Action on Invasive Species: Control strategies of *Parthenium hysterophorus* L. on smallholder farms in Kenya

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Abstract

Parthenium hysterophorus L. (Asteraceae) is an alien invasive weed with detrimental effects on agricultural production and threatens rural livelihoods in Asia and Africa. The problem emerged recently in the Kenyan Rift Valley, where it began to affect the landholdings of both agro-pastoralists and crop farmers. These vulnerable smallholders depend heavily on the quality of the resource base for their livelihoods. In this study, we hypothesize that the implementation of existing control strategies depend on the state of parthenium invasion, on household economic attributes, and on the site-specific effectiveness of control strategies. We assessed the severity of parthenium invasion and farmers' management responses using a sample of 530 agro-pastoralists in Baringo County, Kenya, in 2019. The prevalence and severity of parthenium invasion differed greatly among field plots. To control weeds, farmers resort to either hand weeding, the use of synthetic herbicides, or intensive tillage, sometimes in combination with mulching and mineral fertilizer application. A multivariate probit regression model shows that household socio-economic characteristics determine the type of control strategies used as well as their complementarity and substitutability. Hand weeding is the most common option, adopted by almost 40% of farmers. The use of agrochemicals or soil-based control strategies appears to be related to knowledge and information characteristics such as access to extension services, membership in organizations, and educational level of household heads. While hand weeding and the use of synthetic herbicides depict significant substitutability, the latter strategy is limited to a few larger farms with market-oriented production. As parthenium invasion continues, policies need to improve farmer awareness and access to knowledge to enable pro-poor and environmentally sustainable control of parthenium on smallholder farms.

Keywords: Herbicides, Invasive species, Land-use change, Probit model, Weed control

1. Introduction

Alien invasive plant species continue to wreak havoc on many smallholder farms in developing countries, threatening food security and livelihoods. They have detrimental effects on crop yields, pasture productivity, and tree plantations, but can also negatively impact the biodiversity of the natural environment (Mack *et al.*, 2000). In addition, invasive plants can have negative impacts on human and animal health (Rai and Singh, 2020). With progressive land-use change and agricultural intensification, coupled with physical infrastructure development, biological invasions have increased over the past decade (Pyšek *et al.*, 2020), and are predicted to continue to increase by at least one-third over the next two decades (Seebens *et al.*, 2020).

Kenya has a relatively low proportion of alien species in its flora (about 6%), with America and Europe being the main origins of introduction (Stadler *et al.*, 2000). However, the accuracy of information on alien invaders in Kenya is low due to the lack of comprehensive and complete lists of alien plant species. In general, anthropogenic disturbances and land degradation are the main causes of the invasive dispersal dynamics (Witt *et al.*, 2018).

Parthenium hysterophorus L., native to South America, belongs to the family Compositae (Asteraceae) and is considered a noxious weed and one of the most invasive species in the world (Shabani *et al.*, 2020). *Parthenium hysterophorus* (further referred to as parthenium) was accidentally introduced into Kenya and Ethiopia in the early 1970's (Tamado and Milberg, 2000), possibly with contaminated wheat seeds from Australia (Pratt *et al.*, 2017). Through allelopathic effects, parthenium inhibits seed germination and growth of a variety of crops and pasture species. Depending on water availability, it may flower throughout the year, increasing its dispersal pressure. In addition, the plant provides shelter and fodder (nectar) for mosquitoes that transmit viral diseases (Agha *et al.*, 2020).

Given its bioclimatic preferences, large areas of East Africa are suitable for parthenium spread, and many of these overlap with areas suitable for maize production (McConnachie *et al.*, 2010). Losses in maize production due to parthenium invasion in Africa have been estimated at 3.8 to 7.7 million USD per year (Pratt *et al.*, 2017), while parthenium-related yield losses in sorghum in Ethiopia range from 40% to 97% (Tamado *et al.*, 2002).

While various chemical, mechanical, and cropping system management practices have been recommended to control or reduce the incidence of parthenium in croplands (Shabbir, 2014), few attempts have been made (1) to define under which social-ecological conditions farmers can effectively use these recommended practices and (2) to understand the inherent constraints to their use (Adkins and Shabbir, 2014).

While much attention has been paid to the drivers of parthenium spread and the economic losses it inflicts on production, little is known about the decision-making process for adopting different management strategies in farming systems in rural Africa. This is particularly important in parts of the Kenyan Rift Valley, where the spread of parthenium is a very recent phenomenon (Wabuyele et al., 2014) and where smallholder farmers are highly vulnerable because their livelihoods depend heavily on the quality of natural resources (Greiner et al., 2013).

We hypothesize that the implementation of control strategies will depend on the perceived and actual state of parthenium invasion, the economic characteristics of households, and the site-specific effectiveness of control strategies. This paper therefore examines the relevance of parthenium infestation in Baringo County in Kenya to smallholder decision-making based on their socio-economic context and exposure to parthenium invasion.

2. Materials and methods

2.1 Description of the study site

This study was conducted in the Baringo County, which is located in the Rift Valley of Kenya. It is characterized by both lowlands and highlands with varying altitude, precipitation and vegetation formations. The highlands, represented in our study by the Tugen hills, are formed on volcanic rocks at altitudes of 800-2000 m above sea level. They are mainly used as rangelands. The lowlands are located 700 m above sea level with loamy sediment soils and alluvial clay deposits from the lakes. The undulating landscape is used for both crop- and rangelands. The area, also known as the 'Njemp flats', is bordered on the west by the Tugen hills, on the east by the Laikipia Escarpment, and on the north by the Elgeyo Escarpment and the Lake Baringo catchment. The area also comprises the Bogoria salt water lake, which is home to many migratory water birds (Mwangi and Swallow, 2008).

The area has an annual precipitation of 1000-1500 mm in the highlands and 300-700 mm in the lowlands (Mbaabu et al., 2020), which follows a bimodal distribution pattern with peaks in April and in November. Temperatures range from 10^0C in the highlands to 35^0C in the Njemp flats. Based on the Köppen–Geiger climate classification, Baringo falls into the BSh zone, which is a hot, semi-arid savannah climate (Peel et al. 2007)..

The area has historically been settled by the Ilchamus and the Tugens, with some Pokots migrating seasonally from the north. The Ilchamus, also known as the Njemps, are a maa-speaking group, while the Tugens are Kalenjin-speaking. The main livelihood strategy of all these groups is semi-nomadic livestock keeping, which is increasingly being supplemented or replaced by rainfed maize cultivation and by irrigated agriculture near the shores of the lake (Greiner et al., 2013). Fishing and apiculture are also gaining importance as economic activities. Around the Lake Bogoria National Reserve and in areas near to Lake Baringo, tourism and biodiversity conservancies are common. There, charcoal production is gaining importance as another new livelihood strategy and as part of management initiatives to reduce the negative impacts of the spread of another alien invasive species, *Prosopis juliflora*, in areas near Lake Baringo (Alvarez et al., 2019).

2.2 Farm household survey

This study relies on a farm household survey which was carried out between July and August 2019 using a two-stage sampling technique. In the first stage, 35 villages were randomly selected from 4 wards in the Baringo County.[1] The wards were purposely selected due to the rapid spread of the invasive parthenium coupled with the established *Prosopis juliflora* invasion (Alvarez et al., 2019). Villages were selected in collaboration with the Kenya National Bureau of Statistics using the probability proportional to size random sampling technique. Village-level household lists were prepared with village authorities in all 35 sampled villages. From these lists, 15 to 16 households were randomly selected in each village, resulting in a total sample size of 530 households.

These households were interviewed using a structured questionnaire developed based on the initial visits to the study area. The questionnaire was designed on the World Bank's Survey Solutions platform and tested prior to implementation. To ensure that respondents were able to understand the questions, the questionnaire was translated into the local languages, i.e., Ilchamus and Tugen. Interviews were conducted with household heads or their spouses in their local languages at a time convenient to the households. Each interview lasted 45 to 75 minutes and questionnaires were administered by a team of eight local enumerators who had received prior training.

The survey collected information on (1) awareness of parthenium as an invasive species, (2) management options to control its spread, (3) socio-economic and demographic characteristics of households, and (4) access to information, extension contacts, and membership in social organizations. To assess knowledge and awareness of parthenium, we showed pictures of parthenium and asked farmers if they could identify the plant. After they identified the plant, we jointly visited field sites where farmers had reportedly seen parthenium in both rangelands and crop fields. The presence of and/or damage caused by

[1] The administrative structure of Kenya is organized into counties, sub-counties, wards, and villages.

parthenium was quantified using an ordered scale from 0 to 4, representing the percentage of ground cover (0 = no parthenium; 4 = 75-100% ground cover).

2.3 Statistical analysis

A combination of descriptive and econometric methods was used to analyze the collected data. Descriptive statistics were used to assess farmer awareness and knowledge of parthenium, as well as reported severity and extent of damage. Descriptive statistics were also used to identify the different control options used by farmers.

While most farmers use single parthenium control options, some farmers apply multiple strategies. Thus, determinants for using individual control options may mask potential complementary or substitutive effects of different options. Failure to account for such interactions may result in biased effects, since both the number and type of options adopted may be path-dependent (Cowan & Gunby, 1996) and their adoption may be influenced by past experience of prior use. Farmers may thus consider a bundle of management options to maximize expected benefits. In view of assessing determinants for adopting control strategies and to account for possible interactions and intercorrelations in the error terms, we applied a multivariate probit model (MVP), implemented in the statistical program STATA, and using the 'mvprobit' command for the conditional recursive mixed process (Roodman, 2011). Depending on the sign of the correlation, control options can be complements (positive correlation) or substitutes (negative correlation). Thus, a positive correlation between two control options implies that the two options are complementary, while a negative correlation implies substitutive effects. The MVP is represented as a set of binary dependent variables (Y_i) as shown below:

$$Y_{im}^* = \boldsymbol{X_{im}\beta_m} + \varepsilon_{im} \quad (1)$$

$$Y_{im} = \begin{cases} 1 \; if \; Y_{im}^* > 0 \\ 0 \text{ otherwise} \end{cases} \quad (2)$$

$m = 1,2,3$

where i represents the rational farmer, and m denotes the management choices available, Y_{im}^* is a latent variable representing utility differences in using the different management options. It captures the unobserved preferences associated with the use of these options. Y_{im} denotes the various management options used to control parthenium. Y_{im} is assumed to be a linear combination of observed characteristics $\boldsymbol{X_{im}}$ representing a vector of household and farm characteristics thought to influence the use of the different management options, while $\boldsymbol{\beta_m}$ is the vector of parameters to be estimated. ε_{im} is the stochastic error term.

If farmer's adoption of a particular control option is independent of that of another one, and if thus the error terms are independent and identically distributed, we can employ univariate probit models using equations (1) and (2). However, since the error terms in equation (1) follow a multivariate normal distribution (MVN) with a conditional mean of zero and a normalized variance of 1, the covariance matrix is represented as ($\varepsilon_{ijm} \sim MVN(0, \Sigma)$) with:

$$\Sigma = \begin{bmatrix} 1 & \rho_{12} & \rho_{13} & \cdots & \rho_{1m} \\ \rho_{12} & 1 & \rho_{23} & \cdots & \rho_{2m} \\ \rho_{13} & \rho_{23} & 1 & \ldots & \rho_{3m} \\ \vdots & \vdots & \vdots & 1 & \vdots \\ \rho_{1m} & \rho_{2m} & \rho_{3m} & \cdots & 1 \end{bmatrix} \quad (3)$$

Off-diagonal elements in the covariance matrix, ρ_{im}, captures unobserved correlations between weed control strategies. The specification with off-diagonals, which are non-zero, allows for correlating error terms of different latent equation models. These are reflective of both the unobserved and unmeasured factors driving the choice of the management option.
As the maximum likelihood function of a multivariate normal distribution depends on multi-dimensional integration, we used the Geweke-Hajivassiliou-Keane simulator for recursive conditioning, thus viewing and evaluating the multivariate normal distribution as a product of univariate normal distributions (Cappellari & Jenkins, 2003).

3. Results

3.1 Knowledge on invasion and management strategies applied

In terms of knowledge and awareness of parthenium, about 67% of the surveyed farmers correctly identified parthenium, with about 40% reporting infestations in their own fields (Table 1). About 40% of the households were faced with the presence of Parthenium in both their pasture and croplands. Of these households, the ground cover of parthenium reported was about 65%. Knowledge of weeds and their harmful effects on crops or forage productivity is an important step in managing them. In most cases, knowledge of parthenium did not imply a direct infestation in individual farmers' fields but could also concern infestation in neighbors fields. Figure 1 shows the map of the study area showing the spatial occurrence and reported extent of parthenium invasion.

Farmers in the study area used three main strategies, namely manual weeding, application of synthetic herbicides, and intensive tillage, sometimes in combination with mulching. Hand weeding was the most popular management strategy. Nearly 60 % of the surveyed households did not experience infestation of their plots with parthenium and hence did not apply any specific weed control strategy. Among farmers afflicted by parthenium infestation, the largest share (90%), or 38% of all surveyed households manually removed parthenium from crop fields.

Table 1. List of variables recorded by a household survey on parthenium control strategies in in Baringo County, Kenya.

	Data type	Mean	Std. Dev.
Dependent variables (parthenium control strategies)			
Manual weed removal in field crops	Binary	0.38	0.49
Spray application of herbicides	Binary	0.15	0.36
Intensive soil tillage	Binary	0.03	0.17
Explanatory variables			
Age of household head (years)	Continuous	45.15	15.62
Gender (male =1, female =0)	Binary	0.74	0.43
Education level (years of schooling)	Continuous	7.90	4.90
Cultivated area (ha)	Continuous	0.53	0.73
Household size (number of members)	Continuous	5.9	2.8
Level of infestation of parthenium (%)	Continuous	0.65	0.99
Farming experience (years)	Continuous	13.4	13.0
Membership in producer organization (Yes =1, No=0)	Binary	0.33	0.47
Access to credit (Yes =1, No=0)	Binary	0.43	0.50
Off-farm activities (Yes =1, No=0)	Binary	0.27	0.45
Extension contacts (Yes =1, No=0)	Binary	0.26	0.44
Use of M-pesa (Yes =1, No=0)	Binary	0.83	0.38
Livestock ownership (TLU[a])	Continuous	3.2	5.1
Awareness of parthenium (Yes =1, No=0)	Binary	0.67	0.47
Infestation by parthenium (Yes =1, No=0)	Binary	0.40	0.49

TLU: Tropical livestock units

The second most popular option, used by 15% of all farmers (about 40% of those afflicted by parthenium invasion), was the application of synthetic herbicides. Only about 3% of households used intensive soil tillage such as ploughing, harrowing and mulching to control parthenium. While hand weeding is very labour intensive, the use of synthetic herbicides requires financial investment to purchase agrochemicals, and the use of intensive tillage requires access to machinery or draft animals. These latter options were considered more desirable than hand weeding because they limit farmers' physical contact with parthenium, which reportedly can cause allergic reactions in humans. On the other hand, capital requirements limit the use of agrochemical- and machinery-based options to better-off households with generally high wealth, with only about 3% of farmers in the sample meeting these conditions. No single farmer was aware of or used biological control measures as recommended for example in South Asia (Adkins and Shabbir, 2014).

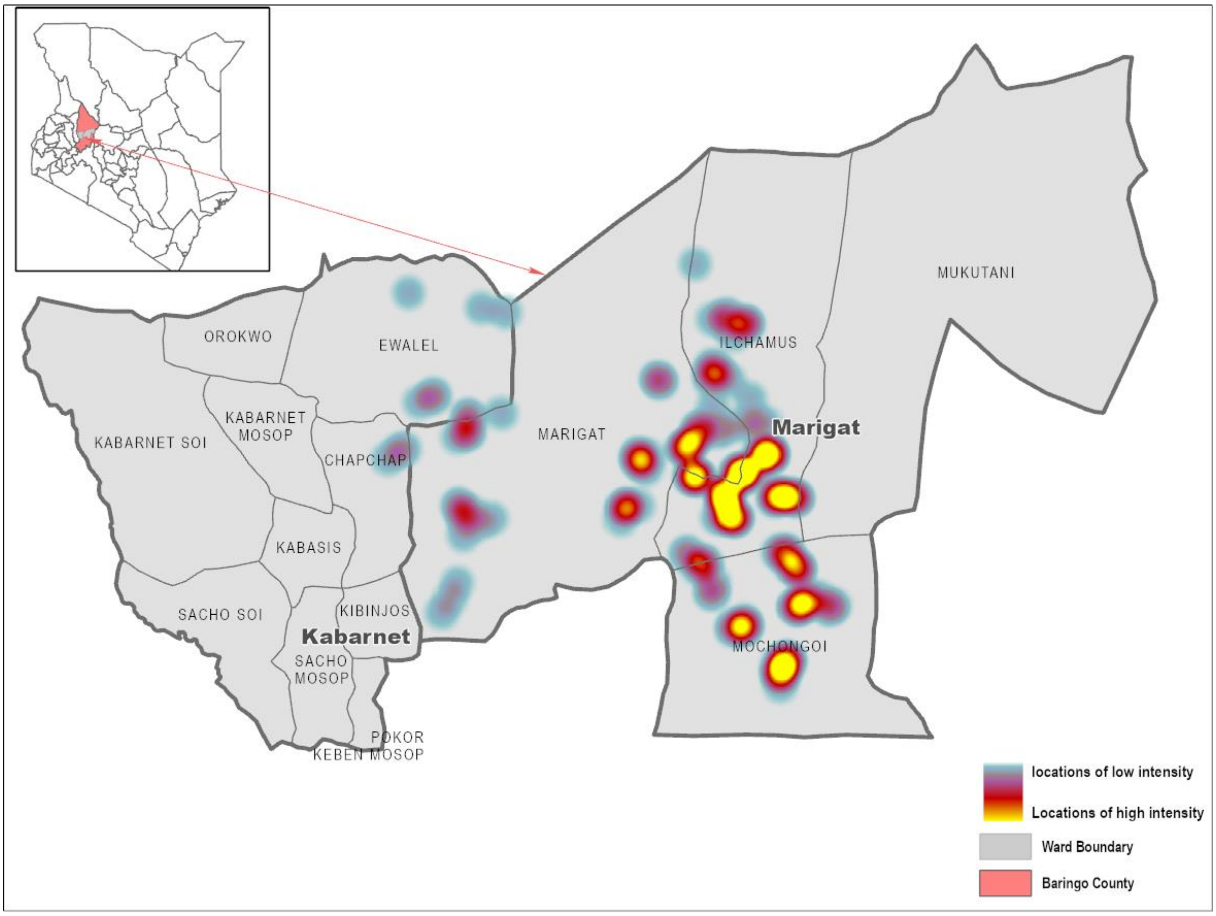

Figure 1. Study area showing reported intensity of the parthenium invasion and the share of ground cover in Baringo County in the northern region of Kenya. Marigat and Kabarnet (in bold) are the administrative headquarters of Baringo South and Baringo Central sub-counties, respectively. All other units represent some of the wards (administrative sub-units) in the two sub-counties. Characterization of parthenium intensity is based on farmer-reported levels of invasion, ranging from low (<25% infestation - blue color), average (25-50% infestation - red color), high (50-75% infestation – orange color) to very high (>75% infestation – yellow color). The percentages are the proportion of present/absent values in a range of fields. The map was created using ArcGIS mapping and analysis software.

3.2 Socio-economic and demographic characteristics of farmers

The socio-economic, demographic, and farm characteristics of the farmers surveyed are also shown in Tables 1 and 2. While Table 1 shows mean values of socio-economic characteristics, Table 2 shows the summary statistics of some of the variables by ethnicity.

Farmers in the study area were on average 45 years old, with more than one-third of households being headed by women. The household heads had a moderate level of education of about 8 years of schooling, which is equivalent to primary plus post-primary school education. The households can be characterized as smallholders based on their farm size of about 0.53 hectares.

About one-third of the farmers in the sample belonged to associations such as cooperatives and saving groups. Off-farm income was quite low, with only about one-fourth of the households obtaining revenues from off-farm enterprieses. Access to credit was available to just under half of the 530 households. Access to extension services was even lower, with only about 26% of farmers reporting to have had contact with extension agents in the course of the last 12 months. In contrast, access to and use of a mobile money account was widespread, with about 83% of farmers reporting using M-pesa[2] for financial transactions. Ownership of an M-pesa account requires ownership of a mobile phone, through which some farmers also reported to have received important extension information. Livestock ownership is represented by the Food and Agriculture Organization (FAO) tropical livestock unit index, where each livestock represents a specific unit, depending on the live weight of the animal. Since the study area is a pastoralist community, livestock ownership significantly represents rural wealth. Households reported owning an average 3.2 tropical livestock units (TLUs).

Table 2. Summary statistics of variables by ethnicity in Baringo County, Kenya

	Ilchamus			**Tugen**		
	Mean	**Min**	**Max**	**Mean**	**Min**	**Max**
Age of household head (years)	41.6	20	79	47.1	18	104
Gender (male =1, female =0)	0.7	0	1	0.72	0	1
Education level (years of schooling)	6.91	0	17	8.37	0	1
Cultivated area (ha)	0.57	0	7	0.50	0	8.1
Household size (number of members)	6.67	1	15	5.59	1	15
Farming experience (years)	11.6	0	50	14.6	0	69
Membership in producer organization (Yes =1, No=0)	0.39	0	1	0.18	0	1
Distance to market (km)	10.5	0.5	60	8.97	0.12	90
Access to credit (Yes =1, No=0)	0.40	0	1	0.44	0	1

[2] M-pesa is a mobile phone-based money transfer service, payments and micro-financing service.

Off-farm activities (Yes =1, No=0)	0.16	0	1	0.32	0	1
Extension contacts (Yes =1, No=0)	0.31	0	1	0.24	0	1
Use of M-pesa (Yes =1, No=0)	0.83	0	1	0.83	0	1
Livestock ownership (TLU[a])	3.17	0	34.6	3.27	0	60.7
Household income (1000 Ksh)	11.8	1	100	10.3	1	120
Awareness of parthenium (Yes =1, No=0)	0.77	0	1	0.61	0	1
Infestation by parthenium (Yes =1, No=0)	0.58	0	1	0.30	0	1
Observations	179	179	179	338	338	338

Farmers in the lowlands (Ilchamus) were younger than those in the highlands (Tugens), where crop farming is recent and not very widespread. They also had larger cultivated areas, more household members, and participated more in cooperatives (twice as much as the Tugens). However, they had fewer educated household heads, less farming experience, less access to credit, and less participation in off-farm activities. Farmers in the lowlands had more contact with extension agents and were somewhat more distant from markets than farmers in the hills. In terms of wealth, we observed that lowland farmers had a higher average income than farmers in the hills. The opposite was true for livestock ownership, which represents a significant part of rural wealth, particularly in the pastoralism-dominated systems in the highlands.. Thus, the Tugens agro-pastoralist own more livestock than the Ilchamus farmers. Finally, regarding parthenium infestation, knowledge of parthenium is more widespread among farmers in the Ilchamus area. This is also true for parthenium infestation, as they reported more infestations in their fields.

3.3 Differential of household attrbutes based on weed management strategies

We compared group means and standard deviations of key household attributes to understand socio-economic differences and drivers of adoption for different parthenium control strategies (Table 3). Younger household heads differed significantly from older ones in that the former used more herbicides, while the latter preferred manual weed control. Furthermore, male-headed households applied more herbicides than female-headed ones, suggesting a gender-differenciated access to and use of external, capital- and knowledge-inensive inputs. Male-headed households are better connected with extension agents as a source of information and have a more social capital (belonging to organization) which may improve their access to knowledge and to herbicides.

Farmers with larger land holdings differed significantly from those owning little land regarding the adoption of manual and chemical parthenium control strategies, while no apparent differences accorred regarding tillage-based weed control.. Similar differences were also observed with respect to household size (number of members ina household). There is a positive relationship between a large family and hence the availability of labor for manual manual weeding, a trend that is expected as manual weeding is usually labour-intensive and time-consuming. The trend appears less plausible for the observed correlation between household size and herbicide use. On the other hand, herbicide application is not scale neutral and may depend on a large family labour force for high levels of invasion, particularly in relation to large land holdings.

We also observed significant differences between households applying parthenium control strategies based on the extent of damage caused by parthenium. Thus households controlling parthenium reported higher area covers and experienced more crop damage due to parthenium compared to households that did not use any weed control. In addition, farmers who practiced weed control were more experienced in growing crops and also had experienced parthenium infestations since longer times than farmers who did not weed. Their experience in managing other crop weeds also increased their willingness (and the bneed) to manage parthenium. Farmers applying herbicides were usually members of village organizations, had larger land holding and more capital resources (owning portable phones and having larger numbers of livestock), and they had easier access to credit and extension support than their counterparts who are not members of such social g groups.

3.4 Covariate relationship to management options

Because some of the covariates in the MVP model (Table 4) are potentially endogenous, we are are not able to imply causal relationships, rather referring to these relationships as associations or correlations of farmers' management options. Younger farmers are more likely to perform manual weeding than older ones. While weeding is often described as an activity mainly completed by women and children (Mcconnachie et al., 2011), our analysis finds no evidence to support this claim. We even observed a positive correlation between the gender of the household head (male) and the use of manual weeding, though the variability in the sampel of households was very large.

While the educational level of the household head was not associated with the weed control strategies applied, the number of years in formal education has a negative relationship with the use of synthetic herbicides. Thus, each additional year spent in formal education reduced herbicide use by 3.4%. This is related to an increased awareness of likely harmful effects of some herbicides on the environment and on human and livestock health. Finally, households cultivatinglarger areas of land are more likely to apply herbicides as a labor-saving strategy for parthenium control.

Table 3 Mean differences between households in Baringo County, Kenya based on the different management strategies for the control of the alien invasive species Parthenium Hysterophorus

Variables	**Weeding**		**Herbicide application**		**Intensive cultivation**	
	Yes (1)	**No (0)**	**Yes (1)**	**No (0)**	**Yes (1)**	**No (0)**
Age of household head (years)	40.740*** (0.954)	47.824 (0.892)	41.987** (1.389)	45.721 (0.758)	47.687 (3.431)	45.071 (0.691)
Household head is male (1=Yes)	0.780 (0.029)	0.718 (0.024)	0.827** (0.042)	0.726 (0.021)	0.875 (0.085)	0.737 (0.019)
Educational level of household head	8.400* (0.327)	7.593 (0.274)	8.098 (0.541)	7.861 (0.229)	9.062 (1.062)	7.861 (0.215)
Area of cultivation (ha)	0.694*** (0.060)	0.422 (0.033)	0.886*** (0.135)	0.459 (0.027)	0.896* (0.216)	0.514 (0.031)
Household size (number)	6.515*** (0.188)	5.587 (0.150)	6.703*** (0.297)	5.799 (0.133)	5.812 (0.541)	5.941 (0.125)
Damage level (%)	1.655*** (0.065)	0.048 (0.015)	1.666*** (0.096)	0.472 (0.042)	1.312*** (0.150)	0.634 (0.043)
Experience in crop production (years)	11.335*** (0.712)	14.651 (0.792)	13.395 (1.132)	13.400 (0.636)	16.750 (3.939)	13.295 (0.570)
Farmer group (1=Yes)	0.370 (0.034)	0.303 (0.025)	0.456*** (0.055)	0.305 (0.021)	0.500 (0.129)	0.322 (0.020)
Access to credit (1=Yes)	0.565*** (0.035)	0.348 (0.026)	0.567*** (0.055)	0.405 (0.023)	0.322*** (0.020)	0.420 (0.021)

Off-farm participation (1=Yes)	0.295	0.257	0.234	0.278	0.312	0.270
	(0.032)	(0.024)	(0.047)	(0.021)	(0.119)	(0.019)
Access to extension services (1=Yes)	11.335***	14.651	13.395	13.400	16.750	13.295
	(0.712)	(0.792)	(1.132)	(0.636)	(3.939)	(0.570)
Use of M-pesa (1=Yes)	0.920***	0.769	0.901**	0.812	0.875	0.824
	(0.019)	(0.023)	(0.033)	(0.018)	(0.085)	(0.016)
Livestock ownership (TLU)	3.895***	2.747	5.235***	2.810	4.429	3.142
	(0.368)	(0.271)	(0.746)	(0.218)	(1.562)	(0.221)
Number of observations	200	330	81	449	16	514

Notes: Standard errors are shown in parenthesis. For obtaining the mean differences between households based on their use of the different management strategies, we used the classical means test. The "1" and "0" in parenthesis signify dummies representing whether households used a particular strategy or not respectively. They represent the categorization in the various groups (weeding, herbicide application and intensive cultivation. p***<0.01, **p<0.05; *p<0.1

The perceived amount of damage caused by parthenium in farmers' crop fields strongly enhanced the adoption of all the three parthenium control startegies, and farmers who reported strong crop damage to from parthenium were more likely to apply any of the management strategies.

Table 4 Covariate relationships to farmer's choice of parthenium management options in Baringo County, Kenya

	Weeding	**Synthetic herbicides**	**Intensive cultivation**
Age of household head (years)	-0.016**	-0.009	0.012
	(0.009)	(0.006)	(0.016)
Household head is male (1=Yes)	0.092	0.244	0.225
	(0.186)	(0.214)	(0.294)
Educational level of household head (years)	-0.006	-0.034**	0.023
	(0.029)	(0.016)	(0.028)
Area of cultivation (hectares)	-0.006	0.076***	0.031
	(0.075)	(0.028)	(0.035)
Household size (number)	0.046**	0.018	-0.039
	(0.023)	(0.020)	(0.037)
Damage level (%)	2.750***	0.577***	0.254***
	(0.461)	(0.088)	(0.078)
Experience in crop production (years)	-0.004	0.006	0.005
	(0.006)	(0.007)	(0.013)
Farmer group (1=Yes)	0.099	0.396***	0.163
	(0.125)	(0.137)	(0.201)
Access to credit (1=Yes)	0.195	-0.011	0.479*
	(0.178)	(0.190)	(0.274)
Off farm participation (1=Yes)	-0.022	-0.088	0.077
	(0.140)	(0.158)	(0.240)
Access to extension services (%)	-0.014	0.426**	0.068
	(0.218)	(0.189)	(0.199)
Use of M-pesa[3] (1=Yes)	0.076	-0.133	-0.136
	(0.197)	(0.278)	(0.357)
Livestock ownership (TLU)	-0.023	0.024**	-0.004
	(0.034)	(0.012)	(0.015)
Constant	-1.508**	-1.635***	-3.210***
	(0.742)	(0.384)	(1.202)
Ward dummies	Yes	Yes	Yes
Number of observations	530	530	530

Numbers in parenthesis present standard errors of the mean; ***p<0.01, **p<0.05; *p<0.1.

Households belonging to village groups were more likely to use herbicides than households not belonging to such groups. This result could be due to several likely reasons. First, because groups increase households' access to farm inputs such as herbicides due to their economic ability to purchase in bulk, and households often obtain these herbicides at reduced and sometimes even subsidized prices. Second, such households have frequently received training on the effective use of agrochemicals, not only in view of controlling parthenium in croplands, but also in view of reducing human and animal exposure to the chemical products. Third, belonging to an organization is associated with improved extension contacts, thus improving households' information and knowledge base. In summary, better-of or more wealthy household are more able to apply these agrochemicals. Thus, the ownership of livestock also positively influences herbicide use as livestock represents wealth in most rural communities, and particularly in agro-pstoral societies.

3.5 Complementarities and substitutability in the management options

One of the objectives of the analysis was to identify complementarities or substitutability among the different parthenium management options. Table 5 shows a significant correlation between the error terms of the use of weed control and the use of herbicides. This justifies the use of the multivariate probit regressions over the univariate probit regressions. The correlation is negative, indicating substitutability in the use of weed control and herbicide use. This means that farmers using synthetic herbicides are less likely to use manual weeding. Since synthetic herbicide use is costly but less labour-intensive, this strategy dominates in large farms that have capital assets but are labor-strapped. On the other hand, manual weeding is labour-intensive and time-consuming, and hence dominates in smaller farms or in poor households with large numbers of members. No correlations were observed between the use of intensive tillage such as ploughing, harrowing and mulching and the use of manual weeding and /or the use of synthetic herbicides.

Table 5 Complementarity and substitutability amongst strategies for controlling the alien invasive weed *Parthenium hysterophorus* in Baringo County, Kenya

Strategies	**Correlation coefficient**
Synthetic herbicides versus weeding	-0.299**
	(0.130)
Intensive cultivation versus. weeding	-0.115
	(0.096)

Intensive cultivation versus synthetic	0.047
herbicides	(0.139)

Numbers in paranthesis represent standard errors of the mean; ***<0.01, **P<0.05; *P<0.1.

4 Discussion

4.1 Management options used by smallholder farmers

From the results presented, it is apparent that farmers in Baringo County of Kenya applied a different management strategies in view of controlling the new and recently emerging problem of infestation of agricultural land by the alien invasive plant species parthenium, including physical methods such as manual weeding,chemical control by herbicide application, and cultural methods such as intensive soil tillage, sometimes in combination with mineral fertilizer use and/or mulching. Manual weeding remains the most widely-used strategy that has been attributed to be done mainly by women and children (Mcconnachie et al., 2011), but is actally being applied in equal propotions by male farmers. It is the strategy of choive for resource-poor households that rely mainly on family labour for all agricultural activities as financial constraints prevent hiring of external labour or applying synthetic herbicides. The latter additionally require access to knowledge as consistent dosing and timely applications are imperative to achieve good weed control (Goodall et al., 2010).

Some households resort to intensive soil tillage operations to control parthenium, both in the process of initial land preparation before seeding, but also by inter-row harrowing during early maize development stages. Such practices are time-consuming, they require access to rented tractors or own draft animals, and in the latter case as well as for manual weeding impact children who perform much of these activities. Thus, instead of going to school, children may spend considerable time during the early crop growth stages in weeding parthenium (Pratt et al., 2017). Intensive tillage is costly, particularly when the renting of four-weel tractors is involved, requiring financial kliquidity or access to credit. Thus, our analysis shows that households with access to credit are more likely to adopt intensive tillage such as ploughing and mulching to control parthenium infestations.

One management option tested in mainly South Asis is biological control by spray application of microbial pathogens such as *Puccinia abrupta* var. *partheniicola* (Dhileepan & Wilmot Senaratne, 2009) or the release of insects that preferably fees on parthenium such as the leaf-feeding beetle *Zygogramma bicolorata* (Shesthra et al., 2015). While such biological control strategies, particularly when combining several control agents, have been successful and are widely advocated for parthenium control in South Asia, none of the farmers in Baringo was aware or used such approaches. This may be considered and possibly hinted as a promising future control strategy of parthenium in the Central Rift Valley, but would require support from both the public and possibly the private sector for establishing mass rearing facilities in conjunction with targeted release of these natural enemies.

Regarding ethnic differences among the surveyed households, we observed some wealth differences between the Ilchamus in the lowlands and the Tugens in the hills, suggesting that households engage in different livelihood activities. Farmers in the Ilchamus region engage in more arable farming than farmers in the Tugen hills, who are more involved in livestock rearing. This is most likely due to the agro-ecological suitability and soil characteristics of the area. In the hills, farming is not an easy task as most of the soils are rather rocky and not suitable for cultivation. Since most farmers in the lowlands practice arable farming, which is reflected in their larger cultivated areas, it is not surprising that they have better access to extension services.

The differentiation of management strategies for parthenium control by enthic groups is however biased by environmental factors. Thus, the lowlands of the Ilchamus-dominated areas around the shores of Lake Baringo are characterized by a hot tropical climate with often deep alluvial soils that are suited for crop production. On the other hand, the cool tropical highlands that are mainly occupied by Tugen are characterized by shallow soils and rocky outcrops that are mainly used as pasture land, while crop uses is largely restricted to slope shoulders and the bottom lands of small inland valleys, with a soil depth that suffices for maize cultivation. Similarly, environmental conditions with sufficient soil depth and water / soil moisture availability are more favourable for the spread of Parthenium in the Inchamus lowland and spatially restricted in the Tugen highlands. As a result, sedentarized ways of life with crop cultivation, but also the spread of parthenium in croplands, are more widespread, more long-standing and occupy larger land areas with associated longer experiences in farming and farmers’ exposure to parthenium in the lowlands than in the more recently used highlands.

4.2 Covariate association to management options

Farmers adoption of parthenium control strategies appears in the very first place to be driven by the intensity of infestation and the perceived extent of damage to the crop caused by parthenium Evidence from the MVP showed that the choice of pathenium control strategies correlates with various socio-economic factors that drive their adoption. Among those attributes, farmers’ knowledge and access to information appear key in adopting options and effectively controlling parthenium infestation in croplands of Baringo. Farmers chose the management options depending on the level of infestation and the their resource endowment. Thus, resource poor household with high labor availability, small land holdings and young household heads tend to opt for manual weeding, while more wealthy households with social linkages and access to credit and extension services, but also labor-strapped households tend to opt for more labour-saving mechanical (tillage-based) or chemical control strategies. Such relationships between relative resource endownment of farmers and the adoption of land-labor, capital- or knowledge-intensive crop management startegies has been recently conceptually summarized for systems in Asia by Becker and Angulo (2019). Accordingly, with small land areas and large numbers of members in the household, labor-intensive strategies such as manual tillage and hand weeding are favoured options. With access to machinery or draft animals, and particularly in larger land holding and labor strapped households, intensive tillage appears to be the stzrategy of choice. Only labor-strapped households with capital (market-oriented production systems) and access to knowledge (education level and access to extension advise) will opt for synthetic herbicides. Similar findings were obtained by Tambo et al. (2020) when considering the use of insecticides in controlling fall armyworm. The sign of the respective coefficient is consistent with the results of other studies. Households practicing large-scale cultivation are less likely to use weed control because it is more labour intensive (Harrison et al., 2019), but the relationship is not statistically significant. Similarly, households with more household members are more likely to engage in manual weeding. Due to the lack of a market for labour in most rural areas, households rely largely on family labour for many agricultural activities such as weeding, which is both labour intensive and time consuming. Gitonga et al. (2010) and Tambo et al. (2020) obtained similar results in controlling *Liriomyza* spp. Leafminers and the fall armyworm in Kenya, Zimbabwe, and Rwanda, respectively.

Herbicide use is predominantly driven by knowledge and information access variables such as household heads' educational level, access to extension services, and participation in village organizations, as well as wealth characteristics such as land and livestock ownership. This finding has important implications for the design and formulation of invasive management strategies. Any intervention that improves the knowledge base and access to information for households would go a long way towards strengthening farmers' capacity to fight invasive species. Institutional characteristics such as access to credit also play a role in very costly management options such as the use of intensive farming methods. Indeed, farmers would adopt costly strategies only to the extent that their liquidity constraints are offset. From an institutional perspective, our results suggest that households are constrained in accessing some institutional services such as farmer groups and credit services. However, institutional services such as the use of M-pesa are currently high. This also implies the prevelance of mobile phones and the associated benefits they offer.

4.3 Substitutability between hand weeding and herbicide application

We also observed significant substitutability between the use of hand weeding and the use of herbicides, implying that any policy initiative that promotes the use of physical control methods such as weeding would greatly reduce the use of herbicides, which can be toxic to both humans and the environment. At this point, it is also important to note that the farmers who suffered most from the health effects of parthenium were particularly exposed to weeding. Furthermore, since weeding is labour and energy intensive (Mcconnachie et al., 2011; Pratt et al., 2017), households may not fully utilize it. As substitution effect also works in the opposite direction, the use of synthetic herbicides may reduce reliance on weeding. But again, synthetic herbicides are costly and and their successful application is both capital- and knowledgeintensive, and hence will be restricted to more wealthy household and to farm types with market-oriented production . Improving the access to herbicides (e.g., through subsidies) may reduce parthenium invasion and crop damage, but only when accompanied with proper inforformation on dosage and timing and on possible harmful effects on health and the environment. Biocontrol strategies by using natural enemies, may be a another workable alternative for future parthenium control in Baringo County and beyond..

4.4 Conclusions and outlook

Invasive species continue to cause detrimental effects on smallholder farms. This is particularly true for the alien invasive plant *Parthenium hysterophors* in Baringo County, Kenya, where the weed is spreading rapidly. While sveral management strategies have been proposed to control parthenium in croplands, it remains unclear whether farmers are adopting these options and if so, which option is most appropriate for which farm type or household category . This study addressed this knowledge gap through an on-farm survey involving 530 households. We could show that depending on the intensity of parthenium infestation and the perceived damage it causes, the resource endowment of households, and particularly their access to knowledge are shaping adoption patterns..

The study has two limitations that should be addressed in future research. First, generalizations from Baringo County to other areas in the Central Rift Valley, to wider Kenya or rural Africa are limited due to the specific social-ecological context of the study area with specific biophysical features and the recent phenomenon of sedentarization of former pastoralists. Second, we do not infer causal relationships and note that our analysis correlates potential determinants with the different management options used by farmers. Being the first preliminary study of this type on the emergent issue of oarthenium spread in Kenya, future research may build on this work but needs to identify causal relationships in view of targeting control options and upscaling recommendadtions.

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