Journal of Eastern African Studies

ISSN: 1753-1055 (Print) 1753-1063 (Online) Journal homepage: http://www.tandfonline.com/loi/rjea20

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To cite this article: Mathias Becker, Miguel Alvarez, Gereon Heller, Paul Leparmarai, Damaris Maina, Itambo Malombe, Michael Bollig & Hauke Vehrs (2016) Land-use changes and the invasion dynamics of shrubs in Baringo, Journal of Eastern African Studies, 10:1, 111-129, DOI: 10.1080/17531055.2016.1138664

To link to this article: http://dx.doi.org/10.1080/17531055.2016.1138664

JOURNAL OF EASTERN AFRICAN STUDIES, 2016
VOL. 10, NO. 1, 111–129
http://dx.doi.org/10.1080/17531055.2016.1138664

Land-use changes and the invasion dynamics of shrubs in Baringo

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ABSTRACT
In the semi-arid savannahs around Lake Baringo, Kenya, the recent spread of bush encroachment by the invasive alien species *Prosopis juliflora* and the native *Dodonaea viscosa* has changed human–environment interactions. This article suggests how the spread dynamics of *Prosopis* and *Dodonaea* have operated. It also describes the strategies Baringo's peoples have adopted in the face of this dramatic bush invasion, relates these dynamics to current invasion theory, and analyses possible implications for Baringo's social–ecological systems. It is suggested that recent increased climate variability has triggered changes in land management and livelihoods around Lake Baringo, paving the way for bush encroachment and species invasion. The extent and speed of these changes has exceeded the capacity of local communities to adapt their productive systems, destabilizing the socio-ecology of the dryland savannahs around Lake Baringo and placing them in imminent danger of collapse.

ARTICLE HISTORY
Received 2 April 2015
Accepted 7 December 2015

KEYWORDS
Disturbance hypothesis; *Dodonaea viscosa*; invasive plant species; mesquite; *Prosopis juliflora*; social–ecological systems

Processes of ecological change and the growing competition for resources continue to heavily impact human–environmental relations around the world. The interface between human action and environment can be described as a 'social–ecological system'. These social–ecological systems are defined as integrated systems of geo-biophysical, social and cultural sub-systems, which display reciprocal feedback, inter-dependence and self-organization.[1] Faced with social–ecological transformations, populations tend to react creatively to new challenges by buffering risks and locally re-organizing regimes of regulation.[2] On the other hand, the notion of collapse refers to the breakdown of a social–ecological system, or some of its parts. It is the result of the culmination of processes of increasing vulnerability, and frequently associated with war or climatic perturbations as triggering mechanisms.[3] Depending on their reaction, populations and ecosystems are labelled as either vulnerable and collapse-prone, or resilient and capable of reorganization.[4]

In African dryland savannahs, like those found in Baringo region to be considered here, soil degradation, loss of biodiversity and bush encroachment, are typically associated with ecological transformations.[5] Simultaneously, the socio-political systems embedded within

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these environments have experienced resource exploitation, precarious livelihoods, famine disasters, state failure, and violent conflict. The resulting discourses about these dynamics have sometimes characterized African dry lands as being in a permanent state of chaotic socio-ecological affairs, or at the edge of collapse.

We have investigated the resilience, collapse and reorganization in the social–ecological systems of eastern African savannahs since 2010, within the framework of an inter-disciplinary research project. This research emphasizes cross-scale interactions of resilience, focusing on the wider catchment area of Lake Baringo, including the Laikipia Plateau, and the Tugen Hills. The region is characterized by the interaction and competition of pastoral nomadic and small-scale farming systems. Many former nomadic pastoral households have recently settled, adopting small-scale farming in addition to livestock keeping, thereby enhancing competition for land.[6] A new dimension of further stress on an already fragile social–ecological system is brought about by the recent aggressive spread of invasive species that are rapidly expanding in both the lowland and the highland savannah ecosystems, reducing forage availability and enhancing resource competition between user groups. In the face of bush encroachment and the resulting acceleration of human–environment interactions, both the extent and the scale of social–ecological systems responses warrant further clarification.

This article provides an overview of our current understanding about invasion dynamics, their drivers and mechanisms, their implications on the social–ecological system in and around Lake Baringo, and their relationships to current invasion theory. The observations reported are based on field surveys, interviews, and rapid assessments of vegetation and soil attributes conducted during three short-term, inter-disciplinary fieldwork seasons in 2005, 2009, and 2012, as well as two extended field surveys in 2013 and 2014.

The species invasions reported here present only the latest challenge to the resilience of the human–ecology interaction in Baringo, but should be viewed in terms of the longer-term responsiveness of the societies in this region to a variety of challenges to their production systems. However, even in this historical context of adaptation it is clear that the current invasions present a fundamental threat to current productive systems that will require novel and innovative responses if production systems are indeed to adapt and evolve.

Invasive species in Baringo

In East Africa there is a general concern about the impact of invasive woody species on the well-being of communities, especially those inhabiting arid regions.[7] In Baringo, the spread of *Prosopis juliflora* (Sw.) DC. and probably hybrids with *P. pallida* (Humb. & Bonpl. ex Willd.) Kunth in the arid plains around Lake Baringo, and of *Dodonaea viscosa* Jacq. in the dry mesic shrublands between East Pokot and Laikipia, is a recent phenomenon. While *P. juliflora* (henceforth *Prosopis*) originates from America and the Caribbean,[8] *D. viscosa* (henceforth referred to *Dodonaea*) is native to arid and semi-arid East Africa.[9] Both species started to develop expansionist behaviour in the late 1980s and early 1990s. They show truly invasive/encroaching[10] characteristics in the early 2000s, and are today shaping the savannah environment and the livelihood strategies of pastoral and farming communities around Lake Baringo. Information on plant population characteristics and their dynamics for *Dodonaea* originates from 276 geo-referenced observation grids of 10 × 10 m for assessing stand densities in 2014 as well as a survey conducted in 2015 in the Churo highlands (97 interviews with household heads). In the case of *Prosopis* a number of informal interviews were conducted along the southern shores of Lake Baringo in 2014–2015. Additionally, satellite data (LandSat and RapidEye scenes) from 1990, 2000, and 2010 document the spread dynamics.

Prosopis is a fast-growing, thorny, and strongly branching shrub or tree belonging to the family of the Fabaceae. Classified as a phreatophyte, its roots require access to the groundwater table. At all reported sites in Africa (Kenya, South Africa, Ethiopia), dense stands of *Prosopis* strongly reduces the availability of pasture and crop land and also increasingly restrict the physical access of both humans and animals to lake shores and river banks. *Prosopis* was introduced in Kenya in 1973 through a governmental initiative to restore quarries near Mombasa.[11] About 10 years later, it was planted in Baringo in the context of the 'Fuelwood Afforestation Extension Project' to increase the availability of firewood and to restore soils affected by over-grazing and erosion.[12] Since 2000, *Prosopis* has rapidly spread, predominantly in the south-western side of Lake Baringo as interviewed farmers in different settlements ascertained and remote sensing data underlines. The plant is highly competitive with natural savannah vegetation, preventing regeneration of the former *Acacia tortilis* stands and displacing grass vegetation. Dense *Prosopis* stands also restrict the physical access of both humans and animals to the southern and south-western lake shores and river banks.[13] The northern shores of the lake are only marginally affected by the *Prosopis* invasion at present. Hence, Il Chamus herders are more challenged by the invasion than Pokot herders.

The invasion of dry wooded grasslands by *Dodonaea* is less known. It belongs to the family Sapindaceae and is a wide-spread native woody shrub in the highlands of East Africa, where it occupies a niche as pioneer plant on steep rocky outcrops and on debris slides.[14] *Dodonaea* is not the only case of a native woody species invading grasslands. Similar examples comprise the invasion by *Solanum campylacanthum*[15] and by *Euclea racemosa*[16]. Interviewed farmers ($n = 53$) consensually saw first evidence of untypical *Dodonaea* spread in the late 1980s and of proper encroachment in the Churo highlands in the early 2000s. In the past few years, dense stands of *Dodonaea* have become a characteristic vegetation component in the pastoral landscape of the East Pokot highlands. *Dodonaea* is not palatable for browsing animals and reportedly inhibits the growth of grasses, thus affecting the availability and quality of forage. Today, Pokot people view *Dodonaea* with growing concern. They see a clear relation between, lack of fallows, field clearing by fire and land preparation by ploughing and *Dodonaea* spread. They also alleged that once there is an over-growth of *Dodonaea* on these fields, pasture production declines.

While *Prosopis* and *Dodonaea* have different origins, they also occupy different niches in their natural habitat and have distinctly different edaphic and hydrological requirements. However, these species both change savannah ecosystems and affect the livelihood of pastoral and crop farming communities in a similar way. Their invasive spread dynamics can be seen to accelerate human–environment interactions, to increasingly upset the balance of the social and the ecological sub-systems in the region, and to push an already fragile social–ecological system to the edge of collapse. We hypothesize that specific interactions between natural and anthropogenic factors initially triggered and are still driving the spread dynamics of the two invaders. Understanding the underlying processes will help to predict the future invasion dynamics, explain social–ecological interactions, and allow for risk assessment and derive possible management strategies of *Prosopis* and *Dodonaea* in the Baringo region of Kenya and beyond.

Invasion history

After having been initially introduced into the Baringo area in 1983, *Prosopis* started to invade the lake littoral only in the late 1990s and early 2000s.[17] A period of accelerated spread occurred around 2007–2008, when *Prosopis* formed dense stands on lacustrine sediment soils around the sites of its initial introduction in the Njemps flats to the south of the lake at the villages of Ng'ambo and Salabani. By 2015, *Prosopis* was to be found in nearly every soil type along the southern, western and eastern lake shores, and in all land-use systems (pastures, cropland, home gardens) of the lowland savannah ecosystems around Lake Baringo. Only in intensively used croplands under year-round cultivation has in been held at bay, where weed control management prevents the establishment of woody plants.[18] During the same period, aggressive spreading behaviour of *P. juliflora* was also reported from the fringes of the River Turkwel on the West of Lake Turkana[19] and in some lowlands in Ethiopia[20] and South Sudan. Similar trends have also been observed in the subtropical environments in the southern Kalahari, South Africa, involving the closely related species *Prosopis velutina* and *P. glandulosa* that originate from Argentina and were introduced to Namibia some 40 years ago.[21] While severe drought events also coincide with the starting of the invasiveness at these sites, the drivers of spread dynamics require further elucidation.

Parallel to the spread dynamics of *Prosopis* in the Baringo lowlands, similar trends were observed in the case of *Dodonaea* in the highlands. Again the late 1990s and early 2000s were reported as the start of invasive spread around the village of Tebelekwo in the highland area around Churo. This was ascertained during interviews with elders knowledgeable about vegetation processes in the region. In this area, *Dodonaea* left its natural habitat on shallow soils, and started to colonize adjacent grasslands on deeper and potentially highly productive soils. In 2008–2009, we observed a high abundance of individuals and some dense stands of *Dodonaea* in both grassy pastures, in savannah shrublands, and in abandoned crop fields. In late 2013 and early 2014, *Dodonaea* was observed in some environments of the Pokot highlands (such as Churo, Korossi, Maron but not Paka and Silali). At the same time, we observed first indications of *Dodonaea* encroachment on abandoned farm and on pastoral land around Rumuruti (Laikipia West), in Kabarnet (Tugen Hills) and in Machakos. Thus, and despite occurring in different ecological zones, both species started to became invasive in the late 1990s (start of invasion), showed rapid spread dynamics around 2008 (first wave of invasion), and expanded spatially into neighbouring regions and districts in 2013–2014 (second wave of invasion). The initial trigger for and the subsequent drivers of spread dynamics will now be analysed.

Drivers of invasive spread

Invasive behaviour of a plant species usually requires an initial trigger that may comprise a single event; drivers of spread dynamics, on the other hand, usually involve processes of long-term change.[22] The introduction of a foreign species into a 'new' environment favours an unchecked and rapid spread provided the ecological conditions are favourable to the invader. Atypical climate extremes, or disaster events, can also provide the trigger for such an invasion. Furthermore, deforestation and erosion, as well as soil degradation by over-grazing, may also favour the establishment of a new species.[23] Long-term environmental attribute changes may act as drivers and comprise gradual ecosystem changes, as in the context of climate change, or anthropogenic interventions and management shifts, creating conditions of disturbances, providing the conditions for species spread, or creating mechanisms of seed germination and dispersal for an invasive spreading behaviour.

The coincidence in the timing of establishment and expansion of the invasive spread of both species suggests the occurrence of large-scale phenomena to be the triggering event. Indeed, the start of the invasion and the aggressive spread of *Prosopis* around Lake Baringo, and of *Dodonaea* in fallows and grasslands of the highlands, coincide with a period of prolonged drought, associated with La Niña/El Niño phenomena (Figure 1).[24] During the La Niña/El Niño-related periods of drought before 1998, famines and losses of livestock did occur. However, it was only during and after the extended drought of 1997–2000 that the adaptive responses of the social sub-system drastically changed and that bush encroachment of land by *Prosopis* and *Dodonaea* began. Against a background of demographic growth, land shortages and inter-ethnic violence, this period saw changed patterns in the migration of pastoralists and a general diversification of economic activities in response to drought, including emerging sedentarization of former nomadic pastoralists.[28]

The prosopis *case*

In the proximity of Lake Baringo, human and animal densities are high, particularly during the dry season. Extended household surveys among Pokot show that more livestock migrate to the lake shores and that the borders to neighbouring ethnic communities are increasingly contested (similar evidence is lacking at this stage for Il Chamus and Tugen households). Faced with severe drought between 1997 and 2000, but also with a restriction of cross-scale adaptive measures such as the seasonal migration, the Il Chamus communities around Lake Baringo faced dramatic livestock losses, with an estimated 250,000 cattle dying by starvation in Baringo district alone (1.7 million in the Rift Valley).[25] Cattle herds were only partially restored, while the number of the more resistant goats increased from 240,000 (census of 1990) to over 1.5 million in 2000, and to nearly 2 million animals in 2010 (Figure 1). In contrast to cattle, goats browse the sweet yellow pods and distribute them with their faeces, a process termed endozoochory.[26] This shift from grazers to browsers was instrumental in creating a dispersal mechanism for *Prosopis* seeds. The exceptionally wet years of 2012 and 2013 provoked a dramatic rise of the water table of Lake Baringo, forcing people living along the lake shores to leave the littoral, moving up-slope to drier ground. In addition, the rising groundwater table increased the area with access to deeper water sources required by phreatophytes and thus the wet period resulted in a massive lateral spread. Today *Prosopis* is found not only in the littoral zone but also on lower slopes all around the larger Baringo basin.

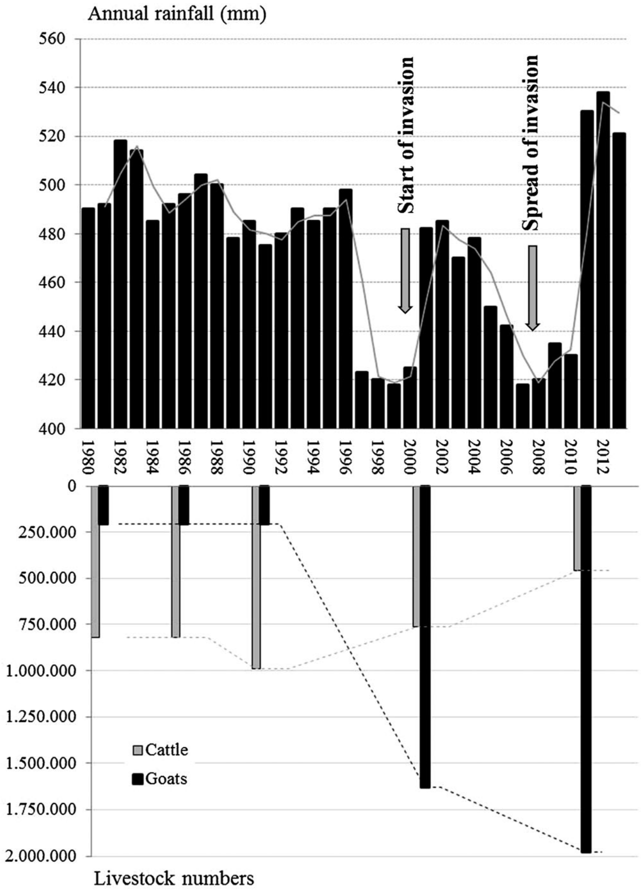

Figure 1. Annual rainfall in Lake Baringo between 1980 and 2013[a] and trends in livestock numbers (cattle and goat, no data to sheep and camel) in East Pokot between 1980 and 2010[b].
Notes: [a]Kenya agricultural research institute (KARI), Marigat, Kenya. [b]Dairy training centre, Naivasha, Kenya. Accessed November 21, 2015. www.opendata.go.org.

The dodonaea *case*

Particularly in the highlands, droughts tended to accelerate the emerging process of sedentarization of former nomadic pastoralists. Claiming land for maize production was associated with the building of fences and land clearing by burning and subsequent mechanical tillage for cultivation.[27] In addition, large land areas in the Churo highlands were transformed to conservancies by local elites acting in conjunction with environmentalist NGOs in view of receiving tourist revenues in future. Conservancies of 19,750 and 8000 hectares were established in 2002 at Ltungai and Kaptuya respectively, and another of 16,400 hectares was founded at Ruko in 2006. The concomitant further shortage of available pastures entailed an over-stocking of the remaining available grasslands with ruminants, resulting in wide-spread emergence of bare soil patches.[28] Also, wild native browsing and grazing mammals are known to control the cover of woody plant species.[29] Hence, the displacement of wildlife as a consequence of the population increase in East Pokot, and a generally negative attitude of the population towards wildlife conservation, also have contributed to the bush encroachment in Baringo.[30] In addition, fire and soil tillage that were applied in the context of emergent agricultural practices in a pastoral setting generated disturbances in the wooded grasslands that most likely paved the way for the establishment of *Dodonaea*. This colonization of grasslands by *Dodonaea* contributed to a further reduction of available forage for ruminants, intensifying the adaptive land-use changes, spatially expanding seasonal livestock migrations, and accelerating further spread dynamics. The heavy rains in 2013 then provided the boost in growth to the now well-established *Dodonaea* stands that further out-competed the grasses. Discussions with pastoralists and recently sedentarized crop farmers in the area in 2014, underlined their growing concern and despair with this 'new weed'. The invasive behaviour of *Dodonaea* is thus increasingly limiting the choice of adaptation strategies in some localities.

With land shortages and inter-ethnic violence, the response to the consecutive drought events of the late 1990s and mid-2000s were associated with shifts in land and herd management.[31] These droughts of 1997–2000 thus constitute the trigger that started the invasiveness, while the adaptive management responses can be considered to be the drivers for the further spread of both *Prosopis* and *Dodonaea*. The high rainfall in 2012–2013 consolidated the established invaders by stimulating their growth and spread.

Mechanisms and effects of invasion

This following section analyses findings on the linkages between climatic perturbations, changing livestock demographics and altered settlement patterns and the expansion of *Prosopis* and *Dodonaea*.

The prosopis *case*

> Where you see *Prosopis*, no more grass will grow.[32]

Prosopis is known to produce enormous numbers of seeds, several 100 pods per plant and 12–20 seeds per pod being produced annually. The large and heavy pods drop to the ground underneath older individuals. Being firmly embedded in the tough fibres of the pod tissue, it can take several months (possibly even years) of physical and microbiological decay before the seeds are released into the environment. The hard coat of the dormant seeds prevents imbibition and germination. Thus, without a scarification process that removes the seeds from the pod and alters the seed coat structure in a way enabling them to absorb water, germination of the abundantly produced seeds is very poor. Also, without a vector to distribute the seeds in the wider environment, their spread is spatially restricted. With the shift in herd structures and the massive increase in the number of goats, this stationary behaviour of *Prosopis* suddenly changed. We initially observed a clustering of germinating *Prosopis* seedlings around droppings of goats. Further studies confirmed that the intestinal passage not only removes the seeds from the pods, but also provides the scarification required for rapid seed germination, removing the wax layer and physically altering the seed coat. Our investigations revealed that such seeds started imbibing after only 24 hours, and 30% of the seeds had germinated within 10 days of having been deposited by the goat.[33] Compared to naturally shed pods from *Prosopis* individuals in fenced areas, the rate of germination and the vigour of seedling growth is enhanced several-fold after the intestinal passage through the goat. Consequently, endozoochory has provided the missing stimulation of seed germination and the mechanism of seed spread.[34]

Prosopis seedlings produce two root systems, one spreading just below the soil surface and a second, which is a tap root able to penetrate beyond 1 m and access to ground water.[35] This flexible use of water resources points the success in the establishment of *Prosopis* even under dry conditions. In addition, *Prosopis* has an enormous re-sprouting capacity after clear-cut, indicating that mechanical control by cutting is unlikely to be effective. Once established, *Prosopis* grows very rapidly, possibly due to its capacity to extract water from deep layers or alternatively the soil surface and its ability for atmospheric N_2-fixation in symbiosis with rhizobia. Being highly competitive, *Prosopis* impede the regeneration of native woody species (e.g. *A. tortilis* and *Balanites aegyptiaca*) and to suppress the growth of grasses. This competitive ability has been related to the excretion of allelochemicals.[36] While roots reportedly exude tryptophan-like substances,[37] the litter of the continuously shed leaves release diverse other phenolic compounds.[38] These chemicals inhibit the growth of most other plants[39] and prevent grass seeds from germinating.[40] This alters completely the composition of pastureland and, as its leaves are not palatable to ruminants, reduces the availability of forage. While the seed scarification by passage through the goats' intestine and their spatial distribution by the animals constitute the key mechanism of the spread, the fast growth, rapid re-sprouting and the allelopathic properties ensure the competitive ability of the invader species.

The dodonaea *case*

> Burning their wings, makes tabalak seeds [*Dodonaea*] fall on the ground and there they start to grow.[41]
>
> When tilling or burning the land, you are seeding tabalak [*Dodonaea*].[42]

Similar to *Prosopis*, *Dodonaea* produces large amounts of seeds already in the second or third year after germination. The seeds are disc-shaped with encircling papery venose wings, allowing their spread by wind.[43] It is thus not surprising that initial spread dynamics were observed along roads where turbulences created by passing cars whirl the seeds into the air and distribute them along the main traffic ways. However, the seeds of *Dodonaea* do not germinate readily and require several weeks to establish. Thus the 'removal' of the fruit wings, allowing the seeds to drop to the ground in a 'stabilized position' without constant displacement by wind is perceived to contribute to the plant's establishment.

The absence of competing vegetation in bare soil is likely to favour the initial establishment of *Dodonaea*. Whether burning promotes directly the germination of *Dodonaea* seeds or rather favours its establishment by suppressing competition requires further investigation. It appears that *Dodonaea* plants are extremely resistant against burning,[44] and even completely burned individuals are reportedly able to re-sprout from basal buds.[45] This type of fire resistance has not been observed in other woody species of the region, except for *Combretum molle*, which have a corky bark.[46] Abundant young seedlings are observed on bare soil patches that had been created by either bush fires, soil tillage operations or over-grazing. While it has been reported from Australia that

Dodonaea is able to colonize bare soils,[47] the abundance of such patches and generally of sites disturbed by burning or soil tillage in East Pokot has dramatically increased with the recent phenomenon of sedentarization of former nomadic pastoralists[48] and also recent heavy over-stocking of grasslands due to severe pasture shortages.

As in *Prosopis*, the release of bioactive substances (allelopathy) appears to hinder the germination or the growth of other species associated with *Dodonaea*, as highlighted by the displacement of native grasses and of planted vegetation.[49] Bio-assays applying aqueous extracts from *Dodonaea* inhibited the initial growth of lettuce seeds and the germination of seeds of several grass species.[50] This is further supported by both our observations and reports by Pokot farmers: 'where tabalak grows, the grass disappears'. In addition, the resinous leaves are not palatable for livestock, conferring advantages for the establishment of *Dodonaea* against other woody species that are affected by browsing.[51]

We conclude, therefore, that following the triggering events of the consecutive drought periods in the late 1990s and mid-2000s, recent land-use changes and associated soil disturbances, constitute the mechanism required to start the invasive spread of *Dodonaea*. Some changes in migration patterns may also have accelerated the southward spread of *Dodonaea*.

Relation to invasion theory

Invasiveness is defined as the undesired spread of a foreign or native species, resulting is the displacement of other species, the loss of (productive) land, and changes to the ecological and social systems.[52] Several factors may contribute to invasiveness. A frequently challenged determinant is the species' relatedness or genetic *similarity as formulated in the* 'naturalisation conundrum' by Darwin in 1864.[53] The availability of an 'empty niche', in the case of native species,[54] and the absence of natural enemies, in the case of foreign species,[55] were defined as prerequisites for invasive spread dynamics. The extent, intensity and speed of invasive spread have been linked to the invaders competitive ability,[56] and to the amount and frequency of produced seeds and their dispersal.[57] In all cases, a trigger event is usually required to start the invasiveness. This trigger can be the introduction of a foreign species or the creation of 'new' empty niche environments, that is, by disturbances related to climate anomalies or land-use and management shifts.[58] These attributes and drivers of species spread have been formulated in several, sometimes conflicting but mostly complementary theories or hypotheses. Table 1 summarizes the six published invasion concepts and indicates their relevance and applicability to the cases of invasiveness of *Prosopis* and *Dodonaea* around Lake Baringo. Let us consider the relevance of each concept in turn.

Concept 1: In his 'naturalisation conundrum', Charles Darwin has surmised that the relatedness or genetic similarity between the native vegetation and the invasive species determines the success of the invader. This is partially true for the case of *Prosopis*, which replaces the morphologically very similar *Acacia* stands in the lowland savannah. It is not applicable to the case of *Dodonaea*, however, as it occupies disturbed sites or bare patches and mainly replaces grass vegetation.

Concepts 2 *and* 3: The presence of a niche that is not populated by vegetation (empty niche theory) or any disturbance that (temporarily) removes other species competing for

Table 1. Theories and hypotheses explaining the invasive behaviours of plant species and their relation to the recent invasiveness of *Prosopis* and *Dodonaea* in Baringo.

	Relevance/applicability of theories	
Theories/(author)	*Prosopis*	*Dodonaea*
(1) Similarity hypothesis	Y (Similarity to *Acacia spp.*)	N (shrubs vs. grassland)
(2) Empty niche hypothesis	N (dense littoral vegetation)	Y (land clearing, bare patches)
(3) Disturbance hypothesis	N (only extensive grazing)	Y (burning, tillage, over-grazing)
(4) Natural enemy hypothesis	Y (no imported pests, diseases)	N (native species, native pests)
(5) Competitive ability hypothesis	Y (fast growth, allelopathy)	Y (resprouting, allelopathy)
(6) Seed dispersal hypothesis	Y (endozoochory, goats)	Y (wind and fire)

Notes: Y: yes (theory applicable); N: no (theory not applicable).

space and resources (disturbance theory) as well as the presence of a species adapted to the specific conditions occurring in this empty or disturbed niche have been related to invasion success.[59] The 'disturbance hypothesis', predicts the establishment of ruderal species following the 'opening' of places for establishment and by relieving the stress from competition by other species.[60] Such niches may be created by soil tillage and vegetation burning and by over-grazing (bare patches) for colonization by *Dodonaea*, but are less clear in the densely vegetated lake fringes where *Prosopis* is spreading.

Concept 4: Frequently the absence of natural enemies has been related to invasiveness of imported foreign species. Thus, in its natural habitat of South America and the Caribbean, the growth and spread of *Prosopis* is controlled by the plants' infestation with leaf-feeding bugs of the genus *Homoeocerus*[61] *and* seed-feeding *bruchid* beetles of the genus *Algarobius*,[62] which are absent in East Africa. On the other hand, even in its natural habitat, *Dodonaea* is rarely affected by pests or diseases. Occasionally, young shrubs may be infested in arid environments by sucking insects. Also *Verticillium* wilt has been reported from garden-grown plants.[63] However, none of these pests and diseases (apart from a small-scale occurrence of a not further identified gally wilt) have so far been observed in East Pokot. Consequently, the spread of neither *Prosopis* nor *Dodonaea* appears to be hindered by natural enemies.

Concept 5: Many plants have the possibility to out-compete associated vegetation by successfully acquiring resources such as light, nutrients and water. Additionally the release of bioactive substances (allelopathy) can hinder the germination or the growth of other species. While rapid growth, lateral spread of branches and fast closure of the canopy shade-out any competing vegetation under *Prosopis*, the competition for light appears less relevant in the case of the open-canopy as observed in *Dodonaea*. However both species can reportedly 'repel' competitors by resorting to chemical 'warfare' via the release of allelopathic substances, enhancing their competitive abilities.

Concept 6: The amount and the frequency of seed production and the efficiency of seed dispersal are key attributes for a successful invasion. Both *Prosopis* and *Dodonaea* produce enormous quantities of seeds. However, it was the management shifts (from cattle to goat; from cattle to corn) that have provided the mechanisms for spread and enhanced germination. With high seed production, effective dispersal mechanisms and fast growth of seedlings, both *Prosopis* and *Dodonaea* can be classified as ruderal species.[64]

An additional factor possibly favouring invasive spread dynamics may be the ecological flexibility conferred by the large intra-specific genetic variability in both species. *Prosopis* belongs to the taxonomically rather undefined *pallida–juliflora* complex wherein individuals are self-incompatible, avoiding sexual reproduction within clones, and forming inter-specific hybrids.[65] Being a dioecious species (separated into male and female individuals), and with two varieties (*angustifolia* and *viscosa*) occurring in the region, *Dodonaea* also shows a large variability.[66] Genetic variability implies morphological and functional diversity, and consequently high adaptability of the species to diverse environments.

We conclude that the disturbance hypothesis applies for *Dodonaea* and possibly for *Prosopis*. Key constituents of successful invasion in both species are related to the competitive ability and the seed dispersal theories, and possibly a high adaptability due to genetic variability and diversity. These processes, however, became only relevant for the invasive behaviour after management shifts in response to climatic anomalies. Thus, the responses of people to adapt to climatic uncertainties provided the multi-level and cross-scale driving forces of invasion by *Prosopis* and *Dodonaea*.

Social–ecological implications

> With no more available pasture land, I have to bring my animals all the way
> into the land of the Turkana and the Samburu.[67]

Traditionally ecology has focused on the concept of succession when a phase of colonization after a disturbance is followed by a phase of conservation. This concept, however, neglects the interactions of the ecological with the social system and hence the additional phases of release and reorganization. Thus, periods of change or resource transformation in the ecological sub-system create opportunities for innovation by the social sub-system. The model of the adaptive cycle (Figure 2) provides a more complex view of dynamics of social–ecological systems, linking resilience, collapse and re-organization.[68] Thus, a phase of change (r) and subsequent accumulation (K) is followed by response or reorganization phase (W1ANGLE1MSOINS2ANGLE2)1ANGLE1/MSOINS2ANGLE2, leading to renewal or a new state of equilibrium (α). The adaptive cycle of vegetation is embedded within a larger cycle of the social–ecological system running though at a different speed and displaying autonomous characteristics.[69] The changes a system can absorb and still retain its functions and structure, the degree to which the system is capable of self-organization, and the ability to build and increase the capacity for learning and adaptation define the resilience of a linked social–ecological system.[70]

Resource availability and resource-base quality are the hinges by which the social and the ecological spheres of the social–ecological system are coupled. People have traditionally adapted their land-use and livelihood strategies to gradual changes in the environment (i.e. rainfall variability). In turn, the environment has responded to changes in land-use and management, resulting in adaptive cycles of human–environment interactions. Invasiveness by both *Prosopis* and *Dodonaea* strongly reduces the resource availability and increasingly unhinges the ecological from the social sub-system. This low connectedness affects the resilience of the socio-ecological system in Baringo and East Pokot in an unprecedented way. Thus, instead of recurring adaptive cycles, we rather observe a spiral of

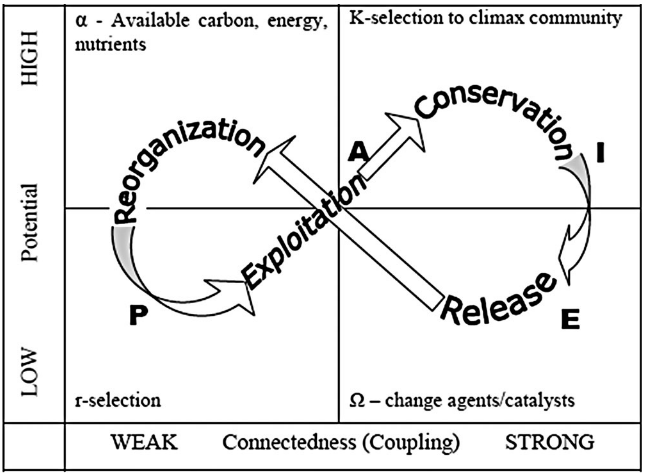

Figure 2. The concept of the adaptive cycles in social–ecological systems. PAEI – structures of concern: the four dimensions of living activity.
Note: Holling, Gunderson, and Ludwig, 'In Quest', 3–24.

events during the past 25 years (triggers, responses, mechanisms and effects) that may potentially lead to a collapse of the social–ecological systems (Figure 3).

Initial drought events and subsequent land-use changes and associated practices of tillage, burning or increased pasture stocking densities, have triggered and driven the recent invasion dynamics by *Prosopis* and *Dodonaea*. The adaptive changes by the social sub-system have accelerated the change processes in the ecological sub-system, negatively affecting resource-base quality and the availability of pastureland, and increasingly forcing people out of traditional livelihood strategies. Non-farm income, migration of livestock to neighbouring regions and out-migration affect the system beyond the spatial scale of currently affected areas, and may even contribute to an accelerated spread dynamics (i.e. via migrating animals). Changes in the social–ecological system, drivers and coupling processes in the face of invasion are currently being studied.

Today, much of southern and the western shores of Lake Baringo are no longer accessible to nomadic pastoralists that seek water for their cattle herds during the dry season. Most of the littoral pastures of the local Il Chamus no longer exist, and the traditional migratory routes are severely eroded as tracks become waterways during rains. Migration patterns of the herds of the pastoralists are strongly restricted due to contested land on the borders and ethnic violence with neighbouring tribes. Only in commercial crop land with mechanical tractor tillage can *Prosopis* be kept at bay. Consequently, local populations are increasingly forced to adopt changes in their agriculture-based livelihood strategies. They engage in wage employment in the Perkerra Irrigation Scheme, or move into small-scale enterprises such as honey and charcoal production. Some former pastoralists have started small-scale cereal and vegetable farming along the shores of Lake Baringo. However, these areas are also becoming over-grown with *Prosopis*. In any event, none of these activities appears to compensate economically for the loss of livestock-based livelihoods that thrived in former times.

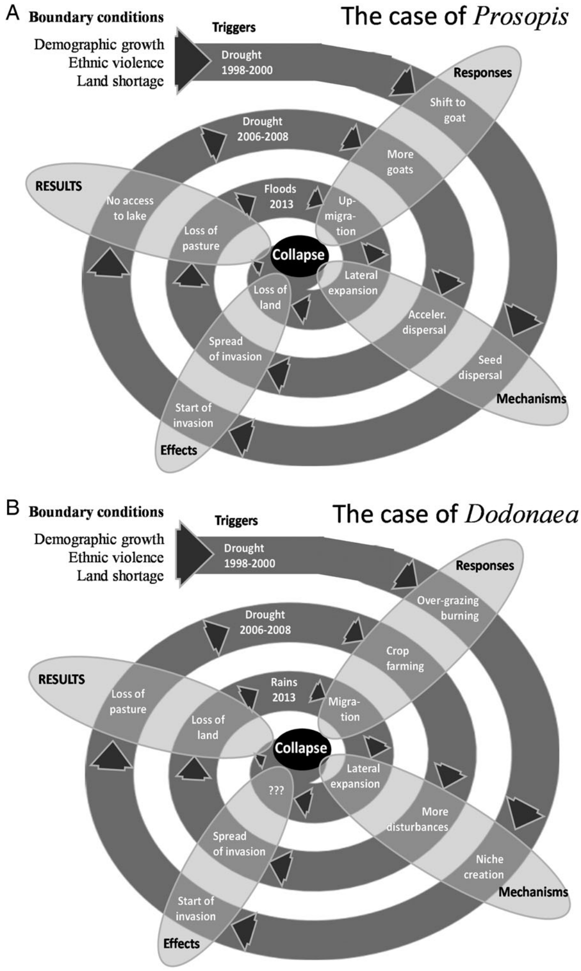

Figure 3. The spiral of events during the past 25 years leading to a collapse of the social–ecological systems in Baringo. Upper: the case of *Prosopis* invasion around Lake Baringo; lower: the case of *Dodonaea* invasion in East Pokot.

The so far undocumented aggressive behaviour of *Dodonaea* as a 'new' invader of the East Africa highlands is also likely to entail rapid changes in the social–ecological systems, even beyond the area affected by the current invasion. Similar explosive and aggressiveness in colonization has already been witnessed elsewhere in Kenya, and in the Bugesera District of Rwanda.[71] With the disappearance of productive pastures and farmlands, the general land shortage is leading to greatly heightened social tensions. The settling of land disputes among Pokot has become a daily task of village elders and community leaders. Faced with loss of productive land for grazing their herd or indulging in crop farming, the losers in such land disputes must move their livestock further away to 'greener grounds' in the Rift Valley or onto the Laikipia plateau, where inter-ethnic conflicts are not only frequent but also increasingly violent.

Direct uses or economic benefits derived from the invaders are very limited. Many land-users around Lake Baringo have started to producing charcoal from *Prosopis*, but also from the few remaining *Acacia* trees, further destabilizing a fragile ecosystem. Most of the socio-economic activities, including bee-keeping, the local sale of *Prosopis* honey, and the sale and use of the thorny branches as fencing material, are unviable. A possible alternative and hence a way to adapt to change by re-organization and to break the spiral leading to collapse may be the use of *Prosopis* for commercial energy generation through the recently started, but not yet operational, 'Cummins' project close to Marigat.[72] Cummins Cogeneration Ltd. proposes to buy *Prosopis* logs locally and use these in the generation of electrical power. The cost benefit analysis to transport sufficient biomass of *Prosopis* to the factory, and the price to be paid out by the company remains to be determined, and so it is not clear how successful this new business concept will be.

The most frequently observed use of *Dodonaea* is for fencing material around crop fields and homesteads to prevent animal trespass. With sedentarization, fencing has been spreading rapidly in East Pokot: a bundle of 30 flexible *Dodonaea* sticks now sells at about 30 KES (approximately 0.25 EUR). A few farmers also mentioned medicinal uses for *Dodonaea*: the stems, leaves, seeds, roots, and bark can be used for their antibacterial, analgesic, antiviral, anti-inflammatory, and antiulcer properties.[73] Powdered roots are used for treating intestinal ailments, and as stimulant for lactating women, and young twigs are used to treat sore throats. Leaves are occasionally used as a source of resin and for embalming. Twigs are also reportedly used as walking and digging sticks, for roof support, and as tool handles,[74] traps or weapons.[75]

Most of these uses are highly localized, are of minor economic importance, and have no relevance in controlling the *Dodonaea* invasion or in providing a means to enhance the peoples' adaptive capacity to catastrophic ecological change processes. In contrast to the theory of the adaptive cycles, the weak connectedness and a poor adaptive capacity of both the social and the ecological sub-systems in Baringo, but also the extent and the speed of the 'release' or W stage in the face of invasion dynamics, hamper the α stage (or the reorganization of the social sub-system) and consequently prohibit exploitation (r stage), pushing the social–ecological systems of Baringo and East Pokot towards the edge of collapse.

Outlook

The research reported here is a warning signal. The rapid spread of *P. juliflor*a and *D. viscosa* has accelerated ecological transformations in Baringo and exerted massive pressure on local social systems. Increased variability in rainfall during the past decades appears to have been the trigger for both the land-use and the herd management changes that were the drivers of this shrub invasion. With the prognosis of climatic changes to substantially affect the region in the coming 15–30 years,[76] and with the rapidly progressing shortage of land, both triggers and drivers for an invasive spread are likely to increase in number and intensity. Thus, beyond the reported encroachment of *Dodonaea* and *Prosopis* in Baringo, invasive spread dynamics involving other species and affecting other regions are likely to gain importance in the future.

Without measures controlling the spread of the invaders and adaptation of the social sub-system to the rapidly evolving change processes, the socio-ecological system of the dryland savannahs around Lake Baringo are expected to head for a state of collapse, further exacerbating the degradation of the resource base, and generating increasingly violent conflicts associated with competition for scarce resources. Detailed social–ecological studies, systematic surveys, and spatially explicit mapping are currently underway to predict future spread dynamics of the invaders, hopefully making it possible to develop social responses and to target possible strategies for containing or adapting to the invasion. Without these measures, the collapse of Baringo's socio-economic systems seems imminent.

Notes

1. Anderies, Janssen, and Ostrom, "Framework."
2. Berkes, "From Community-based," 45; Gunderson et al., "Water RATs," 1–10.
3. Nightingale and Cote, "Resilience Thinking," 475–89.
4. Newell et al., "Conceptual Template," 299–307.
5. Folke et al., "Regime Shifts," 557–81; Marchant, "Understanding Complexity," 101–8.
6. Greiner, Alvarez, and Becker, "From Cattle to Corn," 216–37.
7. Obiri, "Invasive Plant Species," 417–28.
8. Andersson, "Spread."
9. Davies and Verdcourt, *Flora of Tropical East Africa*; Anilreddy, "Preparation," 1–9.
10. Invasion refers to the undesired spread of an imported or exotic organism, while encroachment is used in the case of indigenous or native species.
11. Choge et al., "Prosopis Pods," 419–24.
12. Andersson, "Spread."
13. Mwangi and Swallow, "Prosopis juliflora Invasion," 130–40.
14. Davies and Verdcourt, *Flora of Tropical East Africa*; Harrington and Gadek, "A Species Well-travelled," 2313–23.
15. Pringle et al., "Low Functional Redundancy," 1–9.
16. Field observations.
17. Mwangi and Swallow, "Prosopis juliflora Invasion," 130–40.
18. Field observations.
19. Muturi, Mohren, and Kimani, "Prediction," 628–36.
20. Rettberg and Müller-Mahn, "Human-environment," 297–316.
21. Smit, P. "Prosopis," 13; Kohli et al., *Invasive Plants*.
22. Rodríguez-Labajos et al, "Multi-level Driving Forces," 63–75.
23. Hierro, Maron, and Callaway, "Biogeographic Approach," 5–15.
24. Anyamba et al, "From El Niño to La Niña', 3096–3103.
25. Lelenguya, "Effects of climate variability."
26. Eichberg, Storm, and Schwabe, "Endozoochorous Dispersal," 3–26.
27. Greiner, Alvarez and Becker, "From Cattle to Corn," 1478–1490.
28. Gillson, "Evidence," 883–94.
29. Augustine and McNaughton, "Regulation," 45–58; Sankaran et al., "Determinants of Woody Cover," 846–9.
30. Gadd, "Conservation," 50–63.
31. Greiner, "Guns, land and votes", 216–37; and Bollig and Österle, "Changing Communal Land Tenure".
32. Interview, Il Chamus farmer, Marigat, June 2013.
33. Field data, as yet unpublished.
34. Leparmarai, et al, "The role of endozoochory."
35. Yoda et al., "Root System Development," 13–16.
36. Maundu et al., "Impact," 33–50.
37. Nakano et al., "Growth Inhibitory," 587–91.
38. Kaur et al., "Community impacts".

39. Goel, Saxena, and Kumar, “Comparative Study,” 591–600; Getachew, Demissew, and Woldemariam, “Allelopathic Effects,” 105–14.
40. Mehar, “Effect of Prosopis juliflora,” 9–18.
41. Interview, Pokot farmer, Churo, May 2014.
42. Interview, Pokot farmer, Tebelekwo, June 2014.
43. Davies and Verdcourt, *Flora of Tropical East Africa*.
44. Hodgkinson, “Water Relations,” 467–73.
45. Clarke et al., “Post-fire Recovery,” 221–39.
46. Field observations.
47. Cunningham, Joubert, and Adank, “Dodonaea angustifolia,” 11–18.
48. Greiner, Alvarez, and Becker, “From Cattle to Corn,” 1478–1490.
49. Maraschin-Silva and Aqüila, “Allelopathic potential,” 91–8.
50. Barkatullah and Ibrar, “Allelopathic potential,” 2383–2390.
51. Cunningham, Joubert, and Adank, “Dodonaea angustifolia,” 11–18.
52. Weber, *Invasive Plant Species*.
53. Cited by Diez et al., “Darwin’s Naturalization Conundrum,” 674–81.
54. Hutchinson, “Homage,” 145–59.
55. Gopal, *Water Hyacinth*.
56. Blossey and Nötzold, “Evolution,” 887–9.
57. Cain et al., “Long-distance,” 1217–27.
58. Hierro, Maron and Callaway, “Biogeographic Approach,” 5–15.
59. Hierro et al., “Disturbance,” 144–56.
60. Hierro, Maron and Callaway, “Biogeographic Approach,” 5–15.
61. Haldhar, “Report of Homoeocerus variabilis,” 848–53.
62. Zimmermann, “Biological,” 175–86.
63. University of California, “Dodonaea, Hopbush, Hopseed tree”.
64. Grime, “Vegetation Classification,” 26–31.
65. Sherry et al., “RAPD and Microsatellite,” 251–64.
66. Harrington and Gadek, “A Species Well-travelled,” 2313–23.
67. Interview, Pokot farmer, 7 October 2013.
68. Holling, Gunderson, and Ludwig, “In Quest,” 3–24.
69. Gunderson and Holling, *Panarchy*.
70. Walker et al., “Resilience Management,” 14; Resilience Alliance, “Key Concepts: Resilience”.
71. Field observations.
72. <https://www.cummins-power-kenya.com>, accessed 20 November 2015.
73. Anilreddy, “Preparation,” 1–9.
74. Liu and Noshiro, “Lack of Latitudinal Trends,” 232–39.
75. Prendergast and Pearman, “Comparing Uses,” 184–6.
76. IPCC, “Africa”.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was conducted in the context of the project ‘Resilience, Collapse and Reorganisation in Social–Ecological Systems of African savannahs’ supported by the German Research Foundation (DFG) [grant number BE-2491/4–2], [grant number BE-2491/8-1].

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