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Original Articles

How well do local stakeholders' perceptions of environmental impacts of an invasive alien plant species relate to ecological data?

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1. Introduction

Anthropogenically driven environmental changes have led to a significant degradation of ecosystems across the world, thereby negatively affecting biodiversity, ecosystem services such as water and food production and ultimately human well-being (Keller et al., 2009; Pejchar and Mooney, 2009). However, the understanding of these changes and of their underlying factors may not be uniform. Environmental change is a complex phenomenon which is exacerbated by the fact that drivers are dynamic, interact with each other and may be context-dependent in different social-ecological systems (Hulme, 2006; Berkes et al., 2008; Steffen et al., 2015). In the framework of the theory of planned behavior (Ajzen, 1991), understanding human perceptions on environmental change provides key information about people's level of commitment and potential responses regarding the protection of natural resources, support for respective public policy options and potential conflicts (Botzen et al., 2009; Abate et al., 2010; Vanderhoeven et al., 2011; Bennett, 2016; Shackleton et al., 2019a).

Invasive alien species (IAS) are human-induced drivers of environmental change (Wardle et al., 2011). While some IAS, particularly those that were intentionally introduced into a region outside their native range, provide some socio-cultural or economic benefits (Bekele et al., 2018a), these benefits often come at the expense of significant losses of other ecosystem services which impact human well-being (Pejchar and Mooney, 2009; Bekele et al., 2018b; Linders et al., 2020). The way stakeholders, including members of rural communities, understand and weigh the positive and negative effects of an IAS implicitly affects the uptake and success of management interventions (García-Llorente et al., 2008; Schüttler et al., 2011; Urgenson et al., 2013; Estévez et al., 2015), because an individual's perception influences his/her behavior (Ajzen, 1991). For instance, if local stakeholders perceive that the invasion of an IAS results in net negative impacts on ecosystem services, they may be motivated and committed to planning and implementing management options that reduce the negative effects (Andreu et al., 2009; Shackleton et al., 2019a). On the other hand, stakeholders may be aware that the net long-term effect of an IAS on the environment and on society is negative, but they may still perceive that the IAS provides important short-term economic benefits and thus not be willing to implement management options, particularly at the early stages of invasion (Shackleton et al., 2007). Also, local stakeholders may have started using an IAS for balancing the losses of ecosystem services and income due to land degradation caused by the IAS itself and/or by overexploitation of natural resources (Linders et al., 2020). If little attention is given to stakeholders' perceptions and attitudes (Bremner and Park, 2007; Estévez et al., 2015; Shackleton et al., 2019a; Shrestha et al., 2019), results of conservation-oriented studies may come up with management recommendations that will not be taken up (García-Llorente et al., 2008; Selge et al., 2011; Shackelford et al., 2013). Therefore, an integrated analysis of both the actual and the perceived environmental impacts of IAS (Rochman et al., 2016), ideally collected in the same geographic region, are essential for improving communication and successfully implementing sustainable IAS management (Shackelford et al., 2013; van Wilgen and Richardson, 2014; Shackleton et al., 2019b).

Despite the importance of the human component for sustainable

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environmental management, little is known how well stakeholders' perceptions on environmental change match with ecological evidence (Schüttler et al., 2011; Shackleton et al., 2019a; Shrestha et al., 2019) and further work on this is needed. For example, Chaudhary and Bawa (2011) showed that local perceptions of the impact of climate change on biodiversity in the Himalayas conform to scientific data. In contrast, Deng et al. (2003) found that visitors' perceptions of their environmental impacts on a National Forest Park in China was inconsistent with the actual physical damage inflicted. Similarly, van Wilgen (2012) reported that an invasive tree management program in the Table Mountain National Park in South Africa received, although based on scientific evidence, considerable negative press because of local stakeholders' positive perceptions of the invasive trees. Stakeholders' perceptions may be affected by different demographic, institutional and socio-economic contexts (Andreu et al., 2009; Gozlan et al., 2013). Among others, socio-economic factors including information or experience, livelihood base (Veitch and Mick, 2001; Vanderhoeven et al., 2011; Rai and Scarborough, 2015) or demographic characteristics (e.g., age, sex, household (HH) size and education level) can determine perceptions (Slovic, 1999; García-Llorente et al., 2008; Wachinger et al., 2013; Shackleton et al., 2019b). Individuals may underestimate the environmental effects of an IAS if they have no direct implications for their livelihoods (Botzen et al., 2009). Further, local stakeholders' perceptions of IAS may depend on the environmental conditions before the invasions, e.g., whether the IAS invaded healthy or degraded ecosystems. Thus, as perceptions and actual environmental impacts of IAS may be context-specific, a spatially and temporally explicit comparison of stakeholders' perceptions on environmental impacts with scientific data would be desirable.

One of the most serious invasive woody species in arid and semi-arid ecosystems of the world and Eastern Africa is *Prosopis juliflora* (Sw.) DC. (Bekele et al., 2018a; Shiferaw et al., 2021; hereafter referred to as *P. juliflora*). *Prosopis juliflora* was introduced to Eastern Africa in the late 1970 s and early 1980 s (Pasiecznik et al., 2001), mainly for the provision of firewood, for stabilizing already degraded areas (Elfadl and Luukkanen, 2003) and as feed and forage for livestock. However, shortly after its introduction, *P. juliflora* started escaping from the plantations and invading the surrounding habitats, mainly grasslands, bushland and crop fields (Mbaabu et al., 2019; Shiferaw et al., 2019). *Prosopis juliflora* is able to displace native vegetation, which results in serious reduction in biodiversity and the ecosystem services and livelihoods supported by biodiversity (Linders et al., 2019). Invasive stands of *P. juliflora* also create a favorable breeding environment for mosquitoes with serious consequences for human health (Muller et al., 2017). Owing to its very deep-reaching tap roots and high densities, *P. juliflora* consumes a lot of water within arid ecosystems, thereby reducing water availability (Dzikiti et al., 2013; Shiferaw et al., 2021). In Eastern Africa, *P. juliflora* was introduced in regions with different levels of degradation. For example, it was introduced in Afar National Regional State in Ethiopia (hereafter referred to as Afar) at a time when the region was known for large, healthy grasslands and savannas (Mehari, 2015; Rogers et al., 2017). In contrast, in Baringo County (hereafter referred to Baringo), Kenya, *P. juliflora* was introduced at a time when the ecosystem was already heavily degraded and people experienced sand storms and a shortage of firewood (Johansson and Svensson, 2002). These different environmental states at the time of introduction may also shape local stakeholders' perceptions of the environmental impacts of *P. juliflora*.

In this study, we compared local stakeholders' perceptions of the effects of *P. juliflora* invasions in Afar and Baringo with detailed ecological data. Focusing on biodiversity and water availability, we also analyzed factors affecting local households (HHs') perceptions of *P. juliflora* impacts. Specifically, we aimed to assess a) whether local HHs' perceptions of the effects of *P. juliflora* corresponds with ecological data, b) whether HHs' perceptions of the effects of *P. juliflora* differ between Afar, where *P. juliflora* invaded relatively healthy habitats, and Baringo, where land degradation was advanced at the time the tree was introduced, and c) factors that determine HHs' perceptions of the negative effects of *P. juliflora* invasion on biodiversity and water availability.

2. Materials and methods

2.1. Study areas

Both Afar National Regional State in Ethiopia and Baringo County in Kenya are part of the Great Rift Valley of Eastern Africa. Afar region is located between 39°34′ and 42°28′ East Longitude and 8°49′ and 14°30′ North Latitude in the north-eastern part of Ethiopia, covering about 270,000 km^2 (CSA, 2008). The region covers about 10% of the total landmass of Ethiopia and about 29% of pastoral lowlands. The region is the arid and semi-arid part of the country, with a mean annual temperature of 31 °C. Rainfall is erratic and scarce with annual precipitation between 200 mm and 600 mm. The population is about 1.77 million (CSA, 2015). The production system of the region is dominated by pastoralism (90%). Currently, based on small scale irrigation across rivers, agro-pastoralism (10%) is emerging. The floodplains of Awash River, upon which Afar people are highly dependent for grazing their livestock during the dry season and for small scale agriculture, are invaded or under risk of invasion by *P. juliflora* (Shiferaw et al., 2019).

Baringo County covers an area of 11,075 km^2 and lies between Latitudes 0°13″ South and 1°40″ North and Longitudes 35°36″ and 36°30″ East. The county has two distinct weather patterns with temperatures in the southern part ranging between 25 °C during the cold months (June and July) and 30 °C during the hot months (January and February) while in the northern parts, temperatures range between 30 °C and 35 °C. With two rainy seasons (March to June and November), the lowland areas in the county, which are particularly suitable for *P. juliflora* invasion, receive some 600 mm of rainfall annually. The major economic activities include pastoralism, sedentarized crop production (growing of maize, groundnuts, cotton and coffee), honey production and sand harvesting (Choge and Muthike, 2014).

The main vegetation types in the two study areas comprise bush land, shrub lands, riverine forests, grassland and seasonal marshes and swamps and they all face challenges with *P. juliflora* invasion. The two species of *Prosopis* most widely planted in Eastern Africa are *P. juliflora* and *Prosopis pallida* (Humb. & Bonpl. ex Willd.) Kunth, but in Afar and Baringo only *P. juliflora* has become invasive (Castillo et al., 2020).

2.2. Sampling and data collection methods

2.2.1. Socio-economic data

In 2016, face-to-face interviews were conducted with 253 and 250 sample HHs in Afar and Baringo, respectively. A multi-stage sampling design was applied at different stages of sample selections in both study areas. Afar and Baringo were selected purposively as both areas belong to the most heavily invaded areas in Eastern Africa. In Afar, Gabi Rasu zone was also purposively selected as it is the area most heavily invaded by *P. juliflora* in Ethiopia. The zone has six districts of which Amibara, Gewane and Awash Fentale were randomly selected from most invaded, moderately invaded and the least invaded districts, respectively. Subsequently, the invasion level of each *Kebele* (the smallest administrative unit in Ethiopia) in the selected districts was estimated based on discussions with community representatives and local experts. We then selected five, three and two *Kebeles* from Amibara, Awash Fentale and Gewane districts, respectively, using proportionate random sampling technique. *P. juliflora* cover of the *Kebeles* ranged from 4 to 59% (Linders et al., 2020).

Baringo has six sub-counties of which Baringo South and Tiaty sub-counties are invaded by *P. juliflora*. From the two invaded sub-counties, Baringo South was purposively selected as it is more heavily invaded than Tiaty. Baringo South sub-county consists of 11 locations which are further divided into 18 sub-locations (the smallest administrative unit in Kenya). Using *P. juliflora* invasion levels, these sub-locations were stratified into the three invasion categories. The same procedure was followed as in the selection of *Kebeles* in Afar and a total of 10 sub-locations were selected with *P. juliflora* cover ranging from 7 to 68% (Linders et al., 2020). The final stage involved simple random sampling with probability proportional to size in selecting a total of 253 sample HHs from Afar and 250 from Baringo.

Surveys were conducted by local experienced enumerators who were specifically trained for this purpose. They were recruited in both study areas based on three main criteria, namely: a minimum of diploma certificate, experience in conducting similar surveys in the past and fluency in respective local dominant languages. In order not to compromise the quality of the data, three supervisors were recruited for each study area. With the consideration of all ethical guidelines, data were collected during the surveys using a semi-structured and pre-tested questionnaire.

Respondent's perceptions of the effects of *P. juliflora* on biodiversity (PerPlnt) and water availability (PerWat) were asked in both study areas using a negative statement ("*P. juliflora* decreases…"), while perceptions of the effects of *P. juliflora* on soil stability (PerStbt) and soil fertility (PerSftt) were asked using a positive statement (" *P. juliflora* increases…"). In this section of our questionnaire, respondents were asked to provide ratings on a five-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree).

2.2.2. Ecological data

Ecological data were collected in five to eight 15x15 m plots with different *P. juliflora* cover in each of the ten communities (*Kebele* or Sub-location; Linders et al. 2019). Within a community, plots were chosen to be as similar as possible in terms of land use and land use history, except that they differed in *P. juliflora* cover. All plots were located on (former) grazing land; however, the degree of previous disturbance by overgrazing and the habitat type (floodplain, rain-fed grazing land or shrubland) differed between communities. *Prosopis juliflora* cover was estimated visually by two persons independently. All plots were sampled during the long rains of 2015 and 2016. A total of 76 and 66 sample plots were sampled in Afar and Baringo, respectively (Linders et al., 2019).

Each plot was divided into nine 5x5 m subplots. Sampling was performed in the central and in the corner subplots. Plant species richness was sampled within four subplots, which were randomly selected out of the initial five. Abundances of all plant species were assessed in 1x1 m^2 quadrats located in the center of the subplots. A 1x1 m^2 frame, divided into one hundred 10x10 cm^2, was placed over each quadrat and cover was measured by counting the number of squares occupied by each species. All additional plant species present in the whole 15x15 m plot were also noted. Soil stability and soil fertility were measured in the same subplots in which vegetation was sampled (Linders et al., 2019). Within each of these subplots, two points were randomly chosen where soil stability was scored qualitatively using the methodology described in Tongway and Hindley (2004). The indicators used were litter layer, cryptogam cover, crust brokenness, erosion type, deposited materials, surface roughness and surface nature. As a proxy for soil fertility, we used cation exchange capacity (CEC), a soil parameter which was found to be related to soil fertility under trees in savannas (Becker et al., 2017; Ward et al., 2018). Soil samples were taken from the 0–15 cm layer at two randomly selected places per sub-plot using an Edelman auger. The eight soil samples per plot were pooled and stored at 5 °C until analysis. Soil analyses were done at HrU for Afar and at Kenya Agricultural and Livestock Research Organization (KALRO) in Nairobi for Baringo samples. CEC was measured using the Olsen method (Walmsley and Cornforth, 1973).

The amount of water used by individual *Prosopis* trees was determined using the heat ratio method (HRM) of monitoring tree sap flow (Burgess, 2001). A pair of equally placed (0.5 cm) T-Type thermocouples was installed on either side of the heater to measure the sapwood temperature before and after pulsing the heat. The thermocouples were installed in the sapwood at depths ranging from 0.8 to 1.1 cm under the bark to capture the radial changes in heat velocity (Dzikiti et al., 2017; Shiferaw et al., 2021). In this sap flow monitoring technique, the heat pulse velocity (Vh, cm/h) is logarithmically related to the ratio of temperature increases upstream and downstream from a heater (v1/v2); the heat velocity was changed to flow velocity and then to sap flow as indicated by Burgess et al. (2001). The individual tree sap flow volume in liters per hour were converted to stand level transpiration (in mm per hour) using the approach described by Dzikiti et al. (2013) in which the instrumented trees were assigned to a particular stem size class. *Prosopis juliflora* water use was quantified from 12 instrumented trees of different stem base diameter in two different habitats in Afar region (floodplains of Awash River and dry lands water; Shiferaw et al., 2021). Water use was then estimated by summing up the water use of each individual tree, relative to its stem base diameter, for each plot.

2.3. Data analysis

2.3.1. Comparing perception and ecological data

In order to assess the relationship between perceptions of the environmental effects of *P. juliflora* and ecological data along an invasion gradient, we upscaled values from local plots and HHs to the community level (Kebele or Sub-location). For each community, respondents' perceptions of the effects of *P. juliflora* were assessed by averaging the five-point Likert scale values into one mean score.

To upscale the ecological data to the community level, we first analyzed the change in biodiversity and ecosystem functioning as a function of *P. juliflora* cover using mixed effect models with the *nlme* package (Pinheiro et al., 2018) in R (R Core Team, 2021. *Prosopis juliflora* cover in each plot was fitted as a fixed effect and the community as a random effect to correct for differences between communities. Separate models were calculated for Ethiopia and Kenya. If the regression analysis revealed a significant effect of *P. juliflora* cover on biodiversity or ecosystem functioning, the regression was used to assign values to each 15 × 15 m pixel in fractional cover maps of *P. juliflora* abundance in the two regions (Mbaabu et al., 2019; Shiferaw et al., 2019) and average values calculated per community (see Linders et al., 2020). If the regression models for the biodiversity and indicators of ecosystem services were non-significant, the values for the biodiversity and ecosystem services for a community were calculated as the average value of the results obtained from the plots located in this community. For comparison with the perception data, the ecological data were also transformed to a five-point mean scale by assigning the highest number of plant species in a plot (lowest adverse effect) to the value 1 and the lowest number of plant richness in a plot (highest adverse effect) to the value 5. Regression analyses were then used to assess the effect of *P. juliflora* cover on ecological variables or average HHs' perception across communities.

2.3.2. Econometric model specification: Generalized ordered logit

Following Greene (2005), ordered logit models were used to identify factors affecting individual HHs' perceptions of the impacts of *P. juliflora* on biodiversity and water. An ordered logit model of the dependent variable Y is a function of a latent, unobserved variable y* which is determined by.

$$Y_i^* = X^{'}\beta + \varepsilon_i and \varepsilon / x \; N(0,1) \quad (1)$$

where β is a parameter vector of k number of explanatory variables × excluding a constant; and N represents the normal distribution. The variable y* has"threshold points" or"cut-offs" (μ) and the value of Y depends on whether an observation has crossed these thresholds. Accordingly, $Y_i = 1 if Y_i^*$ is$\leq \mu_1$; $Y_i = 2 if \mu_1$ is $\leq Y_i{}^* \leq \mu_2$; … $Y_i = J if Y_i^*$ is$\geq \mu_{J-1}$. Here, Y denotes the qualitative categorized opinion of respondent i and its indices range from 1 to 5 (see above). X is a matrix representing HHs' socioeconomic characteristics and *P. juliflora* cover which affect the probability of observing $Y_i = j$. The latent variable y* is a function of X plus some level of error as

$$Y_i^* = \sum_{k=1}^{k} \beta_k X_{ki} + \varepsilon_i = Z_i + \varepsilon_i \tag{2}$$

The ordered logit model usually estimates part of this as.

$$Z_i = \sum_{k=1}^{k} \beta_k X_{ki} = E(Y_i^*) \tag{3}$$

Therefore, Z is y* as a function of some disturbance and not a perfect measure of y*. It is of a different scale than Y (e.g. continuous). But our estimates can give us Pr(Y = 1, 2,..5) based on the value of Z. Z is continuous 0–1. Assuming logistic distribution of the error terms, ordered logit estimates the probability that an observation falls into a given Y category based. To find the slope and the threshold parameters, the log-likelihood function (Wooldrige, 2002) for a respondent was estimated using maximum likelihood. Following Williams (2006), appropriate model validation tests were conducted before the results were interpreted.

The dependent variables are a respondent's perception levels about the negative effects of *P. juliflora* invasion on biodiversity and water availability. Important explanatory variables include *P. juliflora* cover and relevant HHs' demographic and socioeconomic characteristics (Table 1). For testing the proportional odds assumption or the parallel lines assumption of the model, the global test of five major tests (Wolfe Gould, Brant, score, likelihood ratio and Wald) was conducted (see Williams, 2006).

3. Results

3.1. Ecological evidence versus local perception of the environmental effects of P. Juliflora

3.1.1. Biodiversity

In Afar, *P. juliflora* cover was significantly and positively related to the loss in plant species richness ($y = 0.032x - 0.213; R^2 = 0.898; p < 0.001$) (Fig. 1). In Baringo, no association was found between plant species richness loss and *P. juliflora* cover ($y = -0.0001x + 2.798; R^2 = 0.005; p = 0.838$). In both regions, the majority of the respondents agreed ('strongly agreed' and 'agreed') with the statement that *P. juliflora* causes negative effects on biodiversity (Afar: 83.4%; Baringo: 94.8%; Table 2). Some 10.3% and 2.8% of the sampled respondents from Afar and Baringo, respectively, disagreed with the statement about the adverse effects of *P. juliflora* on biodiversity. The respondents' perceptions of the negative impacts of *P. juliflora* on biodiversity was not related to *P. juliflora* cover in the respondents' community, in Afar (Afar: $y = 0.005x + 4.003; R^2 = 0.051; P = 0.530$) or in Baringo (Baringo: $y = 0.000x + 4.298; R^2 = 0.003; P = 0.880$).

3.1.2. Water

In both regions, water use by *P. juliflora* increased with cover (Afar: $y = 0.036x + 2.346; R^2 = 0.615; P = 0.007$; Baringo: $y = 0.031x + 2.254; R^2 = 0.834; P = 0.000$). The majority of the respondents agreed ('strongly agreed' and 'agreed') with the statement that *P. juliflora* causes negative effects on water availability (Afar: 66.2%; Baringo: 74.4%; Table 2), while 17.0% and 22.8% of the respondents from Afar and Baringo, respectively, disagreed. However, in both regions, HHs' perceptions of the effects of *P. juliflora* on water availability was not affected by *P. juliflora* cover (Afar: $y = 0.019x + 2.945; R^2 = 0.183; P = 0.218$; Baringo: $y = 0.015x + 2.930; R^2 = 0.218; P = 0.173$) (Fig. 2).

3.1.3. Soil fertility

In both regions, CEC as a proxy for soil fertility was not related to *P. juliflora* cover (Afar: $y = 0.006x + 2.117$; $R^2 = 0.144$; $P = 0.2782$; Baringo: $y = 0.001x + 2.151$; $R^2 = 0.003$; $P = 0.883$). While a majority of the respondents in Baringo agreed that *P. juliflora* enhances soil fertility (84.4%; Table 2), some 36.3% of the sampled HHs in Afar did not agree. The HHs' average perceptions of the effect of *P. juliflora* on soil fertility was not affected by *P. juliflora* cover (Afar: $y = 0.024x + 2.829$; $R^2 = 0.174$; $P = 0.2297$; Baringo: $y = -0.005x + 4.463$; $R^2 = 0.067$; $P = 0.856$) (Fig. 3).

3.1.4. Soil stability

Soil stability did not respond to *P. juliflora* cover in Afar ($y = 0.020x + 2.973; R^2 = 0.141; P = 0.282$), but decreased with increasing *P. juliflora* cover in Baringo ($y = -0.001x + 3.309; R^2 = 0.457; P = 0.037$) (Fig. 4). The majority of the respondents in Baringo agreed that *P. juliflora* enhances soil stability (84.4%; Table 2), but a considerable amount of the sampled HHs in Afar disagreed (38.3%). As with soil fertility, average households' perceptions were not related to *P. juliflora* cover, neither in Afar nor in Baringo (Afar: $y = 0.012x + 2.570; R^2 = 0.089; P = 0.818$; Baringo: $y = 0.001x + 3.953; R^2 = 0.001; P = 0.922$).

3.2. Generalized ordered logit estimates

3.2.1. Factors determining households' perceptions of the effects of P. Juliflora on biodiversity

HHs' perceptions of the effects of *P. juliflora* on biodiversity were affected by different socio-economic and institutional factors. In both study regions, a male-headed HH from highly invaded location was more likely to strongly agree and less likely to strongly disagree that *P. juliflora* has negative effect on biodiversity (Table 3). In Afar, HHs who had more livestock and diversified income sources were more likely to agree that *P. juliflora* causes negative effect on biodiversity. In Baringo, HHs with high social participation were more likely to agree about the negative effects of invasion. In contrast, HHs with larger family size in Afar were generally less likely to agree that *P. juliflora* invasion causes biodiversity loss, and larger family HHs were especially unlikely to strongly agree about the negative effect on biodiversity. In both study areas, younger HH heads with higher income from crop production were more likely to agree about this negative effect and especially unlikely to strongly disagree about this effect. The greatest effects of younger HHs generating higher income from crop production were to pull people to the lowest category of perception (strongly disagree). Further, in Baringo, HHs which generated higher income from charcoal production

Table 1
Socio-economic variables included in models to determine households' perceptions of the effects of *P. juliflora* on biodiversity and water availability.

Variable	Variable description
TLU	Number of livestock (Tropical livestock unit). Tropical Livestock Unit (TLU) is a hypothetical animal of 250 kg live weight; standard conversion factors for different animals are: camels = 1.0; cattle = 0.7; sheep and goats = 0.1. HH = household.
Invasion	Average *P. juliflora* fractional cover within 100-m radius of a HH's homestead (%) (see Bekele et al., 2018b);
Assetval	Fixed asset value of main HH properties (in '000 Birr or KSH)
Hhsize	Number of individuals living under the same roof
Gender	Gender of HH head (1 = male; 0 = female)
Age	Age of a HH head (year)
Edu	Average education of a HH members (years of schooling)
Incmcrop	Annual HH income from crop production (in '000 Birr or KSH)
Incmcharcl	Annual HH income from charcoal and fuel wood selling (in '000 Birr or KSH)
NFIncm	Any HH income out of livestock and crop production (1 = yes; 0 = no)
Participation	Social participation of a HH member in informal and/or formal institutions (1 = yes; 0 = no)
Dist_mkt	Distance to the nearest market center (kilometers)
Nrm_expert (Afar only)	Number of contacts the HH had with natural resources management expert(s) in the last 12 months
Dist_extoff	Distance to extension office (kilometers)
Dist_watrp	Distance to the nearest water point (kilometers)

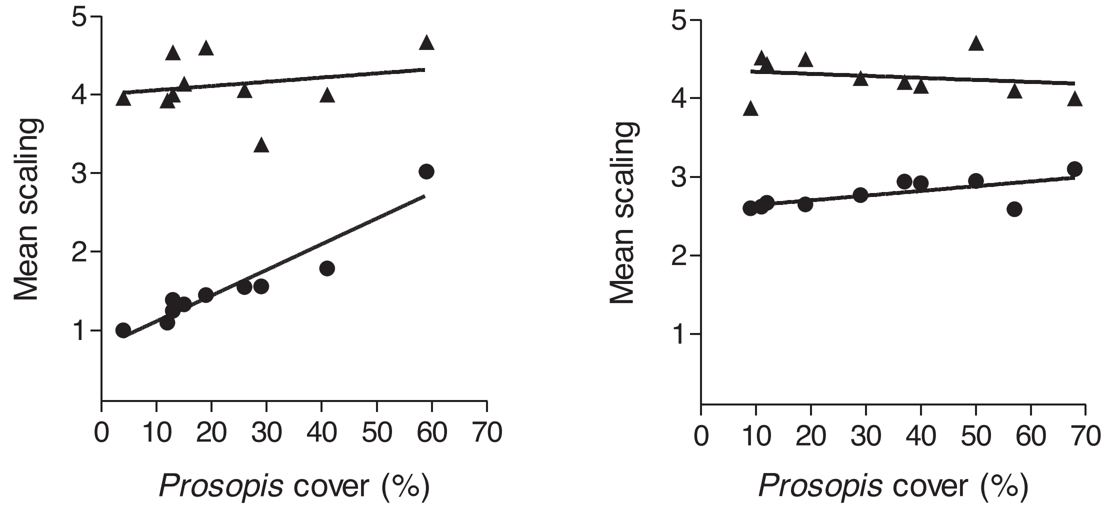

Fig. 1. The relationship between *P. juliflora* cover at the community level and loss in plant species richness (dots) and on the households' perceptions of the negative effects of *P. juliflora* on biodiversity (triangles). Each dot or triangle indicates the average value for a single community (left: Afar; right: Baringo).

Table 2
Sampled households' perceptions (in % responses on a five-point Likert scale) of the effects of *P. juliflora* on biodiversity and selected ecosystem services in their community. *1 = strongly disagree; 2 = disagree; 3 = indifferent; 4 = agree; 5 = strongly agree.

P. juliflora	Afar					Baringo				
	5*	4	3	2	1	5	4	3	2	1
Reduces indigenous plant species	51.8	31.6	6.3	3.2	7.1	41.6	53.2	0.8	1.6	1.2
Reduces water availability	18.6	47.6	16.6	7.5	9.5	38.8	35.6	0.4	7.6	15.2
Enhances soil fertility	14.2	34.4	15.0	14.6	21.7	32.8	51.6	3.2	1.2	10
Reduces soil erosion	29.6	32.0	11.1	13.0	14.2	49.2	48	0.4	0.8	0

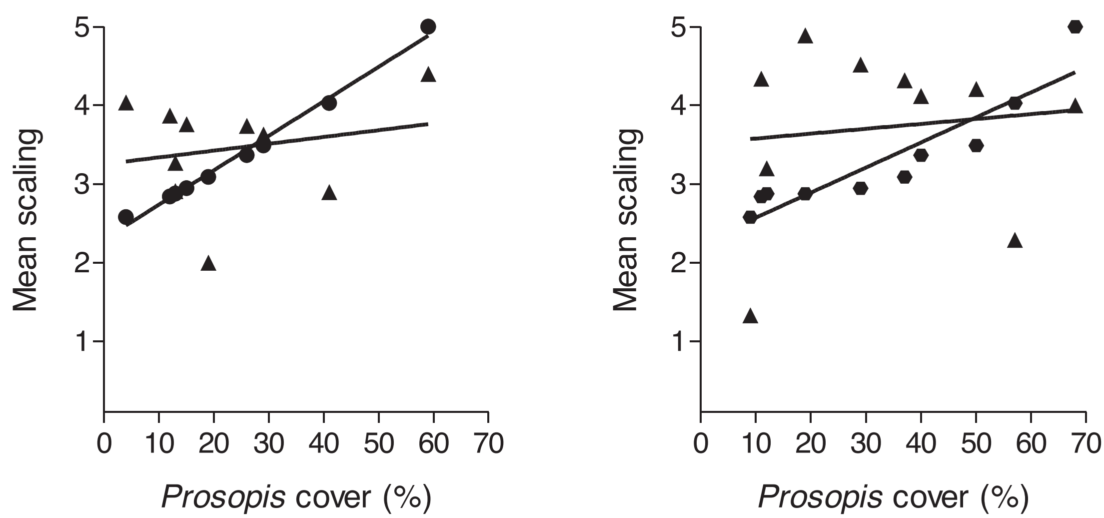

Fig. 2. The relationship between *P. juliflora* cover at the community level and water use of *P. juliflora* (dots) and on the households' perceptions of the water use of *P. juliflora* (triangles). Each dot or triangle indicates the average value for a single community (left: Afar; right: Baringo).

were less likely to agree about the negative effect of *P. juliflora* invasion on biodiversity.

In both study areas, the coefficient of contact with natural resource management experts is negative in the lowest category but positive in the highest category. Individuals who had more contact with natural resource management experts were less likely to be neutral and the greatest/strongest effect of this factor was at the two extreme perception categories (disagree or agree).

3.2.2. Factors determining households' perceptions of the effects of P. Juliflora on water availability

Based on the coefficients from the generalized ordered logit model for Afar (Table 4), livestock population, HH size, education level, diversified income sources, social participation and distance from local market center were found to be positively related to the likelihood of respondents agreeing that *P. juliflora* invasion reduces water availability. Age of the HH head, HH's income from crop production and contact with natural resources management experts reduced the likelihood of agreement about *P. juliflora'* effect on water availability.

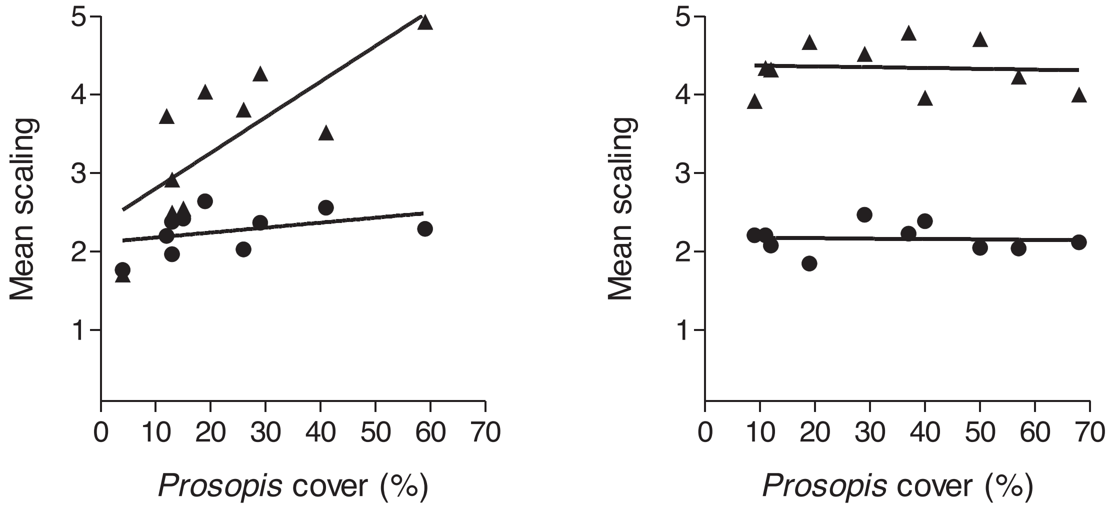

Fig. 3. The relationship between *P. juliflora* cover at the community level and soil fertility (dots) and on the households' perceptions of the positive effects of *P. juliflora* on soil fertility (triangles). Each dot or triangle indicates the average value for a single community (left: Afar; right: Baringo).

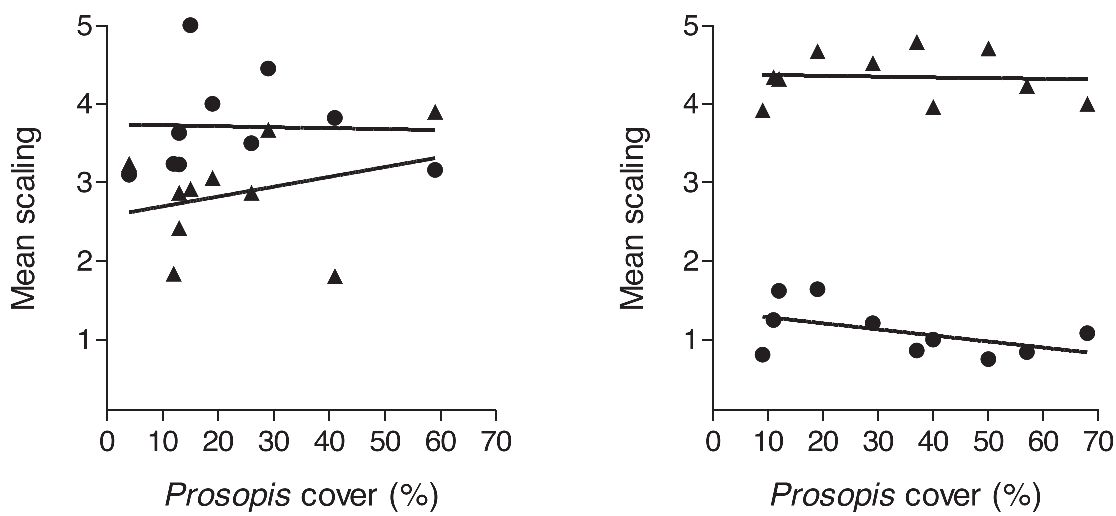

Fig. 4. The relationship between *P. juliflora* cover at the community level and soil stability (dots) and on the households' perceptions of the positive effects of *P. juliflora* on soil stability (triangles). Each dot or triangle indicates the average value for a single community (left: Afar; right: Baringo).

Table 3
Generalized ordered logit models estimates on households' perceptions of adverse effects of *P. juliflora* on biodiversity. Asterisks indicate level of significance: * 0.1, ** 0.05 and *** 0.01.

Variables	Afar				Baringo			
	Disagree		Agree		Disagree		Agree	
	Coef.	SE	Coef.	SE	Coef.	SE	Coef.	SE
Invasion	10.85***	4.00	9.02***	3.25	0.07***	0.02	0.07***	0.02
TLU	0.07**	0.03	0.07**	0.03	0.00	0.02	0.00	0.02
HHsize	−0.58***	0.18	−0.28**	0.12	−0.09	0.06	−0.10	0.11
Gender	−2.62**	1.33	−2.62**	1.33	−1.47***	0.24	−1.30**	0.66
Age	0.07**	0.03	−0.02	0.02	0.28**	0.12	−0.01	0.01
Edu	0.01	0.15	0.01	0.15	0.20	0.50	0.20	0.50
Incmcrop	−6e-05***	0.01	−6.94e-06	0.00	−0.06***	0.08	−0.06	0.08
Incmcharcl	−3e-05	0.00	−3e-05	0.00	−0.13***	0.06	−0.13***	0.06
NFIncm	1.28**	0.54	1.28**	0.54	−0.03	0.05	−0.03	0.05
Participation	0.66	0.53	0.66	0.53	0.88**	0.34	0.88**	0.34
Nrm_expert	−0.28***	0.09	0.13**	0.05	−0.25***	0.08	0.10**	0.04
Dist_mkt	−0.02	0.02	−0.02	0.02	−0.11	0.12	−0.11	0.12
Observation	253				250			
LR chi^2	146.22				178.20			
Pseudo R^2	0.35				0.63			

Table 4
Generalized ordered logit model estimates on households' perceptions of the effect of *P. juliflora* on water availability in their home community. Asterisks indicate level of significance: * 0.1, ** 0.05 and *** 0.01.

Variables	Afar				Baringo			
	Disagree		Agree		Disagree		Agree	
	Coef.	SE	Coef.	SE	Coef.	SE	Coef.	SE
Invasion	1.83	1.24	1.83	1.24	0.07***	0.02	0.04***	0.01
TLU	0.11***	0.03	0.05***	0.02	0.00	0.02	0.01	0.02
HHsize	1.09***	0.25	0.10	0.08	−0.19**	0.08	−0.19**	0.08
Gender	0.76	0.55	0.76	0.55	1.41	1.05	−0.54	0.83
Age	−0.13***	0.03	−0.01	0.02	0.01	0.01	0.01	0.01
Edu	0.49**	0.20	0.06	0.11	0.03	0.09	0.16**	0.06
Incmcrop	−1e-05*	0.00	−1e-05*	0.00	−0.01	0.00	−0.01	0.00
Incmcharcl	0.01	0.00	5.43e-06	0.00	−2.80***	0.87	−0.43	0.01
NFIncm	1.72***	0.65	0.05	0.41	−0.04**	0.01	−0.02**	0.01
Participation	1.58*	0.83	1.45***	0.42	1.17***	0.37	1.17***	0.37
Nrm_expert or (Dist_extoff)	−0.25***	0.05	0.01	0.02	0.04***	0.01	0.02***	0.00
Dist_mkt	0.02*	0.01	0.02*	0.01	0.08*	0.04	0.02	0.03
Dist_watrpoint	−0.01	0.03	−0.01	0.03	−0.01	0.06	−0.01	0.06
Aid					0.81**	0.33	0.81**	0.33
Observation	253				250			
LR chi^2	139.66				178.89			
Pseudo R^2	0.33				0.35			

As distance from local market and income from crop production did not violate the parallel lines assumption, the influences of these two variables on respondents' perception levels were the same across all the three categories. That is, HHs nearer to local market centers and generating incomes from crop production were less likely to agree that *P. juliflora* reduces water availability than their counterparts. On the other hand, the influence of other significant variables varied across perception categories. The strongest effects of the variables violating the parallel lines assumption were related to the extreme categories of perception. For instance, HHs with larger family size, higher social participation, higher education level, diversified income sources and owning more livestock were more likely to agree about the negative effect of *P. juliflora* on water consumption and these HHs were especially unlikely to strongly disagree (considering the five-point scale) about the effects. Hence, the strongest effects of these variables were found with the most extreme perception categories. Surprisingly, older individuals who had higher rates of contact with natural resources management experts were more likely to disagree about the effect in Afar.

In Baringo, respondents' perceptions of the negative effects of *P. juliflora* invasion on water consumption were found to be influenced by *P. juliflora* cover, HH size, education level, income from charcoal and fuel wood, diversified income sources, social participation, distance from extension office, distance from local market center and aid dependency. Of these factors, HH size, income from charcoal and fuel wood, social participation and aid dependency did not violate the parallel lines assumption. Accordingly, in Baringo, HHs with smaller family size, higher income from charcoal and fuel wood production, higher social participation and who are aid dependent were more likely to agree that *P. juliflora* reduces water availability in their localities and the effects of these variables were the same across all the three perception categories. However, the effects of variables which violated the basic assumption of ordered logit vary among the perception categories. That is, HHs from sub-locations with higher *P. juliflora* cover, higher average education level, near to extension offices and far from local market centers were more likely to agree that *P. juliflora* reduces water availability and were especially unlikely to strongly disagree about this effect. In contrast, HHs with diversified income sources were less likely to agree that the invasion reduces water availability and were especially unlikely to agree about the negative effect.

4. Discussion

By comparing ecological data and HHs' perceptions of the effects of *P. juliflora* on indicators of biodiversity and ecosystem services along the invasion gradients in Afar and Baringo, we found that stakeholders' perceptions and ecological data did not necessarily match in the two regions. Moreover, perceptions and ecological data differed partly between the two case study regions, highlighting context-dependency. Stakeholders' perceptions of the environmental effects of *P. juliflora* were also affected by socio-economic and socio-cultural factors, which should also be considered when designing and implementing sustainable management strategies to mitigate the negative effects of *P. juliflora* on the social-ecological systems.

4.1. Local stakeholders' perceptions of the environmental effects of P. Juliflora versus ecological evidence

Previous studies suggested that people's perception of the ecological effects of IAS can vary considerably among individuals (Vanderhoeven et al., 2011; Gozlan et al., 2013; Shackelford et al., 2013) and may not necessarily correlate with the actual environmental effects (Andreu et al., 2009; Gozlan et al., 2013; Shackleton et al., 2019b). The results of our study, which used a spatially nested sampling design to compare perception and ecological data, back up these observations. First, we observed considerable variation among the respondents in their perceptions of the ecological effects of *P. juliflora*. Moreover, we found that at the community level the average HHs' perceptions of the ecological effect of *P. juliflora* did not correspond with the ecological effects in the respective community in most of the cases. While the ecological effects increased with increasing *P. juliflora* cover at the community level, in four of the eight comparisons respondents' perceptions of the ecological effects of *P. juliflora* was not related to the *P. juliflora* cover in their community. The lack of a consistent pattern between stakeholders' perceptions of the environmental effects of *P. juliflora* and ecological evidence may be explained by the fact that stakeholders' perceptions are influenced by other socio-economic factors (see below). Yet, our results from the ordered logit models revealed that *P. juliflora* cover within a radius of 100 m around the HH explained a significant amount of variation in HHs' perceptions of the impacts of *P. juliflora* on biodiversity and water consumption. This suggests that local stakeholders' perceptions are more influenced by the invasion level in the HH's immediate surrounding than by the invasion level at the community level. This is noteworthy since most of the lands in Afar and a significant amount of land in Baringo is held and managed under communal land tenure rights, which allow HHs to use large parts of their home community, and during the dry seasons also land outside their Kebeles/villages (Asaka and Smucker, 2016; Bekele et al., 2018a).

The level of ecosystem degradation at the time *P. juliflora* started to become invasive might also have contributed to the observed variation in perceptions of invasion impacts. Increasing *P. juliflora* cover was related to increased losses in plant species richness in Afar where *P. juliflora* was introduced into less degraded grasslands and savannas. This result from Afar is in agreement with other studies documenting a significant negative impact of *P. juliflora* invasion on biodiversity, herbaceous biomass (Linders et al., 2019) and water availability (Dzikiti et al., 2013; Shiferaw et al., 2021). However, no relationship between *P. juliflora* cover and a loss in plant species richness was found in Baringo where *P. juliflora* was introduced into an already degraded ecosystem (Johansson and Svensson, 2002; Linders et al., 2020). These different contexts may explain why a majority of respondents in Baringo agreed that *P. juliflora* enhances soil stability and soil fertility, while a considerable amount of the sampled HHs in Afar disagreed with these statements. In contrast to the stakeholder's perception, our results suggest that soil fertility decreased in Baringo with increasing *P. juliflora* cover, which may be due to indirect negative effects of *P. juliflora* on soil fertility via a reduction in herbaceous biomass (Linders et al., 2020).

4.2. Socio-economic factors affecting local perceptions of the environmental effects of P. Juliflora

Variation in environmental perceptions among local stakeholders can be explained by relevant socio-economic variables such as education and base of livelihoods (Slovic, 1999; Carlton and Jacobson, 2013; Wachinger et al., 2013; Shackleton et al., 2019a). Our analyses revealed that socio-economic factors related to information communication (proxied by the variables education, social participation and experts' advice), economic livelihood based (with the variables being the number of TLU owned, income from crop, income from charcoal, diversified income sources, aid dependency) and demographic characteristics (age of a HH head and family size) influenced HHs' perceptions of the impacts of *P. juliflora* on biodiversity and water consumption. In both regions, HHs with higher education levels were more likely to agree that *P. juliflora* reduces water availability. This supports the notion that education increases local communities' concerns and awareness on the environmental effects of IAS (Seid, 2012; Dorsch, 2014; Rai and Scarborough, 2015). Furthermore, respondents who are actively participating in different social activities were more likely to understand the environmental effects of *P. juliflora*, corroborating the notion that high social participation increases access to information about local environmental changes through informal discussions (Selge et al., 2011; Estévez et al., 2015; Shackleton et al., 2019ba), and that the sharing of such informal information is highly likely in rural social groups.

Natural resource experts' advice had different influences on local perceptions in our study areas. In Baringo, this variable was captured through distance to the nearest extension service (office) and the result showed that the nearer the HH to an extension office, the more likely the respondents were to agreed that *P. juliflora* reduces water. This might be because HHs near extension offices are more likely to get advice regarding the environmental effects of *P. juliflora* than HHs further away (Selge et al., 2011; Vanderhoeven et al., 2011; Seid, 2012). In Afar, respondents who had regular contact with natural resource management experts were less likely to agree that *P. juliflora* invasion reduces biodiversity and water and the highest effect of this factor was at the two extreme perception categories (disagree or agree). This might be due to the specific issue on which an expert provides advice to an individual. If an individual gets advice on the negative effects of invasion on water consumption, she/he is more likely to agree about this effect. However, if the advice was not related to *P. juliflora* invasion, the individual might lack knowledge about the effects and then is likely to disagree. Natural resource management experts' specific advice of the effect seems critical to increase local communities' understanding on the effects of *P. juliflora*, which in turn, improves commitment to the sustainable management of *P. juliflora* (Vanslembrouck et al., 2002; Abate et al., 2010; Selge et al., 2011).

Our results also showed that HHs' livelihoods base determines local perceptions of the negative effects of *P. juliflora* on biodiversity and water. In Afar, HHs who own large numbers of livestock were more likely to blame *P. juliflora* for its negative effect on biodiversity and water, supporting earlier notions that socio-cultural factors may influence local perception of the effects of IAS (García-Llorente et al., 2008; Schüttler et al., 2011; Shackleton et al., 2019b). A logical explanation for this result is that Afar pastoralists are sensitive to any changes in natural resources that might reduce grass and water availability in their localities (Kassahun et al., 2008; Abate et al., 2010; Tilahun et al., 2016), and they attribute observed reductions to *P. juliflora* invasion. Further, as livestock population indicates wealth level of pastoralist HHs, this finding also supports the notion that wealthier HHs are more aware and more concerned about environmental changes (Dorsch, 2014).

In Baringo, where the coefficient of income from charcoal production was negative and significant for local perception of the effects of *P. juliflora* on both biodiversity and water availability, the coefficient of income diversification was negative and significant only for local perception of the effect of invasion on water. These results indicate that respondents with diversified HH income sources from non-farm activities were less likely to agree that *P. juliflora* reduces biodiversity and water availability and especially HHs which generate incomes through the utilization of *P. juliflora* tend to underestimate its adverse ecological effects (García-Llorente et al., 2008; Maundu et al., 2009; Seid, 2012). In Afar, the HH's income from charcoal selling was not related to the HH perceptions regarding the impact of *P. juliflora,* which may be explained by the fact that charcoal production in this region was prohibited by the government because it led to the harvesting of native tree species (Bekele et al., 2018a). Other non-farm HH income sources included in our survey were casual labor, petty trade, remittance, salary, pension and honey production, which may also cause respondents to become less sensitive to the effects of *P. juliflora*. In Baringo, honey production is acknowledged as a direct benefit of *P. juliflora* (Mwangi and Swallow, 2008). In contrast, food aid dependent HHs in Baringo were more likely to agree that *P. juliflora* reduces water than aid independent HHs. This might be because aid dependent HHs had experienced the negative effect on their prior livelihood base, e.g. livestock or crop production (Maundu et al., 2009).

In Afar, while the age of the HH head was positive and significant at the lower category of perception (disagree) of the negative effect of *P. juliflora* invasion on biodiversity, it was negative for perceptions relating to the water effect. These results indicate that while the effect of invasion on biodiversity was well understood by older people, they were unlikely to agree on the negative effect of *P. juliflora* on water. An explanation might be that, because younger individuals are responsible for herding and mobility, the problem of water stress is more evident to them than to older people. Another reason might be that younger people have better access to information and are aware of IAS impacts belowground, which may be less apparent than changes above-ground (García-Llorente et al., 2008). This is against our *a priori* expectation that experienced individuals are more likely to understand environmental changes. Considering that one of the most serious long-term impacts of invasive alien tree species in drylands is an increased water consumption (Le Maitre et al., 2020), which may exacerbate the impacts of climate change on water scarcity in dryland regions, further research is warranted to better understand the factors affecting local stakeholders' perceptions of the impact of *P. juliflora* and other invasive alien tree species on water availability.

It should be noted that elucidating the effects of *P. juliflora* on the environment, and thus the perceptions of these effects, may not necessarily be straightforward (Linders et al., 2020). *Prosopis juliflora* causes both numerous direct (e.g., a change in *P. juliflora* cover leads to a change plant species richness) and indirect effects (the change in plant species richness then leads to changes in soil properties; Linders et al., 2020). Moreover, as in the case of Baringo, effects of *P. juliflora* may be masked by other drivers of global change, such as prior degradation of rangeland. However, we used plant species richness and water consumption as proxies for a decrease in biodiversity and water (particularly water) availability because the effect of *P. juliflora* on these ecosystem characteristics is well documented in the literature (Dzikiti et al., 2013; Le Maitre et al., 2020). The water used by *P. juliflora* in Afar alone would be sufficient to produce cotton or sugarcane worth approximately US$ 320 and 470 million per growing season, respectively (Shiferaw et al., 2021).

4.3. Management implications

Sustainable environmental management strategies need comprehensive scientific evidence from investigating complex socio-ecological systems. Management strategies derived from a balanced information between ecological and human dimensions are likely to be implemented effectively and sustainably (Schüttler et al., 2011; Urgenson et al., 2013; Shackleton et al., 2019a). A better integration of evidence based on assessments of the impacts of environmental changes provides a more complete picture on which to base conservation and environmental management decisions (Steffen et al., 2015; Bennett, 2016). Against the traditional global environmental conservation view, which considers mainly information of ecological evidence, information from social dimensions such as local stakeholder's perceptions is indispensable in providing important insights into sustainable environmental management processes (Shackelford et al., 2013; Bennett, 2016; Shackleton et al., 2019b). Nevertheless, despite the increasing acknowledgment of scientific information from integrated socio-ecological systems data analyses, the social/human dimension has often been overlooked by many IAS studies (Veitch and Mick, 2001; Hulme, 2006; Shrestha et al., 2019). To our knowledge, our study is the first to use a spatially nested sampling design to assess the relationship between local stakeholder's perceptions of the environmental impacts of an invasive alien plant species with detailed scientific data on density and ecological impacts along an IAS invasion gradient.

Specifically, our results from ordered logit models revealed that local stakeholder's perception of the ecological effects of *P. juliflora* was significantly affected by *P. juliflora* cover at small-scale (surroundings of HH) but not at the community level, despite the fact that communal land tenure is common in both study regions. Also, our results suggest that local stakeholders' perceptions of the negative environmental impact of *P. juliflora* was significantly influenced by the HH's livelihood base. While pastoralist HHs strongly blamed *P. juliflora* for its negative effects on biodiversity and water availability, charcoal producing HHs were less responsive to the environmental effects of *P. juliflora*. Our findings thus confirm that individual knowledge system (Ajzen, 1991), socio-cultural context (Schüttler et al., 2011; Estévez et al., 2015; Rai and Scarborough, 2015) and information symmetry (Vanderhoeven et al., 2011; Robinson et al., 2017; Shrestha et al., 2019) influence local perceptions of the environmental effects of IAS. Further, our results support the notion that previous quality and status of land before invasions can affect ecological impacts and thus perceptions as well.

As most management options are to be implemented locally, local perceptions critically determine support and commitment levels by grassroots implementers – legitimacy and social acceptability (Vanslembrouck et al., 2002; Schwilch et al., 2012) matter for the effectiveness and sustainability of a management option (Bennett, 2016). Thus, local perceptions should be investigated, checked against the ecological impacts and put in the context of the stakeholders' needs. One way to achieve this is by engaging representatives of all major stakeholder groups in co-designing and co-implementation of *P. juliflora* mitigation measures, e.g., in a structured deliberative multi-criteria decision process (Liu et al., 2011; Schwilch et al., 2012). Within such a process, stakeholders can value benefits and costs of land management options and reflect on possible trade-offs and synergies, thereby fostering social learning. It also shows the importance of acknowledging local ecological knowledge and societal understanding for designing effective management strategies.

5. Conclusions

A thorough understanding of the actual and the perceived impacts of drivers of environmental change, ideally collected on the same spatial and temporal scales, are essential for improving communication among actors and for successfully implementing sustainable land management. Using a nested sampling design, we found that stakeholders' perceptions of the environmental effects of *P. juliflora* invasion only partially matched with the ecological evidence in their community. While the awareness of the negative effects of *P. juliflora* on biodiversity and water availability increased with increasing *P. juliflora* cover in the immediate surroundings of the respondents' HH, stakeholder perceptions were also affected by various socio-economic and socio-cultural attributes, including education level, social participation, diversified income sources and demographic characteristics. Because local people's perception determines the uptake and thus ultimately the success of sustainable land management programs, the variation in stakeholders' perception regarding the environmental effects of invasive species like *P. juliflora* and the underlying factors should be well understood before engaging stakeholders in co-defining objectives of invasive species management and implementing management practices at the landscape scale (Schüttler et al., 2011; Shrestha et al., 2019). We propose that a nested sampling design to analyse the relationship between stakeholder perceptions of and ecological evidence for environmental change is a suitable tool to foster our understanding of the factors affecting stakeholder perceptions and how to promote uptake of sustainable land management in complex social-ecological systems affected by environmental change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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