

Assessing the threat of invasive plant species in the Wet Tropics World Heritage Area in Queensland, Australia

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Research Article

Keywords: Non-native plants, Protected areas, Environmental weeds, Biodiversity values, Invasive alien species

Posted Date: April 3rd, 2023

DOI: <https://doi.org/10.21203/rs.3.rs-2690274/v1>

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Version of Record: A version of this preprint was published at Biological Invasions on February 14th, 2024. See the published version at <https://doi.org/10.1007/s10530-024-03260-2>.

Abstract

Invasive species, climate change and the negative impacts of tourism are currently and globally recognised as the three most significant threats to Outstanding Universal Values of natural World Heritage listed areas. This study investigated the threat of incursion of invasive plant species associated with access roads in the Wet Tropics World Heritage Area in Queensland, Australia. We assessed richness, composition, and the spread of invasive plant species along roads and in the adjacent vegetation using 34 transects established in 2015 and remeasured in 2021. Species and foliage cover of all ground-layer plants were recorded. Thirty-one invasive species were recorded, and their richness was found to be significantly higher at the road edge (27 species) than in the adjacent vegetation (16 species). While invasive species richness decreased with distance from the road edge, their foliage cover did not show a consistent trend. Foliage cover for more than 73% of the recorded invasive species at the road edge was < 5%. Invasive species with the highest foliage cover were signal grass (*Urochloa decumbens*) with 65% at the road edge, and Parramatta grass (*Sporobolus fertilis*) in the adjacent vegetation with 64% foliage cover. The abundance of invasive species and the potential for a small set to dominate the road edge and spread into the adjoining environment, highlights the importance of timely surveillance and targeted control of invasive species at road edges to ensure that they do not spread to the adjacent vegetation.

Introduction

In 2013, the Wet Tropics World Heritage Area (WTWHA) of Queensland, Australia was ranked as the second most irreplaceable natural World Heritage site currently included on the World Heritage List based on its biodiversity values (Bertzky et al. 2013). The WTWHA was inscribed in the World Heritage List in 1988 because of Outstanding Universal Value having met all four natural heritage criteria: 1) represents a major stage of the earth's evolutionary history; 2) is an outstanding example of ongoing ecological and biological processes; 3) contains superlative natural phenomena; and 4) contains the most important natural habitats for conservation of biological diversity (DASSET 1986). The WTWHA encompasses 894,420 hectares of mostly tropical rainforest (UNESCO 2022a) and protects more than 3,300 species of plants and more than 700 species of vertebrate animals (QPWS 2021a).

The Wet Tropics World Heritage area in Queensland is protected by a legislative framework, a dedicated and well supported independent Management Authority and a comprehensive suite of management strategies (QPWS 2013a, 2015; IUCN 2020a). However, in the 2020 World Heritage Outlook Assessment, its Conservation Outlook was rated as of "Significant Concern" and the Overall Threats was rated as "Very High Threat" (IUCN 2020a). This rating was based on the threats posed by invasive plants, pest animals and diseases, climate change and tourism to the continuing integrity of biodiversity values (IUCN 2020a). Although these are common threats to many protected areas, they are difficult and costly to manage (Foxcroft et al. 2013). Hence, research and monitoring are required to better understand the current state and extent of threats, and how to effectively mitigate them (Foxcroft et al. 2010, 2013). A one-off weed survey along selected transport corridors in the WTWHA which aimed to provide understanding of their distribution and ecological conditions was reported in 2006 (Goosem and Turton

2006). The inventory reported major weed infestations along some powerline and road networks in the case study area and demonstrated the vulnerability of WTWHA to weed infestation following anthropogenic disturbances (Goosem and Turton 2006).

Geographical distance, isolation, and remoteness of conservation areas with high biodiversity values have in the past helped to reduce the threat of anthropogenic disturbance (Ngugi and Neldner 2017; Liedtke et al. 2020). However, road and trail networks within conservation areas are fundamental in providing access for the purposes of recreational use, fire control and routine resource management (Ngugi et al. 2014). Unfortunately, the disturbance associated with road and trail construction and maintenance provide the opportunity and conducive environment for the establishment of invasive species (Goosem and Turton 2006; Kudo et al. 2014; Le et al. 2018; Liedtke et al. 2020; Hogan et al. 2022). In addition, their utilisation by vehicles, cyclists, horses and their riders, motorbikes and walkers, increases their risk of exposure to invasive plant species propagules, and becoming conduits for further encroachment of invasive species into protected areas (Potito and Beatty 2005; Ansong and Pickering 2013; Ngugi et al. 2014; Liedtke et al. 2020; Aththanayaka et al. 2022; Hogan et al. 2022).

Prevention of new incursions of invasive species into conservation areas is the most effective management action to avoid the impact of invasive plant species (United Nations 1992). But with multiple potential dispersal mechanisms including humans, birds and animals, wind, and water, it is impossible to timely detect and eradicate all new incursions of invasive species (Ngugi and Neldner 2017; McDougall et al. 2018; Keet et al. 2022). In Queensland, the Wet Tropics Conservation Strategy (2004) outlines strategic approach to weed control within the Wet Tropics conservation area (Wet Tropics Management Authority 2004). The strategy includes prevention of introduction of new invasive weeds, eradication of new and localised outbreaks (with priority given to pristine areas rather than to disturbed areas), incorporation of long-term monitoring and rehabilitation, community participation and research. Although resources have been put into weed management within the WTWHA, more research is needed to help guide decisions on invasive species containment and eradication strategies and control priorities (Carmody et al. 2015). It is known that cleared transport and infrastructure corridors are often conduits for invasive species encroachment to conservation areas (Goosem and Turton 2006), but little is known about the infestation dynamics of these species from their point of entry, their likelihood of incursion into the adjacent vegetation over time, and how to best target control actions.

The aim of this study is to demonstrate how a consistent long-term monitoring program can provide the opportunity for early detection and intervention, enabling effective eradication and development of threat mitigation policies, in addition to other tools that are currently used by the managing authority (Goosem and Turton 2006). By design, the monitoring program should investigate, document, and quantify the current state of invasive species as a baseline, monitor new incursions and spread, and the potential risk of invasive species dominance over native species.

This study established a monitoring program to collect baseline data on the state (richness and species composition) of invasive plant species and changes over time. It was conducted along access roads that

traverse two conservation areas: Danbulla National Park and the Herberton Range Conservation Park within the Wet Tropics World Heritage Area in Queensland. The study focused on repeat assessments of ground vegetation found along forest roads and into the adjacent forests. The roads traversed regional ecosystems (REs, which are vegetation communities in a bioregion that are consistently associated with a particular combination of geology, landform and soil (Sattler and Williams 1999)) within the high-elevation wet tropical vegetation communities. These regional ecosystems included complex mesophyll and notophyll vine forests, tall open eucalypt woodlands, and open woodland to open forest on uplands dry rainfall zone (Queensland Herbarium 2021a). The main hypotheses tested were (1) that forest road edges have the highest richness of invasive plant species; (2) that the richness of invasive species decreases with increased distance from road edges; (3) that eucalypt open forests and woodlands are more susceptible to invasive species incursion than rainforests; and (4) that richness and composition of invasive species increase over time with road use and maintenance, and disturbance events.

Materials And Methods

Study location

This study was conducted along forest roads located in the Danbulla National Park and Herberton Range Conservation Park in the Wet Tropics World Heritage Area in Queensland (Fig. 1, Table S1). Danbulla NP is adjacent to Lake Tinaroo, approximately 50 km south-west of Cairns on the Atherton Tableland in the country of the Yidinji indigenous people in north Queensland. It covers an area of 8,133 ha, rises from 700–1261 m above sea level and features high-elevation rainforests on mountainous terrain, with Mount Edith and Mount Haig as distinctive features (QPWS 2013a). The Herberton Range Conservation Park is located near the town of Wondecla which is 104 km south-west of Cairns, and 918 m above sea level on the Great Dividing Range (QPWS 2015). The climate for the region is tropical, with generally hot and humid summers and milder dryer winters. The majority of rainfall in the area occurs during summer between January and March. The average annual rainfall ranges from 1155 mm at Herberton Range to 1308 mm in Danbulla NP and total rainfall for the four months preceding the field survey at each of the two sites exceeded 500 mm. The mean maximum monthly temperatures ranges from 18 °C to 31 °C (BOM 2022).

Vegetation types

The Wet Tropics World Heritage Area is renowned for its rainforests, however it also supports numerous other vegetation communities (Queensland Herbarium 2021a). The forest roads at Danbulla NP (Table S1) mainly traverse granitic substrates (Land Zone 12) and a diverse array of vegetation communities including simple notophyll vine forest on wet and moist uplands (RE 7.12.16a), complex mesophyll vine forest of high rainfall and cloudy uplands on alluvial soils (RE 7.3.36a), tall open eucalypt forests to tall woodland in the uplands of the cloudy wet to moist rainfall zones (RE 7.12.22a), and medium open forest and woodland in uplands and highlands of the moist rainfall zone (RE 7.12.27a) (Queensland Herbarium 2021a). In the Herberton range the road traverses *Eucalyptus tereticornis* open forest to tall open forest

and woodland on foothills (RE 7.12.61a), tall open forest to tall woodland in the uplands of the cloudy wet to moist rainfall zones (RE 7.12.22a), and woodland to open forest in the uplands dry rainfall zone (RE 7.12.34) (Queensland Herbarium 2021a).

Site selection and Sampling

Sampling sites were located along the main access road at each of the Parks (Table S1). Protected area maps for Danbulla NP and for Herberton Range Conservation Park were overlaid with forest roads and the regional ecosystem mapping layer. Vegetation monitoring sites were distributed along the major access road to sample the intersected regional ecosystems at one or several points along the road network, depending on the extent of the RE (Table S1). Permanent survey sites were established in May 2015 and remeasured in May 2021. Ground layer vegetation growing along the road edge and in forests adjacent to the roads was sampled using a 25 m long transect laid out perpendicular to the road and starting at the edge of road. This sampling design is very similar to that used by Roover *et al.* (2004), Potito and Beatty (2005), Gower (2008) and Ngugi *et al.* (2014). The start and end of each transect was marked with a steel picket. Two transects were laid at each site to sample vegetation on both sides of the road.

Twelve sites and 24 transects were sampled in Danbulla NP, and five sites and ten transects at Herberton Conservation Park (Fig. 1, Table 1). The road edge was defined as the shoulder edge of the road surface where vegetation growth is evident and from which point vegetation cover continues into the adjacent vegetation. Along each transect a total of 9 quadrats were sampled to estimate distribution of invasive plant species and to accurately determine the distance of influence from the road edge. At the start of each transect, five contiguous 1 x 1 m quadrats extending from the road edge to 5 m into the forest were sampled (road edge zone, 0 to 5 m from road edge). Four more 1 x 1 m quadrats were sampled, with a quadrat located at 10 m, 15 m, 20 m and 25 m along the transect line within the adjacent vegetation (adjacent vegetation zone, 5 to 25 m distance from the road edge). In each 1 x 1 m quadrat, all plant species, and the foliage projective cover (FPC) of each ground layer species (< 1.5 m in height) were recorded. Cover was also estimated for leaf litter, bare-ground and coarse woody debris (> 10 cm diameter) as a percentage of the total area in each quadrat (1 m²).

Table 1

Details of vegetation sampling in two World Heritage areas in north Queensland including Regional Ecosystems, number of transects and quadrats (in parenthesis), and the recorded invasive species with cover > 10%

Protected area	Regional Ecosystem	Transects and quadrats	Species with > 10% cover
Danbulla National Park (DNP)	RE 7.3.36a complex mesophyll vine forest of high rainfall and cloudy uplands on alluvium soils	3 (27) DNP1-3	<i>Oxalis corniculata</i> <i>Polygala paniculata</i> <i>Spermacoce exilis</i>
	RE 7.12.16a simple notophyll vine forest on wet and moist uplands, granite and rhyolite	4 (36) DNP4&5,11&12	<i>Axonopus fissifolius</i> , <i>Dichrocephala integrifolia</i>
	RE 7.12.22a <i>Eucalyptus resinifera</i> , <i>E. acmenoides</i> , <i>Corymbia intermedia</i> , <i>E. cloeziana</i> , <i>Syncarpia glomulifera</i> tall open forest to tall woodland on the uplands and highlands of the moist rainfall zone on granite and rhyolite	3 (27) DNP6-8	<i>Sporobolus fertilis</i> <i>Ageratum houstonianum</i> <i>Crassocephalum crepidioides</i> <i>Lantana camara</i>
	RE 7.12.27a <i>Eucalyptus reducta</i> medium open forest and woodland on uplands and highlands of the moist rainfall zone on shallow granitic and rhyolitic soils	2 (18) DNP&10	<i>Digitaria violascens</i> <i>Bidens pilosa</i> <i>Sporobolus fertilis</i>
Herberton Range (HR)	RE 7.12.22a <i>Eucalyptus resinifera</i> , <i>E. acmenoides</i> , <i>Corymbia intermedia</i> , <i>E. cloeziana</i> , <i>Syncarpia glomulifera</i> tall open forest to tall woodland on the uplands of the cloudy wet to moist rainfall zones on granite and rhyolite	2 (18) HR4	<i>Sporobolus fertilis</i>
	RE 7.12.34 <i>Eucalyptus portuensis</i> , <i>E. drepanophylla</i> , <i>C. intermedia</i> , <i>C. citriodora</i> , <i>E. granitica</i> open woodland to open forest on uplands dry rainfall zone on granite	6 (54) HR1,2,5	<i>Ageratum houstonianum</i> <i>Urochloa decumbens</i> <i>Stachytarpheta jamaicensis</i> <i>Lantana camara</i> <i>Ageratum houstonianum</i>

Protected area	Regional Ecosystem	Transects and quadrats	Species with > 10% cover
	RE 7.12.61a <i>Eucalyptus tereticornis</i> open forest to tall open forest and woodland on foothills and uplands of the moist and dry rainfall zones on granite and rhyolite	2(18) HR3	<i>Urochloa decumbens</i> <i>Ageratum houstonianum</i>

Plant species identification and categorisation

All herbaceous and woody vascular species observed within each plot were identified to species in the field where possible. As necessary, specimens were collected and brought to the Queensland Herbarium for identification. If the available material was insufficient to identify species, identity was recorded at genus level. Nomenclature, and naturalisation status follows the Census of Queensland Flora (CQF) 2021 (Brown 2021).. Classification of species as environmental weeds, weeds of national significance and/or declared weeds under State legislation was done using the *Biosecurity Act 2014* (Biosecurity Qld 2014) and the online facility maintained by the Queensland Department of Agriculture, Fisheries and Forestry (Department of Agriculture and Fisheries 2016).

Disturbance events

Fire is an integral perturbation of eucalypt forests and woodland communities in Australia (Gill 1997). The management of fire in these vegetation communities is guided by the principles contained in Planned Burn Guidelines – Wet Tropics Bioregion of Queensland (QPWS 2013b) in conjunction with the regional ecosystem fire guidelines (Queensland Herbarium 2021b). Fire events data between 2015 and 2021 were obtained from QPWS fire database FLAME (QPWS 2021b). Fifteen of the monitoring sites had at least one fire event during that period (Table S2).

Periodic road maintenance is essential to allow the safe use of these roads, by management staff and by the public where access is permitted. Most of the forest roads sampled in Danbulla NP are kept locked to the public for management or safety purposes. Following severe weather events just prior to the 2021 field survey, the rainforest section of the Mt Edith road in Danbulla NP had been subject to road maintenance including grading of the surface, and road edges, and covering with gravel brought in from outside the park. This meant the vegetation cover in the first four road edge quadrats for transects DNP1 to DNP4 was low or absent due to mechanical disturbance. Future monitoring will focus on observation of weeds emerging due to this essential road maintenance.

Data Analysis

Statistical data analyses were undertaken using Analysis ToolPak which is an add-in application for Microsoft Excel (Halpern et al. 2018). in Preliminary model fitting used different model forms (exponential, logarithmic, power function, polynomial and linear) to determine the general relationship between species richness and total cover and various distances from the road edge to the adjacent

vegetation. Fitted models for the combined dataset were compared using the coefficient of determination (r^2) and the model that had the highest r^2 was selected. Two-sample t-tests were used to compare the species richness of invasive species between the 2015 and 2021 surveys. Analysis of variance (ANOVA) was used to evaluate differences in invasive species richness among the regional ecosystems. To mitigate pseudo replication associated with the use of contiguous plots at the road edge, five 1 x 1 m quadrats located within the 5 m of the road edge were aggregated into a 5 x 1 m quadrat during analysis of variance of invasive species richness and comparisons between road edge and adjacent transects (Ngugi et al. 2014).

The Jaccard similarity index was used to assess community composition between the dataset collected in 2015 and in 2021. Using this index, the list of invasive species recorded in the two datasets were compared to see which species were recorded during both measure dates and which are distinct. The index was expressed on percent scale (Stephanie 2022).

Results

Current state of species richness along forest roads

A total of 206 species were recorded in 306 quadrats along access road edges and in adjacent vegetation in the two study locations. Of these plants, 175 species were natives (85%) and 31 species were invasive (15%) species. In Danbulla NP, 132 native plant species (84%) and 26 invasive (16%) plant species were recorded, whereas in the Herberton Range Conservation Park, 110 native plants (85%) and 19 invasive plant (15%) species were recorded. Overall, invasive species were recorded in 154 of the measured quadrats (approx. 50%), and out of these, 42% of the quadrats were in Danbulla NP and 58% were in the Herberton Range Conservation Park. Invasive species were only absent in ten of the transects and on three of the sites (Fig. 2).

Invasive species richness at road edge versus adjacent vegetation

Invasive species richness recorded in 2015 within the road edge (mean = 1.8 species) was higher and significantly different from that recorded in the adjacent vegetation (mean = 0.8 species) ($t(34) = 3.284$, $P = 0.001$). A similar comparison for data collected in 2021 also showed significantly higher richness of invasive species at the road edge (mean = 1.4 species) compared to the adjacent vegetation (mean = 0.8 species) ($t(34) = 2.264$, $P = 0.015$). In total, 27 invasive species were recorded along the road edge in all sites and 16 species were recorded in the adjacent vegetation. Eleven of the species were observed at both the edge of the road and in the adjacent vegetation while five species were recorded in the adjacent forest but not at the edge of the road (Table S3).

Vegetation cover of invasive species at the edge transect (mean = 5.4%) was significantly higher than in the adjacent forest zone (mean = 1.0%) in the 2015 dataset ($t(33) = 1.880$, $P = 0.034$), but no statistically significant difference was obtained between the two zones in the 2021 dataset ($t(33) = 0.227$, $P = 0.411$).

The richness of invasive species recorded in both 2015 and 2021 among sampled regional ecosystems indicated considerable variability as shown in Fig. 2. The highest number of invasive species observed in a transect in a single sampling event was 10 species in RE 7.12.27a, 10 species in RE 7.12.34, eight species in RE 7.3.36a and eight species in RE 7.12.22a. A comparison among REs showed significant differences in invasive species richness recorded over the monitoring events ($F(5, 28) = [5.019]$, $P = 0.002$), but the differences among the sclerophyll forest REs (7.12.22a, 7.12.27a, 7.12.34 and 7.12.61a) was not significant ($F(3, 16) = [2.901]$, $P = 0.067$). This suggested a difference in invasive species richness between rainforest sites and sclerophyll forests. The list of invasive species recorded in each RE are provided in supplementary Table S4. Although many of the species were recorded in several REs, 42% of the species (13 taxa) were recorded in only one RE, but on average, 14 invasive species were recorded in each sclerophyll REs and six species in the rainforest REs (Table S4).

Trend of invasive species incursion and spread to adjacent forest

Using a combined dataset for species observed in 2015 and 2021, a strong negative correlation (-0.908) between invasive species richness and distance along the assessment transect (0 to 25 m) was observed. This relationship fitted a regression line with $r^2 = 0.87$ and $p < 0.0002$ (Fig. 3a). The number of invasive species was highest at the road edge and decreased with increasing distance from the edge into the adjacent native vegetation as shown in Fig. 3a. The average cover of invasive species along the transect did not show a similar consistent trend with an increase in distance from the road edge to the adjacent forest (Fig. 3b). The FPC of most of the recorded invasive species (73%) at the road edge was below 5%, and only 16% of the species had a cover of $> 10\%$. In the zone adjacent to the road edge, 65% of the invasive species had a cover of $< 5\%$ and the remaining 35% of the species had a cover of $> 10\%$.

Invasive species with the highest FPC are presented in Table S5. Within the 0–5 m road edge zone in the Danbulla NP, these were *Axonopus fissifolius* (20%) and *Dichrocephala integrifolia* (20%), and in the Herberton Range Conservation Park, it was *Urochloa decumbens* (65%). Invasive species with the highest cover in the 5–25 m zone from the road edge, were *Sporobolus fertilis* (64%) in Danbulla NP, and *Urochloa decumbens* (12%) in the Herberton Range Conservation Park in sclerophyll forest REs. The recorded covers for other species with cover greater than 10% are presented in Table S5. The species with the highest overall cover were *Urochloa decumbens* recorded in RE 7.12.27a, 7.12.34, 7.12.61a and 7.3.36a, *Sporobolus fertilis* in RE 7.12.22a, 7.12.27a and 7.12.61a, *Ageratum houstonianum* in RE 7.12.22a, 7.12.34, 7.12.61a and 7.3.36a, *Oxalis corniculata* in RE 7.12.22a, 7.12.34, 7.12.61a and 7.3.36a, *Lantana camara* in RE 7.12.22a, 7.12.34 and 7.12.61a, and *Stachytarpheta jamaicensis* in 7.12.22a, 7.12.27a, 7.12.34 (Table S4).

Invasive species in rainforest verses eucalypt forests

Invasive species richness recorded in 2015 along the road edge in the rainforest ecosystems (mean = 0.8 species) was significantly lower than that recorded in the eucalypt forest (mean = 2.5 species) ecosystems ($F(1, 32) = [6.178]$, $P = 0.018$). Similarly, invasive species richness recorded in the adjacent

vegetation in rainforest ecosystems (mean = 0) was significantly lower than that recorded in eucalypt forest ecosystems (mean = 1.4 species) ($F(1,32) = [13.901], P = 0.0007$).

Although the average FPC of invasive species recorded in 2015 at the road edge in sclerophyll forest sites (mean = 8.3%) was higher than that of rainforest sites (mean = 1.5%), the difference between them were not statistically significant ($F(1,32) = [2.004], P = 0.166$). This result was associated with a large variation of FPC recorded among the sclerophyll forest sites (SD = 17.5%) and that recorded in rainforest sites (SD = 4.8%). When invasive FPC in the adjacent forests to the road was compared, the mean FPC (1.7%) in sclerophyll forests was higher than in rainforest sites, where no invasive cover was recorded, but because of large variation of FPC among the sclerophyll forest sites (SD = 3.1%), the difference was not statistically significant ($F(1,32) = [4.110], P = 0.051$).

Invasive species changes over time

Over time and based on data from all sites, there was no significant difference in species richness between the 2015 (mean = 2.4 species) and 2021 (mean = 2.0 species) datasets ($t(33) = 1.063, P = 0.148$). Although no significant difference in FPC between 2015 and 2021 ($t(33) = -0.471, P = 0.320$) was obtained, several of the invasive species showed great increase in FPC between the two measuring events. In sclerophyll forests, there were increases for *Sporobolus fertilis* (an increase of 86%), *Praxelis clematidea* (85.7%), *Spermacoce remota* (66.7%), *Richardia brasiliensis* (57.1%) and *Bidens pilosa* (52.9%). There was also a 60.9% increase in *Ageratum houstonianum* both in sclerophyll RE and rainforest RE. Two species decreased in cover in sclerophyll forests *Urochloa decumbens* decreased from 66.3% in 2015 to 33.7% in 2021 and *Lantana camara* decreased from 57% in 2015 to 43% in 2021 following fire disturbance, a decrease of 14%.

Out of the 34 transects established in 2015, fifteen transects were disturbed by fire by 2021 (Table S2), 11 were unburnt, and road edge quadrats in eight transects in the rainforest section had been mechanically cleared few weeks prior to the 2021 survey due to road maintenance following damage due to severe weather. The composition of invasive species calculated using the Jaccard's similarity indices showed large variability within and among regional ecosystems (Fig. 4). The greatest variability was in RE 7.12.34 and ranged from 26.3 to 85.7%, and in RE 7.12.22a it ranged from 33.3 to 84% (Fig. 4). The mean similarity index for sclerophyll sites was 51.7% and for rainforest sites was 36.3%. Additionally, when the sites were segregated into burnt and unburnt sites, the differences in the similarity indices for the burnt (mean = 49.2%, standard deviation (SD) = 13%) and unburnt (mean = 46.7%, SD = 19.9%) sites were not significantly different ($F(1, 24) = [0.1529], P = 0.6993$). Ten species recorded in the 2015 surveys were not recorded in the 2021 surveys, and three species recorded in the 2021 surveys were not recorded in the 2015 surveys. However, 18 species were recorded in both the 2015 and 2021 surveys (Table S6). A summary of the outcomes of the four hypotheses is provided in Table 2.

Table 2
Summary of hypotheses tested and the findings

Hypothesis	Supported or not supported	Evidence
1. That forest road edges have the highest richness of invasive plant species.	<i>Supported</i>	A highly significant difference was obtained ($P < 0.001$) for the comparison between invasive species richness at the road edge zone (mean = 1.8 species) and that from adjacent vegetation (mean = 0.8 species).
2. That richness of invasive species decreases with increase in distance from road edge into the adjacent vegetation.	<i>Supported</i>	A strong negative correlation (-0.908) between invasive species richness and increase in distance from the road edge was obtained. The richness decreased with increase in distance from the road edge to adjacent forest.
3. That eucalypt open forests and woodlands are more susceptible to invasive species incursion than rainforests.	<i>Supported</i>	Significantly more invasive species were recorded in eucalypt forests at the road edge ($P = 0.018$) and in adjacent forests ($P = 0.0007$) than in the rainforests.
4. That richness and composition of invasive species increased over time with road use and maintenance, and disturbance events.	<i>Not fully supported</i>	Firstly, the differences in species richness and foliage cover between the 2015 and 2021 were not statistically significant. Secondly, the differences in species composition similarity indices between sites that had been burnt and those unburnt between 2015 and 2021 were not statistically significant. Foliage cover dominance of few species was obtained following disturbance.

Discussion

Currently, the three most significant threats to conservation values in World Heritage Areas at global level are invasive species, climate change and the negative impacts of tourism (IUCN 2020b; UNESCO 2022b). This study examined the threat of incursion by invasive plant species in two protected areas within the Wet Tropics World Heritage Area in Queensland. Invasive species richness and composition were monitored at 34 sites and 306 quadrats in 2015 and revisited in 2021. Richness and composition of invasive species and spread to adjacent vegetation was investigated. All transects, apart from six, contained invasive species and in total, 31 invasive species were recorded. However, these species were only recorded in 50% of the monitored quadrats and most of the species were recorded along the road edge.

Trails and roads traversing protected areas inadvertently provide corridors and pathways for movement and incursion of pest plants (Foxcroft et al. 2013; Ngugi et al. 2014; Boston 2016; McDougall et al. 2018). We hypothesized that the richness of invasive plants would be highest along the road edge zone because

of routine usage and disturbance associated with road maintenance. The hypothesis was supported by our data that showed that invasive species richness from the road edge was significantly higher than that from adjacent vegetation. These findings support the assertion that roads that traverse protected native forest communities become corridors for entry of invasive species (Kudo et al. 2014; Boston 2016; McDougall et al. 2018; Liedtke et al. 2020). The results are consistent with reports from road edge vegetation monitoring conducted in southeast Queensland using a similar methodology along horse riding trails within conservation areas (Ngugi et al. 2014). In addition, there were significantly greater numbers of invasive species in the road edge zone than in the adjacent forest (73% versus 27%), supporting the assertion that disturbed road edges are vulnerable to invasive species incursion (Seipel et al. 2012; Boston 2016; Lisboa et al. 2022). The results also concur with the findings from a grassland study in the North America's Great Plains that roadsides can be major sources of rangeland exposure to tree invasions (Hogan et al. 2022).

Our data on the richness of invasive species for the sampled regional ecosystems showed a significant difference among them from the 2015 and 2021 visits. On average two invasive species were unique in each of the REs, but there was no evidence that those species would not invade other REs except for *Spermacoce exilis* and *Spermacoce latifolia* which seemed to only prevail along the moist exposed edges of complex mesophyll vine forest in high rainfall and cloudy uplands on alluvial soils (rainforest RE 7.3.36a).

Secondly, we hypothesised that the richness and abundance of invasive species would decrease with increasing distance from the road edge into the adjacent vegetation. This hypothesis was supported by the strong negative correlation between invasive species richness and increase in distance from the road edge. This trend suggests that many of the invasive species fail to progress in their invasion beyond the zone of disturbance along the road edge and into the adjacent forests. This was confirmed by data that showed that from the 31 invasive species recorded in the study, only 11 were observed at both the edge of the road and in the adjacent vegetation. Our observations suggested, that beyond the road edge disturbance, the intact ground cover in adjacent vegetation dominated by native species, shrub layer and tree cover deterred the incursion of the invasive species. These results are consistent with the trend in invasive species richness reported along forest roads in seven national parks in southeast Queensland (Ngugi et al. 2014). A decline in invasive species richness away from the road was also reported in conservation areas including the Montana-Yellowstone National Park and the Blue Mountains in Oregon, United States, and the Australian Alps, and was associated with less favourable establishment conditions in the dense forests away from the road (Seipel et al. 2012).

The results also found five species that were recorded in the adjacent forest but not at the edge of the road. These invasive species included *Lantana camara*, *Ageratum conyzoides*, *Megathyrsus maximus*, *Melinis repens* and *Praxelis clematidea*. They may represent species that were once at the road edge but escaped into adjacent vegetation before they were kept under control during routine park management. Alternatively, the species may have been dispersed by other mechanisms such as overland rainwater flow from the road edge or birds as is the case for *Lantana camara* (Biosecurity Queensland 2020). Seipel et al

(2012) reported similar results in a study in the Australian Alps, in which invasive species richness at 75 m from the roadside was found to be very low and independent of roadside species.

Invasive species FPC was significantly higher at road edge zone than in the adjacent vegetation. However, FPC along the transects was characterised by variability and did not show a consistent decreasing trend with increase in distance from the road edge. In the rainforest sites, no invasive species were recorded in the adjacent forest zone. This can be attributed to the poor invasive species establishment conditions associated with dense canopy cover and low light penetration to the ground layer, characteristic of these forest. The data indicated that although majority of the invasive species were recorded at the road edge, the majority had low foliage cover (83.8% had < 10%, 16.2% had > 10%). This suggested that only few of the species eventually dominated the disturbed area at the road edge.

Two invasive species that recorded the highest cover were *Urochloa decumbens* (signal grass) with 65% foliage cover recorded at the road edge in the Herberton Range Conservation Park, and *Sporobolus fertilis* (Parramatta grass) with 64% foliage cover recorded in the adjacent vegetation zone at Danbulla NP. Signal grass is known to grow vigorously and to colonise disturbed environments, corridors created for powerlines and roads and often forming dense stands in the understorey of open woodlands, along waterways and on floodplains (Brisbane City Council 2022a). Parramatta grass is known to invade native grasslands, open woodlands, conservation reserves and wetland areas and when fully established it excludes native plants (Brisbane City Council 2022b). Because of this already documented fast rate of expansion of FPC and distribution for these two species, they pose a major threat to the protected values. It is recommended that timely control of the spread of the species be undertaken accompanied with appropriate weed hygiene to prevent further spread through slashing and movement of vehicles and machinery.

A small number of newly-emerging invasive plant species of extreme management concern have been reported in the Wet Tropics of Queensland. These are: *Miconia calvescens*, *M. racemosa*, *M. nervosa*, *Mikania micrantha*, *Clidemia hirta* and *Chromolaena odorata* (Department of Environment and Science Queensland 2020). Fortunately, none of these species was recorded in the monitored transects in this study.

Thirdly, we hypothesised that eucalypt open forests and woodlands which generally have less dense canopy cover relative to rainforests are more susceptible to invasive species incursion. This hypothesis was supported by our data that showed that invasive species richness within the rainforest regional ecosystems was significantly lower than in the eucalypt forests. With less dense canopy cover in the eucalypt forests, more light can reach the ground fostering better seed germination conditions for invasive species compared to low light conditions on the ground that characterises rainforest environments (Grice and Setter 2003).

Fourthly, we hypothesised that invasive species richness and composition would increase over time with continued use and maintenance of the forest roads, and with routine fire disturbance events (Foxcroft et al. 2013). This hypothesis was not fully supported. Firstly, the differences in species richness and FPC

between the 2015 and 2021 were not statistically significant. Secondly, the differences in species composition assessed using similarity indices between sites that had been burnt and those unburnt since the 2015 were also not statistically significant. This result may have been compounded by time since fire event and recovery after the fire. For burnt sites, the result suggests that some invasive species were impacted or the recovery of native vegetation after fire events may have limited the potential for re-establishment of affected invasive species or incursion by new invasive species. However, although the differences in similarity indices were not statistically significant, large variability was obtained among sites within the same regional ecosystem suggesting that there were differences in the response of individual species to both the duration between sampling and the fire altered local conditions. Additionally, the low similarity index on many of the transects was caused by species absence and presence associated with forest type (sclerophyll/rainforest), species lifeform, life cycle, disturbance, or timing of field observation.

Many disturbances increase the availability of resources for plant growth. For example, disturbance in rainforests is principally associated with increase in light availability, while soil movement associated with road construction creates an environment conducive for germination and establishment of plants (Boston 2016). In this early successional environment, invasive species have been reported to often outcompete native species for the limited resources (Zouhar et al. 2008). In the case of fire events, these often increase light availability by reducing vegetation cover and can increase nutrient availability by consuming surface organic layers (Zouhar et al. 2008). The response of invasive species to fire events in this study in sclerophyll forests was consistent with reported studies on the effects of fire on non-native species (Brooks et al. 2004; Zouhar et al. 2008). Following the fire, some of the species showed great increase in FPC while others showed a decrease. For example, there was an 86% increase in the FPC of the grass, *Sporobolus fertilis* in RE 7.12.27a in the Danbulla NP after a fire event, and FPC increase of 60.9% for *Ageratum houstonianum* in the Herberton Range CP following a fire event in 2020. This suggests that the post fire conditions favoured the growth of these species in sclerophyll forests. However, as tree and shrub canopy recover from the effects of fire, accompanied by a decrease in light levels to the ground layer, the conditions are likely to become less favourable for shade intolerant invasive species (Zouhar et al. 2008).

In contrast, there was a 33.7% decrease in the FPC of *Urochloa decumbens* and a 14% decrease for *Lantana camara* on sites that had been burnt. This supports the recommendation that planned fires play crucial role in the management of these two invasive species (Biosecurity Queensland 2020). Among the observed invasive plants species, *Lantana camara* is the only species that is classified as a weed of National Significance in Australia (Biosecurity Qld 2014), but *Lantana camara* and *Sporobolus fertilis* are both listed as restricted invasive species in Queensland (Biosecurity Qld 2014).

Conclusions

This study initiated and trialled a consistent and repeatable invasive species monitoring program in the Wet Tropics World Heritage Area in Queensland. The study captured the baseline inventory of invasive

species, including richness, abundance and spread, and the repeat measure helped to characterise changes in invasive species attributes over time and in response to disturbance. It was therefore possible to determine the environmental pest classification status of each species, to inform invasive species management strategy for each park. Thirty-one invasive species were recorded, and their richness was consistently higher at the road edge relative to that in the adjacent vegetation and decreased with increasing distance from the road edge. Additionally, only about a third of the species found at the road edge were also present in the ground layer of the adjacent vegetation. Moreover, the FPC for more than 73% of the recorded invasive species at the road edge was < 5%, suggesting that only few of the species dominated the disturbed sites. Eucalypt forests were generally more vulnerable to invasive species incursions because of their mostly more open canopy compared to dense rainforest canopy. These results imply that roads represent an important component of integrated invasive species management strategy in the WTWHA. They also suggest that timely control of invasive species along the access roads and especially those with foliage cover dominance has the potential to significantly limit their incursion in the adjacent native vegetation. Continued monitoring of these sites on a five yearly basis is recommended to support strategic weed management.

Declarations

Funding

This study was funded by the Department of Environment and Science, Queensland government.

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Authors Contributions

Both authors contributed to the study conception and design. Material preparation, data collection was performed by both authors, and analysis were performed by Dr Michael Ngugi. The first draft of the manuscript was written by Dr Michael Ngugi. Dr John Neldner edited, enhanced, and commented on all previous versions of the manuscript. All authors read and approved the final manuscript.”

Data availability

The datasets generated during the current study are available from the corresponding author on reasonable request.

Supplementary Information

Supplementary information is included.

Acknowledgements

This study was funded by the Department of Environment and Science. Field site establishment assistance provided by Mark Newton, Queensland Tropical Herbarium, Cairns and logistics assistance provided by Queensland Parks and Wildlife Service & Partnership (QPWS&P) staff in Atherton is acknowledged. Fire history data provided by Robert Miller QPWS&P Mareeba, map preparation and GIS assistance provided by Jiaorong Li and data management provided by William Dodt at Queensland Herbarium and Biodiversity Science (QHBS) are gratefully acknowledged. Peer review and comments provided by Andrew Millerd, Program Director Performance, Improvement and Change at Atherton (QPWS&P) and Dr Eda Addicott and Dr Melinda Laidlaw (QHBS) are gratefully acknowledged.

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Figures

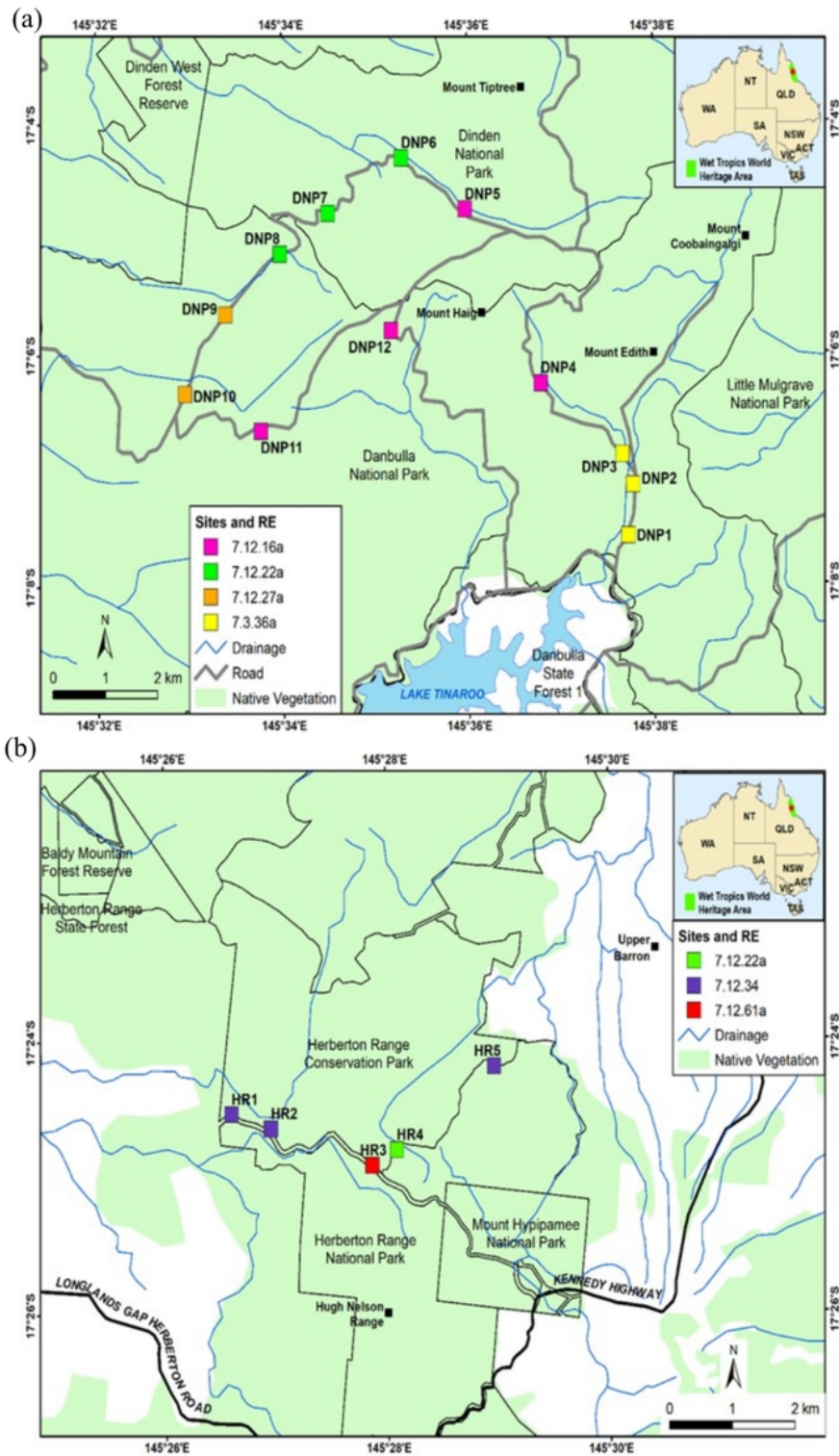


Figure 1

Location and regional ecosystem of monitoring sites in (a) Danbulla National Park and (b) Herberton Range Conservation Park in the Wet Tropics World Heritage Area in Queensland

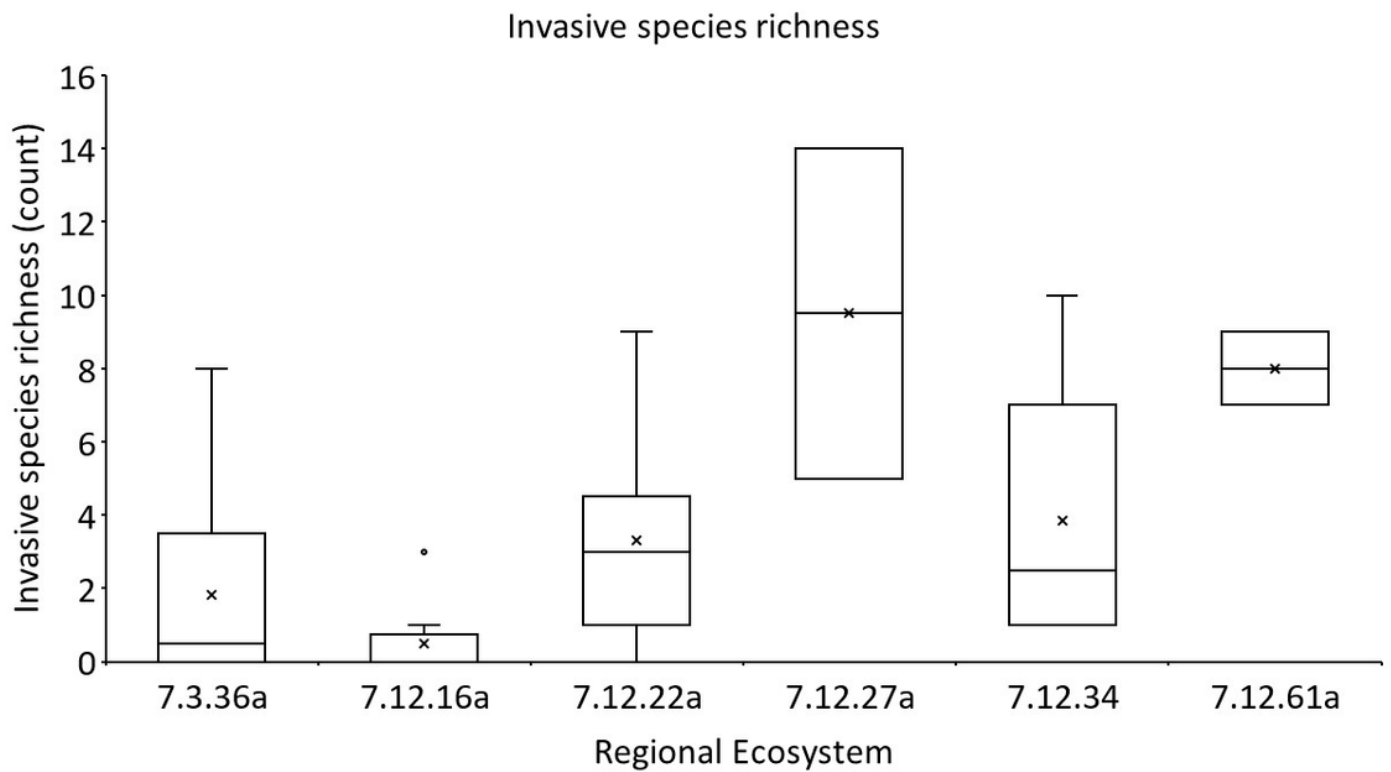


Figure 2

Boxplot of invasive species richness recorded in each of the sampled regional ecosystems. Error bars show minimum and maximum values, X is the mean, and the middle bar is the median of richness values. RE 7.3.36a (n = 6) and 7.12.16a (n = 8) are rainforest sites, and 7.12.22a (n = 10), 7.12.27a (n = 2), 7.12.34 (n = 6) and 7.12.61a (n = 2) are sclerophyll forests

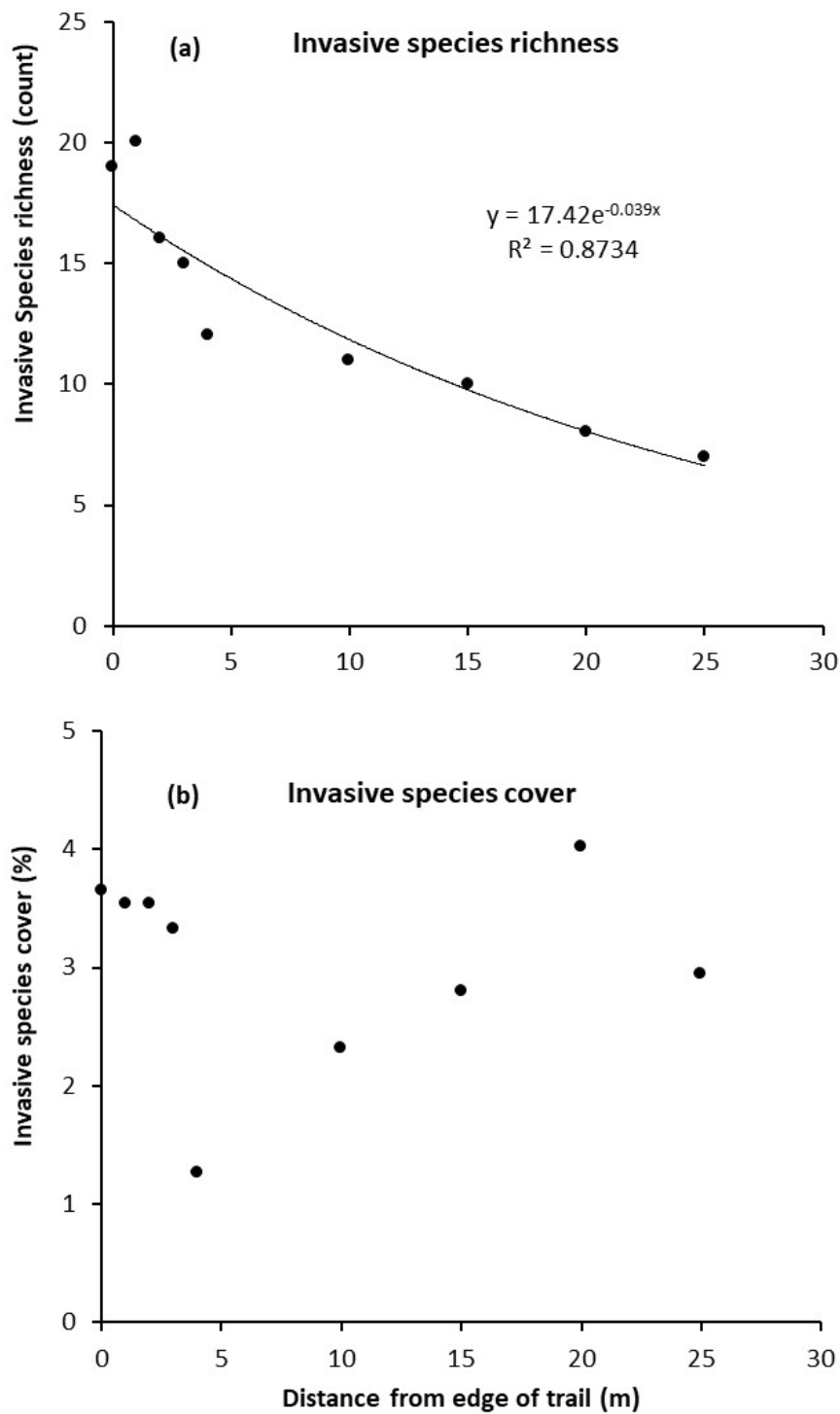


Figure 3

Relationship between invasive plant species (a) richness and (b) foliage projection cover with distance from road edge in Danbulla and Herberton Range Conservation Park in the Wet Tropics World Heritage Area in Queensland

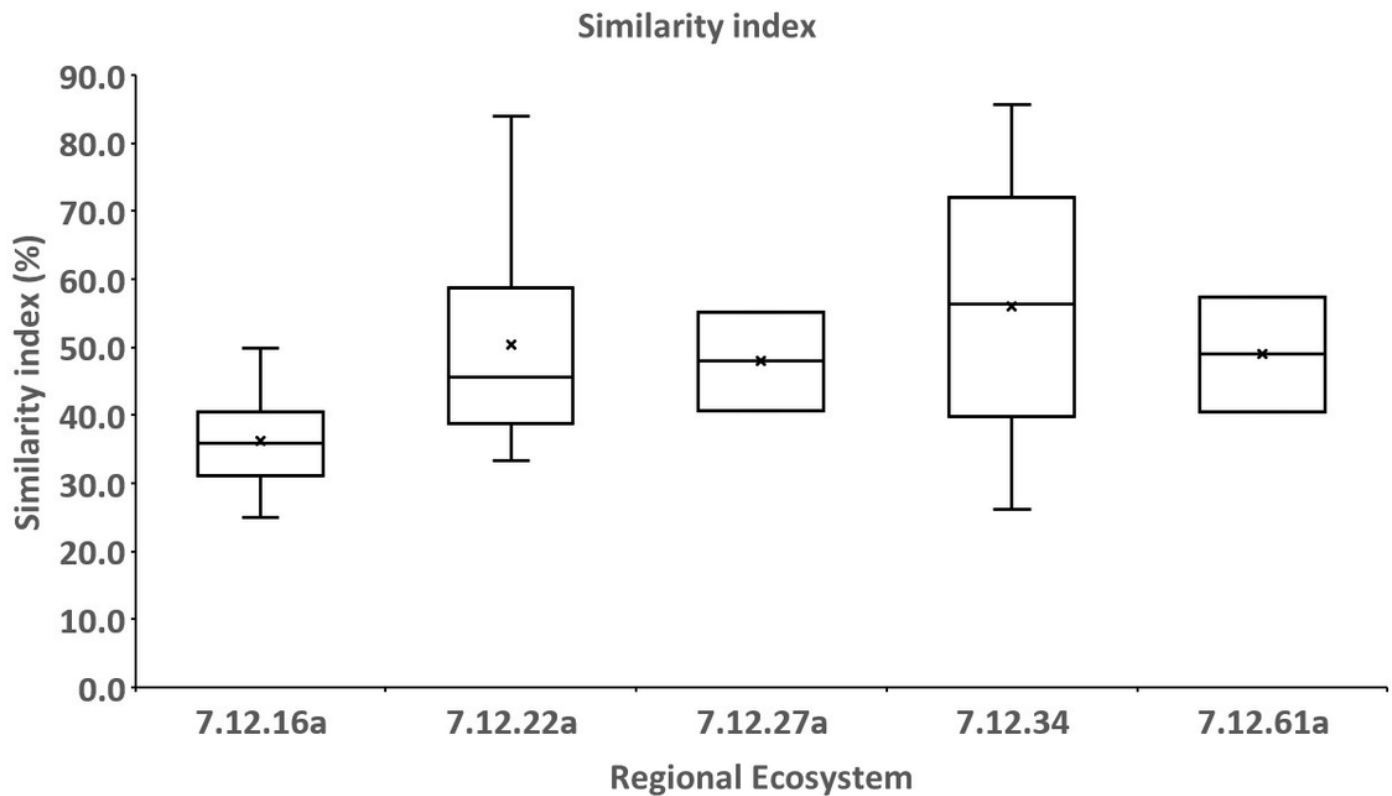


Figure 4

Boxplot of Jaccard similarity indices comparing invasive species in sites measured in 2015 and 2021 within each of the sampled regional ecosystem (RE) except rainforest RE 7.3.36 which had road scrapped for maintenance prior to 2021 survey. Error bars show minimum and maximum values, X is the mean and middle bar is the median value. Regional ecosystem 7.12.16a is rainforest, and 7.12.22a, 7.12.27a, 7.12.34 and 7.12.61a are sclerophyll forests

Supplementary Files

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