). In this case, agents engage in a cost-benefit analysis; if the perceived value of adopting a specific strategy is greater than its cost, the agent can select a management method costlier than the least costly method. Although the cost-benefit analysis in the model occurs at the micro-level, the process is similar to Ostrom's theory of institutional change where individuals engage in a cost-benefit analysis and agree to institutional change if a 'minimum coalition' is achieved (Ostrom 2005, p. 61). Instead of the change taking place on the scale of the entire community simultaneously (i.e. individuals are not voting or agreeing on a threshold where everyone will adopt one institution after the 'minimum coalition' is met, such as a majority in democratic voting processes), the change takes place as individuals adopt specific strategies over time.
- 2.9** Our second perspective of change investigated is cultural diffusion, based on Axelrod (1997). Axelrod explored how simple interactions between agents with some level of cultural similarity stimulated changes in cultural heterogeneity over time. We modify the model to examine institutional change by modeling Mikania management strategies and norms and tracking the changes in these and Mikania patterns over time. They change via individual agent interactions and the mechanism of change can be thought of as social learning (Caldas et al. 1999).

2.10 Human decision making under assumptions of bounded rationality has been supported in some experimental studies, but these studies have also been criticized for bias, particularly regarding the narrow type of participants that have been included in the research (e.g. college educated, western, rich; Henrich et al. 2010). The model of cultural dissemination or diffusion has not been empirically validated, a common issue with many computational social science models (Railsback & Grimm 2011). However, Stivala et al. (2014) employed an empirical dataset related to public opinions to analyze the importance of spatial configurations in the results of the Axelrod model and discovered that the level of cultural diversity varied depending on spatial configurations. It is difficult to observe institutional change and there remains opportunity for computational models validated with empirical data to contribute to understanding institutional change and provide new directions for future empirical research.

Conceptual Model

3.1 This model is informed by ethnographic fieldwork and survey data collected in 2014 and 2015 in Chitwan, Nepal. The ethnographic fieldwork included semi-structured interviews with 87 individuals focusing on governance relationships in community forestry and Mikania in five community forests, while the survey included 1041 households in 21 community forests. All community forests in the fieldwork and survey are located around the border of Chitwan National Park in the area known as the buffer zone. The fieldwork and survey include data on Mikania management strategies and norms in communities and the specific strategies and norms employed by each household (Table 2). The ethnographic data are used to inform the removal cost parameters, while the survey data are compared to the model results to explore which perspective of institutional change best fits the data. The agents in this model represent households distributed on a virtual landscape. The model code is available at: <https://www.openabm.org/model/5231/version/1/view>.

Strategies and norms	Characterization of time intensiveness (from ethnographic data, informs cost parameters)	Percent using method (from survey data, used for model validation)
Burning	Low cost	17
Mechanical removal	Medium cost	34
Pulling and burying	High cost	7
Best practice	Highest cost	0

Table 2: Ethnographic and survey data inform strategies and norms.

3.2 We provide an overview of the model setup and processes, including a summary of input and output variables in Table 4 in the Appendix, which follows the Overview, Design concepts, and Details (ODD) protocol (An et al. 2014; Grimm et al. 2006, 2010). We implemented our model using NetLogo (version 5.3.1) (Wilensky 1999).

Set up

3.3 The model includes two elements: the landscape and the agents. The agents represent households that make individual decisions regarding Mikania management. The model can be initialized with 100 to 1000 agents; all simulations analyzed here were initialized with 100 agents because this represents an average neighborhood size. The agents are aware of their geographic location (in NetLogo, their patch ID), their own features, and the environment (Mikania cover and land productivity). Agents are randomly placed on a landscape composed of individual spaces, called patches in NetLogo, and each patch represents one plot within a forest. The landscape is set up with a gradient of Mikania cover, with patches ranging from 0 to 75 percent initial cover (see Appendix).

Model sequence

3.4 After initializing model parameters, the model enters procedures to ‘remove Mikania’ and ‘redistribute Mikania.’ In order to manage Mikania (the ‘remove Mikania’ procedure), agents enter the rational choice or cultural diffusion sub-models, depending on which sub-model the model analyst has selected (the cultural diffusion and rational choice sub-models are independently processed). The ‘redistribute Mikania’ procedure impacts

Mikania distribution depending on the removal method an agent used in that time step (i.e. Mikania in a given patch may change) based on a rate of increase. See pseudo code below.

```
Initialize parameters
Set up world
Each time step...
    Manage Mikania
        If Mikania is present in patch...
            If rational choice is selected, enter rational choice sub-model
            If cultural diffusion is selected, enter cultural diffusion sub-model
        Redistribute Mikania
            Mikania cover in a patch and/or surrounding patches changes
            (or not) depending on the removal method selected
End
```

Managing Mikania

Rational choice

- 3.5** In the ‘rational choice’ sub-model (Figure 1), an agent enters a cost-benefit analysis and observes their neighbors to adopt a Mikania management strategy (see pseudo code below). The cost (in terms of time and personal effort) associated with each strategy is ranked based on the ethnographic fieldwork, essentially an ordinal variable. The ordering is accurate, but the distance between the numbers is unknown (i.e. how much costlier it is to conduct mechanical removal versus burning). Because of this, we systematically varied the value of each cost parameter to understand the impact of different costs for each strategy, while maintaining the ranking of the costs (Yang & Gilbert 2008). The analysis showed that as long as the ranking is not altered (i.e., not sensitive to the distance between different strategies), the pattern in adoption of strategies holds. The agent’s preferences and their observation (and possible imitation) of their neighbors’ strategies drives change. In absence of empirical data on management preferences, they are modeled as a random value between 0 and 1. In reality, this value could be influenced by income, reliance on forest resources, household size, and other factors. Similar factors have been modeled this way (Broekhuizen et al. 2011; Zhang & Vorobeychik 2016) and we subject this parameter to sensitivity analysis (for example, to understand what happens when more than half of agents have a value above 0.5, representing a strong preference to remove Mikania). This assumption is a limitation of the model, but the parameter can be recalibrated in the future with empirical survey data to explore the impact on the results, similar to the methods employed by Parker et al. (2012).

```
Each time step...
Conduct a cost-benefit analysis
    Select an initial removal strategy
        If the agent’s value-threshold is greater than patch productivity
        (i.e. even when patch productivity is low)
        the agent can select a costlier strategy (i.e. not burning or doing nothing)
        Otherwise, initially set removal method to burning
    Observe the removal strategies of the closest eight agents
        If more than half have the same strategy, adopt that strategy
    Remove Mikania with selected strategy if the productivity of the patch
    is greater than the cost of the removal strategy
End
```

Cultural diffusion

- 3.6** The cultural diffusion sub-model is a modification of the “Diffusion of Culture” model from openABM (Lozano & Maes 2008), based on Axelrod’s (1997) article. It operates on the premise that agents interact with culturally similar agents, and have the possibility to imitate the Mikania management practices of culturally similar agents (Figure 2). The agents are initialized with high levels of mechanical burning (40 percent) and low levels of burning (10 percent) and best practice removal (5 percent), informed by the removal patterns in Chitwan from the ethnographic fieldwork. This percentage of agents initially adopting different strategies is varied in 16 different

Figure 1: A simplified conceptual view of the rational choice sub-model. Mikania cover (the squares) changes over time based on changing removal strategies. Agents engage in a cost-benefit analysis and observation to adopt and change removal strategies over time.

Figure 2: A simplified conceptual view of the cultural diffusion sub-model. Mikania cover (the squares) changes over time based on changing removal strategies in each model. Agents interact based on the similarity of their set of cultural traits.

experimental scenarios later on. Agents each have a set of cultural traits represented as a randomly assigned string of length n (n ranges from 1 to 20 traits). Each of these traits has m possible features (m can range from 1 to 20). The first trait in the string represents the Mikania management strategy that an agent adopts, with five possible features (for the first trait, $m = 5$: doing nothing, mechanical removal, pulling and burying, burning, best practice). Agents evaluate whether to interact or not with the spatially closest agent based on the similarity of their features. If agents are similar, it is possible they will interact. If they interact, the active agent may adopt a feature of the other agent, increasing their similarity. Here again, if an agent engages in removal, they remove Mikania from their current location.

Each time step...

Select one of the agents

That agent examines the cultural traits of their nearest agent

Calculate the similarity of the cultural traits

If the agents' similarity is between a random number from 0-1 and 1,
the selected agent randomly adopts a new trait from the nearest agent

Remove Mikania (the first trait reflects the Mikania removal strategy)

End

Redistributing Mikania

- 3.7** Each Mikania removal strategy is tracked within the model based on the cost of an agent's current strategy (rational choice) or the value of the feature of an agent's first trait (cultural diffusion). Each removal strategy

corresponds to a parameter that influences how likely Mikania will increase and possibly spread into a neighboring patch, which was determined by discussing the different strategies with experts and was subject to a sensitivity analysis where the redistribution parameter for each strategy was varied between 0 and 1, in increments of 0.1, while holding other parameters constant. The analysis showed little variation in the overall model outcomes (e.g. the higher the removal parameters, the more Mikania increased).

Cultural diffusion scenarios

- 3.8** We additionally assess experimental scenarios to explore the impact of different percentages of agents adopting the best practice removal method in the cultural diffusion sub-model (Table 3). These scenarios are designed to test the hypothesis that higher initial percentages of agents adopting the best practice removal method will reduce Mikania, even with burning still occurring. We selected scenarios varying the initial percentage of agents adopting the best practice removal method from 5 to 50 percent informed by the ethnographic fieldwork. There are four scenarios with high, low, or moderate burning. Scenario C follows the observed management patterns (high mechanical removal, low burning). Scenarios A, B, and C are respectively high, moderate, and low burning paired with high levels of mechanical removal. Scenario D pairs moderate levels of burning with moderate levels of mechanical removal. In each scenario, we vary the percentage of agents initially adopting the best practice removal strategy from 5 to 50 percent, which represents part of our sensitivity analysis (ten Broeke et al. 2016).

	Initial best practice	Initial burning	Initial pulling
(A) High burning, high mechanical removal	0.05	0.4	0.4
	0.1	0.4	0.4
	0.3	0.35	0.35
	0.5	0.25	0.25
(B) Moderate burning, high mechanical removal	0.05	0.25	0.4
	0.1	0.25	0.4
	0.3	0.25	0.4
	0.5	0.25	0.4
(C) Low burning, high mechanical removal	0.05	0.1	0.4
	0.1	0.1	0.4
	0.3	0.1	0.4
	0.5	0.1	0.4
(D) Moderate burning, moderate mechanical removal	0.05	0.25	0.3
	0.1	0.25	0.3
	0.3	0.25	0.3
	0.5	0.25	0.3

Table 3: Cultural diffusion scenarios. The initial percentage of agents adopting the best practice strategy is varied from 5 to 50 percent in scenarios A-D. The values are percentages of agents adopting a given strategy.

Results

- 4.1** The results are the averages of 30 model runs. Due to the agents' fixed spatial configurations, the model parameters stabilized around 100 time steps; thus, each model was stopped after 100 time steps. In both the rational choice and cultural diffusion cases, Mikania gradually decreases over time, but Mikania decreases slightly more with cultural diffusion. In the rational choice case, most agents select the least costly management strategy (burning) even with observation of their neighbors' strategies (Figure 3, top). In the cultural diffusion case, few agents (10 percent) begin with the best practice management strategy, and this amount is reduced as agents interact and adopt other common strategies (Figure 3, bottom).

Figure 3: Top: change in agents' adoption of Mikania management strategies over time in rational choice model. Bottom: change in number of agents adopting Mikania management strategies over time in cultural diffusion model.

4.2 In the cultural diffusion scenarios, we explore the change in management strategies over time when the percentage of agents initialized with the best practice strategy is altered (see cultural diffusion scenarios in the methods section). In the first analysis, the scenarios outlined in Table 3 were run with the initial amount of Mikania removed (by an agent participating in removal) set to less than 20 percent (Figure 4). Second, the scenarios were run with initial amount of Mikania removed set to greater than or equal to 20 percent (Figure 5). The results revealed a tipping point around 20 percent. With the initial amount removed varied between 0 and 19 percent, Mikania gradually increases over time, while with the initial amount removed varied between 20 and 70 percent, it gradually decreases over time. Regardless of the amount of Mikania initially removed, increasing the percentage of agents adopting the best practice method resulted in Mikania either increasing the least or decreasing the most.

Figure 4: Cultural diffusion scenarios with lower initial Mikania removal. (Mod. = moderate).

Figure 5: Cultural diffusion scenarios with higher initial Mikania removal. (Mod. = moderate).

Discussion

- 5.1** The primary objective of the model analysis was to assess which theoretical perspective of institutional change best fits empirical data on efforts to manage the invasive plant *Mikania micrantha*. The rational choice perspective explored institutional change subject to agents seeking to reduce their costs, while also considering what their neighbors were doing (Figure 3, top). The cultural diffusion perspective examined how institutions gradually shifted over time in response to interactions with other culturally similar agents (Figure 3, bottom; Figure 4 and 5). The model results from these perspectives are largely intuitive based on common pool resource, cooperation, and economics literature but the computational approach allowed us to alter and analyze features of these perspectives such as observation and the initial amount of Mikania removed. We found somewhat counterintuitively that the initial percentage of agents adopting the best practice Mikania removal method was not as important in reducing Mikania spread as the initial amount of Mikania removed (i.e. using any removal strategy was more effective if greater than 20 percent of the Mikania was removed). These results imply that it may be beneficial to conduct a study empirically assessing the impact of the initial amount of Mikania removed on the success of management efforts (i.e. amount of Mikania present a specified time after removal). This seems especially relevant to understand because the best practice strategy for Mikania removal is also the most time consuming strategy. If the success of less time consuming strategies could be increased by initially removing more Mikania, this would be useful information for community forest members in Chitwan allocating their limited time and hoping to maximize the success of their management efforts.
- 5.2** Many of the results from the rational choice case are intuitive from previous research. In particular, the finding that the majority of agents select the least costly common pool resource management strategy (burning Mikania) is consistent with utility-maximizing agents (Figure 3, top). In the cultural diffusion sub-model, the initial percent of agents adopting a given management strategy influenced the change in strategies, via meetings between culturally similar agents. There was variation in agents adopting different types of strategies, as opposed to primarily burning (Figure 3 bottom, 4, 5).

Validation: which perspective better fits empirical data?

- 5.3** To understand which of our theoretical perspectives, rational choice or cultural diffusion, most closely represents data on Mikania management in Chitwan, we compare model results to surveys of households near Chitwan National Park. Fieldwork and an understanding of on-the-ground conditions can be an important indicator of model validity (Ghorbani et al. 2015; Yang & Gilbert 2008).
- 5.4** In the rational choice perspective, most of the agents adopt the least costly strategy (burning). This was not the case in survey data from Chitwan, where only 17 percent of households reported burning Mikania. Based on interviews, discussing burning can be a sensitive subject as some community forests have rules against burning or restrictions on when burning can be conducted. Thus, the actual number of households engaging in burning

is possibly higher than that reported in the household survey, but it is unlikely the percentage of agents engaging in burning reaches the levels in the rational choice sub-model. Consistent with empirical and experimental literature on rational choice and natural resources (Ostrom 2005), it is unlikely that the rational choice sub-model captures how institutional change occurs in Chitwan community forests. People reported engaging in collective action to remove *Mikania* based on their neighbors' decisions or informal social norms that required at least one person from a household to participate. This decision making process is similar to the learning and imitation that is the primary mechanism of change in the cultural diffusion sub-model (as opposed to only partially influencing change, like observation in the rational choice case). Many humans do not conform to the rational actor model (e.g., Richerson & Henrich 2012's review) and humanity's ability to socially learn and imitate is likely what has allowed humans to thrive in changing environmental conditions (Mathew & Perreault 2015). Our survey data are most consistent with the results of the cultural diffusion scenario C, where only 10 percent of agents end with the burning strategy and 3 percent with the best practice method (from the survey, 17 percent burn and no one had yet adopted the best practice method). The observation that the results from the cultural diffusion sub-model better fit empirical data on *Mikania* management indicate that it is a possible mechanism of institutional change in Chitwan, but the results of this model cannot confirm that cultural diffusion is the actual or only way institutions will change over time. The challenges of empirically validating model parameters, like those influencing how *Mikania* spreads, means that our model results should be interpreted with caution, with a focus on the general patterns observed and possibilities identified for future empirical data collection and validation. Next steps include collecting additional data to empirically validate model parameters and comparison of cultural diffusion with other theories of institutional change.

Institutional fit and future directions

- 5.5** In cases where there are historical institutions that exacerbate a newer social-ecological disturbance, implementing best practices for common pool resource management, like monitoring and sanctioning, may not be effective. In Chitwan, the norm of burning for other reasons (i.e. traditional agricultural or forest management practices) is long standing (Nagendra & Southworth 2009), but unintentionally aids in *Mikania* dispersal (Murphy et al. 2013). Because of the relative ease of burning in terms of labor/time compared to other management options, some agents still opt for this strategy even with sanctioning, which contributes to *Mikania*'s continued spread. The case of fit between existing institutions and current social-ecological challenges has been previously addressed (Dietz et al. 2003; Folke et al. 2007; Young 2002), with the conclusion that institutions need to change and evolve to support sustainable governance of the commons. Where existing institutions and new social-ecological challenges conflict, the introduction of outside information may be useful in supporting such governance and change.
- 5.6** In the case of Chitwan and *Mikania*, people engage in burning both because it is a less costly strategy, but also because they believe it will have some level of success in removing *Mikania*. *Mikania* is a relatively new disruption and issues of trust between actors in Chitwan can limit information sharing, resulting in many households and community members lacking access to information on effective removal (Sullivan et al. 2017a). As new disturbances appear as global climate and social structures continue to change, natural and common pool resource management situations may benefit from increased access to new knowledge coupled with implementing best practices. The introduction of new information to communities that are managing their own natural resources, particularly indigenous communities, may not always be welcome due to past experiences with colonialism, paternalistic knowledge imposition, and the disrespect of local ecological knowledge (Gratani et al. 2011; Mazzocchi 2006; Nightingale 2005). Thus, the information provider, an outsider versus a community member, is important (Nightingale 2005). It is also important that the community desires outside information or assistance with assuaging a disturbance or information provided is unlikely to be embraced or implemented. When exogenous institutions are imposed, they may crowd out a community's intrinsic environmental motivation to manage a resource sustainably. In contrast, when endogenous, participatory management norms (established at least partially by community members) are in place, intrinsic environmental motivation can facilitate successful natural resource management (Vallino 2014). This is important to consider in the context of Chitwan when introducing a new management method or other information, including suggestions informed by modeling such as to conduct empirical experiments on initial amount of *Mikania* removed.
- 5.7** Institutions can also change via migration processes, which can introduce new institutions, or shift the composition of existing ones. Migration is an integral part of the history of the Chitwan Valley, with new migrants regularly entering and others emigrating to nearby countries to work and send remittances to family members (Bohra & Massey 2009; Massey et al. 2010). The introduction of new institutions via migration is a process that could be explicitly modeled in future efforts. The model could also be extended to include local specifics (like

geographic information systems data, social networks, etc.) to attempt to explicitly predict *Mikania* distribution in Chitwan or elsewhere. Further, agent-based models have also been designed in a process known as companion or participatory modeling where stakeholders are actively involved in structuring the model from the start to increase its structural validity and community relevance (Moss 2008), which is another potential avenue.

Conclusion

- 6.1** In this research, we assessed an agent-based model to explore how two different perspectives of institutional change fit empirical data in a social-ecological system facing rapid change. Agent-based models can serve as virtual laboratories that simultaneously allow researchers to explore generalizable properties and local implications (Magliocca et al. 2015). In this sense, they can further the study of different theories of institutional change important to natural resource management that would otherwise be challenging to observe and assess. We used survey data to understand the validity of the two perspectives and concluded that (1) it is unlikely the rational choice perspective represents how institutions change in Chitwan over time and (2) it is possible institutional change in Chitwan follows the cultural diffusion perspective, underscoring the importance of social learning in communities faced with variable environmental conditions (Mathew & Perreault 2015). The latter is an important area for further study, especially comparing cultural diffusion to other perspectives of institutional change and analyzing institutional change in other social-ecological systems.

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Appendix: Model details and ODD protocol

Overview

In this appendix, we follow the ODD protocol (Grimm et al. 2010), with a few modifications and additions for coupled human and natural systems (CHANS) based on An et al. (2014), to present details of the agent-based model in the accompanying manuscript.

Purpose

The model is intended to explore how institutions for invasive species management change over time. Two perspectives of institutional change are examined, rational choice and cultural diffusion. The model is informed by data from locally governed community forests in Chitwan, Nepal and seeks to understand how management strategies influence the spread of a rapidly growing invasive plant, *Mikania micrantha*. The primary purpose of this model is to explore which theoretical perspective of institutional change best fits empirical data from Chitwan.

Entities, state variables, and scales

The model is constructed in NetLogo, where spaces are represented as “patches.” Agents are randomly placed on a landscape composed of individual spaces, called patches in NetLogo, and each patch represents one plot within a forest. The landscape is represented by a two-dimensional grid, consisting of 1024 patches. Patch, agent, and global variables are in Table 4.

Agents in the model represent households and the model can be initialized with 100 to 1000 households, which are randomly distributed on the landscape; the baseline is 100 households. Each patch represents an area of community forest land. The patch can either be highly productive to an agent, or completely degraded. Each

patch is invaded by a percentage of Mikania, which varies depending on the set up (gradient distribution versus random distribution; see Table 4). The ranking/ordering of some of the parameters was determined from ethnographic fieldwork conducted in Chitwan in 2014. The model runs indefinitely (no stopping condition), but all simulations were stopped after 100 time steps because outcomes stabilized at this point.

Variable	Features	Explanation
Agent_removed	Initialized to 0 for every agent	Changes to 1 if agent removes Mikania
Num_HH	100-1000 in increments of 50	The number of agents in the model
Mikania_cover	Patch variable; initialized between 0 and 1	A value of zero corresponds to zero percent Mikania, a value of 1 corresponds to 100 percent of the patch being covered with Mikania
Redistribute_Mikania	0-1 in increments of 0.5; Default is 0.1 for pulling/burying, 0.2 for pulling; 0.3 for burning	The higher the parameter, the more likely Mikania will spread; default parameter values were ranked based on discussion with experts; the range allows for sensitivity analysis
Only used in cultural diffusion sub-model		
Number_of_regions	Initial value varies depending on number of features and traits selected	An outcome variable; the number of distinct cultural regions currently in the model
Regions_list		A list of identifiers for each region
Closest-person	Equals the closest agent to the current agent based on agents' x and y coordinates	Used to determine who the agent will evaluate if they interact
Feature_nb		After two agents have interacted, this is used to copy the value of one of the agent's features to the active agent
Overlap		The overlap between two agents, i.e. their similarity. This determines whether the agents will interact and adopt traits
Chosen-feature		The feature that will be adopted by the active agent
New-trait		The feature adopted from the active agent's neighbor
Feature	Initialized as a string of length N ($N = 1$ to 20; number of traits)	Abstract numerical list of the cultural features (including shared strategies and norms) of each agent
Region_id		The region an agent belongs to
Institution_type	Equals 0, 1, 2, 3, or 4, corresponding to the first item in the feature list	Used to track the management strategy the agent has adopted
Featval0	Equals the value of the first item in an agent's feature list (0, 1, 2, 3, or 4)	Used to model the 5 different Mikania management norms and the change in their composition over time
Number_of_traits	Ranges from 1 to 20	The rate of mutation, via random change in features. Set to zero for all model analyses; an area for future exploration
Number_of_Features	Ranges from 1 to 20	
Mutation_rate	Ranges from 0 to 0.1 in increments of 0.0005	
Random_interaction	Ranges from 0 to 100 percent	Set to zero for all model analyses; an area for future exploration
Only used in rational choice sub-model		
Productivity_value	Patch variable; randomly initialized between 0 and 1	A value of 0 indicates the patch is completely degraded/not useful to the agent; the lower the value, the less likely an agent will remove Mikania from the patch
Value_threshold	Each agent is randomly assigned a value between 0 and 1	Used in the cost-benefit analysis; if the value is greater than 0.5, the agent selects a method other than the least costly method
Removal_cost	Initialized at zero, changes as agents make management decisions	Keeps track of the current management strategy an agent has adopted
Removal_list	List containing the possible Mikania removal costs (0.2, 0.3, 0.35, 0.5)	Each removal strategy corresponds to a cost
Three_removal_list	List containing the Mikania removal costs, less burning	Used when excessive burning fee is implemented (can only be implemented when "monitor_and_sanction_burning?" is turned on); agent selects alternative removal method if engaging in removal
Times_burned	0 when simulation begins; updated after agent burns	Count of times agent has burned; used when "monitor_and_sanction_burning?" is turned on
Num_bp	Ranges from 0 to 1	Slider in NetLogo; used to set the initial percentage of agents employing the best practice strategy
Num_nothing	Ranges from 0 to 1	Slider in NetLogo; used to set the initial percentage of agents not engaging in removal

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Variable	Features	Explanation
Num_pull	Ranges from 0 to 1	Slider in NetLogo; used to set the initial percentage of agents employing the mechanical removal strategy
Num_pull_bury	Ranges from 0 to 1	Slider in NetLogo; used to set the initial percentage of agents employing the pulling and burying strategy
Num_burn	Ranges from 0 to 1	Slider in NetLogo; used to set the initial percentage of agents employing burning
Monitor_and_sanction- _burning?	True, False	Button in NetLogo. Turns on/off the monitor and sanction burning procedure
Observe?	True, False	Button in NetLogo. Turns on/off the observe procedure

Table 4: Variables included in the model.

Process overview and scheduling

In each time step, an agent makes decisions about which Mikania management strategy to adopt (including doing nothing). An agent will either enter the rational choice or cultural diffusion sub-model to make this decision depending on which is turned “on” in NetLogo (the sub-models can be controlled using a “button” in NetLogo). The agents only enter one of the decision making sub-models at a time. After making management decisions, the next procedure updates the amount of Mikania in each patch based on the agents’ selected strategies.

Set up

The landscape is represented by a two dimensional grid, consisting of 1024 patches. Each patch has a randomly assigned corresponding ‘productivity value’ ranging from 0 to 1, where 0 represents highly degraded land or land that is otherwise useless to an agent. Each patch additionally has an initial ‘Mikania cover’ value, ranging from 0 to 1, that represents the percent of the patch that is populated with Mikania. The landscape can be setup with a gradient of Mikania cover, with groups of patches initially ranging from 0 to 75 percent cover (0 to 0.75), or with a random distribution of Mikania cover, with each patch randomly assigned a cover value. Conversations with ecological experts working with Mikania data in Chitwan indicated that a gradient of cover more accurately reflects the actual distribution, so it is used as the basis for all analyses presented and discussed.

Remove Mikania

Rational choice

The cost (in terms of time and personal effort) associated with each strategy is ranked based on the ethnographic fieldwork, essentially an ordinal variable. The ordering is consistent with empirical observations, but the distance between the numbers is unknown (i.e. how much costlier it is to conduct mechanical removal versus burning). Because of this, we conducted a sensitivity analysis to explore the impact of different costs for each strategy, while maintaining the ranking of the costs. See Yang & Gilbert (2008) for a conversation on parametrizing qualitative data.

Cultural diffusion

The “Diffusion of Culture” model that this sub-model is based on investigates a variety of variables that influence how quickly culture homogenizes over time, including a rate of mutation and the inclusion of random interactions. In this modification, we focus on tracking the impact of the initial percentage of agents with each Mikania management strategy and do not analyze these additional variables.

Redistributing the Mikania

The values for the rate of increase for each strategy were selected based on a combination of literature and expert opinion. The values for the rate of increase were also systematically varied in the model to explore the impact of different rates and can be adjusted as new information is available. When the Mikania cover of a patch is greater than 0.5, the Mikania from that patch spreads to a neighboring patch.

Design concepts

Basic elements

The model draws on theory from common pool resource and collective action literature, as well as literature on cultural dissemination, cooperation, and social learning (An 2012; Axelrod 1997; Mathew & Perreault 2015; Ostrom 1990). Changes in institutions (shared strategies and norms for Mikania management) influence the amount of Mikania in a given patch, which influences the cost of the agent's actions and future management decisions/institutional change.

Adaptation

In the cultural diffusion sub-model, agents can adopt another agent's Mikania removal strategy if their list of cultural traits are similar. Other adaptation could be possible in future models, but is not currently present. For instance, agents can change their behaviors (their selected removal strategy) in response to others and the environment, but the parameters that determine these behaviors are currently fixed. For instance, an agent's "value threshold" in the rational choice sub-model does not change over time.

Observation

Data are collected for testing and observation using the BehaviorSpace extension in NetLogo (see <https://ccl.northwestern.edu/netlogo/docs/behaviorspace.html> and <https://www.openabm.org/book/3138/how-use-behavior-space>). We observe two primary outcomes: the change in Mikania over time and the change in composition of management strategies over time. The model allows for additional observation of other factors including the impact of a mutation rate and random interactions in the cultural diffusion case. However, these are not explored in this analysis of the model.

Emergence

Changes in the composition of Mikania removal strategies and amount of Mikania emerge over time based on low-level agent interactions and decisions. The agents' interactions and decisions are governed by the sub-model components, either rational choice or cultural diffusion.

Objectives

The objective of the agents depends on the sub-model. In the rational choice case, an agent's goal is to maximize their utility subject to a set of preferences. In the cultural diffusion sub-model, agents do not seek to maximize an objective; they may adopt other similar agent's strategies and norms on the basis of interactions.

Prediction

Agents do not use prediction in their decisions.

Learning

One feature in the rational choice sub-model is "observation." Agents observe their closest eight neighbors when the "observe" feature is turned on and may change their behavior to the most common behavior. In the cultural diffusion sub-model, the implicit mechanism of exchange of norms and strategies between similar, interacting agents is social learning or imitation.

Sensing

Each agent knows their own set of preferences in the rational choice sub-model. Each agent is assumed to know the productivity of each patch. These each inform agent decisions in the model. The agents do not know the total amount of Mikania in the world (global information).

Interaction

In the rational choice sub-model, agents check the behavior of other agents if the observe feature is on. In the cultural-diffusion sub-model, an agent has the opportunity to interact with the closest agent at each time step. If they are similar enough, they will possibly exchange cultural information.

Collectives

There are no collectives in the model.

Initialization

See Table 4 for the values agents and patches are initialized with.

Input data

No input data is used in this model.

Submodels

Both the rational choice and cultural diffusion sub-models are theoretically driven. The parameters for the cost of each of the management strategies in the rational choice sub-model were ranked based on ethnographic fieldwork. The model code is available at <https://www.openabm.org/model/5231/version/1/view>.

CHANS characteristic features

Human-environment systems have been known to exhibit features such as time lags, resilience, heterogeneity, and feedback loops (An et al. 2014). This model exhibits resilience to Mikania reduction beyond specific thresholds (once Mikania takes over the world, it is very difficult to remove or control). There is heterogeneity in the management strategies adopted over time. One of the feedbacks observed in the rational choice sub-model includes the relationship between the selected strategy, Mikania redistribution, and subsequent impacts on agents' strategy selection. For example, an agent may select burning as their removal strategy; burning is associated with the highest rate of Mikania increase in the agent's current patch after removal. If an agent continues to select burning as their removal method due to its low cost, the amount of Mikania in the patch will continue to increase and there will be an additional removal cost to the agent in patches with a density greater than 0.5; if the cost of removal becomes greater than the productivity of the patch the agent may decide to stop removing Mikania (a "do nothing" strategy).

Verification and validation

Model validation is discussed in the accompanying manuscript, with a general discussion here. Following advice from Railsback & Grimm (2011) and An et al. (2005), model validation included checks for structural validity, including conversations with experts, and a comparison of empirical fieldwork and model output. Verification was an iterative process that included a continuous debugging of the model as it was coded, running extreme value tests (where model responses when parameters were set to extreme values were assessed), and sensitivity analyses (assessing how the model responded to small parameter changes). The results of the extreme value tests and sensitivity analysis are largely consistent with our qualitative data and field observations.

The model parameters are primarily informed by previous literature and empirical observations from ethnographic fieldwork conducted in Chitwan in 2014. Although most agent-based models are validated using quantitative data, there has been a growing conversation about the importance of incorporating qualitative data into the model creation and validation processes and several authors have assessed agent-based models informed by ethnographic data (Dean et al. 2000; Agar 2005; Huigen et al. 2006; Yang & Gilbert 2008).

Simulation experiments and sensitivity analysis

Below are results from sensitivity analyses and extreme value tests.

Parameters	Default value	Min, Max	Mikania cover: min, max
Initial-people	100	100, 1000	542.3, 1080.7
Monitor_and_sanction_burning?	False	False, True	542.4, 528.5
Observe?	False	False, True	542.3, 541.4

Table 5: Extreme value tests: Rational Choice.

At $t = 100$, average of 30 runs.

Parameters	Default value	Min, Max	Mikania cover: min, max
Initial-people	100	100, 1000	524.2, 1061.3
Num_bp	0	0, 1	507.8, 524.3
num_burn	0.15	0, 1	527.2, 538.1
Number_of_Features	5	1, 20	546.2, 529.3

Table 6: Extreme value tests: Cultural diffusion.

At $t = 100$, average of 30 runs. To calculate the sensitivity S_x , below, the following formula was used (An et al. 2005; ten Broeke et al. 2016): $S_x = \frac{(\frac{\Delta D}{D})}{(\frac{\Delta I}{I})}$ where I is the value of the independent variable, ΔI is the change in I , D is the value of the dependent variable, and ΔD is the change in D in response to the change in I .

Variable	Default value	Perturbation 50%	+ Change in Mikania cover (number of patches with > 50% cover)	Sensitivity
Initial-people	100	150	4.6	0.006
Initial-mikania	0.3	0.45	2.8	0.004

Table 7: Sensitivity analysis for selected model parameters: Rational Choice.

At $t = 100$, average of 30 runs.

Variable	Default value	Perturbation 50%	+ Change in Mikania cover (number of patches with > 50% cover)	Sensitivity
Initial-people	100	150	1.1	0.001
Initial-mikania	0.3	0.45	1.8	0.002
Num_bp	0	0.05	0.1	0.0001
num_burn	0.15	0.25	2.3	0.003
Number_of_Features	5	8	5.9	0.007

Table 8: Sensitivity analysis for selected model parameters: Cultural diffusion.

At $t = 100$, average of 30 runs.

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