ORIGINAL ARTICLE

WILEY *African Journal of Ecology*

Classification of *Prosopis juliflora* invasion in the Lake Baringo basin and environmental correlations

Miguel Alvarez[1] [iD] | Gereon Heller[1] | Itambo Malombe[2] | Kennedy W. Matheka[2] | Simon Choge[3] | Mathias Becker[1]

[1]INRES, University of Bonn, Bonn, Germany

[2]National Museums of Kenya, Nairobi, Kenya

[3]Kenya Forestry Research Institute, Marigat, Kenya

Correspondence
Miguel Alvarez, INRES, University of Bonn, Bonn, Germany.
Email: malvarez@uni-bonn.de

Abstract

The spread of *Prosopis juliflora* in the Baringo basin, Kenya, has led to severe changes in the ecosystem with negative socio-economic impacts. The drivers that foster the invasiveness of *Prosopis* are not fully understood. Thus, a method to quantify the degree of infestation will support the determination of environmental preferences and the risk assessment of future *Prosopis* invasion. We developed a methodology for characterising and classifying degrees of *Prosopis* infestation in vegetation stands and propose its application in environmental correlation models. The relative cover was identified as the most suited attribute for assessing and monitoring the invasion of *Prosopis*. The distance of invaded stands from original plantations and environmental attributes related to water availability (ground water table, rainfall and soil water–holding capacity) have potential to predict potential or future invasion risks.

RÉSUMÉ

L'invasion de ***Prosopis juliflora*** dans le bassin de Baringo, au Kenya, a entraîné de profonds changements dans l'écosystème, avec des impacts socio-économiques négatifs. Les facteurs qui favorisent l'invasion de ***Prosopis*** ne sont pas entièrement compris. Ainsi, une méthode permettant de quantifier le degré d'infestation aidera la détermination des préférences environnementales et l'évaluation des risques de la future invasion de ***Prosopis***. Nous avons développé une méthodologie pour caractériser et classifier des degrés d'infestation de ***Prosopis*** dans les peuplements végétaux et proposer son application dans les modèles de corrélation environnementale. La couverture relative a été identifiée comme l'attribut le plus approprié pour évaluer et surveiller l'invasion de ***Prosopis***. La distance des peuplements envahis des plantations d'origine et des attributs environnementaux liés à la disponibilité d'eau (nappe phréatique, précipitations et capacité de rétention d'eau du sol) ont le potentiel de prédire les risques d'invasion potentiels ou futurs.

KEYWORDS
East Africa, invasion ecology, spatial distribution, vegetation structure, woodland

1 | INTRODUCTION

Non-native plants, with large dispersal capacity and causing negative ecological, economic and social impacts, are labelled as invasive species (Richardson et al., 2000; Wakie, Evangelista, Jarnevich, & Laituri, 2012). Several species of the genus *Prosopis* are considered among the most threatening invasive species worldwide (Shackleton, Le Maitre, Pasiecznik, & Richardson, 2014) and *Prosopis juliflora* (Sw.) DC. (henceforth called just *Prosopis*) is one prominent example. *Prosopis* is native to northern South America (Venezuela and Colombia), Central America and the Caribbean Islands (Burkart, 1976), but it is currently widespread throughout the tropics (Catalano, Vilardi, Tosto, & Saidman, 2008; Kaur et al., 2012). It has been spread globally and has become naturalised and invasive in many places (Rejmánek and Richardson, 1996), as reported for Brazil (Gonçalves, Alves de Andrade, Gonçalves, Bezerra de Oliveira, & Dias, 2013), Australia (Robinson, van Klinken, & Metternicht, 2008) or for India (Tewari et al., 2013).

Prosopis was introduced to Kenya in 1973 through a government initiative to restore quarries near Mombasa. Ten years later, it was brought to the Baringo County to increase the availability of fire wood and to restore soils affected by heavy erosion. The invasive spread started from the original plantation sites in the late 1990s, invading the local vegetation and increasingly restricting physical access to lake shores and river banks (Coppock, Aboud, & Kisoyan, 2005). This trend is consistent with other *Prosopis* introductions turning to invasions in Kenya as described by Kyuma, Wahome, Kinama, and Wasoga (2016) for Magadi County, Zeila (2011) for Garissa County and Muturi, Mohren, and Kimani (2010) for Turkwell County.

Several factors contribute to *Prosopis* species becoming successful invaders. Thus, seed dispersal by endozoochory has been claimed as one of the most important autecological drivers of invasive spread, especially due to its facilitation by abundant and widespread free-roaming livestock in the area (Alvarez, Leparmarai, Heller, & Becker, 2017; Becker et al., 2016). Another factor contributing the competitive ability of *Prosopis* is the release of allelochemicals, inhibiting growth of other species and resulting in low plant diversity under the canopy of *Prosopis* (Getachew, Demissew, & Woldemariam, 2012). Additionally, rapid growth rates and the ability to coppice after damage, pruning or fire (Shiferaw, Teketay, Nemomissa, & Assefa, 2004) can favour its invasive spread and make an eradication of *Prosopis* almost impossible. Being a phreatophyte, *Prosopis* develops two types of root systems, horizontal roots in the topsoil layer close to the surface and a taproot penetrating into deep soil layers for reaching the water table (Yoda, Elbasit, Hoshino, Nawata, & Yasuda, 2012). This is consistent with observations of Ayanu et al. (2015), who reported *Prosopis* invasion to occur mainly in floodplain wetlands with shallow groundwater tables. Such sites have initially been dominated by *Vachellia tortilis* (Forssk.) Galasso & Banfi woodlands (see also Muturi, Poorter, Mohren, & Kigomo, 2013).

Apart from the water table depth, the establishment of individuals and the invasion of *Prosopis* may also be related to other environmental variables, including climate, soil type, landscape forms and land uses. An important step to study causes and drivers of invasion at landscape scale is to define degrees of infestation in a way that can be objectively measured, repeatable and comparable and to relate the extent of the invasion to biophysical landscape or land management attributes. In this context, geographic information systems and modelling algorithms are increasingly being used to map both the current and the potential future distribution of invasive species (Wakie et al., 2012). Such approaches are currently hampered in the case of *Propsis* invasion by a lack of available methods to quantify the degree of infestation and the variability of invaded stands.

The aim of this work is thus to develop such a methodology for characterising and classifying degrees of infestation in vegetation and to apply this typology to derive environmental preferences of *Prosopis* in view of predicting and mapping the future invasion potential.

2 | MATERIALS AND METHODS

2.1 | Study site

Data were collected and samples taken from the Eastern Rift Valley, in an area between the basins of Lake Baringo in the North and Lake Bogoria in the South (Figure 1). This area is characterised by an annual rainfall of 450–900 mm (Odada, Onyando, & Obudho, 2006) and a mean temperature of 24.6°C (Fick & Hijmans, 2017). The geological basement is composed by basalt plateaus, which are cracked and tilted due to tectonic movements, alternating with sedimentary deposits of clay and loam (Alvarez et al., 2017; Touber, 1989). The dominant vegetation in the area has been described as *Acacia-Commiphora* bushlands (Lillesø et al., 2011) and *V. tortilis* (formerly *Acacia tortilis*) woodlands (Alvarez et al., 2017). The main land use is pastoralism, dominated by goats and cattle. Crop cultivation is patchy and restricted to the short wet season, with exception of the irrigation schemes of Perkerra, Ng'ambo, Eldume and Sandai (see figure 5 in Andersson, 2005).

2.2 | Samples collection

The sampling strategy followed the approach suggested by Beuel et al. (2016). The map of the study area was gridded into 250 m by 250 m tiles, and 57 tiles were preferentially selected for detailed mapping. The selection aimed at an even distribution of sampling tiles across the area, avoiding large gaps between selected tiles. Tiles reflected the observed variability in the degree of *Prosopis* infestation and dominating vegetation physiognomy. The selected tiles were differentiated into polygons of homogeneous physiognomy ("assessment units") and were mapped using a GPS device (Garmin eTrex 30). Within each assessment unit, a 10 m by 10 m plot was established for detailed recording of vegetation structures. In total, 72 assessment units in 57 tiles were surveyed. All occurring vascular plants were listed, and their percentage cover was estimated. In those cases
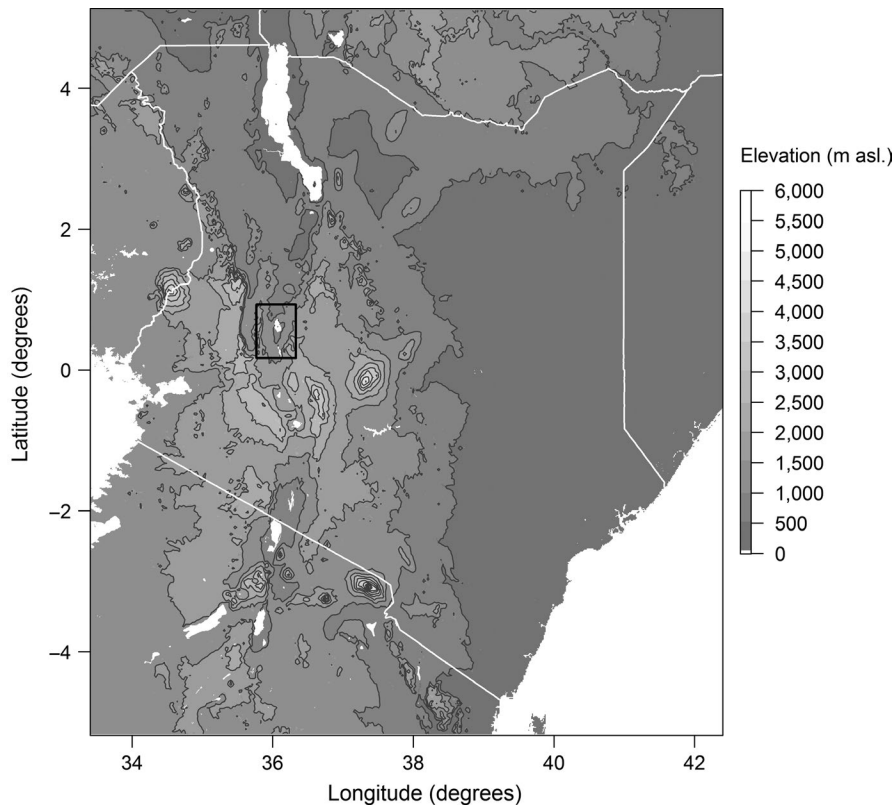
FIGURE 1 Map of Kenya indicating the extension of the study site (black rectangle)

where multiple layers were recognised (e.g. herb, shrub and tree layers), the layers were used as sub-units in the vegetation records as suggested for "phyto-sociological relevés" (Braun-Blanquet, 1964). Since the focus of the study was the invasion with *Prosopis*, we estimated its total cover, its cover shares, density (individuals per m^2) and maximum height (measured by TruPulse 200 device) in addition to the summed up cover of all vascular plants in the plot.

2.3 | Classification of invasion

To quantify the degree of *Prosopis* invasion, we applied the variables "maximum height," "density," "number of affected layers" and "cover." The *Prosopis* cover was calculated both in relative and absolute terms, whereby the relative cover was calculated as the sum of *Prosopis* cover, divided by the cover sum of all plants occurring in the respective plot. The maximum height, the density, the number of affected layers, the relative cover and the absolute cover of

TABLE 1 Median of variables used to define invasion classes of *Prosopis* and their correlations with category boundaries of the relative cover by Spearman rank correlation index

Variable	Median	Spearman
Maximum height (m)	4.00	0.31
Density (individual m^{-2})	0.07	0.44
Affected layers	2.00	0.24
Absolute cover (%)	27.57	0.79
Relative cover	0.70	0.86

Prosopis were used for a classification by hierarchical clustering. The dissimilarity between plots was quantified by Bray–Curtis index. A classification tree was generated using Ward's algorithm (Murtagh & Legendre, 2014). Variable values were re-scaled, setting mean values to 0 and the standard deviations to 1, and the relative and the absolute covers were weighted by a factor of 10. The relation between resulting classes and biophysical attributes of invaded stands (ordinal variables) was quantified by the Spearman rank correlation index (Dormann & Kühn, 2012).

2.4 | Regression models

Simple regression related the relative cover of *Prosopis* to environmental attributes. Main factors considered comprised the macroclimate, the land form, groundwater depth, the soil type and the distance to the originally established *Prosopis* plantations. Macroclimatic variables such as annual mean temperature and rainfall, as well as their respective seasonality (referred to as BIO1, BIO4, BIO12, and BIO15 in the original data set) were extracted from the WorldClim 2 database (Fick & Hijmans, 2017). Land forms were inferred from a digital elevation model (DEM) with a resolution of 30 arcsec (SRTM version 3.0), calculating the topographic position index at a scale of 2,000 m (Weiss, 2001). The eastness was calculated by overlaying a circle of 300 m radius (10 pixels of the DEM) around each pixel. Circles were divided into an eastern and a western half, and the mean elevation in each half was extracted using "moving windows." Eastness was calculated as "west elevation minus east elevation," with strong positive differences
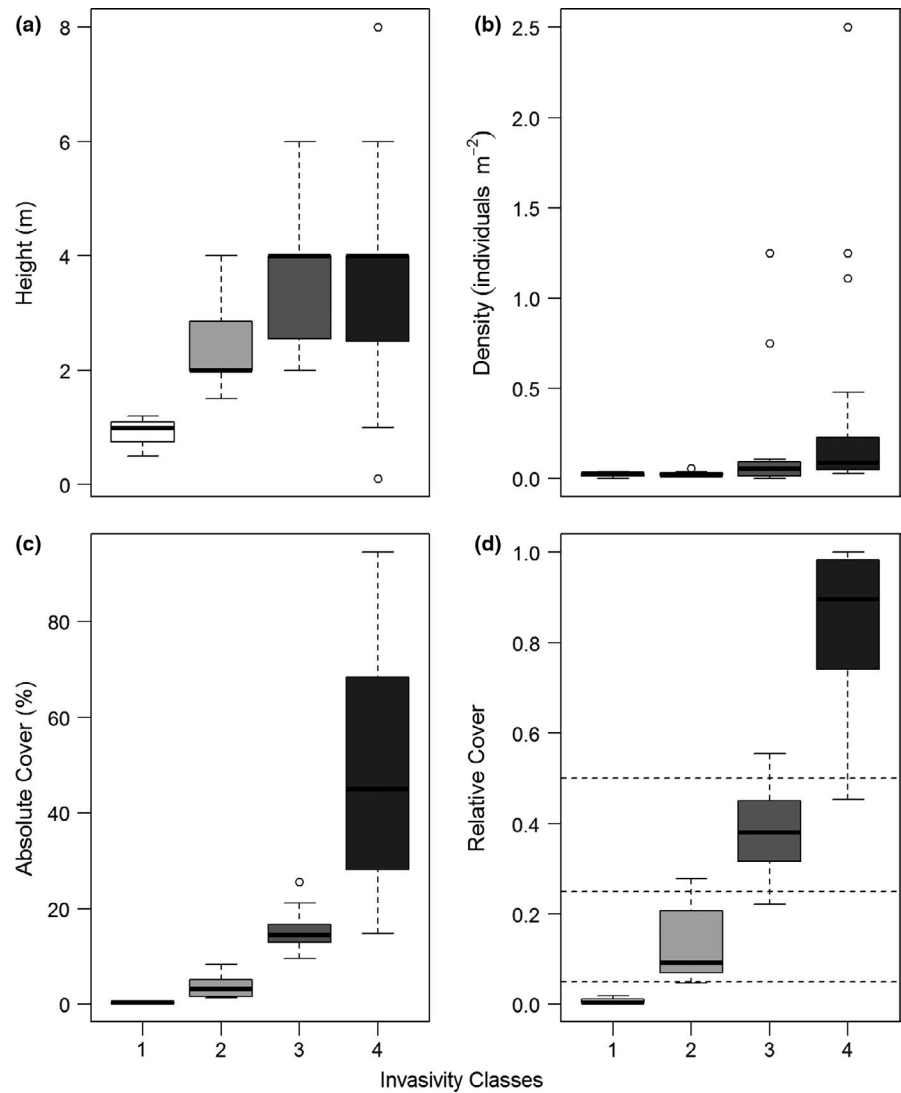
FIGURE 2 Distribution of numeric variables (a: height, b: density of individuals, c: absolute and d: relative cover) among invasion classes of *Prosopis* defined by hierarchical clustering. Box shadings indicate a gradient from least (white) to most (dark grey) invaded plots. Dashed lines in (d) represent the proposed cut levels for defining invasion classes by relative *Prosopis* cover

TABLE 2 Goodness of fit for environmental correlations of *Prosopis* invasion degrees. Correlations are grouped into logistic (monotonic) and Gaussian (unimodal) response patterns. The goodness of model fits was quantified by modelling efficiencies (ME) and root mean square errors (RMSE)

Predictor	Units	RMSE	ME	Relation	Optimum
Logistic responses					
Distance to plantation	m	4.34	−1.18	Negative	–
Soil erosion class	–	5.16	−2.35	Negative	–
Soil water–holding capacity	–	5.29	−6.48	Positive	–
Rainfall seasonality	–	6.71	−81.14	Negative	–
Gaussian responses					
Annual rainfall	mm	4.72	−21.24	–	657.9
Temperature seasonality	–	4.82	−11.80	–	112.1
Ground water table	m	5.16	−0.64	–	1.8
Eastness	m	5.19	−0.02	–	2.3
Mean temperature	°C	5.21	−127.74	–	24.0
Elevation	m a.s.l.	5.24	−15.46	–	1,008.6
Topographic position index	–	5.88	0.00	–	−0.6

indicating steep slopes with eastern exposition, and strong negative differences indicating steep slopes with western exposition. Since the escarpment in the study area has a dominant north–south orientation, the northness was not calculated.

Groundwater depth was extracted from Fan, Li, and Miguez-Macho (2013) and tended to be related to land form (slope inclination) and elevation. Soil parameters were based on the Baringo area soil map (Touber, 1989), comprising the water holding capacity and the soil erosion index. Finally, the location of the original *Prosopis* plantations was used to calculate their distance from the assessment units. All raster data sets were processed to an identical spatial reference and resolution and associated to the exact geographical position of the respective pixel nodes.

Prior to calibrating regression models, 100 points were randomly selected to identify pseudo-absences or "backgrounds" (Elith et al., 2011). Using plot location and random points, variable values were extracted from the raster data sets and transposed to table. The response or relation of relative *Prosopis* cover to individual predictor variables was described either by a logistic function (in the case of monotonic relations) or by a Gaussian function (in the case of unimodal relations) as follows:

$$\text{Logistic Model:} \hat{y} = \frac{1}{1 + e^{-A(x-B)}} \quad (1)$$

$$\text{Gaussian Model:} \hat{y} = \frac{e^{-(x-A)^2}}{2B^2} \quad (2)$$

wherein $\hat{y}$ is the relative *Prosopis* cover and x is the predictor variable. A and B are model parameters retrieved by the quantile regression (Cade & Noon, 2003), being the method of choice in cases where responses are influenced by multiple, nonobserved attributes. The value of τ was set to 0.8, meaning that only the upper 0.2 error quantile was considered for the regression. Since the regression calculates the "maximum" effect, the model outcome represents the potential relative cover of *Prosopis* which may differ from the actual or observed one. Model performances were assessed by the root mean square error (RMSE) and the modelling efficiency (ME; Bennett et al., 2013; Janssen & Heuberger, 1995). Both indices (and the visual assessment of curve shapes) were used to define suitable model functions (logistic or Gaussian). Finally, a prediction map of likely future *Prosopis* invasion was produced by averaging the predicted values according to distance to plantation, annual temperature, annual rainfall and elevation.

All analysis were done in R version 3.4.1 (R Core Team, 2017), including the packages dismo, quantreg, raster, rgdal, rgeos, sp and vegan.

3 | RESULTS AND DISCUSSION

3.1 | Classification of invaded stands

Four classes of vegetation stands invaded by *Prosopis* were defined by hierarchical clustering. Those classes can be categorised from
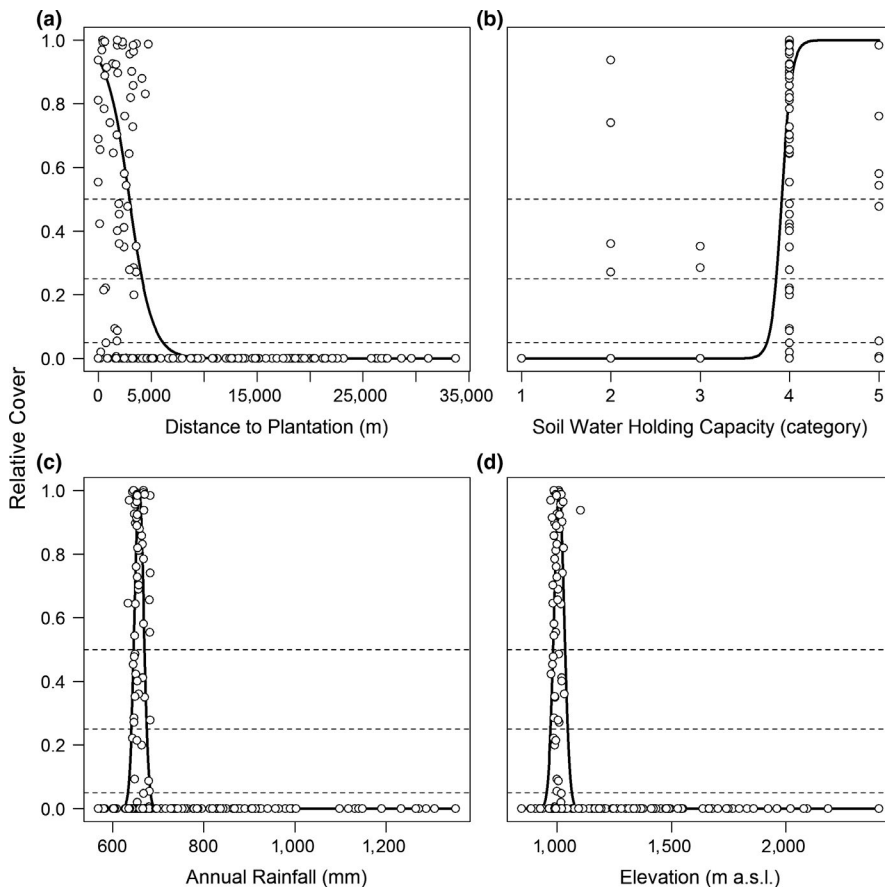
FIGURE 3 Examples of regression models for relative cover of *Prosopis* in response to environmental factors. (a) represents a negative logistic, (b) a positive logistic model, while (c and d) are Gaussian models. Solid lines show the relative cover predicted by the respective regression model, dots are the observed values and dashed lines indicate the suggested cut levels for invasion classes
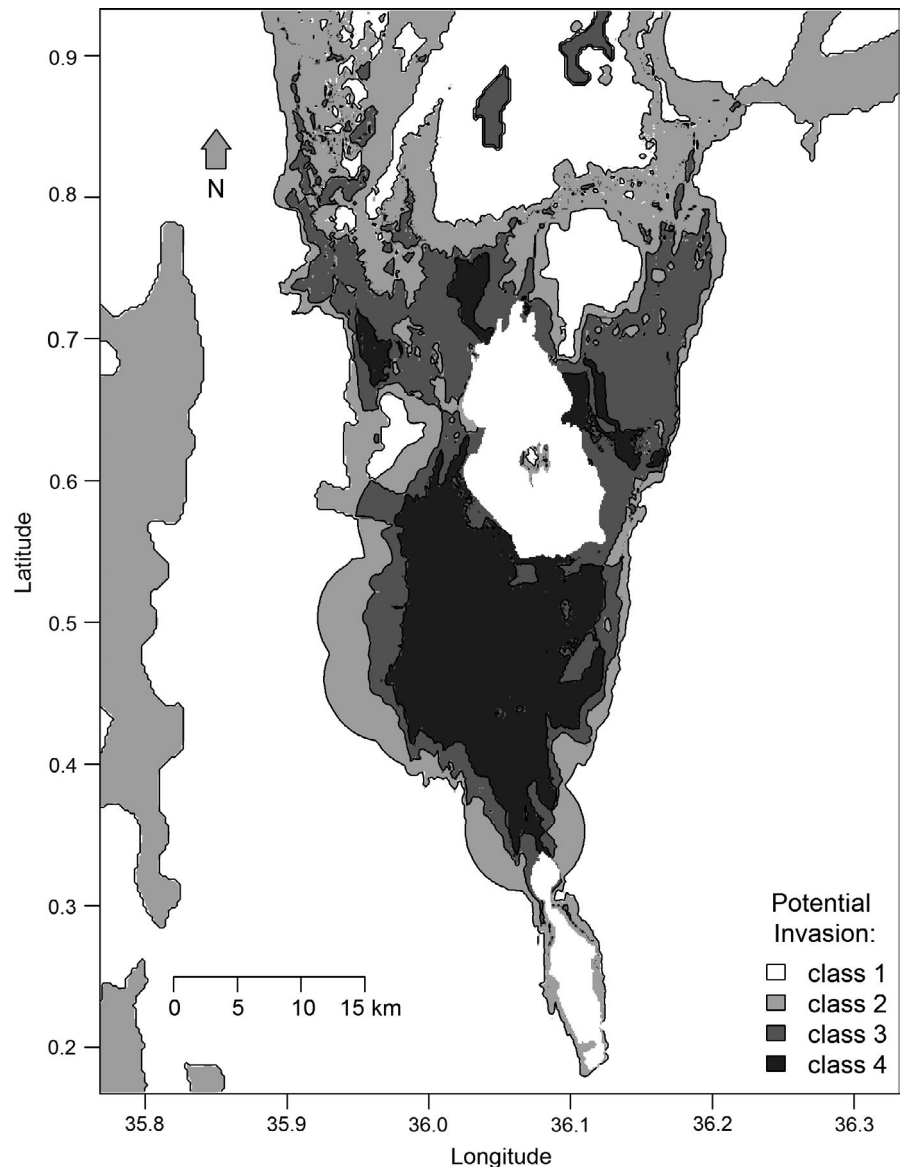
FIGURE 4 Distribution of risk of invasion by *Prosopis*. This model was constructed by averaging answers of models from Figure 3 and classifying relative cover into four classes (1: 0%–5%, 2: 5%–25%, 3: 25%–50%, 4: 50%–100%)

nonsignificant, less concerning invasion (class 1) to strongly invaded stands (class 4). Invasion classes are associated with increasing maximum height, density of individuals, number of affected layers, and both, absolute and relative *Prosopis* cover (Table 1). This differentiation is visualised using boxplots of numerical variables (Figure 2). While most variables show overlaps between classes, the relative *Prosopis* cover does not, suggesting it as the best suited to discriminate between invasion classes. This overlap also highlights the variability of the measured attributes and variables. Thus the typical gradient from "stands of lower cover with small individuals" to "stands with high cover and tall individuals" is diversified by stands with "high cover but small individuals." This latter category may refer to either young individuals with massive invasion or to high re-sprouting after logging activities as also reported by Shiferaw et al. (2004).

While small patches cleared from formerly dense *Prosopis* stands reflect attempts to prepare land for crop cultivation, larger *Prosopis*-free areas reflect intense logging for charcoal production. The same explanation can be argued for the weak correlation between numbers of vegetation layers and the degree of *Prosopis* invasion.

Previous studies focussed mainly on the density of *Prosopis* individuals or on the distribution of breast height diameter (e.g. Muturi et al., 2010; Muturi et al., 2013). In the present work, we suggest that the relative cover of *Prosopis* may reflect more appropriately the complex structure of invaded stands. We consequently propose category boundaries of relative cover at 0.05, 0.25 and 0.5, resulting in four classes (see dashed lines in Figure 2d). This variable is also directly linked to stands' physiognomy and it is fast to record in the field. Additionally, the relative cover may be easier to detect by remote sensing than density or breast height stem diameters.

3.2 | Environmental correlations

Eleven variables were used to predict potential invasion by *Prosopis*. In four cases, the relation to relative cover of *Prosopis* was best described by a logistic function, with soil water–holding capacity

having a positive relation, while distance to plantation, soil erosion and rainfall seasonality show negative relations (Table 2). Seven variables (annual rainfall, temperature seasonality, groundwater table, eastness, mean temperature, elevation and topographic position index) show unimodal effects and were thus described by a Gaussian function (Table 2).

All modelling efficiency (ME) values but topographic position index were negative, indicating that the predicted invasion was generally higher than the observed one. This outcome is consistent with the quantile regression, which is estimating an optimum answer, thus most of the observations may generate negative residuals (Cade & Noon, 2003). While ME values are highly scale-dependent, the root mean square error (RMSE) appeared relatively robust (Table 2).

A negative relation of *Prosopis* invasion with the distance to original plantations was expected, as plantations were the starting points of invasive spread (Figure 3a). While this relation is useful for simulating future spread dynamic (see Wilson et al., 2007), a documentation of plantation sites may not be available at other invaded localities. The observation that soil erosion was negatively related to *Prosopis* invasion may surprise as the area has been early reported as heavily affected by erosion (Snelder & Bryan, 1995). Nevertheless, Touber (1989) estimated the erosion at the Njemps flats as lower than at the slopes of the surrounding escarpments, probably on the sole basis of the steep slopes. Likewise, the observed negative relation of invasion to rainfall seasonality and the positive relation to soil water–holding capacity highlight the preference of *Prosopis* to conditions of ample and constant water availability both between and within years, as frequently associated with floodplain and riverine wetlands (Ayanu et al., 2015; Muturi et al., 2013). A relatively high optimum of *Prosopis* in response to mean temperature and temperature seasonality is indicative of its preference for hot and arid environments with high seasonal temperature fluctuation, as they occur in areas where *Prosopis* is native (Burkart, 1976).

The relation between the observed and the predicted degrees of invasion is best described by logistic models for the attributes "distance to plantation" and "soil water–holding capacity" and by Gaussian models for "annual rainfall" and "elevation" (Figure 3). In these cases, quantile regression characterises well the upper limits of observed invasion in response to the respective environmental gradients. As a result, the areas with highest predicted future invasion risks (potential class 4) are concentrated in the area of the Njemps flats on the southern end of Lake Baringo and small areas at the north–western, northern and eastern sides of the same lake (Figure 4).

4 | CONCLUSIONS, RECOMMENDATIONS AND OUTLOOK

The cost-efficiency of large-scale assessment of *Prosopis* invasion in Kenya and beyond will require remote sensing approaches. While the relative cover in vegetation stands has been shown to be the most suited attribute for assessing and monitoring the invasion with

Prosopis, additional variables or stand attributes may improve and refine invasion classes at other sites. Also, the effects of *Prosopis* invasion on biodiversity will require further studies.

ORCID

Miguel Alvarez 🆔 https://orcid.org/0000-0003-1500-1834

REFERENCES

Alvarez, M., Leparmarai, P., Heller, G., & Becker, M. (2017). Recovery and germination of *Prosopis juliflora* (Sw.) DC seeds after ingestion by goats and cattle. *Arid Land Research and Management*, *31*, 71–80. https://doi.org/10.1080/15324982.2016.1234521

Andersson, S. (2005). *Spread of the introduced tree species* Prosopis juliflora *(Sw.) DC in the Lake Baringo area, Kenya*. Umea, Sweden: SLU.

Ayanu, Y., Jentsch, A., Müller-Mahn, D., Rettberg, S., Romankiewicz, C., & Koellner, T. (2015). Ecosystem engineer unleashed: *Prosopis juliflora* threatening ecosystem services? *Regional Environmental Change*, *15*, 155–167. https://doi.org/10.1007/s10113-014-0616-x

Becker, M., Alvarez, M., Heller, G., Leparmarai, P., Maina, D., Malombe, I., … Vehrs, H. (2016). Land-use changes and the invasion dynamics of shrubs in Baringo. *Journal of Eastern African Studies*, *10*, 111–129. https://doi.org/10.1080/17531055.2016.1138664

Bennett, N. D., Croke, B. F. W., Guariso, G., Guillaume, J. H. A., Hamilton, S. H., Jakeman, A. J., … Andreassian, V. (2013). Characterising performance of environmental models. *Environmental Modelling and Software*, *40*, 1–20. https://doi.org/10.1016/j.envsoft.2012.09.011

Beuel, S., Alvarez, M., Amler, E., Behn, K., Kotze, D. C., Kreye, C., … Becker, M. (2016). A rapid assessment of anthropogenic disturbances in East African wetlands. *Ecological Indicators*, *67*, 684–692. https://doi.org/10.1016/j.ecolind.2016.03.034

Braun-Blanquet, J. (1964). *Pflanzensoziologie*. Springer, Vienna: Grundzüge der Vegetationskunde.

Burkart, A. (1976). A monograph of the genus *Prosopis* (Leguminosae subfam. Mimosoideae). *Journal of the Arnold Arboretum*, *57*, 450–525. 219–249

Cade, B. S., & Noon, B. R. (2003). A gentle introduction to quantile regression for ecologists. *Frontiers in Ecology and the Environment*, *1*, 412–420. https://doi.org/10.1890/1540-9295(2003)001[0412:AGITQR]2.0.CO;2

Catalano, S. A., Vilardi, J. C., Tosto, D., & Saidman, B. O. (2008). Molecular phylogeny and diversification history of *Prosopis* (Fabaceae: Mimosoideae). *Biological Journal of the Linnean Society*, *93*, 621–640. https://doi.org/10.1111/j.1095-8312.2007.00907.x

Coppock, D. L., Aboud, A. A., & Kisoyan, P. K. (2005). *Agro-pastoralist's wrath for the prosopis tree: The case of the Il Chamus of Baringo District, Kenya*. Davis, CA: University of California.

Dormann, C. F., & Kühn, I. (2012). *Angewandte Statistik für die biologischen Wissenschaften*. Leipzig-Halle, Germany: UFZ.

Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E., & Yates, C. J. (2011). A statistical explanation of MaxEnt for ecologists. *Diversity and Distributions*, *17*, 43–57. https://doi.org/10.1111/j.1472-4642.2010.00725.x

Fan, Y., Li, H., & Miguez-Macho, G. (2013). Global patterns of groundwater table depth. *Science*, *339*, 940–943. https://doi.org/10.1126/science.1229881

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*, 4302–4315. https://doi.org/10.1002/joc.5086

Getachew, D., Demissew, S., & Woldemariam, T. (2012). Allelopathic effects of the invasive *Prosopis juliflora* (Sw.) DC. on selected native plant species in Middle Awash, Southern Afar Rift of Ethiopia.

Management of Biological Invasions, 3, 105–114. https://doi.org/10.3391/mbi.2012.3.2.05

Gonçalves, G. S., Alves de Andrade, L., Gonçalves, E. P., Bezerra de Oliveira, L. S., & Dias, J. T. (2013). Qualidade fisiológica de sementes de algaroba recuperadas de excrementos de muares. *Semina: Ciências Agrárias*, 34, 593–602. https://doi.org/10.5433/1679-0359.2013v34n2p593

Janssen, P. H. M., & Heuberger, P. S. C. (1995). Calibration of process-oriented models. *Ecological Modelling*, 83, 55–66. https://doi.org/10.1016/0304-3800(95)00084-9

Kaur, R., González, W. L., Llambi, L. D., Soriano, P. J., Callaway, R. M., Rout, M. E., … Inderjit, (2012). Community impacts of *Prosopis juliflora* invasion: Biogeographic and congeneric comparisons. *PLoS ONE*, 7, 1–13. https://doi.org/10.1371/journal.pone.0044966

Kyuma, R. K., Wahome, R. G., Kinama, J. M., & Wasoga, V. O. (2016). Temporal relationship between climate variability, *Prosopis juliflora* invasion and livestock numbers in the drylands of Magadi, Kenya. *African Journal of Environmental Science and Technology*, 10, 129–140. https://doi.org/10.5897/AJEST2015.2034

Lillesø, J.-P.-B., van Breugel, P., Kindt, R., Bingham, M., Demissew, S., Dudley, C., … Graudal, L. (2011). *Potential natural vegetation of Eastern Africa (Ethiopia, Kenya, Malawi, Rwanda, Tanzania, Uganda and Zambia)*. Hørsholm, Denmark: University of Copenhagen.

Murtagh, F., & Legendre, P. (2014). Ward's hierarchical agglomerative clustering method: Which algorithm implement Ward's criterion? *Journal of Classification*, 31, 274–295.

Muturi, G. M., Mohren, G. M. J., & Kimani, J. N. (2010). Prediction of *Prosopis* species invasion in Kenya using geographical information system techniques. *African Journal of Ecology*, 48, 628–636.

Muturi, G. M., Poorter, L., Mohren, G. M. J., & Kigomo, B. N. (2013). Ecological impact of *Prosopis* species invasion in Turkwel riverine forest, Kenya. *Journal of Arid Environments*, 92, 89–97. https://doi.org/10.1016/j.jaridenv.2013.01.010

Odada, E. O., Onyando, J. O., & Obudho, P. A. (2006). Lake Baringo. In World Lakes Network (Ed.), *World Lake Basin Management Initiative: Experience and lessons learned briefs* (pp.31–43). World Lakes Network. Retrieved from:http://www.worldlakes.org.

R Core Team (2017). R: A Language and Environment for Statistical Computing. https://www.R-project.org.

Rejmánek, M., & Richardson, D. M. (1996). What attributes make some plant species more invasive? *Ecology*, 77, 1655–1661.

Richardson, D. M., Pyšek, P., Rejmánek, M., Barbour, M. G., Panetta, F. D., & West, C. J. (2000). Naturalization and invasion of alien plants: Concepts and definitions. *Diversity and Distributions*, 6, 93–107. https://doi.org/10.1046/j.1472-4642.2000.00083.x

Robinson, T. P., van Klinken, R. D., & Metternicht, G. (2008). Spatial and temporal rates and patterns of mesquite (*Prosopis* species) invasion in Western Australia. *Journal of Arid Environments*, 72, 175–188. https://doi.org/10.1016/j.jaridenv.2007.05.011

Shackleton, R. T., Le Maitre, D. C., Pasiecznik, N. M., & Richardson, D. M. (2014). Prosopis : A global assessment of the biogeography, benefits, impacts and management of one of the world's worst woody invasive plant taxa. *AoB Plants*, 6, 1–18. https://doi.org/10.1093/aobpla/plu027

Shiferaw, H., Teketay, D., Nemomissa, S., & Assefa, F. (2004). Some biological characteristics that foster the invasion of *Prosopis juliflora* (Sw.) DC. at Middle Awash Rift Valley area, north-eastern Ethiopia. *Journal of Arid Environments*, 58, 135–154. https://doi.org/10.1016/j.jaridenv.2003.08.011

Snelder, D. J., & Bryan, R. B. (1995). The use of rainfall simulation tests to assess the influence of vegetation density on soil loss on degraded rangelands in the Baringo District, Kenya. *Catena*, 25, 105–116. https://doi.org/10.1016/0341-8162(95)00003-B

Tewari, J. C., Mathur, B. K., Tewari, P., Singh, Y., Singh, M., Ram, M., & Sharma, A. (2013). *Prosopis juliflora*: A miracle species of hot arid and semi-arid regions of India. *Popular Kheti*, 1, 53–59.

Touber, L. (1989). *Landforms and soils of Baringo District, Kenya*. Wageningen, the Netherlands: Winand Staring Centre.

Wakie, T. T., Evangelista, P. H., Jarnevich, C. S., & Laituri, M. (2012). *Mapping current and potential distribution of non-native* Prosopis juliflora *in the Afar Region of Ethiopia*. Washington, DC: USAID.

Weiss, A. D. (2001). *Topographic position and landforms analysis*. Seattle, WA: The Nature Conservancy. Retrieved from:www.jennessent.com/downloads/tpi-poster-tnc_18x22.pdf

Wilson, J. R. U., Richardson, D. M., Rouget, M., Procheş, Ş., Amis, M. A., Henderson, L., & Thuiller, W. (2007). Residence time and potential range: Crucial considerations in modelling plant invasions. *Diversity and Distributions*, 13, 11–22. https://doi.org/10.1111/j.1366-9516.2006.00302.x

Yoda, K., Elbasit, M. A., Hoshino, B., Nawata, H., & Yasuda, H. (2012). Root system development of *Prosopis* seedlings under different soil moisture conditions. *Journal of Arid Land Studies*, 22, 13–16.

Zeila, A. (2011). *Mapping and managing the spread of* Prosopis juliflora *in Garissa County, Kenya*. Nairobi, Kenya: Kenyatta University.