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Impact of weed invasion on Kahikatea forest fragments in the Waikato region and review of the 'Green Wheel' recovery ranking tool

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Impact of Weed Invasion on Kahikatea Forest Fragments in the Waikato Region and Review of the Green Wheel Recovery Ranking Tool

Mark C. Smale

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Executive summary

Kahikatea (*Dacrycarpus dacrydioides*) forest fragments that have arisen after land development for agriculture are a widespread and iconic feature of the Waikato Region. There are over 3000 of them, totalling 2760 ha, in the region today. They are typically small; 70% in the central Waikato are less than 1 ha. Along with severely reduced peat bogs, they are the only significant reservoirs of native biodiversity left over wide areas of intensively farmed dairy landscapes. Recent visits to a small number of fragments revealed serious weed invasion. Continuing deterioration indicates urgency to find ways of arresting decline and ensuring sustainability.

Permanent plots established in 2001-2002 in six rural and one urban kahikatea forest fragment in the Waikato Region on gleyed silt loams with different recovery periods (since grazing ceased) and ranging in size from 1.2 to 9.9 ha, were remeasured in the summer of 2017-2018. Objectives were:

(1) To assess the impact of weed invasion on the ecological integrity and indigenous vascular floristic diversity of kahikatea fragments in the Waikato Region;
(2) To assess the applicability of the 'Green Wheel' recovery ranking tool (adapted from SERA 2016, refer to Denyer 2019) to measuring the ecological integrity of kahikatea forest fragments in the Waikato Region; and
(3) To remeasure permanent plots in kahikatea forest fragments and to assess and track ecosystem recovery in remnant kahikatea ecosystems in the Waikato Region. In each stand, four 20 X 20 m permanently marked plots were relocated, two at the margins and two in the interior, and vegetation was recorded quantitatively and semi-quantitatively. Indigenous species richness, alien species richness, basal area, tree (>10 cm dbh), sapling (2.5–10 cm dbh) and established seedling (>15 cm tall, <2.5 cm dbh) density, and ground cover were recorded in each plot. Plots at Marychurch Rd, Matangi, had been so modified by human use that they were abandoned.

The Green Wheel method (without Physical Conditions and External Exchanges criteria in this instance, refer to Denyer 2019) provides robust assessments of Ecological Integrity which can be repeated over time, with considerably less time and labour than the Plot method. However, the Plot method does provide additional detailed quantitative data on population structure and biomass at the individual species and fragment level which can also be repeated over time.

A total of 87 indigenous and 33 alien vascular species was recorded in the 22 plots. The number of alien species and Regional Pest Management Strategy weed species decreased in plots in almost all fragments. The number of threatening weed species increased in plots in all fragments except those subject to weed control. Indigenous species richness showed no clear pattern of change but decreased sharply where invaded by tradescantia (*Tradescantia fluminensis*). Basal area (≈biomass) increased at a similar rate in plots across most fragments, except long-fenced Claudelands Bush, where it remained almost stable.

Although a high percentage of characteristic alluvial kahikatea forest species is present across all fragments, the proportion in the individual fragment with the best representation, Whewell's Bush, was <60%, highlighting the relative floristic poverty of isolated sites with past grazing histories. The longest fenced fragment, Claudelands Bush, had only 40%, reflecting partly past occupancy by tradescantia and consequent major loss of species.

Despite the confounding of size and recovery period (smaller sites with shorter recovery periods and larger sites with longer recovery periods), and weed control only in the latter, an underlying pattern can be discerned. More recently fenced (<c. 25 years ago) fragments have tree populations comprised entirely or almost entirely of indigenous species and sapling and

seedling populations entirely or largely of alien species, and longer fenced fragments have all tiers comprised entirely or almost entirely of indigenous species.

Although weeds are scarce in larger, longer fenced sites, two of which are subject to weed control, ecological integrity as assessed by the plot method is still only Medium-High because of the relatively poor representation of characteristic kahikatea species even at the best sites. The relative contributions to this floristic poverty of past grazing and of fragmentation can only be determined by a study involving a large number of fragments with different recovery times and of varying sizes and degrees of isolation

At <1 ha, most fragments are too small to encompass the full species complement of this forest type. Despite the confounding of fragment size and recovery period, the prevalence of largely or wholly indigenous shrub and ground layers in fragments fenced before the early 1990s, and of largely or wholly alien shrub and ground layers in fragments fenced since then, suggests that a major shift may be occurring in the native/alien dynamic of the intensively developed landscapes of the Waikato. The vacant growing space that used mostly to be occupied by indigenous species when grazing pressure ended in kahikatea forest fragments is being occupied increasingly by alien species. Populations of some weed species in the region appear to have reached a critical mass where they are able now to exploit every opportunity for expansion. Although alien pasture species are still disappearing after fencing, successional trajectories involving re-establishment of indigenous ground layer and understorey species and recovery of population structures of major species are being deflected by invasion by alien species. With ever-growing weed pressure, additional management such as interior planting may be necessary to help re-establish indigenous lower tiers before they become dominated by weeds.

Although biomass is still increasing in the smallest fragment, the lack of effective replacement of canopy trees there suggests that fencing alone may not be sufficient to ensure long-term survival of fragments less than 2 ha in size. Both replanting of representative kahikatea species within fragments (Marychurch Rd) and weed control (Claudelands Bush, Whewell's Bush) can increase ecological integrity. There is a pressing need to ascertain the minimum critical size below which more intensive management such as replanting is needed to ensure long-term survival, and also to ascertain whether development of lower tiers dominated by weeds in recently fenced fragments is an artefact of small size, the result of a major shift in the native/alien dynamic in the intensively developed landscapes of the Waikato, or both.

Objectives

(1) To assess the impact of weed invasion on the ecological integrity and indigenous vascular floristic diversity of kahikatea fragments in the Waikato Region;
(2) To assess the applicability of the 'Green Wheel' recovery ranking tool (adapted from SERA 2016, refer to Denyer 2019) to measuring the ecological integrity of kahikatea forest fragments in the Waikato Region; and
(3) To remeasure permanent plots in kahikatea forest fragments and to assess and track ecosystem recovery in remnant kahikatea ecosystems in the Waikato Region.

Methods

Permanent plots established in 2001-2002 in six rural and one urban rural kahikatea forest fragment on gleyed silt loams but with different recovery periods (since grazing ceased) from 1.2 to 9.9 ha in the Waikato Region were remeasured in the summer of 2017-2018. In each stand, four 20 X 20 m permanently marked plots were located, two at the margins and two in the interior, and vegetation recorded quantitatively and semi-quantitatively. Indigenous species richness, alien species richness, basal area, and tree (>10 cm diameter at breast height:

dbh) density were recorded in the whole plot, sapling (2.5–10 cm dbh) and established seedling (>15 cm tall, <2.5 cm dbh) density, and ground cover in a 10 X 10-m subplot. Plots at Marychurch Rd, Matangi, had been so modified by human use that they were abandoned. Two to three hours were spent in each fragment searching for additional species not present in plots.
Each fragment was also assessed by the Kahikatea Green Wheel recovery ranking tool method (Denyer 2019).

Results

Ecological integrity assessed by the Green Wheel method (without Physical Conditions and External Exchanges criteria, refer to Denyer 2019) mirrored that provided by the Plot method, achieved with considerably less time and labour.

Although 82% of characteristic alluvial kahikatea forest species were present across all fragments combined, the proportion in the individual fragment with the best representation, Whewell's Bush, was <60%, highlighting the relative floristic poverty of isolated sites with past grazing histories. The longest fenced fragment, Claudelands Bush, had only 40%, partly reflecting past occupancy by tradescantia (*Tradescantia fluminensis*) and consequent major loss of species.

Lower tiers in fragments fenced before the early 1990s are comprised largely or entirely of indigenous species, and lower tiers in fragments fenced since then largely or entirely of alien species.

The number of alien species and Regional Pest Management Strategy weed species decreased in plots in almost all fragments, because of shading out of pasture grasses and herbs. The number of threatening weed species increased in plots in all fragments except those subject to weed control. Indigenous species richness showed no pattern of change in plots across fragments, but decreased sharply where invaded by tradescantia. Basal area (≈biomass) increased at a similar rate in plots across most fragments, except Claudelands Bush, where it remained almost stable.

Discussion and Conclusions

The Green Wheel method (without Physical Conditions and External Exchanges in this instance, refer to Denyer 2019) provides robust assessments of Ecological Integrity which can be repeated over time, with considerably less time and labour than the Plot method. However, the Plot method provides additional quantitative data on population structures and biomass at the individual species and fragment level which can also be repeated over time.

Despite the scarcity of weeds in larger, longer fenced sites, two of which are subject to weed control, ecological integrity is still only Medium to High because of the relatively poor representation of characteristic kahikatea species even at the best sites.

At less than 1 ha, most fragments are too small to encompass the full species complement of this forest type. Despite the confounding of fragment size and recovery period (smaller sites with shorter recovery periods and larger sites with longer recovery periods), and weed control only in the latter, the prevalence of largely or wholly indigenous lower tiers in fragments fenced before the early 1990s, and of largely or wholly alien lower tiers in fragments fenced since then, suggests that a major shift may be occurring in the native/alien dynamic of the intensively developed landscapes of the Waikato. The vacant growing space that used mostly to be occupied by indigenous species when grazing pressure ended is being occupied increasingly by alien species. Populations of some weed species in the region appear to have reached a critical mass where they are able now to exploit every opportunity for expansion.

Although alien pasture species are still disappearing after fencing, successional trajectories involving re-establishment of indigenous ground layer and understorey species and recovery of population structures of major species are being deflected by invasion by alien species. With ever-growing weed pressure, additional management such as interior planting may be necessary to help re-establish indigenous lower tiers before they become dominated by weeds. Replanting of representative kahikatea species, edge (buffer) planting and weed control can increase ecological integrity in these fragments.

1 Introduction

Forest fragments dominated by kahikatea (*Dacrycarpus dacrydioides*) occupy 0.15% of the dairy landscape of the middle Waikato Basin (Burns et al. 2000). Most are less than 1 ha in extent and have resulted since widespread land development for agriculture beginning c. 150 years ago. Kahikatea forests once covered large areas of the Waikato Region but have since been reduced to 1.1% of its original extent.

Such fragments are almost the sole reservoirs of indigenous forest biodiversity remaining in parts of the region and represent the only prospects for its survival. Although valued by farmers for stock shelter, their ecological integrity has been widely compromised by grazing and their long-term survival is uncertain. Ecological integrity is used here to mean "a condition that is determined to be characteristic of its natural region and likely to persist, including abiotic components and the composition and abundance of native species and biological communities, rates of change and supporting processes" (National Parks Act (Canada) 2000). Some farmers are reluctant to fence natural areas, believing it encourages weed populations (Parminter & Wilson 2002). After earlier qualitative descriptions, e.g., Esler (1978), there have been recent quantitative studies in tawa (*Beilschmiedia tawa*)-dominant forest in the Waikato Region of the long-term impacts of stock grazing (Smale et al. 2008), of resilience to those impacts (Dodd et al. 2011), and of the effects of management (retirement, pest control) on them (Burns et al. 2011). Vegetation recovery in kahikatea forest fragments has been modelled over 74 years after retirement from grazing (Smale et al. 2005) and an overview – based on fieldwork in the 1980s – of the flora of 'dry' kahikatea forest remnants in the southeastern Hamilton Basin written by de Lange (2014).

Kahikatea is the signature tree of the Waikato Region, and kahikatea forest fragments are one of its quintessential natural features. These fragments are unique in the large areas of intensively farmed landscapes in the Waikato in several ways. They are often the only reservoirs of indigenous biodiversity, the only remaining ecosystems dominated by indigenous species, and the only examples of undisturbed original soil profiles. They are major contributors in intensively farmed landscapes to the maintenance of natural landscape character, the maintenance of indigenous biodiversity, the movement of indigenous flora and fauna, especially birds (corridors) and ecosystem services like water quality (nutrient sinks). The ongoing loss of kahikatea forests has been addressed by the Waikato Regional Policy Statement (RPS) 4 and 11.1.

Fencing is the most widely used tool in the restoration of forest fragments (Smale et al. 2005) and to a lesser extent, pest control (Burns et al. 2011). In summer 2001-2002, a suite of permanent plots was established by Landcare Research in seven kahikatea forest fragments in five localities (Hamilton, Gordonton, Matangi, Walton, Piarere) in the Waikato Region to model vegetation recovery after fencing (Smale et al. 2005). At the time, the invasive small-leaved privet (*Ligustrum sinense*) was present as seedlings in all fragments. A recent visit to the Walton fragment revealed a major increase in privet abundance and an apparent concomitant decrease in the abundance of indigenous species. In mixed hardwood forest in northeastern North America, this species severely reduced ground-layer herbaceous species and almost completely suppressed regeneration of canopy trees over 20 years (Merriam & Feil 2002). Its potential for disrupting ecological processes in New Zealand forest is unknown. Weed invasion after fencing is becoming a major issue in the sustainability of forest fragments in the Waikato Region.

The Green Wheel recovery ranking tool (Denyer 2019) was adapted for local use from the Recovery Wheel developed recently by the Society for Ecological Restoration Australasia (SERA 2016). It allows restoration practitioners to evaluate the degree of recovery of a restored site compared with the reference ecosystem. The Ecological Recovery Wheel uses an intuitive 1 to 5 ranking approach of abiotic and biotic criteria in six categories: Absence of threats, Physical

conditions, Species composition, Structural diversity, Ecosystem function, and External exchanges. The average of the criteria within categories provides a score for that category. The sum of all category scores provides the overall score of ecological integrity/degree of recovery.

2 Objectives

(1) To assess the impact of weed invasion on the ecological integrity and indigenous vascular floristic diversity of kahikatea fragments in the Waikato Region.

(2) To assess the applicability of the 'Green Wheel' recovery ranking tool (adapted from SERA 2016, refer to Denyer 2019) to measuring the ecological integrity of kahikatea forest fragments in the Waikato Region.

(3) To remeasure permanent plots in kahikatea forest fragments and to assess and track ecosystem recovery in remnant kahikatea ecosystems in the Waikato Region.

3 Study sites

Seven kahikatea-dominant forest stands varying in size from 1.2 to 9.9 ha with different grazing histories on Te Kowhai silt loam, a widespread and archetypal gleyed soil of kahikatea stands, were identified in Hamilton and on dairy farms at Gordonton, Matangi, Walton and Piarere (Fig 1) in the Waikato Region (Table 1).

Table 1: Kahikatea forest fragments in the Waikato Region used in this study. * denotes uncertainty about recovery period. / denotes two different fencing histories within a fragment.

Site	Walton	Marychurch Rd, Matangi	Lee Martin Rd, Matangi	Gordonton	Whewell's Bush, Matangi	Piarere	Claudelands Bush, Hamilton	Mean of all fragments
Recovery period (yrs)	10*/17	18	21	31	41	26/48	90	34
Area (ha)	2.6	3.1	1.2	2	9.9	3.8	5.2	4
Management	None	Edge and interior planting, weed and pest control	None	Some pest control	Edge planting, weed and pest control	Minor past weed control	Edge planting, weed and pest control	Some

4 Methods

4.1 Green wheel review

Peer review of the 'Green Wheel' recovery ranking tool (adapted for kahikatea forest from

Society for Ecological Restoration Australasia 2016) was undertaken and provided to Waikato Regional Council (WRC). The tool and its attributes was adapted for specific use in kahikatea forest fragments in the Waikato Region by KJ Denyer in consultation with Dr Yanbin Deng (WRC) and the author (MCS), using existing knowledge of kahikatea forest fragments and their environment (Denyer 2019).

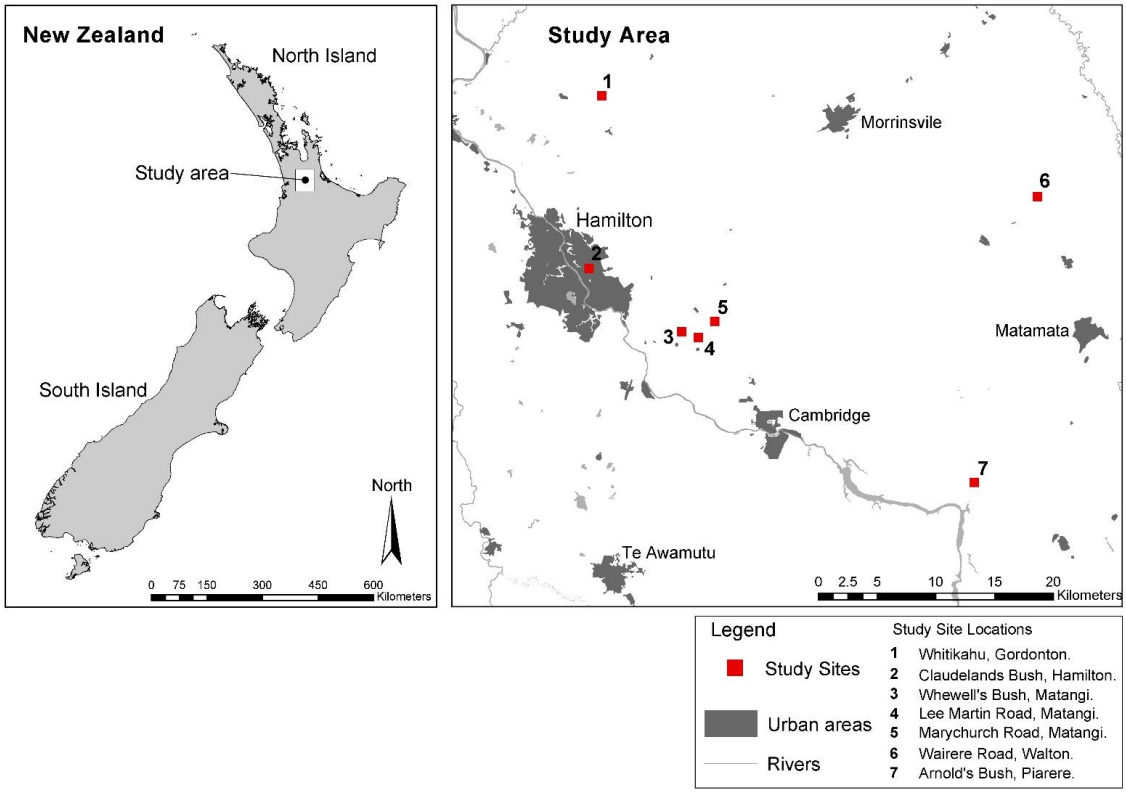

Fig. 1. Location of kahikatea forest fragments in the Waikato Region sampled in this study

4.2 Fieldwork

Four permanently marked 20 x 20-m plots following Hurst & Allen (2007), with one nested 10 x 10-m sapling subplot were established randomly within each fragment, two at the edge and two in the interior, in 2001-2002 (Smale et al. 2005). One fragment, Lee Martin Rd, Matangi, was only large enough to allow two plots to be placed in it.

Within each 20 by 20-m plot, all vascular species were recorded and all tagged trees (>10 cm dbh) recorded and measured for dbh.

Within each nested 10 x 10-m sapling subplot,

(1) All saplings (2.5–10 cm dbh) were measured for dbh, and all established seedlings (>15 cm tall, <2.5 cm dbh) recorded by species.
(2) Cover of herbaceous species (including ferns, sedges, grasses, and lianes) were recorded semi-quantitatively by species in seven classes: <1, 2–5, 6–25, 26–50, 51–75, 76–95, >96%.

Plots were remeasured in the summer of 2017-2018. Plots at Marychurch Rd, Matangi, had been so modified by human use that they were abandoned.

Two to three hours were spent in each fragment searching for additional species not present in plots.

All sites were assessed using 'Green Wheel' recovery ranking tool (Denyer 2019).

4.3 Data analysis

(1) Ecological integrity of each fragment and across all fragments was assessed by two methods:

(i) Ecological integrity assessed semi-quantitatively on the basis of three quantitative individual indicators:

a. Species occupancy (Lee et al. 2005): Percentage of characteristic alluvial kahikatea forest species (see Appendix 1) present across all plots.
b. Percentage of Regional Pest Management Strategy (RPMS) weeds present across all plots.
c. Indigenous/alien density ratio (a measure of indigenous dominance: cf. Lee et al. 2005) derived from total indigenous and total alien density of trees, saplings and established seedlings across all plots.

(ii) Ecological integrity as per the 'Green Wheel' recovery ranking tool (adapted from SERA 2016, refer to Denyer 2019). Two sets of attributes, Physical Conditions (B) and External Exchanges (F) which are based on GIS analysis, were not included in the current analysis.

(2) Change in invasive weed frequency in each fragment and across all fragments.

Change in total alien species, weed species listed in the Waikato Regional Pest Management Strategy (RPMS) and threatening weed frequency between measurements.

Threatening weed species: bangalow palm (*Arconotophoenix cunninghamiana*), smilax (*Asparagus asparagoides*), barberry (*Berberis glaucocarpa*), spindleberry (*Euonymus japonicus*), ivy (*Hedera helix*), tree privet (*Ligustrum lucidum*), small-leaved privet (*Ligustrum sinense*), honeyusuckle (*Lonicera japonica*), phoenix palm (*Phoenix canariensis*), cherry laurel (*Prunus laurocerasus*), flowering cherry (*Prunus serrulata*), evergreen buckthorn (*Rhamnus alaternus*), selaginella (*Selaginella kraussiana*), woolly nightshade (*Solanum mauritianum*), tradescantia (*Tradescantia fluminensis*).

(3) Change in indigenous vascular floristic diversity in each fragment and across all fragments.

Change in indigenous species richness between measurements.

(4) Change in biomass (≈biomass) in each fragment and across all fragments.

Change in total basal area between measurements.

5 Results

Photographs of all sites except Marychurch Rd, Matangi, are presented in Appendix 2.

5.1 Green wheel review

Peer review of the Green Wheel recovery ranking tool (Denyer 2019), adapted from Society for Ecological Restoration Australasia (2016) and amended by Waikato Regional Council for use in kahikatea fragment restoration, was undertaken and provided to Waikato Regional Council.

5.2 Ecological integrity by the plot method

5.2.1 Species occupancy by characteristic alluvial kahikatea forest species

There was a general increase with recovery period in the percentage of characteristic alluvial kahikatea forest species present in plots in fragments (Table 2). A high percentage (82%) was present across all six fragments. The relatively low percentage (40%) present in Claudelands Bush, the longest fenced fragment, reflects partly the long past occupancy there by the smothering invasive weed tradescantia (*Tradescantia fluminesis)* (Whaley et al. 1997).

Table 2: Percentage of characteristic alluvial kahikatea forest species present across four plots in each of six kahikatea fragments (recovery period in years) and in all plots across all fragments in the Waikato Region in 2018. * denotes uncertainty about recovery period.

Walton (10)*	Walton (17)	Lee Martin Rd (21)	Piarere (26)	Gordonton (31)	Whewell's Bush (41)	Piarere (48)	Claudelands Bush (90)	All fragments
6	25	21	37	35	57	51	40	82

5.2.2 RPMS weed frequency

RPMS weed frequency in plots showed no pattern with recovery period (Table 3), possibly because two of the longer fenced sites, Whewell's Bush and Claudelands Bush, are both subject to weed control. The most widespread and common species were Jerusalem cherry (*Solanum pseudocapsicum*) and small-leaved privet (*Ligustrum sinense*), each accounting for 41% of individuals of alien species across all plots.

Table 3: Percentage of RPMS weeds present across four plots in six kahikatea fragments (recovery period in years) and in all plots across all fragments in the Waikato Region in 2018. * denotes uncertainty about recovery period. W denotes subject to weed control.

Walton (10)*	Walton (17)	Lee Martin Rd (21)	Piarere (26)	Gordonton (31)	Whewell's Bush W (41)	Piarere (48)	Claudelands Bush W (90)	All fragments
4	6	5	8	10	5	2	4	17

5.2.3 Proportion of trees, saplings and seedlings comprised by indigenous species

Tree populations in plots across all fragments are comprised entirely or almost entirely of indigenous species (Table 4). Sapling and seedling populations in plots in fragments fenced for more than c. 25 years are comprised entirely or largely of indigenous species. However, in fragments fenced for less than c. 25 years, sapling and seedling populations are comprised entirely or largely of alien species.

Table 4: Percentage of trees (>10 cm DBH), saplings (2.5-10 cm DBH) and established seedlings (>15 cm high) comprised by indigenous species across four plots in six kahikatea fragments (recovery period in years) and in all plots across all fragments in the Waikato Region in 2018. * denotes uncertainty about recovery period. W denotes subject to weed control

	Walton (10)*	Walton (17)	Lee Martin Rd (21)	Piarere (26)	Gordonton (31)	Whewell's Bush W (41)	Piarere (48)	Claudelands Bush W (90)	All fragments
Trees	100	100	96	100	98	100	100	100	99
Saplings	0	0	0	100	79	100	82	100	74
Seedlings	0	11	19	91	52	95	98	99	83

5.2.4 Ecological integrity by the Plot method

Ecological integrity varied from Very low in the very small, relatively recently fenced fragment at Lee Martin Rd, Matangi, to Medium-High in the three larger, longer fenced fragments: Whewell's Bush, Piarere (longer-fenced part), and Claudelands Bush (Table 5).

Table 5: Ecological integrity assessed semi-quantitatively by the plot method in six kahikatea fragments (recovery period in years) and across all fragments in the Waikato Region in 2018. * denotes uncertainty about recovery period. W denotes subject to weed control

Walton (10)*	Walton (17)	Lee Martin Rd (21)	Piarere (26)	Gordonton (31)	Whewell's Bush W (41)	Piarere (48)	Claudelands Bush W (90)	All fragments
Very low	Low	Low	Medium	Low-Medium	Medium-High	Medium-High	Medium-High	Medium

5.3 Ecological integrity by the Green Wheel method

Ecological integrity as assessed by the Green Wheel Method (Denyer 2019) (without Physical Conditions and External Exchanges) increased with time since fencing (Table 6; Appendix 3). The relatively high score for Marychurch Rd reflects extensive planting, mostly of representative kahikatea species, and the relatively low score of Claudelands Bush the long past occupancy there by tradescantia.

Table 6: Ecological integrity assessed by the Green Wheel method (Denyer 2019) in six kahikatea fragments (recovery period in years) in the Waikato Region in 2018. * denotes uncertainty about recovery period. W denotes subject to weed control

Walton (10*/17)	Marychurch Rd (18)	Lee Martin Rd (21)	Gordonton (31)	Whewell's Bush W (41)	Piarere (26/48)	Claudelands Bush W (90)	All fragments
12.2	21.1	13.2	15.9	20.8	16.8	21	16.7

5.4 Change in total alien species, RPMS weed and threatening weed species richness

The number of alien species decreased in plots in almost all fragments, increasing slightly in one, Gordonton, since 2001 (Table 7). The greatest decrease occurred in the originally grazed part of the fragment at Walton which was fenced c. 10 years ago and subsequently invaded by tradescantia. The number of RPMS weed species also decreased in plots in almost all fragments (Table 8). Six RPMS species (*Hedera helix, Ligustrum lucidum, Lonicera japonica, Prunus serrulata, Tradescantia fluminensis, Zantedeschia aethiopica*) expanded their range in plots at more recently fenced sites (Table 9). The number of threatening weed species increased in plots in all fragments except Whewell's Bush and Claudelands Bush, both subject to weed control (Table 10).

Table 7: Number of alien species originally present (2001) and change in number across four plots in six kahikatea fragments (recovery period in years) and in all plots across all fragments in the Waikato Region. * denotes uncertainty about recovery period. + indicates an increase, - indicates a decrease in the number of species between measurements. W denotes subject to weed control.

Walton (10)*	Walton (17)	Lee Martin Rd (21)	Piarere (26)	Gordonton (31)	Whewell's Bush W (41)	Piarere (48)	Claudelands Bush W (90)	All fragments
19 (-14)	11 (-4)	11 (-3)	19 (-8)	15 (+2)	11 (-3)	4 (-2)	14 (-7)	48 (-18)

Table 8: Number of RPMS weed species originally present (2001) and change in number (2001-2018) across four plots in six kahikatea fragments (recovery period in years) and in all plots across all fragments in the Waikato Region. * denotes uncertainty about recovery period. + indicates an increase, - indicates a decrease in the number of species between measurements. W denotes subject to weed control.

Walton (10)*	Walton (17)	Lee Martin Rd (21)	Piarere (26)	Gordonton (31)	Whewell's Bush W (41)	Piarere (48)	Claudelands Bush W (90)	All fragments
7 (-2)	9 (-2)	8 (-2)	11 (-2)	8 (+1)	11 (-6)	4 (-2)	8 (-4)	24 (-5)

Table 9: RPMS weed species which have arrived since plot establishment (Y) across four plots in four kahikatea fragments (recovery period in years) in the Waikato Region. * denotes uncertainty about recovery period. W denotes subject to weed control.

Species	Walton (10)*	Walton (17)	Lee Martin Rd (21)	Gordonton (31)	Whewell's Bush (41) W
Hedera helix		Y		Y	
Ligustrum lucidum				Y	
Lonicera japonica				Y	
Prunus serrulata	Y		Y		

Tradescantia fluminensis	Y	Y	Y		
Zantedeschia aethiopica					Y

Table 10: Number of threatening weed species originally present (2001) and change (2001-2018) across four plots in six kahikatea fragments (recovery period in years) and in all plots across all fragments in the Waikato Region. * denotes uncertainty about recovery period. W denotes subject to weed control. + indicates an increase, - indicates a decrease in the number of species between measurements.

Walton (10)*	Walton (17)	Lee Martin Rd (21)	Piarere (26)	Gordonton (31)	Whewell's Bush W (41)	Piarere (48)	Claudelands Bush W (90)	All fragments
2 (+1)	5 (+1)	3 (+2)	4 (+1)	3 (+3)	5 (-2)	2 (+2)	7 (-1)	31 (+7)

5.5 Change in indigenous vascular floristic richness

Indigenous species richness fluctuated slightly in most plots but showed no clear pattern, increasing in some fragments, remaining stable in others, and decreasing in yet others (Table 11). The largest decrease occurred in the originally grazed part of the fragment at Walton which was fenced c. 10 years ago and subsequently invaded by tradescantia.

Table 11: Original (2001) indigenous vascular species richness (number of species) and change (2001-2018) across four plots in six kahikatea fragments (recovery period in years) and in all plots across all fragments in the Waikato Region. * denotes uncertainty about recovery period. + indicates an increase, - indicates a decrease in the number of species between measurements.

Walton (10)*	Walton (17)	Lee Martin Rd (21)	Piarere (26)	Gordonton (31)	Whewell's Bush (41)	Piarere (48)	Claudelands Bush (90)	All fragments
11 (-7)	20 (0)	13 (0)	30 (-2)	23 (+4)	41 (+3)	46 (-4)	43 (-5)	88 (-2)

5.6 Change in basal area (≈biomass)

Basal area (≈biomass) increased at a similar rate in plots across most fragments, although more slowly at Gordonton and Piarere (more recently fenced portion), and in Claudelands Bush where it remained almost stable (Table 12).

Table 12: Original (2001) basal area (m^2/ha) and change (2001-2018: m^2/ha/year) across four plots in six kahikatea fragments (recovery period in years) and in all plots across all fragments in the Waikato Region. * denotes uncertainty about recovery period. + indicates an increase, - indicates a decrease in basal area between measurements.

Walton (10)*	Walton (17)	Lee Martin Rd (21)	Piarere (26)	Gordonton (31)	Whewell's Bush (41)	Piarere (48)	Claudelands Bush (90)	All fragments
107.4 (+0.6)	77.1 (+0.7)	94.7 (+0.8)	76.3 (+0.1)	71.4 (+0.2)	108.3 (+0.7)	164.4 (+0.5)	78.5 (-0.1)	93 (+0.5)

6 Discussion

6.1 Comparison of ecological integrity assessed by the Green Wheel and plot-based methods

Ecological integrity as assessed by the Green Wheel Method (without Physical Conditions and External exchange criteria, Denyer 2019) mirrored closely Ecological Integrity as assessed by the plot method, and is far less time-consuming and labour-intensive. The Green Wheel Method involves a single field assessment which can be completed in a matter of hours by one person; the Plot method involves at least 1-2 days of fieldwork by two people for a fragment. However, the Plot method does provide additional detailed quantitative data on population structure and biomass at the individual species and fragment level. Both can be repeated over time to assess trends in condition.

Although RPMS weeds are relatively scarce in larger, longer fenced sites, two of which are subject to weed control, ecological integrity as assessed by the Plot method is still only Medium-High because of the relatively poor representation of characteristic kahikatea species, even at the best sites. Despite the high percentage (82) of characteristic kahikatea species present across all fragments, the proportion in the individual fragment with the best representation, Whewell's Bush, was less than 60%, highlighting the relative floristic poverty of these isolated sites with past grazing histories. The longest fenced fragment, Claudelands Bush, had only 40%, reflecting partly the long past occupancy there by the smothering invasive weed tradescantia and consequent major loss of species (Whaley et al. 1997). Weed control at two of the longer fenced sites, Whewell's Bush and Claudelands Bush, may have obscured any pattern in weed frequency with recovery period. The relative contributions to floristic poverty of past grazing and of fragmentation can be determined only by a study involving a large number of fragments with different grazing histories, sizes and degrees of isolation.

The general decline in both alien species and RPMS weeds largely reflects the disappearance of pasture species (some of which are listed in the RPMS) through smothering by taller-growing woody species after fencing. Invasion by tradescantia after fencing c. 10 years ago of the originally grazed part of the Walton fragment has largely eliminated both indigenous and alien species from lower tiers there; the only notable decrease in indigenous vascular floristic diversity occurred there.

6.2 Differences in lower-tier composition between recently fenced and long-fenced sites

Despite the confounding of size with recovery period and weed control (the smaller sites having shorter recovery periods and little or no weed control and the larger sites longer recovery periods and weed control in two instances), an underlying pattern can be discerned. There is a stark contrast between more recently fenced (less than c. 25 years ago) fragments with tree populations comprised entirely or almost entirely of indigenous species and sapling and seedling populations comprised entirely or largely of alien species, and longer fenced fragments with all tiers comprised entirely or almost entirely of indigenous species. Without weed control in Whewell's Bush and Claudelands Bush, proportions of alien species in their lower tiers would undoubtedly be higher. Nevertheless, a clear trend is apparent.

6.3 Most widespread weed species

Situated on fertile soils close to intensive human activity and with a history of modification (grazing, fertiliser enrichment (Stevenson 2004) and drainage), kahikatea forest fragments in intensively developed landscapes are very prone to weed invasion (see Timmins & Williams 1991). Jerusalem cherry, present in all rural fragments, is a short-lived (c. 10 years) short (<1.2 m) shrub confined to the understorey tier. Small-leaved privet, also present in all fragments, is

a shrub or small tree (7-(10) m) of unknown longevity that contributes to both the lower subcanopy and understorey. The only other species present in any abundance were tradescantia, flowering cherry (*Prunus serrulata*) and tree privet (*Ligustrum lucidum*).

The effects of tradescantia in reducing indigenous species richness and cover in native forest, dramatically at high volumes, are well documented (McAlpine et al. 2015). Flowering cherry and tree privet are small trees that contribute both to the lower subcanopy and understorey. As prolific seeders, both privet species and flowering cherry are highly invasive and constitute a serious threat to the long-term survival of kahikatea forest fragments as indigenous forest ecosystems.

6.4 Minimum size for full complement of representative kahikatea species

A combined botanical society field trip in February 2019 to Arnold's Bush found additional rarer species, including almost all of those recorded earlier by Gudex (1962), which were not located by the author during his species search. This indicates that several hours by one individual may not be sufficient in larger fragments to compile a complete or nearly complete species list. Even before some likely species loss from the 'relaxation' (Diamond 1972) effects of fragmentation (Tilman et al. 2001) and time-delayed loss of species, known as 'extinction debt' (Tilman et al. 1994), most individual fragments were originally too small to support a complete representation of the alluvial kahikatea forest flora. A vascular indigenous flora of 121 species in White Pine Bush, a 4-ha remnant in the eastern Bay of Plenty, some 45 years after fragmentation (Smale 1984) suggests that 4-5 ha may originally have been large enough to encapsulate almost all the floristic diversity of alluvial kahikatea forest. At <1 ha, most fragments are smaller than this (Burns et al. 2000), so initially would have encompassed only a partial species complement. Nevertheless, some 140-150 years after fragmentation, the current species total (103) across all fragments still represents 75% of the original vascular flora of this forest type.

6.5 Change in basal area

The widespread increase in basal area (≈biomass) is somewhat misleading. Despite basal area increasing even in Lee Martin Rd (1.2 ha), the smallest fragment, because of continuing growth of surviving canopy trees, there is little effective replacement of canopy species. The longer-term future of weed-infested fragments of this size looks bleak.

7 Conclusions

The Green Wheel method (without Physical Conditions and External Exchanges in this instance, Denyer 2019) provides robust assessments of ecological integrity with considerably less time and labour than the Plot method. However, the Plot method does provide additional detailed quantitative data on population structures and biomass at the individual species and fragment level. Both methods can be repeated over time to assess trends in condition.

Despite the confounding of fragment size with recovery period and to a lesser extent, weed control, the prevalence of largely or wholly indigenous shrub and ground layers in fragments fenced before the early 1990s, and of largely or wholly alien shrub and ground layers in fragments fenced since then, suggests that a major shift may be occurring in the native/alien dynamic in the intensively developed landscapes of the Waikato. The vacant growing space that used mostly to be occupied by indigenous species when grazing pressure ended in kahikatea forest fragments is being occupied increasingly by alien species. Populations of some weed species appear to have reached a critical mass in the region and are able now to exploit every opportunity for expansion.

While the impacts of weed invasion on ecological integrity — regardless of how it is assessed — are clearly negative, it is more difficult to assess those impacts on indigenous vascular floristic diversity because of the confounding negative effect on diversity of fragmentation, illustrated by continuing species loss from intensively managed large fragments. Nevertheless, rampant weed (tradescantia) invasion since recent fencing of part of the small Walton fragment has coincided with the greatest loss of diversity in plots at any site. Optimistic earlier predictions about fencing alone being sufficient to restore indigenous biodiversity in kahikatea fragments were predicated on "relatively non-weedy rural environments" and "active control of a small suite of threatening weeds, if present" (Smale et al. 2005). Although alien pasture species are still disappearing after fencing, successional trajectories involving re-establishment of indigenous understorey and ground layer species and recovery of population structures of major species are being deflected by invasion by alien species. With ever-growing weed pressure, additional management such as interior planting may be necessary to help re-establish indigenous lower tiers before they become dominated by weeds.

Despite biomass continuing to increase even in the smallest fragment, the lack of effective replacement of canopy trees there suggests that fencing alone may not be sufficient to ensure long-term survival of fragments less than 2 ha in size. Fencing alone was not sufficient to re-instate tawa (*Beilschmiedia tawa*) regeneration in small (size not specified) tawa-dominant fragments in the Waikato, probably because of desiccation (Morales et al. 2016). Replanting of representative kahikatea species (as at Marychurch Rd), edge buffer planting (as at Claudelands Bush) and weed control (as at Claudelands Bush and Whewell's Bush) can all increase ecological integrity. There is a pressing need to ascertain if there is a minimum critical size below which more intensive management such as replanting is needed to ensure long-term survival, and also to ascertain whether development of lower tiers dominated by weeds in recently fenced fragments is an artefact of small size, the result of a major shift in the native/alien dynamic in the intensively developed landscapes of the Waikato, or both.

8 Recommendations

Further research is needed to ascertain

(1) If there is a minimum critical size below which more intensive management (such as planting) is needed to ensure long-term survival of kahikatea forest fragments in the Waikato Region.
(2) Whether development of lower tiers dominated by weeds in recently fenced fragments is an artefact of small size rather than the result of a major shift in the native/alien dynamic in the intensively developed landscapes of the Waikato Region.
(3) The effectiveness of additional management to ensure long-term survival of kahikatea forest fragments in the Waikato Region. These are particularly important for fragments less than 2 ha in area:

    (i) The success of replanting individual representative kahikatea forest species where they have been lost;
    (ii) The efficacy of different species planted as edge buffers in reducing microclimatic edge effects within fragments;
    (iii) The success of weed control in increasing native species dominance in lower tiers.

(4) The best ways of rapidly re-establishing kahikatea forest to:

    (i) Increase the area and improve the shape of kahikatea forest fragments with convoluted edges;
    (ii) Link small existing fragments to increase area and improve shape;
    (iii) Link kahikatea forest fragments with adjacent wetlands.

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Appendix 1: Characteristic alluvial kahikatea forest species

Alectryon excelsus subsp. excelsus	titoki
Aristotelia serrata	wineberry
Asplenium bulbiferum	hen and chicken fern
Asplenium flaccidum	
Asplenium oblongifolium	
Asplenium polyodon	
Astelia hastata	kahakaha
Beilschmiedia tawa	tawa
Blechnum chambersii	
Blechnum filiforme	
Blechnum fluviatile	
Blechnum novae-zelandiae	kiokio
Blechnum parrisiae	
Calystegia sepium subsp. roseata	rasp fern
Carex dissita	
Carex lambertiana	
Carex uncinata	
Carex virgata	
Carpodetus serratus	putaputaweta
Coprosma areolata	
Coprosma tenuicaulis	
Cordyline australis	cabbage tree
Cyathea dealbata	silver fern
Cyathea medullaris	mamaku
Dacrycarpus dacrydioides	kahikatea
Dacrydium cupressinum	rimu
Deparia petersenii subsp. congrua	
Dicksonia fibrosa	
Dicksonia squarrosa	wheki
Diplazium australe	
Freycinetia banksii	kiekie
Geniostoma ligustrifolium var. ligustrifolium	hangehange
Hedycarya arborea	pigeonwood
Histiopteris incisa	water fern
Knightia excelsa	rewarewa
Lastreopsis glabella	
Lastreopsis microsora subsp. pentangularis	
Laurelia novae-zelandiae	pukatea
Melicytus micranthus	
Melicytus ramiflorus subsp. ramiflorus	mahoe
Metrosideros diffusa	
Metrosideros perforata	
Microlaena avenacea	
Microlaena stipoides	
Microsorum pustulatum subsp. pustulatum	
Muehlenbeckia australis	
Myrsine australis	mapou
Nestegis lanceolata	white maire

Oplismenus hirtellus subsp. imbecillis	
Parsonsia heterophylla	
Passiflora tetrandra	native passionvine
Pellaea rotundifolia	
Pneumatopteris pennigera	
Podocarpus totara var. totara	lowland totara
Prumnopitys taxifolia	matai
Pseudopanax crassifolius	lancewood
Pteridium esculentum	bracken
Pteris macilenta	
Pteris tremula	
Pyrrosia eleagnifolia	
Ripogonum scandens	supplejack
Streblus heterophyllus	turepo

Appendix 2: Photographs of kahikatea forest fragments

Fig. 2. The more degraded portion of a 2.4 ha fragment at Walton fenced within the past decade, showing an absence of understorey and a ground layer of tradescantia. Very low ecological integrity (Plot method); 12.2 for the whole fragment (Green Wheel method, Denyer 2019). March 2018.

Fig. 3. The less degraded portion of a 2.4 ha fragment at Walton fenced 17 years ago, with a subcanopy partly of small-leaved privet and ground layer partly of tradescantia. Low ecological integrity (Plot method); 12.2 for the whole fragment (Green Wheel method, Denyer 2019). March 2018.

Fig. 4. The northern end of a 1.2 ha fragment at Lee Martin Rd, Matangi, fenced 21 years ago, with a subcanopy mostly of tree privet and a ground layer partly of tradescantia. Without edge planting, the interior is exposed to desiccating winds. Already very impoverished in the 1980s, it has lost almost no more species since then. Low ecological integrity (Plot method); 13.2 (Green Wheel method, Denyer 2019). March 2018.

Fig 5. The western side of the 1.2 ha fragment at Lee Martin Rd, Matangi, fenced 21 years ago, showing the recent windfall of a canopy tree. There is no effective replacement. Fragments of this size are entirely "edge" and even with fencing, may not be sustainable unless intensively managed. Low ecological integrity (Plot method); 13.2 (Green Wheel method, Denyer 2019). March 2018.

Fig. 6. A 2 ha fragment at Gordonton fenced 31 years ago, with some recovery of the subcanopy, understorey and ground layer. There has been edge and gap planting. Low-Medium ecological integrity (Plot method); 15.9 (Green Wheel method, Denyer 2019). March 2018.

Fig. 7. Whewell's Bush Scientific Reserve, Matangi, a 9.9 ha remnant fenced 41 years ago, with a well developed indigenous subcanopy, understorey and ground layer. It has been extensively edge-planted and is subject to weed and pest control. Medium-High ecological integrity (Plot method); 20.8 (Green Wheel method, Denyer 2019). March 2018.

Fig. 8. Arnold's Bush, Piarere, a 3.8 ha fragment mostly fenced 48 years ago, with a well-developed indigenous understorey and ground layer. Medium-High ecological integrity (Plot method); 16.8 (Green Wheel method, Denyer 2019). March 2018.

Fig. 9. Claudelands Bush (Jubilee Park), Hamilton, a 5.2 ha fragment fenced for 90 years with a

well-developed indigenous subcanopy, understorey and ground layer. After a long period with serious tradescantia invasion, it is now subject to weed and pest control. It has also had extensive edge planting. It had lost up to 33% of its vascular flora by 1980. Medium-High ecological integrity (plot method); 21 (Green Wheel method, Denyer 2019). March 2018.

Appendix 3: Green Wheel Scores

* denotes uncertainty about recovery period. / denotes two different fencing histories within a fragment.

Site (recovery period)	**Walton** (10*/17)	**Marychurch Rd** (18)	**Lee Martin Rd** (21)	**Gordonton** (31)	**Whewell's Bush** (41)	**Piarere** (26/48)	**Claudelands Bush** (90)
Atrribute A	**Absence of threats**						
Stock access	5	5	5	5	5	5	5
Feral ungulates	5	5	5	5	5	5	5
Ground browsers	4	3	4	4	4	4	5
Canopy weed abundance	4	5	5	5	5	5	5
Shrub weed abundance	1	4	1	3	5	5	5
Ground weed adundance	3	5	1	4	5	4	5
Pest plant presence	1	1	1	1	1	1	4
Nutrient input	2	4	4	4	4	4	5
Drainage	5	2	4	4	4	2	2
Human footprint	5	5	4	5	5	5	4
Averaged score	3.5	3.9	3.7	4	4.3	3.5	4.5
Attibute C	**Species composition**						
Native dominance	3	3	3	3	3	2	3
Representative species	2	4	1	2	4	3	3
Averaged score	2.5	4.5	2	2.5	3.5	2.5	3
Attribute D	**Community structure**						
Vegetation layers	2	5	2	3	5	5	5
Canopy condition	5	5	5	5	5	5	5
Averaged score	3.5	5	3.5	4	5	5	5
Attribute E	**Ecosystem function**						
Winter bird-food availability	1	4	2	2	3	3	4

All-season bird-food availability	3	4	2	2	3	4	3
Plant recruitment	1	3	5	5	3	3	4
Averaged score	1.7	3.7	3	3	3	3.3	3.7
Attribute G	**Management regime**						
Legal protection	1	5	1	1	5	1	5
Management plan	1	1	1	1	5	1	5
Animal pest control	1	5	1	3	4	3	4
Plant pest control	1	5	1	3	5	3	5
Revegetation effort	1	4	1	4	5	4	5
Averaged score	1	4	1	2.4	4.8	2.4	4.8
TOTAL SCORE	12.2	21.1	13.2	15.9	20.8	16.8	21