Sustainable management of rangelands: An assessment of invasion cover trajectories and their contribution to invasion management in Marigat Sub-County, Kenya

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Abstract

Invasive alien species have complex spatiotemporal patterns of spread beyond geographical and jurisdictional boundaries. This calls for a coordinated management approach that is spatially explicit, extends beyond individual plot levels, and incorporates land users' perceptions and decisions. This study, therefore, aims at assessing spatiotemporal invasion trajectories of the invasive tree *Prosopis juliflora* in Baringo County, Kenya, and evaluating their possible relation to land users' management decisions. Pre-classified land cover data over a seven-year time period (1988–2016) were reclassified based on the presence or absence of *P. juliflora* and integrated into ArcGIS to produce *P. juliflora* cover trajectories for analysis. The spatiotemporal analysis of *Prosopis* invasion dynamics yields trajectories that can be linked to underlying land users' management decisions. Areas that remained free of *Prosopis* since their first clearance were primarily areas where the invasion would cause the highest loss in terms of income or opportunity costs; areas that were never cleared since they were first invaded tended to be areas where no one could be personally held accountable for their management, while the abandonment of management followed by re-invasion appeared to be linked to different drivers, including diversification of livelihoods and lower market prices for horticultural products. Our findings indicate that invasion trajectories are useful in informing existing management strategies to adopt context-based invasive species management practices. The study recommends scaling up the trajectory analysis approach to be replicated in large-scale invasion management strategies. Since it requires considerable finances and time to conduct such analyses on raw satellite imagery, we suggest further research on how to simplify the approach to make it easily and efficiently replicable for large-scale applications.

Introduction

Background: *Prosopis juliflora* (Sw.) DC. (hereafter referred to as *Prosopis*) is widely recognized as an invasive plant in almost all of the world's Arid and Semi-Arid Lands (ASALs) (Shackleton *et al.,* 2014). Native to South and Central America, *Prosopis* was introduced into Africa in the early 1970s for afforestation, fodder, and fuelwood (Mwangi and Swallow, 2008). However, it became invasive posing adverse impacts ranging from the depletion of groundwater (Shiferaw *et al.,* 2019), displacement of indigenous species (Linders *et al.,* 2019), physical injury to both livestock and humans, and a security threat as it harbors thieves (Maundu *et al.,* 2009). In Kenya, a National *Prosopis* Strategy (NPS) was formulated in 2020 to curtail its spread and control its impacts on ecosystem services and livelihood.

Just like other invasive alien species (IAS), *Prosopis* invasion stretches beyond jurisdictional and geographic boundaries, calling for a coordinated management approach that adopts interventions beyond individual plots (NISC, 2008). Moreover, IAS has complex spatiotemporal patterns (Nehrbass *et al.,* 2006), which influence land users' perception and subsequently their decision to invest or not in implementing IAS management practices. Community-level management strategies should therefore be prioritized while making decisions on invasion management.

The objectives of research was to enhance the effectiveness of local, regional and national IAS management strategies, a better understanding of the spatiotemporal dynamics of *Prosopis* invasion with reference to land users' management decisions is fundamental. We, therefore, propose a methodology to analyze spatiotemporal trajectories of *Prosopis* and outline their possible interrelation to land management decisions. Based on pilot research conducted in Marigat, Baringo County, we developed this approach into a replicable comprehensive methodology building on the analysis of remotely sensed data, cross-referenced with ground-based survey results. If implemented country-wide, the approach would be useful to contextualize and operationalize the NPS in affected counties in Kenya by providing a crucial decision-making basis for the designing of spatially explicit management plans.

Materials and methods

Study site: The study was conducted in Marigat Sub-County of Baringo County, which is a good representation of Kenyan ASALs with heavy *Prosopis* invasion. It is one of four project sites of the Woody Weeds Project (see acknowledgments), which enabled us to use available analyses and data to conduct the present study.

Spatial-temporal Prosopis invasion trajectories*:* Landcover data that were pre-classified in the Woody Weeds project (Mbaabu *et al.,* 2019) were reclassified based on the presence or absence of *Prosopis*. The output, covering 3 decades from 1988 to 2016 and distributed in 7 years intervals, was integrated into ArcGIS to derive individual trajectories as well as types of trajectories of *Prosopis* cover in the area. Open-source thematic shapefiles from World Resources Institute (WRI) and OpenStreetMap data websites were then overlaid to assess the contribution of different drivers to invasion patterns.

Results

Spatial-temporal invasion trajectories

The assessment of land cover data revealed 32 trajectories of *Prosopis* invasion (i.e. distinct successions of *Prosopis* presence and absence between 1988 and 2016). Some of them cover very small areas and others have inconclusive invasion trends. Thus, we limited our scope to thirteen trajectories that are categorized into 3 main trajectory types representing a good proxy for *Prosopis* management practices (Table 1).

Table 1: Spatio-temporal invasion trajectories. 1 (red) and Zero (green) represent presence and absence of Prosopis respectively. "Pixel Count" indicates the number of 30m x 30m pixels falling under a certain trajectory. Source: Calculated by the author on the basis of Mbaabu *et al.,* 2019.

No.	Pixel count	1988	1995	2002	2009	2016	Area (km^2)	Area (%)
	Category 1: Constantly uninvaded after clearance							
1	8448	1	0	0	0	0	7.60	76.08
2	1259	1	1	0	0	0	1.13	11.34
3	1120	1	1	1	0	0	1.01	10.09
4	277	1	1	1	1	0	0.25	2.50
							10.00	3.00
	Category 2: Constantly invaded after first appearance							
5	295397	0	0	0	1	1	265.86	83.48
6	52289	0	0	1	1	1	47.06	14.78
7	6165	0	1	1	1	1	5.55	1.74
							318.47	95.00
	Category 3: Cleared and then reinvaded							
8	3108	1	0	0	1	1	2.80	40.05
9	2268	1	0	0	0	1	2.04	29.23
10	1428	1	0	1	1	1	1.29	18.40
11	522	1	1	0	1	1	0.45	6.73
12	237	1	1	1	0	1	0.21	3.05
13	197	1	1	0	0	1	0.18	2.54
							6.97	2.00
		Total of 13 trajectories:					335.44	100.00

The three categories of trajectories are reflecting land users' decisions to adopt (or not) and continuously use (or not) SLM practices. Hereafter, we briefly describe each category and offer a possible interpretation in relation to land management decisions.

Category 1: Areas that remained constantly free of Prosopis after clearance

This category covers an area of approximately 10 km^2, equivalent to 3% of the considered areas, with the first successful clearance covering an area of 7.6 km^2. It occurred between 1988 and 1995, coinciding with a major drought in Baringo County. Trajectory 4 indicates that in recent years (between 2009 and 2016), long-term *Prosopis* cover was cleared in very few areas (0.25 km^2). This indicates that existing management is unsustainable and that *Prosopis* management is the exception than the rule in the study area.

Category 1 dominates agricultural lands, mainly along water bodies (Figure 1), which are suitable for farming due to constant water supply and fertile soils, thus providing sufficient motivation to land users to keep *Prosopis* at bay.

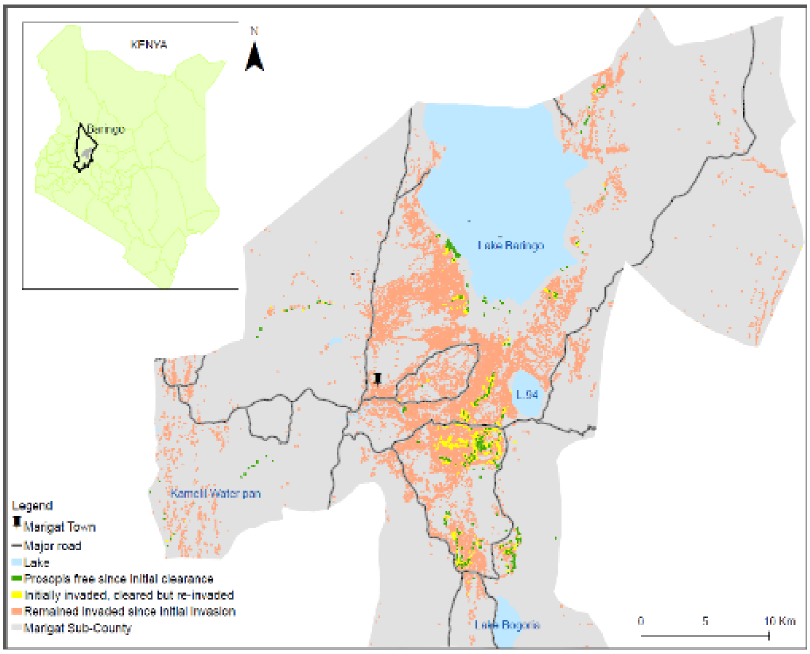

Figure 1: Spatial extent of the three categories of Prosopis invasion trajectories in Marigat Sub-County

Farmers reported that they prioritize the cultivation of parcels close to their homestead, which explains the concentration of category 1 near settlements and the invasion of agricultural land in areas that are further away (Figure 2). Counterintuitively, the immediate surroundings of Marigat town are heavily invaded, which can be explained by the fact that it is a commercial center, whose inhabitants are rather concerned with business than with farming.

Category 2: Areas that were constantly invaded after the first presence of Prosopis

This is the most widespread category in Marigat, even though it includes only 3 trajectories. Trajectory 5 has the largest coverage, indicating that a strong wave of *Prosopis* invasion took place between 2002 and 2009, while the invasion was slower in the prior 7-year period and even slower in the first one (1988 to 1995). Although this category is evenly distributed throughout the area, constant invasion is widespread in the lowlands and is dominant along roads, water bodies, and grasslands which form communal grazing fields (Figure 1). This indicates that *Prosopis* invasion progresses fastest where no one is personally held responsible for its management (e.g roadsides, land with common tenure regimes), or where specific vectors help to spread the plant (e.g. seeds being dispersed by water, livestock, or vehicles).

Category 3: Cleared and then re-invaded areas

This category covers the smallest surface of only 7 km^2 (2 % of areas covered by all trajectories). Six out of the 7 km^2 were first cleared between 1988 and 1995 but later re-invaded within different timeframes. When comparing trajectories 5, 8, and 11, it appears that a rather strong wave of (re-)invasion took place between 2002 and 2009. This category occurs in close proximity to category 1 trajectory (Figure 1) and shows a wave of *Prosopis* clearing roughly between 1995 and 2009 followed by a reinvasion that is also clearly visible in trajectory 5 of the second category.

The main possible explanation for this trajectory are changes in the socio-economic environment: it is possible that in the period between 1995 and 2009 peoples' livelihoods were more dependent on land and therefore they had a higher incentive to clear *Prosopis*, whereas in subsequent years new sources of income might have fostered the abandonment of land. Lower market prices for horticultural products might also be part of the cause, especially in the irrigated areas.

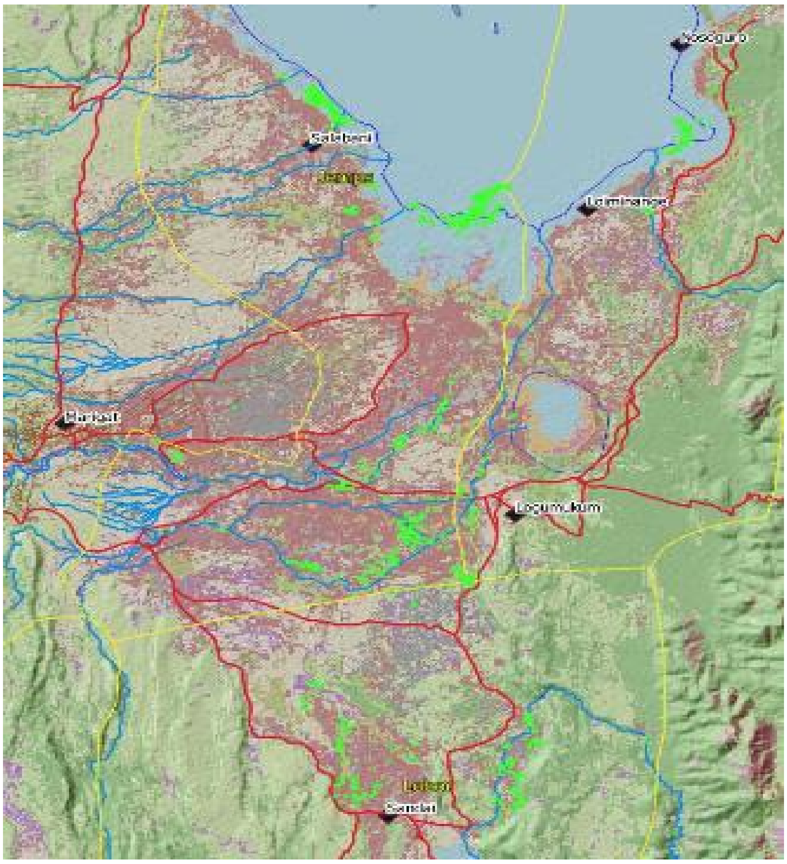

Figure 2: Spatial distribution of category 1 (constantly uninvaded after clearance) in bright green.

Discussions

Our findings provide evidence that a spatiotemporal analysis of *Prosopis* trajectories yields context-based insights into invasion dynamics, which can be linked to underlying land management decisions and their related drivers. The logical assumption is that land users' decisions to implement SLM practices are reflected in the overall spatiotemporal land cover patterns (Zhou *et al.,* 2008). Thus, the latter is useful in determining context-based management strategies to combat invasion (Saguye *et al.,* 2017). The study also shows that the mapping of invasion trajectories alone is not sufficient in explaining drivers to land users' management decisions. It needs to be complemented with further analyses. We identify two main pathways for strengthening the explanatory potential of our approach:

Spatial overlays: The explanatory potential of the trajectory mapping could be enhanced by comparing the resulting invasion patterns with other spatial indicators such as remoteness, proximity to surface water areas, land tenure types, changes of land ownership, etc. A recent study (Schirpke *et al.,* 2020), found that overlay of functional spatial units is fundamental in revealing a combined effect of biotic and abiotic drivers on grassland trajectories. Some of these analyses have been conducted and are presented in Figure 2. However, additional analyses would help to identify key environmental, socio-political, and economic processes that have repercussions on IAS management.

Ground-based surveys: At the present stage, the mapping of trajectories is merely a basis for formulating hypotheses on the drivers influencing the adoption of sustainable land management practices. To verify these hypotheses a more detailed understanding of land management decisions in the area is needed. We are working on achieving this in-depth understanding through a comprehensive survey of local stakeholders whose integration will yield reliable responses based on their real-life experiences (Markard *et al.,* 2012), and systemic analysis of drivers affecting stakeholders' decision-making on SLMs.

Finally, spatial analysis of *Prosopis* trajectory types is time and labor-intensive and might prove to be too slow and expensive if conducted over larger areas and/or when quick results are needed. This mainly concerns the initial analysis of raw satellite imagery to derive land cover classes, as this work includes the collection of ground-based control points (Mbaabu *et al.,* 2019). Furthermore, owing to the relatively new interest in mapping *Prosopis*, it is unlikely that such analysis could be conducted on already pre-processed data (including a reliable mapping of *Prosopis* cover) that would help speed up the process. We intend to address this issue while scaling out the Woody Weeds project (see below) to other counties in Kenya and hope to be able to elaborate alternative faster approaches. The use of drones to determine their potentials and advantages in comparison to approaches based on satellite images may provide an interesting alternative.

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