# Actor Resistance Influences Effectiveness of Ostrom's Design Principles for Governing Contested Landscapes

**SIVEE CHAWLA** [iD]

**TIFFANY H. MORRISON** [iD]

**GRAEME S. CUMMING** [iD]

*Author affiliations can be found in the back matter of this article

## ABSTRACT

Ostrom's principles for the effective management of common pool resources emphasize the importance of local participation by affected actors in the design of rules. Principle 3 proposes that including local knowledge will facilitate the creation of effective rules that fit local social and ecological settings. However, the validity of the design principles is challenged in situations of high actor heterogeneity. We used a dynamic, spatially explicit simulation model to test Principle 3 in a simulated peri-urban area of a fast-growing city. In the model, urban actors appropriate land in a peri-urban social-ecological system. Urban appropriation fragments peri-urban ecosystems while reducing land availability for rural activities such as agriculture. We simulated the consequences of individual rural and urban actor decisions on emerging patterns of land-use types, using game theory to quantify competition for land, and metrics of landscape composition and configuration to quantify the impacts of rural resistance on landscape patterns. Landscape metrics relevant to ecosystem service provision (urban patch area, number of urban patches, clumping of urban patches and edge density of urban patches) had a non-linear response to resistance to urbanisation. Our results suggest that a small percentage of resisting rural actors can influence emerging landscape patterns; resistance as low as 10% of the rural population to urbanisation was sufficient to influence the degree of clumping of urban areas. The non-linear and varying response of emerging landscape patterns to conflict among actors, and the presence of tipping points for ecological processes that depend on connectivity or area, can create significant opportunities and challenges for the sustainable governance of land-use change in a spatially dynamic SES. We conclude that efforts to use Ostrom's design principles to manage complex and dynamic landscapes such as peri-urban SESs must account for actor heterogeneity and the potential influence of actor resistance on landscape patterns.

**CORRESPONDING AUTHOR:**

**Sivee Chawla**

ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville 4810, Australia; Horizons Regional Council, Palmerston North, New Zealand

chawlasivee@yahoo.com

## INTRODUCTION

Global sustainability of natural resources depends on effective governance of human impacts on ecosystems (Morrison et al. 2022). Ostrom's design principles (Ostrom, 1990) are often invoked as best practice governance for common pool resources (CPRs), such as water, pastures, and fisheries. One of the main underpinnings of Ostrom's principles was the finding that groups can self-organise to devise effective institutional arrangements for the governance of the commons (Ostrom, 1990; Schlager, 2004). Ostrom identified eight design principles and linked them to social-ecological sustainability through her Social-Ecological Systems (SES) Framework (Ostrom, 2007, 2009). The principles include identifying the boundaries of the system, congruence between rules and local conditions, collective choice arrangements that allow stakeholder participation, effective monitoring by those accountable, punishments with graduated sanctions for the violation of rules, conflict resolution mechanisms, recognized autonomy of institutions, and multiple layers of organization (Ostrom, 1990). The SES Framework thus provides a structured approach for a systematic evaluation of the governance of CPRs, and supports additional empirical studies by describing the interlinkages and causal relationships between social and ecological components involved in CPR management (Binder, Hinkel, Bots, & Pahl-Wostl, 2013; Partelow, 2015).

Traditionally, researchers have applied Ostrom's design principles and the SES Framework to small-scale CPRs for diagnosis, evaluation, and analysis of governance. More recently, the generality of the design principles has inspired analysts to apply them to a wider group of resources and systems of higher complexity (Fleischman et al., 2014; Tyson, 2017; Wilson, Ostrom, & Cox, 2013). These more complex SESs have multiple social-ecological elements beyond those originally envisaged by Ostrom, including extensive resources, trans-boundary governance, and/ or a large number and diversity of actors (Epstein, Pérez, Schoon, & Meek, 2014; Fleischman et al., 2014; Huntjens et al., 2012; Lacroix & Richards, 2015; Villamayor-Tomas, Fleischman, Ibarra, Thiel, & van Laerhoven, 2014). Early results from these larger and more complex applications have raised the important question of whether Ostrom's design principles and SES framework are directly relevant beyond the scope of the small-scale single use resource problems for which they were originally developed (Fleischman et al., 2014; Foster & Iaione, 2019; Wilson et al., 2013). Additionally, researchers have flagged the urgent need to move beyond the saturated focus on collaborative governance rules to understand other important processes, such as appropriation and resistance (Morrison et al., 2020; Murunga, Partelow, & Breckwoldt, 2021).

Peri-urban SESs, which encompass areas at the boundary between city and country, are more than geographic spaces; they contain complex interactions and feedbacks between institutions, biophysical factors and actors (Narain, 2009), serving as important functional spaces for the well-being of urban centres while also supporting rural livelihoods (Narain, 2009; Vij & Narain, 2016). Importantly, peri-urban SESs often exhibit a complex mix of fast-changing urban, rural, and natural land-use land-cover (LULC) types (Ramachandra, Aithal, & Sanna, 2012; Sarkar & Bandyopadhyay, 2013). Transformation of natural and rural LULC into urban land-use has led to a loss of ecosystem goods and services and disruption of ecological processes around the globe (Hedblom, Andersson, & Borgström, 2017; Ravetz, Fertner, & Nielsen, 2013). In Kolkata and Bengaluru, for example, urban authorities have reclaimed wetlands for urban development, which has rendered both cities vulnerable to flooding (Hettiarachchi et al., 2014; Nagendra, Unnikrishnan, & Sen, 2013). Similarly, urbanization and wetland destruction have severely impacted resilience of cities like Florida and Mississippi to sea-level rise and hurricanes (Noss, 2011).

A commons-based approach has been proposed to manage natural resources in peri-urban SESs (Cerquetti, Nanni, & Vitale, 2019; Menatti, 2017; Vij & Narain, 2016). In a peri-urban SES, heterogeneity among actors is recognized as one of the dominant actor group characteristics that influence outcomes, such as urban sprawl (Chirisa, 2010; Magliocca, McConnell, & Walls, 2015). Actors often have conflicting land-use interests, varying socio-economic attributes, and cultural heterogeneity (Gashu Adam, 2020). Local rural actors engaged in farm-related activities, for example, may compete for land with urban actors seeking land for housing or industry. Additionally, governmental policies often support the urbanization of land in peri-urban areas, over-ruling traditional institutions and marginalising the responses of rural actors to land-use transformation (Gashu Adam, 2020; Patil, Dhanya, Vanjari, & Purushothaman, 2018). However, actors in a peri-urban SES can also frequently lack the social cohesion, trust, and reciprocity that are important in developing norms and rules for natural resource governance (Baggio et al., 2016; Vij & Narain, 2016). Yet little is known about how these characteristics influence applications of Ostrom's design principles in commons situations and for large-scale SES such as a peri-urban SES (Poteete & Ostrom, 2004; Vedeld, 2000). Ostrom's third design principle, emphasises collective choice arrangements by participants or actors for effective governance of shared resources (Ostrom, 1990).

Deslatte et al. (2022) have shown that collective choice arrangement influences intensive landscape changes and emerging spatial patterns, thus, the third design principle has particular relevance for peri-urban SESs (Martin, Le Gal, & Choy, 2016; Teklemariam & Cochrane, 2021).

In applying SES theory and Ostrom's third design principle to interactions between heterogeneous actors in spatially dynamic environments such as in urbanizing landscapes, further complexity is introduced by cross-scale and cross-level interactions (such as conflict) among heterogeneous actors at multiple social and spatial scales (Cox, 2008; Ratner, Meinzen-Dick, May, & Haglund, 2013; Robinson, Ontiri, Alemu, & Moiko, 2017, Deslatte et al., 2022). Based on previous observations of emerging land-use patterns and conflicts among actors (Magliocca et al., 2015; Poteete & Ostrom, 2004; Rauws & de Roo, 2011), we hypothesized that the degree to which the responses of rural actors to landscape change coordinated and oppositional would affect decisions made by urban actors; and that the nature of urban-rural interactions could provide a mechanism that determines emerging land-use patterns (and hence, the future provision of ecosystem services and consequent human wellbeing). To test this hypothesis, we used dynamic simulation models to explore the influence of rural-urban interactions on land-use transformations, contrasting our results with a counterfactual in which there was no simulated conflict among urban and rural actors. Due to the anticipated relevance of cross-scale influences, we expected to find both non-random and non-linear relationships between emergent land-use patterns and conflict between rural and urban actors.

## METHODS

We first explain how we related the components of the peri-urban SES to Ostrom's SES framework, and then describe the simulation model followed by experiments and statistical analysis that we used to test our core hypothesis.

### RELATING COMPONENTS OF A PERI-URBAN SES TO OSTROM'S FRAMEWORK

To ground our analysis we developed a spatially explicit simulation model based loosely on peri-urban areas at the periphery of tier-1 Indian cities, such as Bengaluru and Pune, which are experiencing unprecedented urbanization beyond their traditional boundaries following India's independence in 1947, the IT boom in the 1980s, and economic liberalization post 1990 (Patil et al., 2018; Ramachandra et al., 2012). Peri-urban SESs support rural livelihoods and serve as functional spaces for urban wellbeing. The interactions and feedbacks among institutions, environment, and

actors in a peri-urban SES are characterised by rapid land-use changes, multiple and conflicting land use, corrosion of old institutions and not-so-straightforward evolution of new institutions leading to institutional mismatches, over-exploitation and degradation of resources and lack of planned infrastructure development (Mundoli, Manjunatha, & Nagendra, 2017; Narain, 2009, 2021; Patil et al., 2018; Singh & Narain, 2019). The Indian cities exemplify the challenges experienced in governing peri-urban SESs in fast-growing economies in the Global South (Ramachandra et al., 2012), where they have witnessed a continuous evolution of complex social-ecological interactions (Haase, Frantzeskaki, & Elmqvist, 2014; Nagendra & Ostrom, 2014; Ramachandra et al., 2012).

We used Ostrom's SES Framework to identify the components of the peri-urban SES. The SES Framework is a multi-tiered framework with a nested hierarchy of variables (Figure 1). The purpose of the SES Framework is to identify relevant variables that broadly identify components needed to address a research question (McGinnis & Ostrom, 2014).

We related the components of a typical peri-urban SES to the tier one and tier two components of the framework. Moving beyond the limited sectorial focus on watershed management, pastures, and forests, we focus on the terrestrial resource system (RS) which in a peri-urban SES context is a set of interconnected spatial units with multifunctional land-uses (e.g., farming, housing) that provide a variety of ecosystem goods and services that may be potentially conflicting in nature (Wandl, Rooij, & Rocco, 2016).

We mapped the terrestrial resource system (RS) in geographic space using a lattice of 50 × 50 cells of size 200 × 200 m each. Each cell in the lattice represented one resource unit (RU) or a land parcel, with a single LULC type that belonged to one of eight LULC classes based on the system used by the Government of India (NRSC and ISRO 2011) (Figure 2). Groups of contiguous cells of the same LULC type are termed 'patches'.

The governance system (GS) is included in the model as land-use policy. The Government of India's Department of Land Resources proposed a national level Land Utilization policy in 2013, categorising the country into land-use zones based on criteria such as predominant land-use, ecological, and historical importance (Government of India, 2013). Because India is characterised by a federal system of Government, the Land Utilization Policy is an overarching set of guidelines or recommendations to the state governments (government agencies – GS5) that formulate regionally and locally specific land-use policy. In the model, the land-use policy regulates (GS1) land use in a region through a zoning system and management guidance (Barredo, Kasanko, McCormick, & Lavalle, 2003).
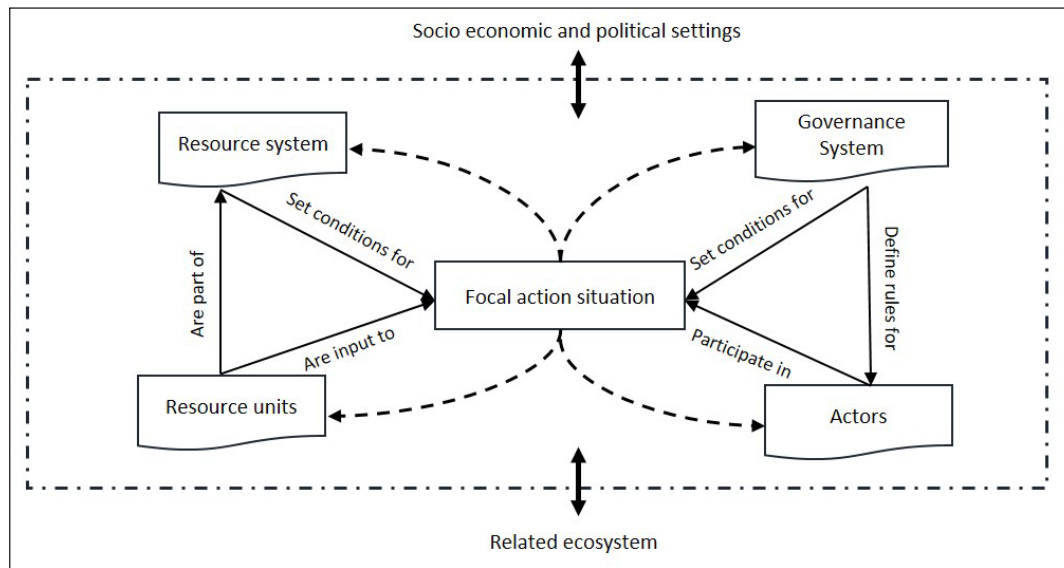
**Figure 1** This diagram shows the first tier of the SES framework, where components of the SES are broadly divided into four subsystems (solid boxes with multiples instances): resource system (RS), resource unit (RU), governance (GS) and actors (A). These components are further unravelled as second tier and third tier variables. The components are linked to and influence each other via a 'Focal Action situation' that includes interactions and outcomes. The exogenous influences from other ecosystems and external social, ecological and political settings are also included that can vary at multiple scale (McGinnis & Ostrom,2014; Ostrom, 2007, 2009).
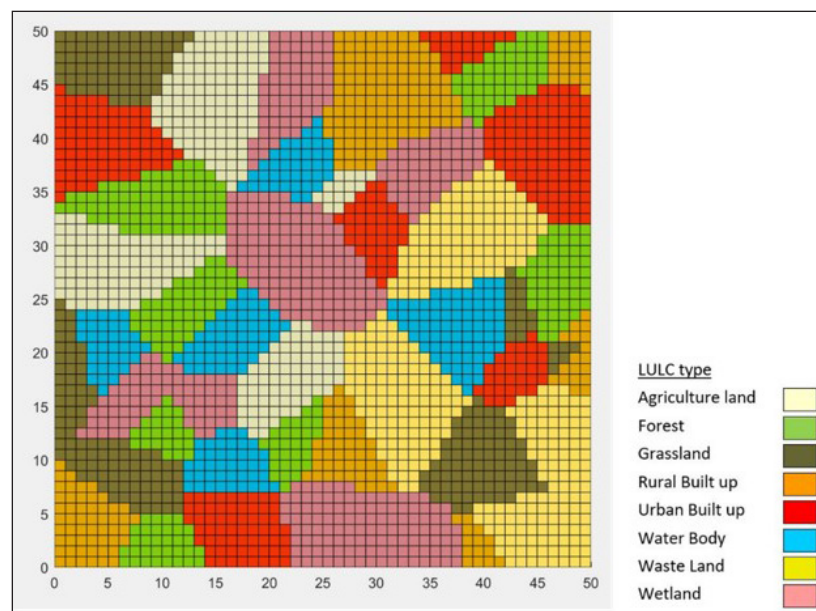


**Figure 2** An example of input simulated image with LULC classification. We defined eight LULC classes-forest, wet land, water body, grassland, rural built-up, agricultural land, wasteland, and urban built-up.

We assigned each cell a land-use zone which identified relevant policy restrictions (see supplement).

In a peri-urban SES, diverse actors depend on peri-urban resources for their livelihoods and/or ecosystem services and goods (Bian, Wang, Wang, Yu, & Qian, 2018). We classified actors into rural or urban actors based on tier-two variables of the SES Framework. These include socioeconomic attributes (A2), geographic location (A4), and importance

of resource (A8). Socio-economic attributes and geographic location are commonly used in India for identifying rural and urban actors (Vidyarthi, Mathur, & Agarwal, 2017). Broadly speaking, we assumed for the purposes of the model that rural actors reside in peri-urban/rural areas before urbanization, have lower population density, and are part of an agrarian-based economy (Purushothaman & Patil, 2017). In the model we also assume that before

urbanization of peri-urban areas begin, urban actors live in more densely populated urban areas and depend on peri-urban areas for ecosystem goods and services such as drinking water and green spaces (Teklemariam & Cochrane, 2021). As urban areas expand beyond the urban periphery, urban actor groups in our simulation gradually appropriate land in peri-urban areas for urban development such as housing, industries, and supporting infrastructure such as roads and highways converting land parcels for urban land-use (Bian et al., 2018).

Rural and urban actors (A8) also differ in their relationships to and reliance on natural resources. Actor resource dependency includes the relationship of actors to their environment, appreciation of ecosystem services provided by the environment, and understanding the impacts of their action on the social and ecological outcomes in the SES (Tidball & Stedman, 2013). In general, rural actors who were already residing in the urban periphery prior to urbanization may have a comparatively stronger association with the SES and a better understanding of social-ecological complexity and the impacts of landscape modification on the outcomes (Beilin, Reichelt, & Sysak, 2013). On the other hand, urban actors are often seen as appropriating resources from peri-urban areas, with limited understanding of SES complexity and the impact of landscape modification on SES outcomes (Bian et al., 2018).

## THE SIMULATION MODEL

We modelled the spread of the urban population into peri-urban areas and the emergence of landscape patterns from choices made at local level by the dominant actor groups in each geographic location (cell). In the model, urban actor groups interact with rural actor groups to appropriate land (used by rural actors) for urban land-use. We developed a spatially explicit simulation model using an adapted reaction-diffusion model to explore SES action situations. We followed ODD + D (Müller et al. 2013) protocol to describe the model (see supplement for the model details).

Reaction–diffusion equations were originally developed in chemistry and then adopted in genetics and ecology to understand the patterns resulting from random, fine-scale movements and interactions of a population in a geographic space (Fisher, 1936; Tilman, Lehman, & Kareiva, 1997). Reaction-diffusion equations have been used more recently by researchers beyond ecology and evolution to explore various diffusive social processes, such as the spatial dynamics of protests (Petrovskii, Alharbi, Alhomairi, & Morozov, 2020) and the propagation of rumours within a social network (Zhu, Tang, & Shen, 2023). A classic reaction-diffusion equation has two main components: a reaction term, and a diffusion term (Cumming, 2002; Kimura,

2014). The reaction term describes population growth within a cell. Once the population reaches a threshold and moves out of the cell, the diffusion term captures the movement of population into other cells; its associated diffusion coefficient controls the ease of movement of the population into other cells (Cumming, Southworth, Rondon, & Marsik, 2012). We have adapted the reaction-diffusion equation to model the spread of urban population into peri-urban areas in a simulated landscape under specified LULC conditions and land use-policies. In addition to the diffusion coefficient, we included a numerically estimated factor (cell score) that used the current state of adjacent cells to influence the direction of movement of urban actors into other cells.

We initialised each cell with LULC classes, Land-Use Zones (LUZ) and a human population (total population, urban population and rural population; Figure 3). In the model, as the urban population increases (due to migration or reproduction) and reaches the carrying capacity of the urban cell, the urban actors occupying the urban cell seek more land for urban land-use outside the cell they occupy. Although real urban populations can move across a range of distances, we restricted the movement of the urban actors to only one of the eight immediate neighbouring cells (Moore's neighbourhood window; Maria de Almeida et al. (2003)) at a given time in order to simulate the effects of local social interactions. In addition, only a fixed percentage of urban actors could move into a neighbouring cell. We have assumed that within a cell, where the urban population is dominant in numbers, majority of the urban actors collectively decide to move out of the cell into one of the neighbouring cells which has the highest score. A score for each cell neighbouring cell is estimated based on based on three factors that combine relevant first-tier variables: land-use zones (LUZ), the neighbourhood LULC information (SC), and the interaction between urban actors who want to appropriate a cell and the population already occupying or using the cell into which urban actors want to move into. We captured the land-use zones by assigning a numerical score, Z, to the different land-use zones. We captured the interaction between actor groups using the Hawk and Dove model (GT) and included the LULC information about the cells in the larger neighbourhood (SI). The model used these three variables to estimate the cell score, D. We designed sub-modules to estimate the three variables LUP, SC and GT using different sub-modules. (See supplement for the details of the variables and the sub-modules).

$$D = Z\left[\lambda(SI) + (1-\lambda)(GT)\right] \qquad (1)$$

The score D was calculated for each of the eight cells in the neighbourhood window and urban actors moved into
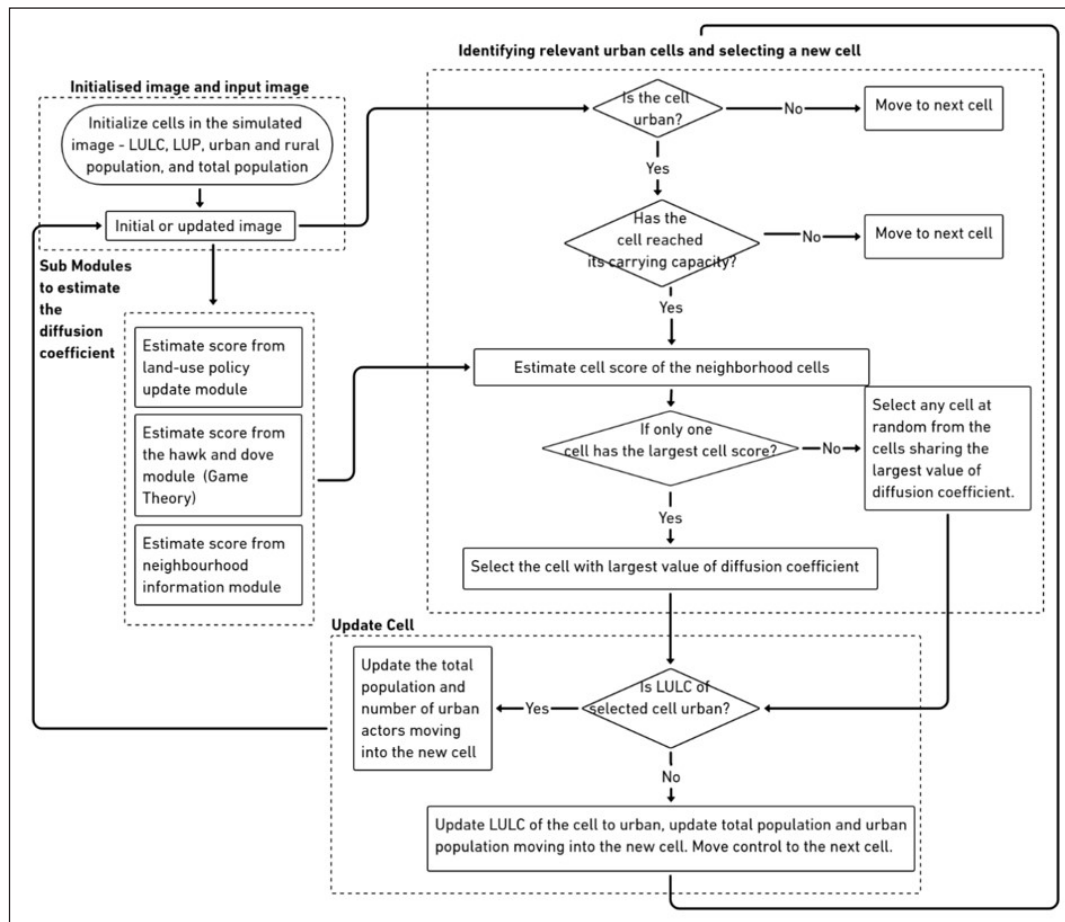
**Figure 3** Flow diagram summarizing the steps followed in the model for urban land-use transformation.

the cell with the highest value of D. For simplicity, it was assumed that the group of urban actors selected only one cell at a time to move into. It is important to note that if a cell into which urban actors group move into was previously a non-urban cell, it was reclassified into urban class, in the model.

We focussed on capturing the interactions among urban actor group within a cell who wanted to appropriate a cell for urban land use and rural actor groups who already were occupying the cell or use the cell for non-urban land use such as for their livelihood; and their influence on emerging landscape patterns, in the presence of other interacting social and ecological components (land-use policies and neighbourhood LULC information). In the model, urban actor groups dominated the urban cells and rural actor group dominated non-urban cells. Ideally, as a local (within-cell) urban population increases, the urban actors collectively decide to occupy a neighbouring ('target') non-urban cell, which then becomes urban. Actor groups in the target cell and urban actor group who seek to occupy the cell collectively decide to permit land-use transformation if the land-use policy allows it. In the model, the rural

actors dominating the target cell can either resist land-use transformation or give up their position as rural actors and allow transformation to occur (for reasons discussed in the Hawk and Dove model below).

We modelled the interactions (resist or comply) between urban and rural actor groups using the Hawk and Dove model from game theory (Maynard Smith, 1974). Game theory in general seeks to explain the formal interactions between players (individuals or groups) in 'game' situations where the actions of the players depend on choices made by others. The aim of each player is to maximize their payoffs, which allow quantitative evaluation of the results of the interactions between players (Krivan & Cressman, 2022). The Hawk and Dove model allows players to select between two behavioural strategies (compete or cooperate), which means that a player in a Hawk and Dove game adopts a strategy to either compete (Hawk) or cooperate (Dove) (Kohli & Haslam, 2017). In the model, if both players adopt the same strategy then both can be hawks and enter combat; both can be doves, a cooperative outcome; or one can be a hawk and the other a dove, leading to different payoffs between players. Payoffs are

assigned based on the outcomes of the strategy adopted by each player. However, in social science a game can be played as a two part game where first part is individual choice part followed by a collective choice part (Margreiter, Sutter, & Dittrich, 2005). In this paper, the individual choice part is implicit and we explicitly focus on the collective choice part where the game is played between urban and rural actor groups and not as individual actors as players.

In the model, the game of cooperation and conflict was played between the actor groups at the cell level (where actors in each cell could adopt either a hawk or a dove strategy). The dominant kind of actor (rural or urban) in each cell made the decision to adapt a particular strategy for that cell. The Hawk and Dove model allows both rural and urban actor groups within a cell to adopt same (Hawk-Hawk or Dove-Dove) or different strategies (Hawk-Dove and vice-versa) which allows actors to have multiple combinations of strategies. In the model, we assumed that an urban Hawk seeks to acquire land parcels for urban land-use (Xie & Wu, 2019). An urban Dove avoids conflict with rural actors and mutually decides not to appropriate a cell for urban land-use. In real-world peri-urban areas of the Global South, there are various reasons (such as value systems, lack of sufficient alternative jobs and skills, and a sense of security) why rural actors may not be ready to give up their land. We categorised those rural actors who resisted land-use transformations (e.g., by refusing to sell their land or staging protests (Tyson, 2017; Vidyarthi et al., 2017)) as rural Hawks. In the model, a cell in which the dominant rural population adopted a Hawk strategy was a rural Hawk. Rural Doves corresponded to cells that were occupied by rural actors who were ready to give up land and comply with an urban Hawk to allow land-use change (either because of shift in environmental conditions that longer support rural livelihood such as farming, or change in institutional drivers such as change in land management or economic reasons such as higher opportunity cost of giving up the land (Vidyarthi et al., 2017)). For simplicity, we implemented the traditional, symmetrical Hawk and Dove model. It can be further adapted as an asymmetric Hawk and Dove model, where the probability of winning or losing between Hawks and Doves will not be same, allowing the scenario to be more realistic and adding to the scalability of the model (Krivan & Cressman, 2022).

## EXPERIMENTAL DESIGN

We developed a simulated dataset of 100 land cover images using the NLMR package in R (Sciaini, Fritsch, Scherer, Simpkins, & Golding, 2018). We limited the size of images to 50 × 50 cells of 200 m × 200 m each, due to computational limitations. We kept the number of classes

and level of heterogeneity constant and randomly assigned a patch size and distribution to all 100 images.

To explore the impact of the response of the rural actors on resulting land-use patterns, we fixed the strategy for urban actors to urban Hawk and changed the strategy of rural actors in discrete steps by adjusting their level of resistance to urbanisation. We defined the level of resistance as the percentage of cells with rural population resisting the change (i.e., the percentage of rural Hawks). We assigned a strategy to all non-urban cells irrespective of their spatial location. The level of resistance ranged from 1 to 10 with a step size 1. Each level represented the percentage of rural Hawks. For example, Level 1 implied 10% rural Hawks, level 2 as 20% rural Hawks, and level 10 as 100% rural Hawks. We also included level zero, with no rural Hawks. Because Hawks pay a cost for fighting against other Hawks in a Hawk and Dove model (Nowak & May 1992), urban Hawks received a lower payoff when urban Hawks fought against rural Hawks and a higher payoff when they fought against rural Doves.

We ran the model for all simulated images over 150 iterations (where one iteration can be thought of as being one year) for all 11 resistance levels (from 0 to 10). Each simulated image corresponds to one model run, therefore, we ran multiple model runs for the same combination of parameters. We calculated the mean and standard deviation of the resultant values such as number of urban cells at each time step and value of landscape metrics used for reporting the results (see figure c1, supplement). We used the average value of landscape metrics for statistical analysis (for example, in Table 2).

As the model is run in a finite space, the landscape reaches a saturation point after which the total urban area does not change significantly. We estimated the saturation point using the *findchangepts* function of Matlab (MATLAB, 2016) on a plot of time against landscape change, using the iteration when the slope of the curve depicting the number of urban cells first shifted, and calculated landscape configuration and composition metrics for the entire landscape at this point.

## LANDSCAPE METRICS

Land-use policies will ideally seek to support a sustainable peri-urban landscape with appropriately distributed land uses (Botequilha Leitão & Ahern, 2002). Land-use transformation should serve economic needs while maintaining natural resources and providing benefits to society. Change in land parcels is spatially interdependent, and the resulting spatial patterns that emerge at broader scales (e.g., green space area and connectivity) influence social-ecological processes and resulting ecosystem goods

and services (Banerjee, Crossman, & de Groot, 2013; Cumming et al., 2012).

The relationships between the maintenance of ecological processes (e.g., carbon storage, dispersal, nutrient cycling) and the spatial characteristics of a landscape (e.g., patch size, distance from other patches, and patch complexity) are well documented (Campos, Rosas, de Oliveira, & Gomes, 2013; Turner & Gardner, 2015). We thus used standard landscape ecology measures of the areas of different land-uses (composition), and their shapes and relative positions to one another (configuration) (Turner & Gardner, 2015). The landscape ecology measures or metrics (Table 1) indirectly evaluate the impacts of urbanisation policies on ecosystems, ecosystem service provision, and social-ecological sustainability (Botequilha Leitão & Ahern, 2002). In general, we assumed that larger and more connected patches of natural habitat will make a stronger contribution to the conservation of biodiversity and maintenance of ecological function.

## STATISTICAL ANALYSIS

We first tested whether differences in the landscape patterns resulting from various level of rural resistance were a result of a random process or not. We used null models to test this hypothesis. Null models exclude a mechanism or process of interest, acting as a counterfactual (Gotelli & Graves, 1996). For the null model, we used the case when there was no resistance at all from the rural actors to land use transformations, which was at level 1 where the number of rural Hawks were 0. We used t-tests and estimated p-values to compare the result of landscape metrics for the null model to those from different levels of resistance.

We then tested for an effect of confounding variables that might influence both the emerging landscape patterns and the level of resistance. In theory, this could distort the true relationship between the response variable (landscape metrics) and the predictor variable (the level of resistance). Urbanization and changes in landscape metrics are interconnected (Yi et al., 2021) and the rate of urbanization may influence the results of the model. We checked for an influence of rate of urbanization on the relationship between landscape metrics and levels of resistance using linear regression (Pourhoseingholi, Baghestani, & Vahedi, 2012).

We estimated the rate of urbanization by calculating the slope of the line representing the number of urban cells from zero iterations to the iteration at the saturation point for all levels of resistance. We then checked for an effect of the potential confounding variable (the rate of urbanization) by estimating the change in variance before and after including it (see supplement).

To explore the impacts of our parameters on model outcomes, we first calculated the mean value of landscape metrics estimated from all 100 images. We fitted standard curves (power, log, logistic and exponential) on the mean values of the resistance level 1 to 10 using the *nls* function in R and selecting the best-fit curve using AIC (Akaike's Information Criterion) and log-likelihood. Lower AIC values indicate a better fit; for log-likelihood, the opposite applies. We estimated the inflection point for each curve using the R function *bese* (library: inflection) (Christopoulos, 2019) to determine where landscape composition was most sensitive to changes in other parameters (Frazier & Wang, 2013).

P-values doesn't have much significance in simulation models unless accompanied by the effect size, therefore, we have included both p-values and the effect size in our results as some readers may still want to know the p-values (White et al., 2014). In the analysis, we have used effect size to explain the significance of the results both for the null model and for the goodness fit for the resulting

| NAME OF LANDSCAPE METRIC | SPATIAL LEVEL | DESCRIPTION |
|---|---|---|
| Number of urban cells | Class | Total number of urban cells in a landscape |
| Total Urban Patch Area (PA) | Class | Total area occupied by the urban class |
| Number of urban patches (NP) | Class | Total number of urban patches |
| Edge Density (ED) | Class | Measure of shape complexity of the resulting urban patches |
| Clumpy Index (CLUMPY) | Class | Aggregation measure independent of landscape composition |
| Aggregation Index (AI) | landscape | Aggregation measure |
| Mean Fractal Dimension index (FRAC_MN) | landscape | Shape complexity measure based on perimeter-area relationship. |

**Table 1** Spatial configuration and composition metrics used to describe outcomes. Cells in the following table correspond to the smallest unit in the image and patch refers to a homogenous area in the landscape which differs from its surroundings. A patch is a non-linear group of contiguous cells belonging to the same class (Turner & Gardner, 2015).

landscape metrics. Effect size gives the measure of the magnitude of the relationship between the two variables of interest (Borenstein 2009). We used Cohen's d coefficient to report the effect size of the null model analysis, where the effect size is interpreted as large (d = 0.8), medium (d = 0.5) and small (d = 0.2) (Baguley 2009). For non-linear models, it is not straightforward to estimate a standardized effect size and therefore, effect size indices are approximated from the test statistics (Friedman 1982). We reported the effect size of coefficients of the fitted model estimated from t-values.

## RESULTS

### NUMBER OF URBAN CELLS AND THE SATURATION POINT

The results in Figure 4 highlight the effect of resistance by rural actors to the decisions made by urban actors as a function of degree of resistance. Urbanization happened faster for a low resistance level than for a higher resistance level. In 25 years, more than 60% of the total area was urbanized at resistance level 1 but only 18% of the total
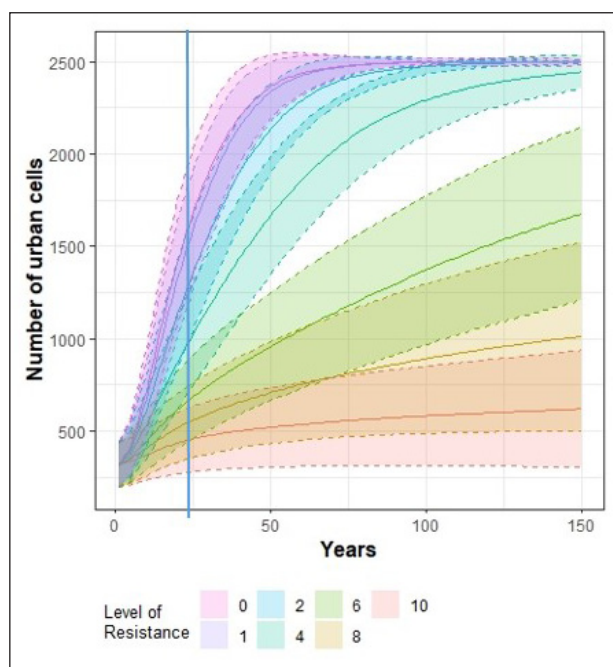


**Figure 4** Number of urban cells occupied at every iteration. For the purpose of clarity, we only include every alternate level of resistance. Blue line at year 24 marks the saturation points for level 1. We take the saturation point of level 1 as the point of references for the landscape metrics. Thick curved lines represent the average value of amount of urban cells for each level of resistance and dotted lines represent the variation (standard deviation) for all 100 images.

area was covered by urban cells at resistance level 10. Urbanization was most rapid when there was no resistance from the rural actors (a condition for the null model). Under these conditions, about 70% of cells were urban in 25 years.
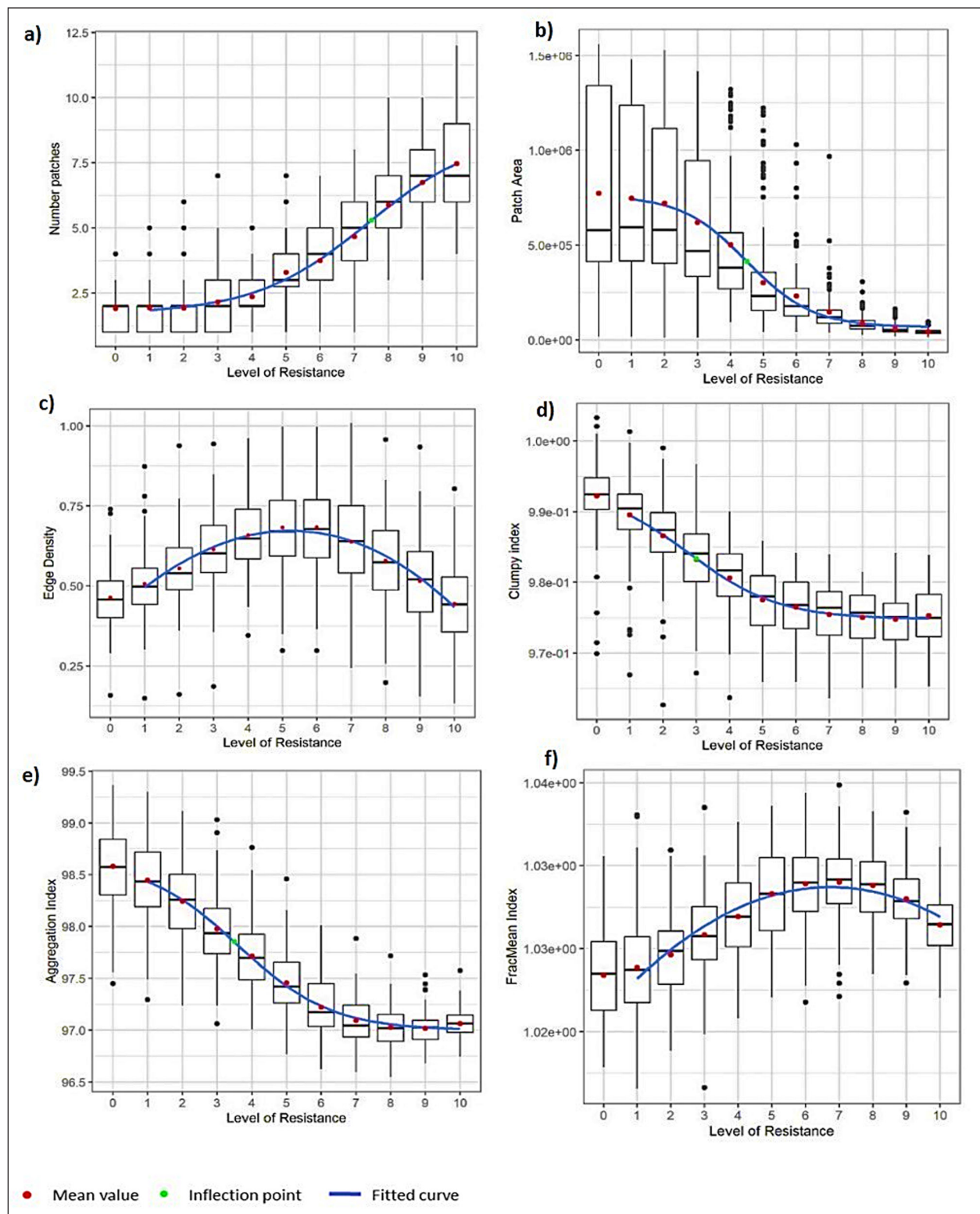
### LANDSCAPE METRICS
The response of the landscape metrics to varying the level of resistance suggested that rural-urban conflict can have a strong and statistically significant effect on emerging land-use patterns (Figure 5). For all six landscape metrics the relationship was significant (p < 0.05), with $r^2 > 0.9$ across the mean values for different level of resistance (Table 2). This was also confirmed by the effect size of the coefficients, which was large (>0.5) for almost all coefficients.

A two-sample t-test comparing the results of null-model and resistance levels 1 to 10 indicated that the response of all six landscape metrics was not random (p < 0.05). Interestingly, the resistance level after which the result of the t-test was significant varied for each landscape metric (Table 2). For example, the number of urban patches and total urban patch area became non-random once the percentage of resisting rural actors reached 40%. For spatial configuration metrics (i.e., clumpy index, edge density, mean fractal dimension index, and aggregation index) the emerging patterns were significant at lower percentage of rural hawks (<20%), suggesting that actor conflict has a stronger influence on landscape configuration than landscape composition. The effect size and Cohen's d value shows the magnitude of effect of resistance on respective landscape metrics compared to the null model. The result of effect size varied for each landscape metrics, for example, for clumpy index and aggregation index the effect size was large (>0.8) at relatively lower percentage of rural hawks (>20%) whereas for patch area of urban cells effect size was large at relatively higher percentage of rural hawks (>40%).

Total urban patch area and clumpy index among urban patches followed a steeply negative logistic curve with a clear inflection point between levels 4.5 and 3. As the total urban patch area increased, the urban patches coalesced, and the number of urban patches decreased. The number of patches was lower at lower resistance and increased with an increase in resistance following a logistic curve. The quadratic curve of edge density indicated that a small change in the resistance lead to significant changes in the shape complexity of the urban patches. The landscape-level metrics also followed a non-linear trend. The aggregation index followed a reverse logistic curve and mean fractal dimension followed a quadratic curve.

Upon correcting for the influence of potentially confounding variables on the curves, we found that the

**Figure 5** Response of six landscape metrics to the varying level of resistance. (a) to (d) are class level metrics including **(a)** number of urban patches, **(b)** patch area, **(c)** edge density and **(d)** clumpy index showing the pattern in the urban class. **(e)** Aggregation index and **(f)** frac_mean index are landscape level metrics showing patterns at the landscape level.

effect of rate of urbanization on landscape pattern was insignificant ($r^2$ <0.04). In addition, the significance of x and its power variants were still significant (p value <0.05). We therefore did not include the potentially confounding variables in the curve fitting process (see supplement).

| LANDSCAPE METRICS | EQUATIONS (X IS THE RESISTANCE LEVEL) | $R^2$ VALUE | COHEN'S d | RESISTANCE LEVELS (T-TEST, INFLECTION POINT) |
|---|---|---|---|---|
| Number of urban patches | $\dfrac{26.7127}{1+20.42e^{(-0.2106x)}}$ | 0.9864 | d (26.7127) = 0.97, d(20.42) = 0.66, and d (–0.2106) = 0.95 | 4,7.5 |
| Total area of urban patches | $\left(\dfrac{6.961\times10^5}{1+e^{x-4.493}}\right)+67230$ | 0.9 | d (6.961 × 10⁵) = 0.69, d(–4.493) = 0.54, and d(67230) = 0.61 | 4,4.5 |
| Edge Density | $-0.0067x^2 + 0.09453 + 0.4086$ | 0.9802 | d(–0.0067) = –0.34, d(2) = 0.92, d(0.09453) = 0.81, and d(0.40862) = 0.98 | 2, Inflection point doesn't exist for a quadratic curve. |
| Clumpy index | $\left(\dfrac{0.0186}{1+0.13e^{-0.735x}}\right)+0.975$ | 0.9846 | d (0.0186) = 0.98, d(0.13) = 0.97, d(–0.735) = 0.72, and d(0.975) = 0.99 | 1,3 |
| Aggregation Index | $\left(\dfrac{1.63}{1+0.068e^{-0.746x}}\right)+96.99$ | 0.9977 | d(1.63) = 0.99, d(0.068) = 0.71, d(–0.74) = 0.97, and d (96.99) = 0.99 | 2,3.5 |
| Mean Fractal Dimension index | $-0.00017x^2 + 0.00226x + 1.026$ | $R^2 = 0.9442$ | d(0.00017) = 0.95, d(.002261) =0.96, d(2) = 0.91, and d(1.026) = 0.99 | 2, Inflection point doesn't exist for a quadratic curve. |

**Table 2** Curve fitted to the mean value of all six landscape metrics and the corresponding statistics. $R^2$ describes the proportion of variance explained by the curve and Cohen's d measures the effect size. There are two resistance levels given in the last column. The first value is the resistance level at which the t-test value was significant and second value of the resistance level which correspond to the inflection point for each curve. For the goodness of fit measures, see supplement.

## DISCUSSION

Our analysis shows that rural-urban interactions can influence landscape spatial composition and configuration strongly and non-randomly. The results further suggest that landscape composition has a non-linear response curve relative to the level of conflict or resistance between actors with different goals. This non-linearity arises because the impact of interaction among rural and urban actors on the landscape patterns is not a process of simple aggregation; other contextual components of the SES also influence the dynamics of the system (Rauws & de Roo, 2011).

Although they share a generally non-linear response, individual characteristics of landscape pattern responded differently to different levels of resistance. For example, both clumpy and total urban patch area decreased with increase in resistance level; but the inflection point for the clumpy index was at resistance level 3, whereas for urban patch area it was at resistance level 4.5. Further, for the clumpy index, the outcome was significant at all levels of resistance when compared to the null-model for all 100 images and the magnitude of significance increased from resistance level 2 (Cohen's d value >0). For the urban patch area, resistance from the rural actors was significant only after resistance level 3 and became largely significant after level 4 (Cohen's d value >0.8). The different inflection points and varying response curves of each landscape metrics suggest that different stages of conflict may influence landscape patterns (and related ecological processes and benefits to people) differently. For example, the clumpy index (low inflection point) was more sensitive to conflict among actors than the number of patches (high inflection point), with relevance for local meta-populations of plants and animals that are likely to require both connectivity and sufficiently large, reservoir patches for persistence.

In the model, an increase in the level of resistance from rural actors implies that urban actors have access to fewer non-urban cells to appropriate and transform. This is evident from the amount of urbanization. Urban actors could still transform some cells even when all rural actors resisted (level 10) because urban and rural hawks had an equal probability of winning. A decrease in urban patch area at higher levels of resistance further confirmed the influence of resistance among actors on urbanization, and increases in the number of urban patches as the resistance level increased reduced connectivity among urban patches (Elmi, Rouhani, & Keshavarz, 2022), (Ramachandra et al., 2012). Patchy urban areas imply mixed urban-rural land-use, which may contribute to lower levels of air pollution (Huang et al., 2021); mixed urban land-use with extensive green space, together with more complex interleaving of urban patches and green spaces, can reduce the particulate matter concentration (PM2.5) in the atmosphere. Since the complexity and aggregation of urban patches was highest when the level of resistance was between levels 5 and 6, when half of the total rural actors resisted land-use transformation, an implied outcome is that landscape patterns resulting from varying levels of resistance may have different implications for processes relevant to ecosystem services and human wellbeing in a landscape.

Models play an important role in theoretical investigations and extending SES theory (Cumming, 2011) by allowing analysis of interactions between one or more subsystems in a simplified yet systematic manner (Ostrom 2005). To explore mechanisms a model should be well formulated and clear; ideally, it should be as simple as possible for the problem being addressed, with a limited number of variables and parameters (Cumming, Southworth, Rondon, & Marsik, 2012; Gotelli & Graves, 1996). Our model, like other simulation models, had its limitations. In the model, we focussed on the response of the rural actors irrespective of their spatial context. In this paper we used a simplified scenario where we broadly classified people into urban and rural actors that take decisions at the cell level. In a real-world peri-urban SES the scenario is much more complex; for example, choices of actors may vary along a rural-urban continuum where the gradient itself is not fixed (Vidyarthi et al. 2017, Murali et al. 2019). For clarity we also focussed on design principle 3 in this analysis, although the Hawk and Dove model can be easily extended to include other design principles (e.g., by varying the strategy of the actors if any sanctions are in place). In addition, the peri-urban SES with a terrestrial resource system is a complex, multi-use resource system with diverse actors and institutions in place; to address such systems, more complex approaches such as nested governance arrangements are recommended (Unnikrishnan et al, 2023).

Our findings raise some challenges for the use of Ostrom's design principle 3 in peri-urban environments and other highly heterogeneous and fluid environments. Heterogeneity among actors can undermine collective action in ways that influence landscape composition and configuration at different stages of conflict, with a wide range of potential impacts on ecological processes such as the movement of organisms, spread and impact of natural disturbances (e.g., fire, disease, flooding), and nutrient distribution (Turner & Gardner, 2015) that underpin or influence different ecosystem services and flows (Banerjee et al., 2013). As the level of resistance to urbanisation in our model increased, different ecological processes (and eventually associated ecosystem services and flows) would have been affected at different levels. Although the peri-urban area of the city functions at least partly as a commons system, there is a considerable amount of private ownership and often strong vested interests. Consultation with local stakeholders to develop appropriate rules for ensuring an ecologically sustainable rural-urban transition is not guaranteed to identify ideal rules for governance, particularly in light of likely power, education and wealth differentials, and other demographic differences between urban and rural inhabitants (Teklemariam & Cochrane, 2021).

Although the latest wave of privatisation of rural and agricultural land en masse has gained global attention under the new critique of 'land grabbing' (Hettiarachchi, Morrison, & McAlpine, 2019; Teklemariam & Cochrane, 2021), detailed study of appropriation and resistance in peri-urban SESs remains comparatively sparse. Individual actors who share common goals, sentiments and demands across space-time can act autonomously over various points in time and enforce transformative changes for natural resource management (Ernstson, 2011). For example, in Stockholm, actors joined hands to enforce the establishment of a National Urban Park (Ernstson, 2011). However, conflicts (such as socio-economic and cultural differences) among actor groups can also hamper collective action efforts for sustainable resource management (Murunga et al., 2021). For example, in the urbanizing landscape of Bengaluru, many previously used commons such as lakes are becoming unavailable to rural actors who depend on them for their livelihoods and day-to-day activities, resulting in conflicts, encroachment, and urban sprawl (Unnikrishnan, Mundoli, Manjunatha, & Nagendra, 2016). Even in our very simple model the non-linearity and presence of inflection points in landscape metrics, together with variation in landscape pattern responses for the same level of resistance, imply that the extrapolation of interactions across scales is not straightforward. Local (cell-level) interactions between heterogeneous actors can create a complex aggregation process at the landscape level, raising significant challenges for sustainable land-use management at broader scales (Milkoreit et al., 2018; Turner & Gardner, 2015). Degradation of traditional institutions around the commons, overlap and/or gaps in policy, and the influx of actors (formal and informal) with little or no connection with existing social-ecological interdependencies require explicitly recognizing cross-scale interactions (Cox, 2008; Mundoli et al., 2017; Unnikrishnan et al., 2016). Further, identifying inflection points using models can help in diagnosing the threshold and tipping points to explore transition pathways that can contribute to the development of strategies in spatially dynamic landscapes (Mathias et al., 2020; Milkoreit et al., 2018).

Ostrom's design principles can provide a systematic, structured framework for governing the use of common property resources (Fleischman et al., 2014), especially when top-down approaches for natural resource governance are ineffective in controlling ecological degradation (Haase et al., 2014; Okpara et al., 2018; Vij & Narain, 2016; Zhang, de Roo, & Rauws, 2019). However, there are gaps in understanding and operationalizing the design principles in the context of spatial relationships and managing the ways in which local interactions scale up to produce regional patterns, as in the case of urbanizing landscapes (Foster &

Iaione 2019, Myers 2020). Our analysis show how exploring the consequences of simple assumptions for a spatially dynamic landscape and urbanizing areas can guide policy decisions, linking heterogeneous local stakeholders to broader institutional context by evaluating the outcomes of conflict across scale (Ratner et al., 2013). In addition, we explicitly link ecological components and land use dynamics to the design principles and SES theory in this paper, contributing to filling the gap in land use change studies trying to explain the interplay between ecological component and social components (Meyfroidt et al. 2018, Turner et al 2012, Turner et al. 2020). Operationalizing Ostrom's design principles for a commons-based approach for governing resources in a spatially dynamic SES – such as an urbanizing landscape – will require further work to understand highly heterogeneous groups of actors and explicitly recognize potential conflicts amongst those involved in the decision-making process. We hope that our approach has provided the building blocks for doing so.

## ADDITIONAL FILES

The additional files for this article can be found as follows:

- **Supplement.** Supplementary file describing the landuse policy and zones in detail, model as per ODD+D protocol, sub the modules and supplementary results. DOI: https://doi.org/10.5334/ijc.1242.s1
- **Appendixes B and C.** Figures and equations for supplementary file. DOI: https://doi.org/10.5334/ijc.1242.s2

## ACKNOWLEDGEMENTS

## FUNDING INFORMATION

## COMPETING INTERESTS

The authors have no competing interests to declare.

## AUTHOR AFFILIATIONS

**Sivee Chawla** orcid.org/0000-0001-8565-1037
ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville 4810, Australia; Horizons Regional Council, Palmerston North, New Zealand

**Tiffany H. Morrison** orcid.org/0000-0001-5433-037X
ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville 4810, Australia; School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Australia; Environmental Policy Group, Wageningen University and Research, the Netherlands

**Graeme S. Cumming** orcid.org/0000-0002-3678-1326
ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville 4810, Australia; Oceans Institute, University of Western Australia, Perth, Australia

## REFERENCES

Baggio, J. A., Barnett, A. J., Perez-Ibarra, I., Brady, U., Ratajczyk, E., Rollins, N., … Janssen, M. A. (2016). Explaining success and failure in the commons: the configural nature of Ostrom's institutional design principles. *International Journal of the Commons, 10*(2). DOI: https://doi.org/10.18352/ijc.634

Baguley, T. (2009). Standardized or simple effect size: what should be reported? *Br J Psychol, 100*(Pt 3), 603–17. Epub 2008 Nov 17. PMID: 19017432. DOI: https://doi.org/10.1348/000712608X377117

Banerjee, O., Crossman, N. D., & de Groot, R. S. (2013). Ecological Processes, Functions and Ecosystem Services. In *Ecosystem Services in Agricultural and Urban Landscapes*. DOI: https://doi.org/10.1002/9781118506271.ch2

Barredo, J. I., Kasanko, M., McCormick, N., & Lavalle, C. (2003). Modelling dynamic spatial processes: simulation of urban future scenarios through cellular automata. *Landscape and Urban Planning, 64*(3), 145–160. DOI: https://doi.org/10.1016/S0169-2046(02)00218-9

Beilin, R., Reichelt, N., & Sysak, T. (2013). Resilience in the Transition Landscapes of the Peri-urban: From 'Where' with

'Whom' to 'What'. *Urban Studies, 52*(7), 1304–1320. DOI: https://doi.org/10.1177/0042098013505654

Bian, Z. X., Wang, S., Wang, Q. B., Yu, M., & Qian, F. K. (2018). Effects of urban sprawl on arthropod communities in peri-urban farmed landscape in Shenbei New District, Shenyang, Liaoning Province, China. *Sci Rep, 8*(1), 101. DOI: https://doi.org/10.1038/s41598-017-18474-9

Binder, C. R., Hinkel, J., Bots, P. W. G., & Pahl-Wostl, C. (2013). Comparison of Frameworks for Analyzing Social-ecological Systems. *Ecology and Society, 18*(4). DOI: https://doi.org/10.5751/ES-05551-180426

Borenstein, M. (2009). Effect sizes for continuous data. In H. Cooper, L. V. Hedges, & J. C. Valentine (Eds.), *The handbook of research synthesis and meta-analysis* (pp. 221–235). Russell Sage Foundation.

Botequilha Leitão, A., & Ahern, J. (2002). Applying landscape ecological concepts and metrics in sustainable landscape planning. *Landscape and Urban Planning, 59*(2), 65–93. DOI: https://doi.org/10.1016/S0169-2046(02)00005-1

Campos, P. R., Rosas, A., de Oliveira, V. M., & Gomes, M. A. (2013). Effect of Landscape Structure on Species Diversity. *PLoS One, 8*(6), e66495. DOI: https://doi.org/10.1371/journal.pone.0066495

Cerquetti, M., Nanni, C., & Vitale, C. (2019). Managing the landscape as a common good? Evidence from the case of "Mutonia" (Italy). *Land Use Policy, 87*. DOI: https://doi.org/10.1016/j.landusepol.2019.104022

Chen, Y. (2009). Spatial interaction creates period-doubling bifurcation and chaos of urbanization. *Chaos, Solitons & Fractals, 42*(3), 1316–1325. DOI: https://doi.org/10.1016/j.chaos.2009.03.022

Chirisa, I. (2010). An Analysis of the Environmental Stewardship Concept and Its Applicability in Peri-Urban Towns: Lessons from Epworth In Zimbabwe. *Journal of Sustainable Development in Africa, 12*(4).

Christopoulos, D. T. (2019). inflection: Finds the Inflection Point of a Curve. Retrieved from https://CRAN.R-project.org/package=inflection

Cox, M. (2008). Balancing accuracy and meaning in common-pool resource theory. *Ecology and Society*. DOI: https://doi.org/10.5751/ES-02683-130244

Cumming, G. (2002). Habitat shape, species invasions, and reserve design: Insights from simple models. *Conservation Ecology, 6*(1). DOI: https://doi.org/10.5751/ES-00373-060103

Cumming, G. S. (2011). *Spatial Resilience in Social-Ecological Systems*. 1st Edition. (pp. 243). Springer Publishing.

Cumming, G., Southworth, J., Rondon, X. J., & Marsik, M. (2012). Spatial complexity in fragmenting Amazonian rainforests: Do feedbacks from edge effects push forests towards an ecological threshold? *Ecological Complexity, 11*, 67–74. DOI: https://doi.org/10.1016/j.ecocom.2012.03.002

Deslatte, A., Szmigiel-Rawska, K., Tavares, A. F., Ślawska, J., Karsznia, I., & Łukomska, J. (2022). Land use institutions and social-ecological systems: A spatial analysis of local landscape changes in Poland. *Land Use Policy*, 114. DOI: https://doi.org/10.1016/j.landusepol.2021.105937

Elmi, M., Rouhani, A., & Keshavarz, E. (2022). Landscape Metrics for Urbanization and Urban Land-Use Change Monitoring from Remote Sensing Images: A case of Shiraz Metropolis, Iran. *International Journal of Earth Sciences Knowledge and Applications, 4*(1).

Epstein, G., Pérez, I., Schoon, M., & Meek, C. L. (2014). Governing the invisible commons: Ozone regulation and the Montreal Protocol. *International Journal of the Commons, 8*(2). DOI: https://doi.org/10.18352/ijc.407

Ernstson, H. (2011). Transformative collective action: a network approach to transformative change in ecosystem-based management. In Ö. Bodin & H. C. Prell (Eds.), *Social Networks and Natural Resource Management: Uncovering the Social Fabric of Environmental Governance*. Cambridge University Press. DOI: https://doi.org/10.1017/CBO9780511894985.012

Fisher, R. A. (1936). The wave of advance of advantageouse genes. *Annals of Human Genetics, 7*, 15. DOI: https://doi.org/10.1111/j.1469-1809.1937.tb02153.x

Fleischman, F. D., Ban, N. C., Evans, L. S., Epstein, G., Garcia-Lopez, G., & Villamayor-Tomas, S. (2014). Governing large-scale social-ecological systems: Lessons from five cases. *International Journal of the Commons, 8*(2), 428–456. DOI: https://doi.org/10.18352/ijc.416

Foster, S. R., & Iaione, C. (2019). Ostrom in the City: Design Principles and Practices for the Urban Commons. In B. Hudson, J. Rosenbloom, & D. Cole (Eds.), *Routledge Handbook of the Study of the Commons*. DOI: https://doi.org/10.4324/9781315162782-19

Frazier, A. E., & Wang, L. (2013). Modeling landscape structure response across a gradient of land cover intensity. *Landscape Ecology, 28*(2), 233–246. DOI: https://doi.org/10.1007/s10980-012-9839-8

Friedman, H. (1982). Simplified Determinations of Statistical Power, Magnitude of Effect and Research Sample Sizes. *Educational and Psychological Measurement, 42*(2), 521–526. DOI: https://doi.org/10.1177/001316448204200214

Gashu Adam, A. (2020). Urban Built-Up Property Formation Process in the Peri-Urban Areas of Ethiopia. In *Land Use Change and Sustainability*. DOI: https://doi.org/10.5772/intechopen.86708

Gotelli, N. J., & Graves, G. R. (1996). *Null Models in Ecology*: Simthsonian Institution Press.

Government of India. (2013). *National Land Utilization Policy (Draft)*.

Haase, D., Frantzeskaki, N., & Elmqvist, T. (2014). Ecosystem services in urban landscapes: practical applications and governance implications. *Ambio, 43*(4), 407–412. DOI: https://doi.org/10.1007/s13280-014-0503-1

Hedblom, M., Andersson, E., & Borgström, S. (2017). Flexible land-use and undefined governance: From threats to potentials in peri-urban landscape planning. *Land Use Policy, 63*, 523–527. DOI: https://doi.org/10.1016/j.landusepol.2017.02.022

Hettiarachchi, M., Morrison, T. H., & McAlpine, C. (2019). Power, politics and policy in the appropriation of urban wetlands: the critical case of Sri Lanka. *The Journal of Peasant Studies, 46*(4). DOI: https://doi.org/10.1080/03066150.2017.1393801

Hettiarachchi, M., Morrison, T. H., Wickramsinghe, D., Mapa, R., De Alwis, A., & McAlpine, C. A. (2014). The eco-social transformation of urban wetlands: A case study of Colombo, Sri Lanka. *Landscape and Urban Planning, 132*, 55–68. DOI: https://doi.org/10.1016/j.landurbplan.2014.08.006

Huang, Q., Xu, C., Jiang, W., Yue, W., Rong, Q., Gu, Z., & Su, M. (2021). Urban compactness and patch complexity influence PM2.5 concentrations in contrasting ways: Evidence from the Guangdong-Hong Kong-Macao Greater Bay Area of China. *Ecological Indicators, 133*. DOI: https://doi.org/10.1016/j.ecolind.2021.108407

Huntjens, P., Lebel, L., Pahl-Wostl, C., Camkin, J., Schulze, R., & Kranz, N. (2012). Institutional design propositions for the governance of adaptation to climate change in the water sector. *Global Environmental Change, 22*(1), 67–81. DOI: https://doi.org/10.1016/j.gloenvcha.2011.09.015

Kimura, Y. T. (2014). *The Mathematics of Patterns: The modeling and analysis of reaction-diffusion equations.*

Koch, J., Dorning, M. A., Van Berkel, D. B., Beck, S. M., Sanchez, G. M., Shashidharan, A., … Meentemeyer, R. K. (2019). Modeling landowner interactions and development patterns at the urban fringe. *Landscape and Urban Planning, 182*, 101–113. DOI: https://doi.org/10.1016/j.landurbplan.2018.09.023

Kohli, I. S., & Haslam, M. C. (2017). An Analysis of the Replicator Dynamics for an Asymmetric Hawk-Dove Game. *International Journal of Differential Equations, 2017*, 1–7. DOI: https://doi.org/10.1155/2017/8781570

Krivan, V., & Cressman, R. (2022). The asymmetric Hawk-Dove game with costs measured as time lost. *J Theor Biol, 547*, 111162. DOI: https://doi.org/10.1016/j.jtbi.2022.111162

Lacroix, K., & Richards, G. (2015). An alternative policy evaluation of the British Columbia carbon tax: broadening the application of Elinor Ostrom's design principles for managing common-pool resources. *Ecology and Society, 20*(2). DOI: https://doi.org/10.5751/ES-07519-200238

Magliocca, N., McConnell, V., & Walls, M. (2015). Exploring sprawl: Results from an economic agent-based model of land and housing markets. *Ecological Economics, 113*, 114–125. DOI: https://doi.org/10.1016/j.ecolecon.2015.02.020

Margreiter, M., Sutter, M., & Dittrich, D. (2005). Individual and Collective Choice and Voting in Common Pool Resource Problem with Heterogeneous Actors. *Environ Resource Econ, 32*, 241–271. DOI: https://doi.org/10.1007/s10640-005-3359-9

Maria de Almeida, C., Batty, M., Vieira Monteiro, A. M., Câmara, G., Soares-Filho, B. S., Cerqueira, G. C., & Pennachin, C. L. (2003). Stochastic cellular automata modeling of urban land use dynamics: empirical development and estimation. *Computers, Environment and Urban Systems, 27*(5). DOI: https://doi.org/10.1016/S0198-9715(02)00042-X

Martin, P., Le Gal, E., & Choy, D. L. (2016). Effect of Social and Institutional Fragmentation on Collective Action in Peri-Urban Settings. In B. Maheshwari, B. Thoradeniya, & V. P. Singh (Eds.), *Balanced Urban Development: Options and Strategies for Liveable Cities* (pp. 465–480). Cham: Springer International Publishing. DOI: https://doi.org/10.1007/978-3-319-28112-4_28

Mathias, J. D., Anderies, J. M., Baggio, J., Hodbod, J., Huet, S., Janssen, M. A., … Schoon, M. (2020). Exploring non-linear transition pathways in social-ecological systems. *Sci Rep, 10*(1), 4136. DOI: https://doi.org/10.1038/s41598-020-59713-w

MATLAB. (2016). *version 9.0.0.3 (R2016a)*. Natick, Massachusetts: The MathWorks, Inc.

Maynard Smith, J. (1974). The theory of games and the evolution of animal conflicts. *Journal of Theoretical Biology, 47*(1), 209–221. DOI: https://doi.org/10.1016/0022-5193(74)90110-6

McGinnis, M. D., & Ostrom, E. (2014). Social-ecological system framework: initial changes and continuing challenges. *Ecology and Society, 19*(2). DOI: https://doi.org/10.5751/ES-06387-190230

Menatti, L. (2017). Landscape: from common good to human right. *International Journal of the Commons, 11*(2). DOI: https://doi.org/10.18352/ijc.738

Meyfroidt, P., Roy Chowdhury, R., de Bremond, A., Ellis, E. C., Erb, K. H., … Verburg, P. H. 2018. Middle-range theories of land system change. *Global Environmental Change, 53*, 52–67. DOI: https://doi.org/10.1016/j.gloenvcha.2018.08.006

Milkoreit, M., Hodbod, J., Baggio, J., Benessaiah, K., Calderón-Contreras, R., Donges, J. F., … Werners, S. E. (2018). Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review. *Environmental Research Letters, 13*(3). DOI: https://doi.org/10.1088/1748-9326/aaaa75

Morrison, T. H., Adger, W. N., Agrawal, A., Brown, K., Hornsey, M. J., Hughes, T. P., Jain, M., Lemos, M. C., McHugh, L. H., O'Neill, S., & Van Berkel, D. (2022). Radical interventions for climate-impacted systems. *Nature Climate Change,*

*12*, 1100–1106. DOI: https://doi.org/10.1038/s41558-022-01542-y

**Morrison, T. H., Adger, W. N., Brown, K., Hettiarachchi, M., Huchery, C., Lemos, M. C.,** & **Hughes, T. P.** (2020). Political dynamics and governance of World Heritage ecosystems. *Nature Sustainability, 3*(11), 947–955. DOI: https://doi.org/10.1038/s41893-020-0568-8

**Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., … Schwarz, N.** (2013). Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol. *Environmental Modelling & Software, 48*, 37–48. DOI: https://doi.org/10.1016/j.envsoft.2013.06.003

**Mundoli, S., Manjunatha, B.,** & **Nagendra, H.** (2017). Commons that provide: the importance of Bengaluru's wooded groves for urban resilience. *International Journal of Urban Sustainable Development, 9*(2), 184–206. DOI: https://doi.org/10.1080/19463138.2016.1264404

**Murali, R., Suryawanshi, K., Redpath, S., Nagendra, H.,** & **Mishra. C.** (2019). Changing use of ecosystem services along a rural-urban continuum in the Indian Trans-Himalayas. *Ecosystem Services, 40*. DOI: https://doi.org/10.1016/j.ecoser.2019.101030

**Murunga, M., Partelow, S.,** & **Breckwoldt, A.** (2021). Drivers of collective action and role of conflict in Kenyan fisheries co-management. *World Development, 141*. DOI: https://doi.org/10.1016/j.worlddev.2021.105413

**Myers, J.** (2020). Fixing Urban Planning with Ostrom: Strategies for existing Cities to Adopt Polycenric, Bottom-up Regulation of Land Use. *Mercatus Research Paper.* DOI: https://doi.org/10.2139/ssrn.3561745

**Nagendra, H.,** & **Ostrom, E.** (2014). Applying the social-ecological system framework to the diagnosis of urban lake commons in Bangalore, India. *Ecology and Society, 19*(2). DOI: https://doi.org/10.5751/ES-06582-190267

**Nagendra, H., Unnikrishnan, H.,** & **Sen, S.** (2013). Villages in the City: Spatial and Temporal Heterogeneity in Rurality and Urbanity in Bangalore, India. *Land, 3*(1), 1–18. DOI: https://doi.org/10.3390/land3010001

**Narain, V.** (2009). Growing city, shrinking hinterland: land acquisition, transition and conflict in peri-urban Gurgaon, India. *Environment and Urbanization, 21*(2), 501–512. DOI: https://doi.org/10.1177/0956247809339660

**Narain, V.** (2021). Social capital and disaster risk reduction in a periurban context. In *Disaster Resilience and Sustainability* (pp. 651–665). DOI: https://doi.org/10.1016/B978-0-323-85195-4.00010-X

**Noss, R. F.** (2011). Between the devil and the deep blue sea: Florida's unenviable position with respect to sea level rise. *Climatic Change, 107*(1–2), 1–16. DOI: https://doi.org/10.1007/s10584-011-0109-6

**Nowak, M.,** & **May, R.** (1992). Evolutionary games and spatial chaos. *Nature*, 359, 826–829. DOI: https://doi.org/10.1038/359826a0

**NRSC and ISRO.** (2011). Manual on "Preparation of Geo Spatial Layers Using High Resolution (Cartosat-1 Pan+LISS-IV Mx) Orthorectified Satellite Imagery". Space Based Information Support for Decentralized Planning (SIS-DP), Remote Sensing and GIS Applications Area National Remote Sensing Centre, Indian Space Research Or-ganisation (ISRO), Department of Space, Government of India, Hyderabad.

**Okpara, U. T., Stringer, L. C., Akhtar-Schuster, M., Metternicht, G. I., Dallimer, M.,** & **Requier-Desjardins, M.** (2018). A social-ecological systems approach is necessary to achieve land degradation neutrality. *Environmental Science & Policy, 89*. DOI: https://doi.org/10.1016/j.envsci.2018.07.003

**Ostrom, E.** (1990). *Governing the commons: The Evolution of Institutions for Collective Action*. Cambridge University Press. DOI: https://doi.org/10.1017/CBO9780511807763

**Ostrom, E.** (2005). *Understanding institutional diversity*. Princeton, NJ: Princeton University Press.

**Ostrom, E.** (2007). A diagnostic approach for going beyond panaceas. *Proc Natl Acad Sci U S A, 104*(39), 15181–15187. DOI: https://doi.org/10.1073/pnas.0702288104

**Ostrom, E.** (2009). A General Framwork for Analyzing Sustainability of Socio-Ecological Systems.pdf. *Science*, *325*, 422. DOI: https://doi.org/10.1126/science.1172133

**Partelow, S.** (2015). Coevolving Ostrom's social–ecological systems (SES) framework and sustainability science: four key co-benefits. *Sustainability Science, 11*(3), 399–410. DOI: https://doi.org/10.1007/s11625-015-0351-3

**Patil, S., Dhanya, B., Vanjari, R. S.,** & **Purushothaman, S.** (2018). Urbanisation and New Agroecologies. *Eoconomic & Poliltical Weekly, LIII*(41).

**Petrovskii, S., Alharbi, W., Alhomairi, A.,** & **Morozov, A.** (2020). Modelling Population Dynamics of Social Protests in Time and Space: The Reaction-Diffusion Approach. *Mathematics, 8*(1). DOI: https://doi.org/10.3390/math8010078

**Poteete, A. R.,** & **Ostrom, E.** (2004). Heterogeneity, Group Size and Collective Action: The Role of Institutions in Forest Management. *Development and Change, 35*(3). DOI: https://doi.org/10.1111/j.1467-7660.2004.00360.x

**Pourhoseingholi, M. A., Baghestani, A. R.,** & **Vahedi, M.** (2012). How to control confounding effects by statistical analysis. *Gastroenterology and Hepatology From Bed to Bench, 5*(2).

**Purushothaman, S.,** & **Patil, S.** (2017). Regional Economies and Small Farmers in Karnataka. *Economic and Political Weekly, 46*(52).

**Ramachandra, T., Aithal, B. H.,** & **Sanna, D. D.** (2012). Insights to urban dynamics through landscape spatial pattern analysis. *International Journal of Applied Earth Observation and Geoinformation, 18*, 329–343. DOI: https://doi.org/10.1016/j.jag.2012.03.005

**Ratner, B. D., Meinzen-Dick, R., May, C.,** & **Haglund, E.** (2013). Resource conflict, collective action, and resilience: an analytical framework. *International Journal of the Commons, 7*(1). DOI: https://doi.org/10.18352/ijc.276

Rauws, W. S., & de Roo, G. (2011). Exploring Transitions in the Peri-Urban Area. *Planning Theory & Practice, 12*(2), 269–284. DOI: https://doi.org/10.1080/14649357.2011.581025

Ravetz, J., Fertner, C., & Nielsen, T. S. (2013). The Dynamics of Peri-Urbanization. In *Peri-urban futures: Scenarios and models for land use change in Europe*. DOI: https://doi.org/10.1007/978-3-642-30529-0_2

Robinson, L. W., Ontiri, E., Alemu, T., & Moiko, S. S. (2017). Transcending Landscapes: Working Across Scales and Levels in Pastoralist Rangeland Governance. *Environ Manage, 60*(2), 185–199. DOI: https://doi.org/10.1007/s00267-017-0870-z

Sarkar, S., & Bandyopadhyay, S. (2013). Dynamics of the Peri-Urban Interface: Issues and Perspectives of Management. *Transactions of the Institute of Indian Geographers, 50.*

Schlager, E. (2004). Common-pool Resource Theory. In *Environmental Governance Reconsidered: Challenges, Choices, and Opportunities* (pp. 145–175). Cambridge, MA: MIT Press.

Sciaini, M., Fritsch, M., Scherer, C., Simpkins, C. E., & Golding, N. (2018). NLMR and landscapetools: An integrated environment for simulating and modifying neutral landscape models in R. *Methods in Ecology and Evolution, 9*(11), 2240–2248. DOI: https://doi.org/10.1111/2041-210X.13076

Simon, H. (1972). Theories of Bounded Rationality. In C. B. M. & R. Radner (Eds.), *Decision and Organization.*

Singh, A. K., & Narain, V. (2019). Fluid Institutions: Commons in Transition in the Periurban Interface. *Society & Natural Resources*, 1–10. DOI: https://doi.org/10.1080/08941920.2018.1559380

Teklemariam, A., & Cochrane, L. (2021). The Rush to the Peripheries: Land Rights and Tenure Security in Peri-Urban Ethiopia. *Land, 10*(2). DOI: https://doi.org/10.3390/land10020193

Tidball, K., & Stedman, R. (2013). Positive dependency and virtuous cycles: From resource dependence to resilience in urban social-ecological systems. *Ecological Economics, 86.* DOI: https://doi.org/10.1016/j.ecolecon.2012.10.004

Tilman, D., Lehman, C. L., & Kareiva, P. (1997). Population Dynamics in Spatial Habitats. In D. Tilman & P. Kareiva (Eds.), *Spatial Ecology*. Princeton University Press. DOI: https://doi.org/10.1515/9780691188362

Turner, B. L., Meyfroidt, P., Kuemmerle, T., Müller, D., & Chowdhury, R. R. (2020). Framing the search for a theory of land use. *Journal of Land Use Science, 15*, 489–508. DOI: https://doi.org/10.1080/1747423X.2020.1811792

Turner, M. G., Donato, D. C., & Romme, W. H. (2012). Consequences of spatial heterogeneity for ecosystem services in changing forest landscapes: priorities for future research. *Landscape Ecology, 28*, 1081–1097. DOI: https://doi.org/10.1007/s10980-012-9741-4

Turner, M. G., & Gardner, R. H. (2015). *Landscape Ecology in Theory and Practice* (second ed.). DOI: https://doi.org/10.1007/978-1-4939-2794-4

Tyson, W. (2017). Using social-ecological systems theory to evaluate large-scale comanagement efforts: a case study of the Inuvialuit Settlement Region. *Ecology and Society, 22*(1). DOI: https://doi.org/10.5751/ES-08960-220105

Unnikrishnan, H., Katharina Gerullis, M., Cox, M., et al. (2023). Unpacking dynamics of diverse nested resource systems through a diagnostic approach. *Sustain Sci*, 18, 153–180. DOI: https://doi.org/10.1007/s11625-022-01268-y

Unnikrishnan, H., Mundoli, S., Manjunatha, B., & Nagendra, H. (2016). Down the drain: the tragedy of the disappearing urban commons of Bengaluru. *South Asian Water Studies, 5*(3).

van Schrojenstein Lantman, J., Verburg, P. H., Bregt, A., & Geertman, S. (2011). Core Principles and Concepts in Land-Use Modelling: A Literature Review. In *Land-Use Modelling in Planning Practice* (pp. 35–57). DOI: https://doi.org/10.1007/978-94-007-1822-7_3

Vedeld, T. (2000). Village politics: Heterogeneity, leadership and collective action. *Journal of Development Studies, 36*(5). DOI: https://doi.org/10.1080/00220380008422648

Verburg, P. H., de Nijs, T. C. M., Ritsema van Eck, J., Visser, H., & de Jong, K. (2004). A method to analyse neighbourhood characteristics of land use patterns. *Computers, Environment and Urban Systems, 28*(6), 667–690. DOI: https://doi.org/10.1016/j.compenvurbsys.2003.07.001

Verburg, P. H., Kok, K., Pontius, R. G., & Veldkamp, A. (2006). Modeling Land-Use and Land-Cover Change. In *Land-Use and Land-Cover Change* (pp. 117–135). DOI: https://doi.org/10.1007/3-540-32202-7_5

Vidyarthi, S., Mathur, S., & Agarwal, S. K. (2017). *Understanding India's New Approach to Spatial Planning and Development: A Salient Shift?* Oxford University Press.

Vij, S., & Narain, V. (2016). Land, water & power: The demise of common property resources in periurban Gurgaon, India. *Land Use Policy, 50*. DOI: https://doi.org/10.1016/j.landusepol.2015.08.030

Villamayor-Tomas, S., Fleischman, F. D., Ibarra, I. P., Thiel, A., & van Laerhoven, F. (2014). From Sandoz to Salmon: Conceptualizing resource and institutional dynamics in the Rhine watershed through the SES framework. *International Journal of the Commons, 8*(2). DOI: https://doi.org/10.18352/ijc.411

Wandl, A., Rooij, R., & Rocco, R. (2016). Towards Sustainable Territories-in-Between: A Multidimensional Typology of Open Spaces in Europe. *Planning Practice & Research, 32*(1), 55–84. DOI: https://doi.org/10.1080/02697459.2016.1187978

White, J. W., Rassweiler, A., Samhouri, J. F., Stier, A. C., & White, C. (2014). Ecologists should not use statistical significance tests to interpret simulation model results.

*Oikos, 123*(4), 385–388. DOI: https://doi.org/10.1111/j.1600-0706.2013.01073.x

**Wilson, D. S., Ostrom, E.,** & **Cox, M. E.** (2013). Generalizing the core design principles for the efficacy of groups. *Journal of Economic Behavior & Organization, 90*, S21–S32. DOI: https://doi.org/10.1016/j.jebo.2012.12.010

**Xie, H.,** & **Wu, Q.** (2019). Analysis of Fallow Farming Decision-Making Behavior of Farmers Based on Hawk-Dove Game Theory: The Case of Guizhou Province. *Sustainability, 11*(14). DOI: https://doi.org/10.3390/su11143821

**Yi, Y., Zhang, C., Zhang, G., Xing, L., Zhong, Q., Liu, J., … Kang, H.** (2021). Effects of Urbanization on Landscape Patterns in the Middle Reaches of the Yangtze River Region. *Land, 10*(10). DOI: https://doi.org/10.3390/land10101025

**Zhang, S., de Roo, G.,** & **Rauws, W.** (2019). Understanding self-organization and formal institutions in peri-urban transformations: A case study from Beijing. *Environment and Planning B: Urban Analytics and City Science, 47*(2). DOI: https://doi.org/10.1177/2399808319888223

**Zhu, L., Tang, Y.,** & **Shen, S.** (2023). Pattern study and parameter identification of a reaction-diffusion rumor propagation system with time delay. *Chaos, Solitons & Fractals, 166*, 112970. DOI: https://doi.org/10.1016/j.chaos.2022.112970