A preliminary analysis of the costs and benefits of the biological control agent *Dactylopius opuntiae* on *Opuntia stricta* in Laikipia County, Kenya

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Abstract *Opuntia stricta* (Haw.) Haw (Cactaceae) is invasive in Laikipia County, Kenya, impacting negatively on biodiversity and livelihoods. To control this invasive plant the biocontrol agent *Dactylopius opuntiae* (Cockerell) (Hemiptera; Dactylopiidae) ‘stricta’ biotype was released in 2014. A preliminary once-off survey to determine the impact of the cochineal revealed that it had contributed to a significant reduction in the number of cladodes, flowers and fruit of plants with cochineal. Fruits that were produced on plants with the cochineal were also smaller and had fewer seeds. Although still preliminary, an analysis of the costs of implementing this biocontrol programme indicates that it is the most cost-effective management intervention compared to physical and/or chemical control. Although the impact of the cochineal is still fairly localized we are confident that it will establish in

much of the invaded range and reduce the impacts of the invasive cactus, consequently improving range-land condition and livelihoods.

Keywords Biocontrol · Cactus · Cochineal · Eastern Africa · Impact

Introduction

A large number of cactus species have been introduced to countries around the world as ornamentals (250) or for food and fodder production (45) (Novoa et al. 2015). About 20% (57) of those species that have been introduced outside of their native range have become invasive, impacting negatively on biodiversity, livestock production, and rural communities dependent on these resources (Ueckert et al. 1990; Beinart 2003; Larsson 2004; Novoa et al. 2017, 2019; Shackleton et al. 2017). South Africa has the highest number of invasive cactus species (35), followed by Australia (26), and Spain (24) (Novoa et al. 2015). However, the tropics are not immune to invasions with *Opuntia stricta* (Haw.) Haw, *O. engelmannii* Salm-Dyck ex Engelm., *O. ficus-indica* (L.) Mill., *O. monacantha* Haw., *O. elatior* Mill., *O. cochenellifera* (L.) Mill., *Austrocylindropuntia subulata* (Muelenpf.) Backeb., *Cereus jamacaru* DC. and *Pereskia aculeata* Mill. having been recorded as invasive in Kenya, while

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other species such as *O. microdasys* (Lehm.) Pfeiff., *Penioecereus serpentinus* (Lag. & Rodr.) N.P. Taylor, and *Cylindropuntia imbricata* (Haw.) F.M. Knuth are present but have not yet escaped cultivation as in other parts of the world (Witt and Luke 2017; Witt et al. 2018).

Of the invasive species present in Kenya *O. stricta* is considered to be the most widespread and problematic (Witt et al. 2018). Introduced to Kenya in 1949 it is most abundant in Laikipia County and Tsavo East National Park, and the adjacent rangelands, where it forms dense stands, preventing access to homes, water resources and pasture (Witt and Luke 2017; Witt et al. 2018). All of the respondents in a socio-economic survey in Laikipia felt that it contributed to the ill-health and death of livestock (Shackleton et al. 2017). Other negative impacts included reductions in native plant populations, rangeland condition, human health, and access to pasture and water resources (Shackleton et al. 2017). These negative impacts resulted in economic losses of US\$ 500–1000 per household per year for 48% of households (Shackleton et al. 2017). Communities in Madagascar reported that *O. stricta* grew fast, invading land used for crop and pasture production, and encroached on villages and roads (Larsson 2004). It was also considered to be useless as a fodder plant and the fruits were regarded as distasteful (Larsson 2004). According to villagers, livestock avoided *O. stricta*, but would eat the cladodes during dry periods, often resulting in animal deaths (Larsson 2004). People who consumed the fruit developed diarrhoea, and the glochids on the fruit caused serious infections. The cactus also had a negative impact on native grasses and herbaceous plants, and even impacted trees by inhibiting their growth and regeneration (Larsson 2004).

Physical and chemical control of cacti is expensive and often ineffective (Novoa et al. 2019). The most cost-effective, sustainable and environmentally friendly control option for invasive alien cactus species is biological control (Paterson et al. 2011; Zachariades et al. 2017; Novoa et al. 2019). For example, the cactus biocontrol programme in Australia is estimated to have cost AU\$21.1 million resulting in a nett present value of AU\$3.1 billion, which is considered to be an underestimate of the total benefits (Page and Lacey 2006). In fact, the biological control programme against *O. stricta* in Australia is considered to be one of the most successful weed

control programmes in the world, reducing invasions of *O. stricta* from an estimated 24 million ha to just a few scattered plants, providing permanent and complete control (Raghu and Walton 2007). South Africa can claim similar successes with the benefit: cost ratio of the biocontrol programme against *Opuntia aurantiaca* Lindl. estimated to be 1154:1 (van Wilgen et al. 2004). In South Africa seven cactus species are considered to be under substantial biological control and eight species are considered to be under complete control (Zachariades 2018). Most of these successes can be attributed to various cochineal species (*Dactylopius* spp.).

There are nine known *Dactylopius* species in the monogeneric, homopteran family, the Dactylopiidae, all of which feed only on cactaceous plants and almost exclusively on the genus *Opuntia* (Mann 1969; De Lotto 1974). The co-evolution of *Opuntia*-feeding insects and their cactus hosts has resulted in the development of specialist insects to the exclusion of nearly all generalist phytophagous insects (see Moran 1980). This prolonged evolutionary relationship between the cochineal insects and cactus makes them especially safe insects to use in biological control programmes (Moran and Zimmermann 1984). It is widely known that there are a number of different biotypes within the species *D. opuntiae*, with each biotype being adapted to feed on a particular cactus species (Volchansky et al. 1999). In South Africa six cochineal species or biotypes have been released for the control of 11 cactus species, all resulting in substantial or complete control with no recorded or known non-target impacts (Zachariades 2018). Six cochineal species or biotypes have been released in Australia (Winston et al. 2014), providing significant control, with at least another seven species or biotypes being considered for release (Jones et al. 2015, 2016). Cochineal species have also been intentionally released in India, Indonesia, Kenya, Hawaii (USA), Madagascar, Mauritius, New Caledonia, Sri Lanka, Tanzania, USA, and Zimbabwe (Winston et al. 2014). *Dactylopius ceylonicus* was introduced to Kenya in 1958 for the control of *O. monacantha*, followed by the introduction of a biotype of *D. opuntiae* on *O. ficus-indica* (Winston et al. 2014). To date there have been no recorded non-target impacts from either of these two species in Kenya, or anywhere else in the world where they have established.

Activities to control the *O. stricta* invasion in Laikipia, Kenya, were initiated in 2010. In March 2011 permission was granted by the Kenya Plant Health Inspectorate Services to introduce the cochineal, a biotype of *D. opuntiae* for the control of *O. stricta*, from South Africa, for further testing. Based on the results of additional host range tests, permission to release the cochineal was granted by the National Environment Management Authority (NEMA) in 2014. The cochineal was subsequently mass-reared and released at a number of localities on Ol Jogi Wildlife Conservancy in Laikipia. Here we provide preliminary data on the efficacy of the cochineal in controlling *O. stricta* by comparing impacts between two sites, one with, and another without the cochineal. Although the methodology has limitations (see Adair and Groves 1998; Morin et al. 2009), it can be used to provide a rapid assessment of the efficacy of biological control agents. We also provide some supporting data on the financial merits of implementing a biological control programme.

Materials and methods

Study site

Laikipia County (0°21'38.1816" N; 36°46'55.0236" E) (c. 9700 km²) is a mix of grasslands, savannah woodland, and forest lying between the Aberdare Mountains to the south and southwest, Mount Kenya to the east and southeast, Eastern (Gregory) Rift Valley to the west, Karisia Hills to the north-west, Mathews Range to the north, and Samburu National Reserve to the northeast (Butynski and de Jong 2014). The dominant land used in the County is ranching, which makes up about 40% of the landscape with the remainder mainly consisting of community-owned lands (LWF 2012). These ranches focus mainly on wildlife conservation, tourism and livestock production while the communities are mainly pastoralists. Laikipia's soils, semi-arid climate, and low water availability, largely dictate these land-use options since only 1.7% of Laikipia is classified as having high potential for agriculture (Butynski and de Jong 2014). With about 65% of Laikipia defined as wildlife habitat (Frank et al. 2005) it still has significant numbers of large wild mammals (Kinnaid et al. 2012). In fact, Laikipia is home to the second highest abundance of

wildlife in East Africa, after the Mara-Serengeti ecosystem, and hosts the highest populations of endangered large mammals in Kenya, including half of the country's rhinoceros population, together with significant populations of elephants, Grevy's zebra, reticulated giraffe and wild dogs (Sundaresan and Riginos 2010).

Laikipia experiences dry and cool weather, which is influenced by the presence of Mount Kenya and the Aberdare mountain range. Daily maximum temperatures are around 25 °C, except for the northern part, which is a little warmer, with December and January being the warmest months. Mean annual rainfall increases with elevation, from 400 mm in the north-east to 1200 mm in the southwest on the slopes of Mount Kenya and the Aberdares (LWF 2012). There are two main rainy seasons with the 'long rains' falling from March to May, with April being the wettest month, followed by the 'short rains' in November.

Surveys

Preliminary surveys to determine the efficacy of the cochineal were undertaken in the Ol Jogi Wildlife Conservancy, Laikipia, in 2017, where the agent *D. opuntiae* 'stricta' biotype was released for the first time in 2014. Two rocky outcrops or "koppies" invaded by *O. stricta* were selected for the study. The cochineal was released on a "koppie" (0°18'31.57" N; 36°56'06.20 E) in the west in 2014 and has subsequently proliferated, impacting most of the cactus plants present. The other "koppie" (0°18'31.73" N; 36°57'40.97" E), about 3 km to the east, with very similar vegetation structure and composition, and similar cactus densities, had no visible cochineal at the time of this survey. Eight 50 m long and 2 m wide transects were laid out at right angles to the "koppie" with cochineal, while five similar transects were placed around the "koppie" with no cochineal. We sampled all individual cactus plants until we reached a pre-determined target of 150 plants in the site with cochineal, and 75 in the site without cochineal, hence the differences in the number of transects at the two sites. The maximum height of all cactus plants in each transect were measured. Height was often the length or breadth of a single cladode, whichever was the greater, often directly rooted in the ground. A 1 × 1 m quadrat was placed on the centre of each plant, above the main stem, and the number of cladodes, flower buds,

flowers, immature and mature fruits within the edges of the quadrat were counted, and directly down to the ground below. As such these records are not a two-dimensional measure of density, in m^2 , but rather three-dimensional as they include all flowers, fruits and cladodes in a three-dimensional volume from below the $1 \times 1 \text{ m}$ quadrat down to the soil surface. A quadrat reduced the amount of time required to undertake surveys, compared to undertaking total counts per plant, and provided us with the required data to demonstrate differences. We collected all fruits in the transects with and without cochineal, then randomly selected 50 from each site, measuring their length and breadth using vernier callipers, and the weight of each fruit using a kitchen scale. The fresh fruits were then dissected and the weight of the outer shell and all seeds within each fruit measured separately using the scale. Ten randomly collected seeds from each dissected fruit were then weighed and the total weight divided by ten to obtain a mean individual seed mass for each fruit. Preliminary data on the costs of the biocontrol programme against *O. stricta* versus physical and/or chemical control interventions was obtained from individuals directly involved in the management of *O. stricta* in Laikipia.

Statistical analysis

All statistical analyses were conducted using R 3.6.0 (R Core Team 2019). We compared differences in the size of plants, and the number of cladodes, flowers and fruits between sites with and without cochineal using independent Welsch's t-tests. Although some data was non-normally distributed, Mann–Whitney U tests generated statistically similar p values to t-tests, therefore only the t-test outputs are included in this paper.

Results

Preliminary surveys, based on a limited number of transects, indicate that the cochineal, *D. opuntiae* 'stricta' biotype has already had a significant impact on *O. stricta* where it was well established (Table 1). Many of the plants with cochineal had collapsed, hence the significant difference in plant height between sites. There were also significant differences in the number of flower buds, flowers, immature and

mature fruits in the sites with and without cochineal (Table 1). Most of the cladodes on plants with cochineal had shrivelled and dried, hence the significant differences in the number of cladodes on plants with and without cochineal. Mature fruits were also significantly smaller and weighed less in the site with the cochineal compared to the site where the cochineal was absent. There were also significantly fewer seeds in fruits collected from plants with cochineal than those from plants without the biocontrol agent, and they were also lighter, but not significantly so.

The biocontrol programme against *O. stricta* in Laikipia cost approximately US\$35,000. This includes the costs of an Environmental Impact Assessment (EIA), and other activities undertaken by the NEMA in Kenya, amounting to approximately US\$15,000. Importation, from a quarantine culture in South Africa, and re-testing of the agent to confirm host specificity, and other associated costs, came to about US\$10,000, while mass rearing and initial releases cost an additional US\$10,000. The latter costs are extremely low with many activities being undertaken at no or reduced costs. The costs associated with current mass rearing and further dissemination by the Northern Rangelands Trust are also unknown.

In comparison, initial physical clearing costs in Laikipia were, on average, $\sim \text{US\$540 ha}^{-1}$ for moderately dense stands, excluding the costs of any follow-up activities. Communities, armed with machetes, picks, hoes, and spades, removed plants which were then buried in huge pits created using a Tractor-Loader-Backhoe. Using this cost of $\sim \text{US\$540 ha}^{-1}$, it would cost US\$540,000 for initial manual clearing of, for example, 1000 ha, significantly more than has been spent on the biocontrol programme to date. However, we do assume that the cochineal will establish widely, and impact significantly, on *O. stricta* throughout the invaded range in Laikipia.

Discussion

This rapid preliminary and limited assessment has demonstrated that *D. opuntiae* 'stricta' biotype is having a significant impact on *O. stricta* populations in Laikipia, Kenya, resulting in a significant reduction in the number of cladodes, flowers and fruit. Impacts have been especially evident in and around rocky

Table 1 Impacts of the cochineal *Dactylopius opuntiae* 'stricta' biotype on *Opuntia stricta* as determined by measures of 150 plants in one site where the cochineal was present, and 75 plants where it was absent, in Laikipia County, Kenya

	Cochineal present (mean $\pm$ SE)	Cochineal absent (mean $\pm$ SE)	t-value	df	P
Plant height (m)	0.6 $\pm$ 0.0	1.0 $\pm$ 0.0	8.26	223	< 0.001
No. of cladodes	24.71 $\pm$ 2.3	117.1 $\pm$ 6.8	12.97	91	< 0.001
No. of flower buds	0.2 $\pm$ 0.1	1.3 $\pm$ 0.2	4.62	84	< 0.001
No. of flowers	0.01 $\pm$ 0.0	0.2 $\pm$ 0.1	2.72	78	0.008
No. of immature fruits	1.1 $\pm$ 0.3	20.4 $\pm$ 2.3	8.37	77	< 0.001
No. of mature fruits	0.6 $\pm$ 0.2	6.8 $\pm$ 0.9	6.65	78	< 0.001
Fruit length (mm)	32.0 $\pm$ 0.7	37.1 $\pm$ 0.9	4.43	96	< 0.001
Fruit breadth (mm)	25.2 $\pm$ 0.4	28.8 $\pm$ 0.5	6.14	94	< 0.001
Fruit weight (mg)	1120 $\pm$ 44.4	1658 $\pm$ 58.3	7.34	92	< 0.001
Fruit shell weight (mg)	800 $\pm$ 25.9	1170 $\pm$ 34.9	8.52	90	< 0.001
Seed weight (mg)	10.2 $\pm$ 0.7	11.4 $\pm$ 0.7	1.34	18	0.196
No. of seeds per fruit	31.7 $\pm$ 2.5	42.6 $\pm$ 2.8	2.94	97	0.004

Number of cladodes, flower buds, flowers, and immature and mature fruits are those within an area of 1 m² from the top of the plant, above the main stem, to ground level. Fifty fruits were sampled in each area

outcrops where heat retention by rocks and boulders appears to be contributing to their efficacy by significantly increasing their rates of development, but this remains pure conjecture at this stage. The number of cladodes was reduced by approximately 80% within a few years after release of the cochineal, if one assumes that the impact of the cochineal within the quadrat was similar to that outside of it. Plants in the site with cochineal had on average $\sim$ 25 cladodes (range 0–161), compared to plants in the site without cochineal which had $\sim$ 117 cladodes (range 14–239), in each sampled quadrat (1 $\times$ 1 m $\times$ plant height). Just over 62 (41%) plants in the site with cochineal had fewer than ten living cladodes. In fact, 19% of plants in transects with cochineal had no “living” cladodes within the sampled quadrat. These results are similar to those obtained in the Kruger National Park (KNP), South Africa, where the cochineal reduced the biomass of *O. stricta* by approximately 90% within six years after being released (Paterson et al. 2011). Impact after release in KNP was somewhat delayed compared to the situation in Laikipia. Heavy rains subsequent to its release in KNP may have delayed the impact by washing immobile females and nymphs from the host plant, causing populations to decline, and allowing plants to recover until the cochineal populations recovered to damaging levels once again (Moran

et al. 1987; Moran and Hoffmann 1987). Fluctuations in cochineal populations, especially during the establishment phase, can therefore largely be attributed to the frequency of high rainfall events. However, since 2002, the biomass of cactus in KNP has remained low, an indication that under high populations, heavy rains may have a negligible impact on the cochineal.

Opuntia fruit production in Laikipia was also significantly reduced with 79 and 81% of *O. stricta* plants in the site with cochineal having no immature or mature fruits within the sampled quadrat (1 $\times$ 1 m²) compared to the site without cochineal where only 13 and 24% of plants had no immature or mature fruits, respectively. Dyck (2017) also found significantly fewer fruits produced by *O. stricta* in Laikipia in 2016 (mean of 15 fruits per plant), two years after release, compared to 2014 (mean of 68 fruits per plant), when the cochineal was first released. Of interest it was found that one of the main dispersers of cactus seeds in Laikipia, olive baboons, appeared to select for cactus fruits, based on the fact that there was no concomitant reduction of seeds in baboon scats despite a reduction in fruit availability. According to J.H. Hoffmann (pers. comm.) very few fruits have also been produced by *O. stricta* in the research plots in KNP since 2001. This decline in fruit production has therefore reduced the long range dispersal potential of *O. stricta* in this protected area (Paterson et al. 2011), and probably also

in Laikipia. On average, the few fruits produced by *O. stricta* in the site with cochineal were also significantly smaller and had fewer seeds than those from the cochineal-free site. Seeds from plants with cochineal were also smaller. Studies, mainly on crop plants, have indicated that larger seeds tend to produce more vigorous seedlings, exhibit improved germination, and result in higher yields (Ambika et al. 2014). As such we assume that small *O. stricta* seeds may be less viable than seeds produced by plants without the cochineal.

Although it is only a preliminary assessment, based on limited data, indications are that there are significant benefits of using cochineal to control *O. stricta*, at least at a local level. Subsequent long-term studies over a wider area will need to be undertaken, resources permitting, to evaluate the impact of the cochineal at a landscape level, and will largely depend on a number of factors, including climate, especially rainfall. However, studies in South Africa are indicative of what could possibly be achieved. For example, without biocontrol, the area occupied by the invasive cactus *Opuntia aurantiaca* Lindl. in South Africa could have been 15 times greater than it is today (Zimmermann et al. 2004). The density and distribution of *O. ficus-indica* invasions in South Africa has been reduced by approximately 90% as a result of multiple biocontrol agents, including cochineal (Annecke and Moran 1978; Moran and Zimmermann 1991). Host specific, and damaging biocontrol agents, many of them cochineals (*Dactylopius* species), have contributed to 75% of the control of species in the family Cactaceae in South Africa (De Lange and van Wilgen 2010).

The cost-effectiveness of biological control, compared to other interventions, also needs to be highlighted to ensure the continued support for biocontrol by governments, donors and development agencies. The costs of introducing and releasing this cochineal in Kenya were significantly lower than the costs of initiating a biocontrol programme against a new target which can range from US\$100,000 to US\$500,000. To put this in perspective the prickly pear biocontrol programme in Australia, which targeted a number of cactus species, cost approximately AU\$18.1 million between 1919 and 1939, while a further AU\$3 million was spent between 1978 and 1987 (Page and Lacey 2006). In our case the agent *D. opuntiae* 'stricta' biotype had already been sourced in its native range,

tested and released by South African scientists, considerably reducing the costs of biocontrol of *O. stricta* in Kenya. In fact this is one of the main benefits of biocontrol in that benefits can be reaped by many stakeholders independent of their financial status and irrespective of whether they contributed to the initial research (Greathead 1995). There are a host of other effective biocontrol agents available for possible release against invasive plants in Kenya and elsewhere on the continent.

However, the true benefits of biocontrol are only really evident when compared to the costs of conventional weed control interventions. Chemical control can also be expensive but less than the costs of physical control. The Working for Water Programme in South Africa has estimated that it costs to clear (foliar spray/stem injection) condensed stands of young invasive cacti is US\$145 ha⁻¹. (6.38 person days ha⁻¹.) while clearing (cut and spray/stem injection) of condensed stands of adult invasive cacti are estimated to be US\$236 (10.37 person days ha⁻¹.) and US\$354 (15.56 person days ha⁻¹.) in rangeland and riparian zones, respectively (Neethling and Shuttleworth 2013). Clearing dense cactus stands over 1000 ha of rangelands would therefore cost in the region US\$236,000, still significantly more than the biocontrol programme in Kenya has cost to date. However, cognisance should be taken of the fact that manual and/or chemical control can result in complete eradication of stands, provided that regular follow-up activities are undertaken, whereas biocontrol does not result in eradication but is a tool which can significantly reduce the costs of these other interventions.

A reduction in the costs of other interventions is even more significant especially if one includes the non-target impacts of chemicals, and in some cases even that of physical control; negative impacts which are generally not included in cost-benefit analyses. For example, physical control can result in extensive damage to non-target species, and in the case of spiny cacti can cause injuries to those involved in clearing operations (Lindsey and Lindsey 1988; Goodheart and Huntley 2001; Dieter et al. 2017). Pesticides can have direct negative health impacts on, among others, people and livestock, natural enemies of crop pests, crop pollinators, and wildlife. According to Pimentel (2005) the major economic and environmental losses due to the application of pesticides in the USA are approximately US\$10 billion year⁻¹ and include

impacts on public health (US\$1.1 billion), pesticide resistance in pests (US\$1.5 billion), crop losses caused by pesticide misuse and overuse (US\$1.4 billion), bird losses of US\$2.2 billion, and groundwater contamination of US\$2.0 billion. The application of three million metric tons of pesticides around the world every year results in more than 26 million cases of non-fatal pesticide poisonings (Richter 2002). Of these, about three million cases require hospitalization with about 220,000 fatalities and about 750,000 chronic illnesses every year (Hart and Pimentel 2002). The benefits of biological control are therefore considerably greater when compared to physical and chemical control. This is especially more so in cases where the impacts of the cochineal result in the complete control of a target cactus species with no other interventions required.

It is still too early to confirm that the agent *D. opuntiae* 'stricta' biotype will contribute to the complete control of *O. stricta* in Laikipia and in so doing reduce the costs of other possible interventions. However, early indications do warrant the re-distribution of the agent to Tsavo East NP and the Serengeti-Mara ecosystem, which has some significant invasions of *O. stricta* (Witt and Luke 2017). A biotype of *D. opuntiae* for the control of *O. engelmannii* has also been sourced in the USA and will hopefully be released in Laikipia once approval from the regulatory authorities has been granted.

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