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Short title: Economic cost of managing weeds

Stakeholders perspective of the economic cost of managing the invasive Navua sedge in tropical Queensland, Australia

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Abstract

Weeds incur up to AUD $4 billion in economic loss annually to Australian agriculture. Despite this knowledge, there are few quantitative data on yield loss and control costs caused by weeds to the industry. Reported herein is the economic cost of managing the emerging, invasive Navua sedge weed to the grazing and cropping (sugarcane) industries of northern Queensland, Australia, following its introduction into the region in the 1970's. Between 2020-2022, through a survey questionnaire given to impacted stakeholders (farmers), information relating to control cost, yield loss, and infestation history were documented. Collated data were analyzed using mainly non-parametric statistics due to the skewed and/or qualitative nature of many of the responses. Invasion history of the weed on farming properties is relatively recent (time: 10-20 yrs), and infestation level, though majorly and currently of low-medium status (median value: 22.5%), varies appreciably amongst properties. Median cost of managing Navua sedge was AU $72.91/hectare (AU $82.06 present value). This cost nor the type of management tactics (chemical *vs.* integrated weed management [IWM]) did not vary between land use types; however, the labor (relative to chemical and machinery) component of the control cost was the greatest. The currently approved herbicide, halosulfuron-methyl (Sempra^{TM}), is largely ineffective in controlling the weed due to its inability to deplete below-ground tubers of the weed. Correlation analyses suggest control costs will continue to increase with increasing Navua sedge infestation over time, especially in grazing lands. Farmers show high awareness of the challenge of managing the new weed incursion. Farmers are using myriads of strategies, including willingness to impose strict biosecurity measures and IWM tactics while waiting for more effective herbicides and promising biocontrol agents to minimize the spread and impact of the weed.

Nomenclature: halosulfuron-methyl; Navua sedge, *Cyperus aromaticus* (Ridl.) Mattf. & Kük

Keywords: Biological-invasion, biosecurity-measure, control-cost, integrated-weed-management, herbicides, weed-impact, weed-spread

Introduction

Navua sedge, a native of equatorial Africa, the Seychelles, Mauritius, and Madagascar, is a monocot weed of a relatively recent incursion in the northern part of the State of Queensland (QLD), Australia (Osunkoya et al. 2021; Shi et al. 2021). Following its introduction into the region in the 70's, the weed experienced a relatively short lag time of ~ 23 years and thereafter became explosive in its spread and abundance (Osunkoya et al. 2021; Figure 1). Navua sedge has since become an aggressive weed, affecting the beef, dairy, and crop (especially sugarcane) industries in both coastal and upland parts of the QLD Wet tropics (see Shi et al. 2021). The weed is known to spread through both seeds and underground rhizomes into agricultural and natural landscapes, including riparian corridors and along roadsides and railway lines, and can form dense monospecific stands, often replacing palatable tropical pasture species of the region (Chadha et al. 2022a; Shi et al. 2022).

In the Cairns region of far north QLD, some sugarcane farmers, because of recurring reinfestation of certain blocks of their farms (in part due to the inability of the canes planted to strike nodes timely in a relatively high rainfall and soil wetness condition of the terrain- see Figure 2), switched to rice production. What the economic cost is and whether such a change in land use should be encouraged is an open-ended question. Despite the above trends and challenges, there are no data on the yield loss or control cost to the grazing and/or cropping industries caused by Navua sedge. This study fills this knowledge gap. The primary purpose of this report is to assess the perspective of affected stakeholders on the economic cost of weed management through quantifying control cost and property productivity loss. Such weed impact measures on agriculture are essential as northern QLD is a significant beef cattle producer - exporting more than 150,000 heads of cattle yearly (Beef Central 2017). The region is also the largest sugarcane producer (20.6 million tonnes yearly) in Australia (Australian Bureau of Statistics 2020).

Materials and Methods

In consultations with field biosecurity officers, research scientists within the Queensland Department of Agriculture and Fisheries (DAF), pest management officers of northern Queensland local governments, and impacted (graziers and cropping) farmers, we formulated a simple survey questionnaire comprising of 20 questions relating to Navua sedge weed management cost and tactics (Table 1). In early 2020, the questionnaires were screened through a series of iterations with local government pest management officers and DAF biosecurity field personnel before final approval by the DAF in-house ethics committee. The survey questionnaire was typically a mix of close- and open-ended questions bordering on property location and farmers' identity (names, property address, and farming type), invasion history of the weed on their properties, the proportional area impacted, and management tactics and cost, including property spelling (lock-up/withholding) duration and dollar cost (opportunity lost) following herbicide treatment, if applicable. The choice of survey respondents was specific, as only grazing and crop farmers with Navua sedge infestations on their properties were invited to undertake the survey. Medium of collection of responses involved physical (individual and group) interviews, telephone conversations, and online participation. Group interviews were undertaken during farmers' town hall meetings, during which survey questionnaires were provided to individual farmers and hence responses transcribed as individual responses. The respondent jurisdictions cover the main extent of the current spread (~ 600 km stretch) of the weed (Figure 1) - from Ingham in the south of the weed major distribution (North Queensland) through to Cooktown in the far north [FNQLD]) of the State and involved both upland (Atherton tablelands) and costal (Cairns to Daintree) farmers of the region. No financial incentives were offered to participating stakeholders. Collated data were analyzed using the SPSS-IBM statistical package ver. 27 using mainly non-parametric statistics due to skewed and/or qualitative nature of many of the responses. A series of Kruskal-Wallis non-parametric statistics were used to test for differences in level of infestations, spelling (withholding) period and control costs between land use types. Within and across land use types, non-parametric (spearman rank) correlation analyses were also carried out on relationships between control cost and infestation level.

All values reported are in Australian Dollars (AU $). The derived control cost gathered in 2020-2022 was integrated forward into present/future values (Costanza et al. 2014) using the expression:

$$\text{Future value} = \text{present value} * (1+\text{inflation rate})^{\wedge\,\text{number of years}} \quad \text{---- --------------------} \quad \text{(Equation 1)}$$

Results and Discussion

Survey respondents were mainly grazers (56%, N=22), cropping (sugarcane) farmers (28%, N=11), and stakeholders involved in both farming practices (mixture) also participated (15%, N=6) in the survey. Other crop farmers (banana and sweet potatoes) responded to the study, but their numbers were very low (one and two, respectively). Hence, their response dataset was

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excluded from further analyses. Following this exclusion, overall, the sample size was moderate (N=39), and confidence in stakeholders' responses was very high and consistent (mean $\pm$ SE: 80.8% $\pm$3.63). The recorded high confidence in the scoring and assessment by the stakeholders (minimum confidence of 70%, irrespective of land use type) suggests the high reliability of the information provided. Very few studies have included confidence measures in invasive alien species control cost (e.g., Osunkoya et al. 2019; Finger et al. 2023). The high confidence reported reflects the farmer's awareness of the problem, the level of proactiveness/preparedness rather than reactiveness to the challenge, and shows farmers have the competencies to manage the challenge (Campbell et al. 2023; Schrader et al. 2024). However, such assertions could have resulted from sampling bias as only impacted farmers were surveyed. In addition, more research is needed in this sector as the work reported herein did not require the assessor to justify their confidence score (Andreu et al 2009; Vanderhoeven et al. 2017).

Property size in hectare of the respondents varied somewhat, but not significantly (Kruskal-Wallis test, X^2_2 = 1.68; P = 0.43) between land use type (mixed farm [mean $\pm$ SE: 494.15 $\pm$ 184.35 ha.] $\geq$ grazing farm [294.71. $\pm$ 95.20 ha.] > sugarcane farm [143.30 $\pm$ 139.36] ha.). The history of awareness and spread of Navua sedge is recent on most stakeholder's properties (time since infestation, ~ 10 - 20 years ago; median:12.86 years) and did not vary between land use types. Consequently, the proportion of stakeholders' land infested by the weed is currently at a low-medium level (median value: 22.5%, range 0 - 100%; mean $\pm$ SE: 30.81% $\pm$ 7.38%). We noted that the distribution of property proportion infested appeared skewed: More than half of the respondents (26 out of 39) reported that the weed infested less than 20% of their properties, while three property owners reported extreme values (~ 100%). In general, infestation was of the following order: Grazing land $\geq$ mixed land use of grazing and cropping > cropping (sugarcane), but the large variation in infestation level within land use type results in only marginal significant differences (P = 0.056) between these land use types (Fig. 3).

Control tactics of mechanical/cultural methods, i.e. integrated weed management (IWM) and sole use of herbicide (chemical) are being employed in similar frequencies to curtail the growth, abundance and spread of the weed. These frequencies did not differ between land use type ($X^2_{2, 36}$ Fisher-Freeman exact test = 2.48: P = 0.19). Halosulfuron-methyl (Sempra™ with Banjo™ as the wetting agent) is the dominant postemergence (registered) herbicide being used, but farmers reported low success rate with this treatment; other infrequently cited (trial) chemicals were

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glyphosate (Roundup™), hexazinone (Velpar™), picloram and triclopyr (Access™), paraquat **(**Gramoxone™) and imazapic (Ranga™)**.** Thus, farmers reported use of both registered (e.g., Sempra™) and other experimental/trial herbicides (listed above) to manage the weed. Many farmers gave indications to have their formulation because, from their experience, the registered herbicide for Navua sedge (Sempra™) has not proven effective due to persistent below-ground rhizome following chemical treatment as well as large soil seed bank population of the weed, and hence high probability of reinfestation (see also Chadha et al. 2022b). Research is ongoing to develop other, more effective herbicides given this concern (Chauhan and Mahajan 2022; Fillols 2024; Florentine Singarayer, personal communication).

Along with varied herbicide usage, the type of IWM tactics also varied widely across farms, including rotational grazing, minimal tillage and disking, targeted spot-spray herbicide application using back-pack and quad bikes, replanting following herbicide treatment with desirable pastures of Humidicola [*Brachiaria humidicola* (Rendle) Schweickerdt], para grass [*Brachiaria mutica* (Forsskål) Stapf], and signal grass [*Urochloa decumbens* (Stapf) R.D. Webster], riparian corridor fencing, strict on-farm biosecurity protocols such as vehicle washdown, minimal/no slashing of nature strips where farm properties abut roadsides maintain by local government councils; the latter tactic (i.e., slashing) refers to the use of a tractor to cut grass and vegetation on roadsides to reduce the risk of fire and improve traffic safety.

Thus, in general, there was a considerable variation among respondents in the weed management strategies. Nonetheless, tabulation using frequency analysis indicated that at least 50% of the respondents used multiple approaches to control the weed, which often resulted in lower costs, especially of chemicals applied (Miller 2016). The use of mechanical/cultural methods for control (i.e., no slashing, limited tillage, rotational grazing, fencing, and imposition of strict biosecurity measure) are least harmful to the environment (Andreau et al. 2009; Miller 2016) and are proven management tactics that can help to slow down the spread of the weed while at the same time minimizing cost.

Though the focus of the work was on control cost, some respondents communicated the importance of prevention, identification of pathways of transmission/spread (e.g. via slashing of roadside infestations, flooding, and bird dispersal), restoration following the weed removal, and ethics - suggesting the needs to work across property boundaries and stakeholder land use types to achieve weed management objectives (Abeysinghe et al. 2024; Schrader et al. 2024).

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Overall, the annual median control cost per stakeholder was $11,630 (95% confidence interval [CI] range: $2,279- 35,609), translating to a median value per hectare of $72.91 (CI range:$33.87-103.97) after standardization by property size (Fig. 4a). The greatest component of control cost per year per hectare is in labor: (median: $34.88, CI range: $14.46 – 152.61) ≥ chemical usage (median: $14.00, CI range: $10.59-29.09) > machinery usage/maintenance (median: $11.61, CI range: $2.46– 34.20) (Figure 4a, b). Farmers in the grazing industry spend significantly more on labor in weed control than other land use types (Fig. 4b). Chemical and machinery usage/maintenance costs are the same across land use types. Labor cost was also the main driver of total control cost – increasing more linearly with increasing proportion of property infested by the weed (spearman rank $r = 0.50$, P = 0.01) than that between infestation level and chemical ($r = 0.46$, P = 0.02) or machinery cost ($r = 0.27$, P = 0.19). Labor cost being the most expensive is not new (see Yadav et al. 2003; Wenger et al. 2018; Ansong et al. 2021) and can be expected to increase even more with time in an industrialized economy like Australia where (minimum) wages are often high. Thus, there is a need to automate the labor component of control measures to reduce overall control costs (e.g., via the use of drones/remote sensing to map weed distribution at the farm and landscape scales) such that spot application of herbicide (and biocontrol in the future) delivery is more precise and less time consuming (see Costello et al. 2022).

Though non-significant due to large variation within land-use type, it appears that crop (sugarcane) farmers are spending less per hectare (median value: $54.66; CI range: 0.00-108.55) on control of Navua sedge compared to graziers (median value: $84.72; CI range: 58.86-139.31) (Figure 4b), even after adjusting for property size**.** Reasons for this possible difference are hard to deduce from this work, though factors such as level of awareness and belief that sugarcanes in planted areas grow taller and hence outcompete the weed in the long run, thus no need to expend cost on the challenge, or there are other well established weeds of higher priority affecting the industry (e.g., nut grass [*Cyperus rotundus* Linnaeus], kikuya grass [*Pennisetum clandestinum* (Hochst. ex Chiov.)], johnsongrass [*Sorghum halepense* (L.) Pers.], and sicklepod [*Senna obtusifolia* (Linnaeus) Irwin & Barneby]) (Ross & Fillols 2017). Another factor could also be that existing weed management practices also assist with control of Navua sedge. As a limited number of other crop (e.g., sweet potato, banana) farmers participated in the survey, investigation of control cost in varying land use types deserve more attention.

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In the grazing industry, the average spelling (withholding) time of the paddock (the period when grazing pressure is removed from a paddock to allow pasture plants to recover and replenish their root reserves) following chemical application to manage the weed was of the order 2-6 weeks (Fig 5a). Economic loss per hectare following spelling appeared negligible for the graziers (median: $13.25; CI range: $0-463.09), but this estimation has a very wide band (Fig. 5b). In contrast, the few sugarcane farmers (N=7) that spell their field blocks following chemical treatment do so for longer time (12-16 weeks), and consequently experience higher economic loss (median: $2,100.35 per ha.; CI range: $1,846.81-3,437.01 (Fig 5a, b). The finding of a longer spelling period and its attendant economic loss will suggest that Navua sedge invasion in cropping lands might have greater effect on yield than in the grazing environment (Figure 5), though such an assertion must be taken with caution as the sample size of sugarcane respondents (farmers) in terms of spelling period was low (N =7). The shorter spelling period (~ 4 weeks) by graziers for cattle following herbicide application to manage Navua sedge has been reported in previous work (Shi et al. 2021). However, more research is needed in this respect. Some stakeholders (graziers) listed no spelling but prefer shifting their animals around paddocks according to pasture growth rates. In general, past studies (e.g., MacLean 1958; McIvor 2012), suggested that longer spelling (> 6 weeks) following herbicide application should be discouraged due to the development of unwanted consequences, including increased competition from other undesirable plant species, i.e., simply eliminating the alien plant from an ecosystem may not always lead to restoration of the original community and sites can often be colonized by other alien species (Hulme and Bremner 2006).

We found moderate ($0.05 < P < 0.10$) or no significant relationship ($P > 0.05$) between control cost and infestation level or time at each land use type (Figure 6a), though it appears that the cost of control increases with increasing weed infestations, up to 40-60% for grazing land, and then decreases thereafter; for sugarcane and mixed farmlands, this threshold appears to be 20-25%. Nonetheless, pooled data suggest control cost increases with increasing Navua sedge weed infestation on properties (Fig. 6b). It should be noted that the estimation (via stakeholder's input) of property level of infestation is crude, as density (abundance per unit area) was not considered. This coarse scale of measure might have contributed to the weak link observed between infestation level or time (year) and many measures of Navua sedge weed control cost and ecology (see also Chandha et al. 2022a for a similar deduction). It is thus an area needing more

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work, including exploring changes in the soil seedbank and tuber density of the focal weed following control treatments as measures of management efficacy. Nonetheless, the increasing proportion of farms infested by the weed appeared to require more control inputs of labor and chemical, especially in grazing lands (Shackleton et al. 2015; Wenger et al. 2018; Yeneayehu et al. 2023).

In conclusion, through stakeholders' consultation, the median control cost for Navua sedge was \$72.91 ha^{-1}. This value, derived in 2020-2022, was integrated forward into present/future values using the expression in equation 1 in the Materials and Methods sections, resulting in control cost at today's value of \$82.06 ha^{-1}. These costs, when integrated backward, are like values reported at the Australian commonwealth and State levels for control of weeds in both cropping and grazing environments (see Sinden 2004; Llewellyn et al. 2016). The derived yield loss due to spelling for grazing land was low. Still, this median value of \$13.25 per hectare has a wide range (\$0- \$463) as some farmers do not spell at all (hence, they report no or minimal dollar cost to spelling) but instead rotate cattle between blocks, perhaps due to the large size of their properties and their willingness to impose strict biosecurity measures. Through elicitation, stakeholders' concern of the economic impact, spread pathways, and control options for the invasive Navua sedge were captured. Labor (compared to chemicals and machinery) appeared to be the more expensive component of control cost. Registered herbicide (Sempra™) for the weed has low efficacy (as below-ground tubers are often not destroyed nor seed bank affected). Consequently, while waiting for more effective chemical and promising biological control agent/s (see Dhileepan et al. 2022), many farmers seem to have developed strong biosecurity protocols and experimental management tactics as part of their short-term arsenals to minimize the spread of the weed.

Practical Implications

Weed impacts can be measured as the direct financial costs of control (herbicide, machinery use, or labor need, etc.), losses in production, changes in net financial benefits, and changes in welfare. In this study, through elicitation from impacted stakeholders (grazing and cropping farmers) via their response to a questionnaire, we addressed some of these issues for Navua sedge - a recent monocot weed spreading and impacting negatively both natural and agricultural landscapes of northern Queensland, Australia. The level of awareness of the spread and impact of the weed is very high (> 80%) amongst stakeholders with property infested by the weed.

Currently, most farmers reported a low-medium level of infestation on properties (~22.5%) but are fearful of the increasing spread of the weed with time and across multiple land-use types and jurisdictions. Farmers identified multiple pathways of transmission/spread and the need for cooperative work across property boundaries and stakeholder types to achieve weed management objectives. Control cost per unit area for Navua sedge did not vary significantly between land use types (though marginally higher in grazing lands) and is chiefly driven by labor demand and, to a limited extent, by chemical (herbicide) usage. However, farmers reported that the approved herbicide, Sempra™, is largely ineffective in controlling the weed due to its inability to deplete below-ground tubers and the seed bank population of the weed. To that extent, many farmers, while waiting for promising chemicals and biocontrol agents, have developed integrated weed management tactics of cultural/mechanical methods (i.e., minimal/no slashing of pasture weeds abutting their properties, limited farm tillage and herbicide usage, rotational grazing, riparian corridor fencing, replanting following herbicide treatment with desirable pastures and imposition of strict biosecurity measures such as washdown facilities to minimize the weed's impact and spread.

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Competing Interests

The authors declare none.

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Tables

Table 1: Survey questionnaire presented to impacted farmers in respect of Navua sedge infestation.

General

A: Please provide your name, address, and details of your farm property (e.g. Lot/Plan, property no.)

B: Please provide your phone contact, e-mail, and postal address

C: Can we contact you for further discission on impact and management of Navua sedge?

Area impacted and management tactics

1. How long have you farmed the property?
2. What is the total area farmed in hectares or acres (choose one)?
3. What is the nature of agriculture on your property (grazing, cropping, horticulture, organic etc)?
4. How long has your property (in years) been affected by Navua sedge?
5. What proportion (%) of your property is impacted by Navua sedge?
6. Do you control Navua sedge on your property?
7. What are the methods you use in control of Navua sedge on your property?
    a. Physical/mechanical: Please explain
    b. Chemical- Please explain
8. Do you use combinations of various management options (i.e., integrated weed management options, e.g., combinations of machinery rollers, rotational grazing, burning, sowing, replanting with competitive pasture grass, chemical etc)?
    Please explain:

Control cost

How much do you spend controlling Navua sedge on your property:

9. In labour (hours and estimated $) (yearly or monthly)?
10. In chemical ($) (yearly or monthly)?
11. In machinery ($ (yearly or monthly)?

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12. Following chemical treatment of Navua sedge on your farm, do you lock up (spell) whole or part of the farm?
13. If yes to Question 12, how long is your pasture spelling period?
14. How much do you lose ($/annum) by spelling the paddock?
15. Overall, how confident are you in your assessment of costs (on a scale between 100% being accurate and 0% being inaccurate)?

Epilogue

16: Any other (additional) comments you would like to make?

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Figures

1500 Km

Figure 1: Spatial extent of distribution of the invasive Navua sedge in Australia (dots are current and confirmed extent of the weed in the State of Queensland and neighboring oceanic island nations). Spatial map generated from Atlas of Living Australia (https://www.ala.org.au/)

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Figure 2: An abandoned block of a flooded sugarcane farm overran by Navua sedge infestation in Cairns, Far North Queensland, Australia.

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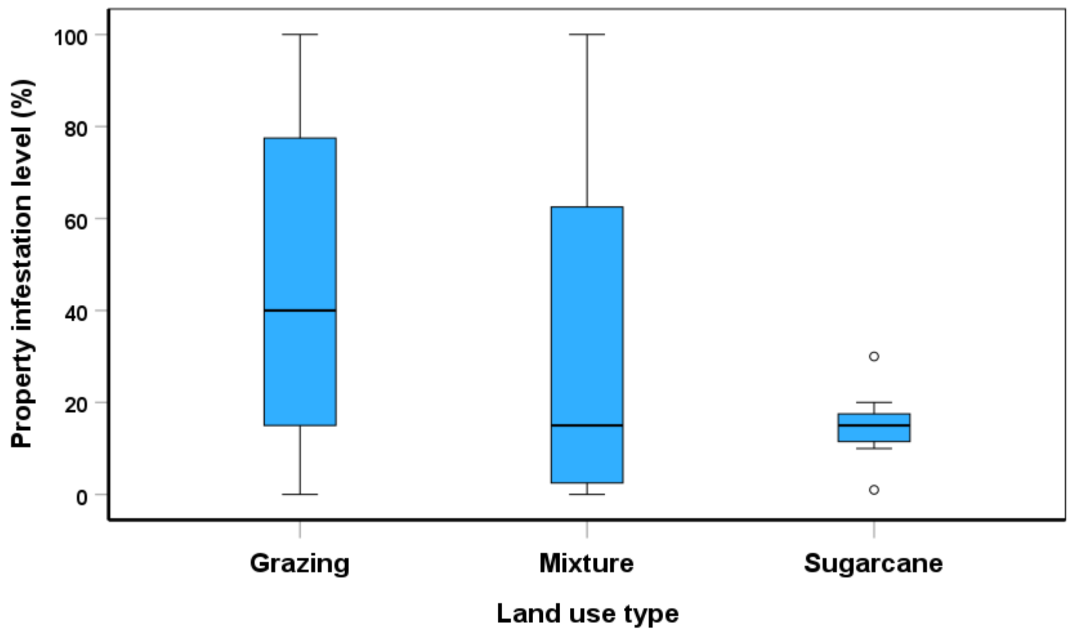

Figure 3: Box plot indicating proportion of properties of Australia farmers in northern Queensland infested by Navua sedge weed as a function of land use type. Mixture refers to properties that are engaged in both grazing (cattle) and sugarcane production. The median values between land use type are only marginally significantly different (P = 0.056) based on Kruskal-Wallis non-parametric test.

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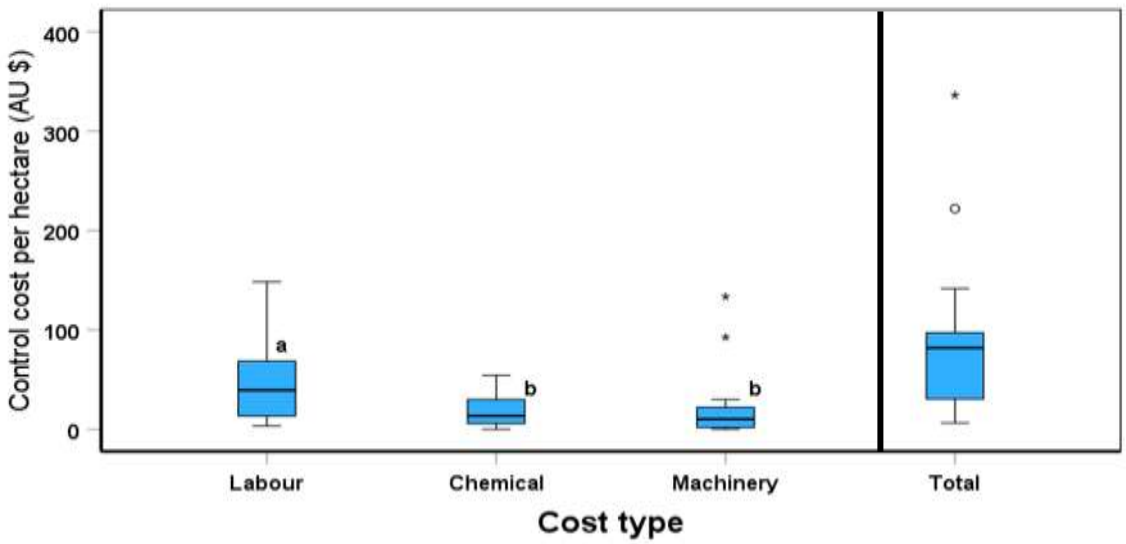
A



B

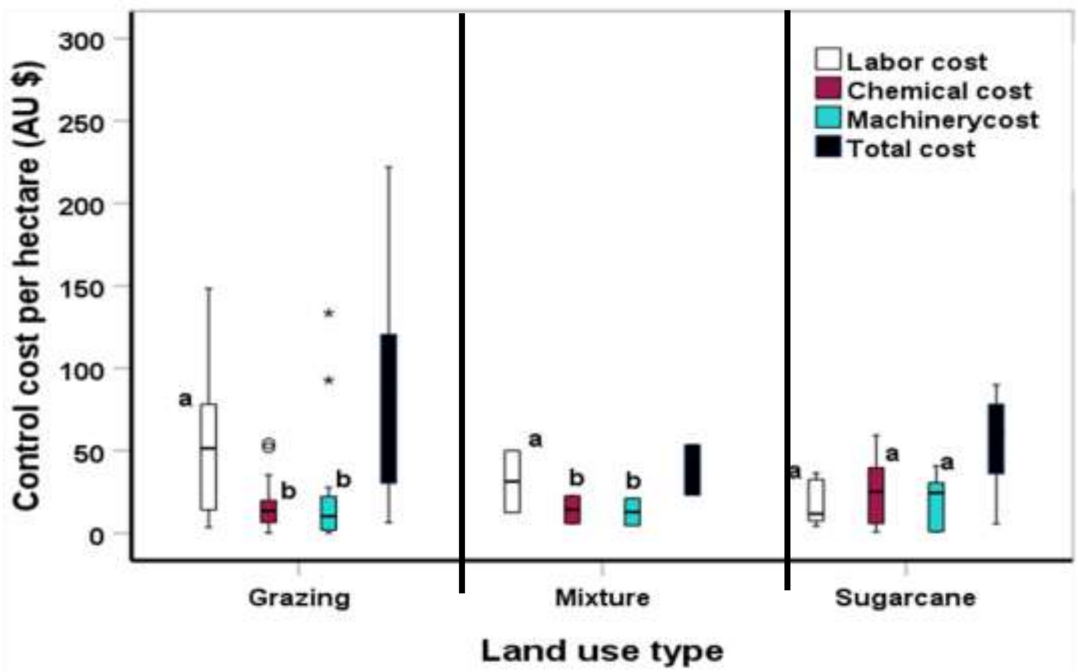


Figure 4: Box plots of three components of annual control cost of Navua sedge weed infestation, with data pooled across land use type (A), and data for each land use type (B). Median values (A: between control cost type; B: within land use type) that are significantly different (P <0.05) are indicated by different letters on the plots based on Kruskal-Wallis non-parametric test.

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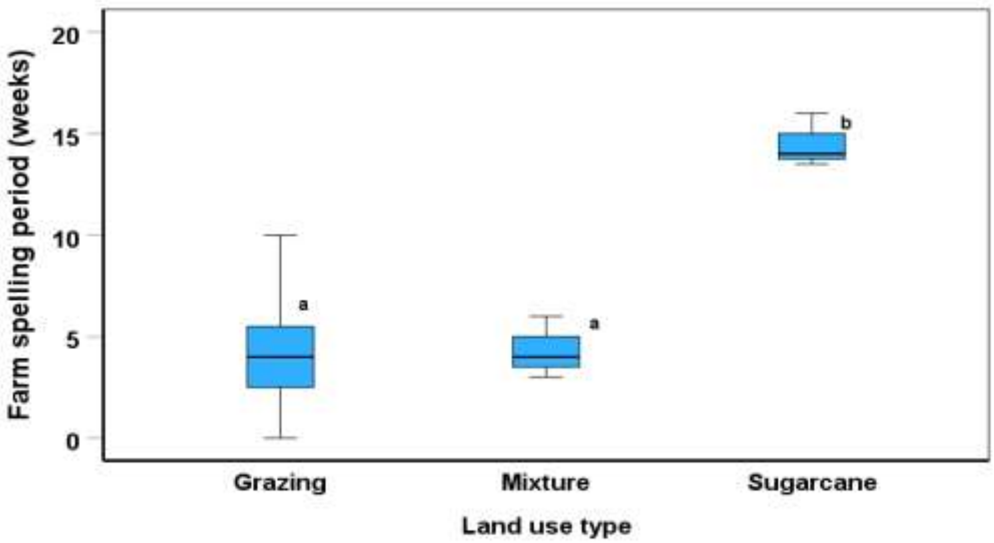
A



B

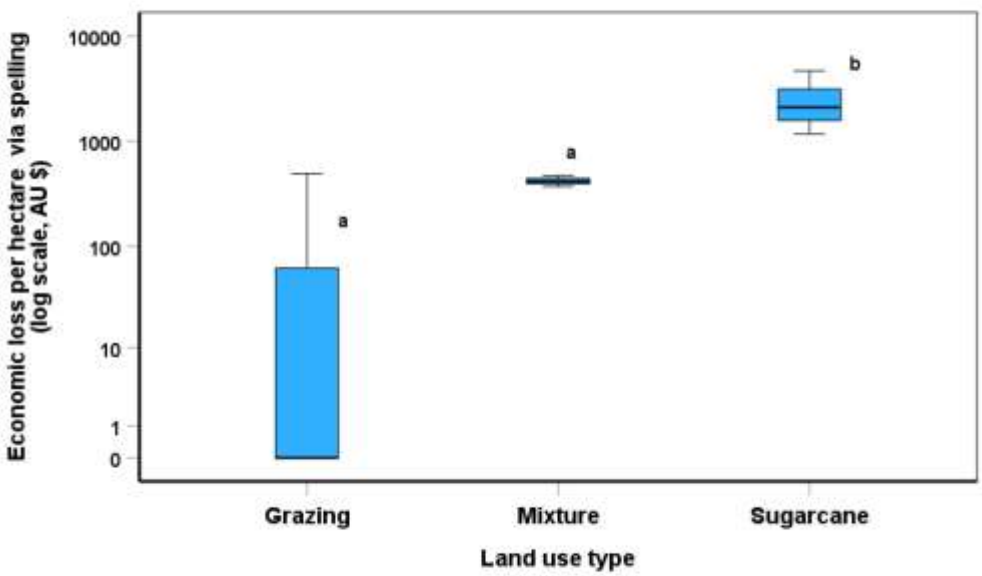


Figure 5: Box plots of property spelling (withholding) period (A), and productivity loss (log scale) by land use type (B) following herbicide treatment of Navua sedge weed infestation. Median values that are significantly different (P < 0.05) are indicated by different letters on the plots based on Kruskal-Wallis non-parametric test.

A

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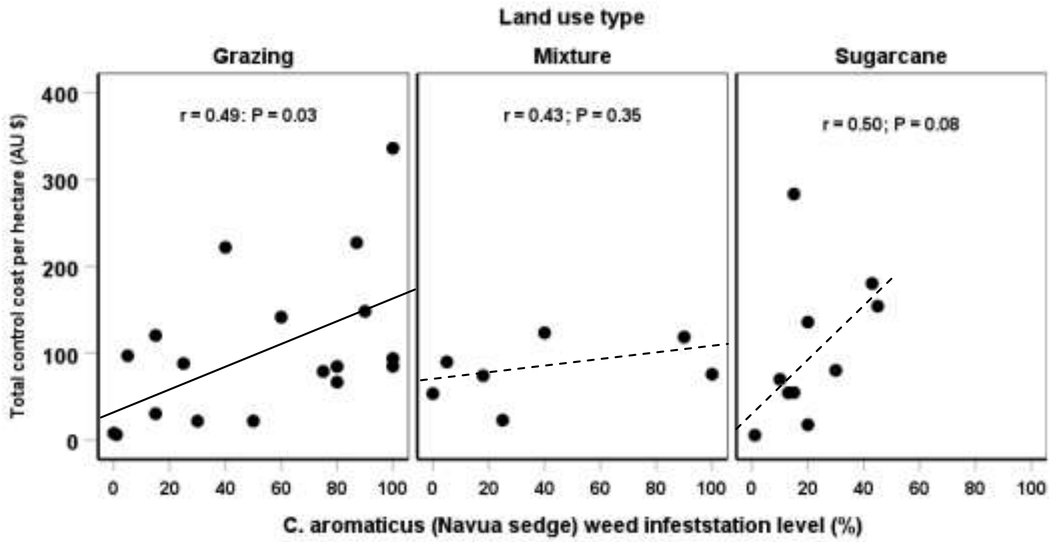

B

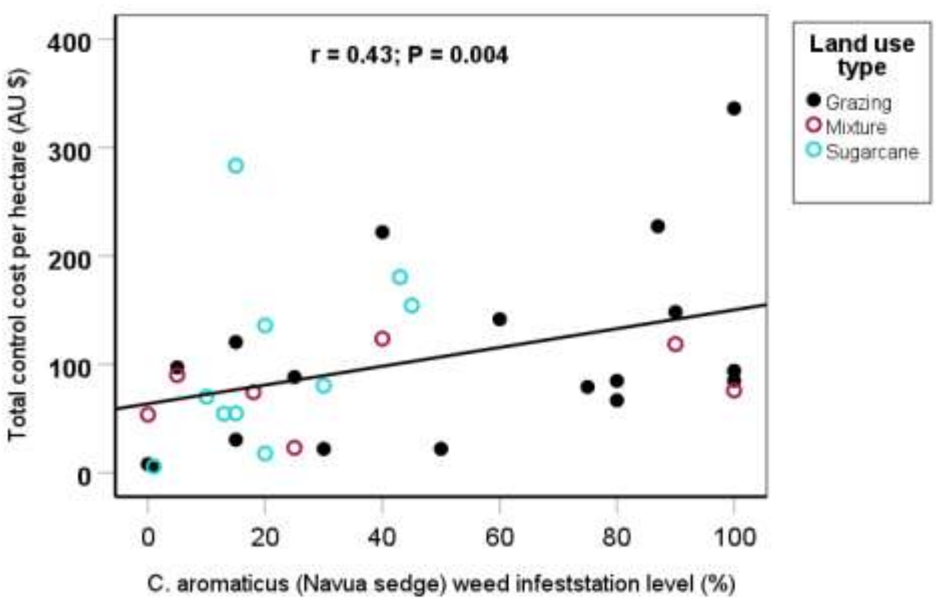

Figure 6: Total (annual) control cost (in AU $) of Navua sedge weed infestation as a function of the fraction of individual northern Queensland property infested for each of the three land-use types (A) and for pooled data (B). Significant (P < 0.05) regression lines are in bold continuous lines, while non-significant trends are in broken lines; *r*= non-parametric (spearman rank) correlation value.

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