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RESEARCH ARTICLE

Implementing integrated measurements of Essential Biodiversity Variables at a national scale

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Abstract

1. There is a global need for observation systems that deliver regular, timely data on state and trends in biodiversity, but few have been implemented, and fewer still at national scales. We describe the implementation of measurement of Essential Biodiversity Variables (EBVs) on an 8 km × 8 km grid throughout New Zealand, with multiple components of biodiversity (vegetation, birds, and some introduced mammals) measured simultaneously at each sample point.

2. Between 2011 and 2017, all public land was sampled nationally (ca. 1,350 points) and some private land (ca. 500 points). Synthetic appraisals of the state of New Zealand's biodiversity, not possible previously, can be derived from the first measurement of species distribution, population abundance, and taxonomic diversity EBVs.

3. Native bird counts (all species combined) were about 2.5 times greater per sample point in natural forests and shrublands than in non-woody ecosystems, and native bird counts exceeded those of non-native birds across all natural forests and shrublands.

4. Non-native plants, birds, and mammals are invasive throughout, but high-rainfall forested regions are least invaded, and historically deforested rain shadow regions are most invaded.

5. National reporting of terrestrial biodiversity across New Zealand's public land is established and becoming normalised, in the same manner as national and international reporting of human health and education statistics. The challenge is extending coverage across all private land. Repeated measurements of these EBVs, which began in 2017, will allow defensible estimates of biodiversity trends.

KEYWORDS
biological invasions, grid-based sampling, non-native birds, state and trend monitoring, systematic biodiversity assessment

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1 | INTRODUCTION

Biodiversity is being lost globally at an increasing rate (Tittensor et al., 2014), caused by habitat destruction, land-use intensification, pollution, overharvesting, climate change, and biological invasions (Dornelas et al., 2014; Gossner et al., 2016). Most evidence of biodiversity trends at national and global scales is aggregated from local data sources, often subjectively placed (McGill, Dornelas, Gotelli, & Magurran, 2015) or otherwise biased (Fournier, White, & Heard, 2019; Geijzendorffer et al., 2016). Different components of biodiversity are often measured at different sample points and seldom simultaneously, which limits understanding of interrelationships among them (Dornelas et al., 2019, Pereira & Cooper 2006). The lack of a harmonised observation system delivering regular, timely data (Pereira et al., 2013) hampers understanding of how biodiversity responds to pressures (Pecl et al., 2017). Despite repeated calls for widespread, objective biodiversity data (e.g. Jackson et al., 2016), there are few examples (e.g. Alberta Biodiversity Monitoring Institute, 2015) and only one that we know of at a national scale (in Mexico; Garcia-Alaniz et al., 2017).

Systematic national biodiversity monitoring requires a range of methods, from those assessing ecosystem structure (e.g. remote sensing; Pereira et al., 2013) to those assessing species populations. Repeated measures of permanent sample points allow assessment of trends in species populations and community composition (Pereira et al., 2013), enabling global meta-analyses (e.g. Dornelas et al., 2014; Vellend et al., 2013). For example repeated measures of permanent vegetation plots reveal changes in plant populations and community composition at large scales (e.g. Mayor, Cahill, He, & Boutin, 2015). Systematic national monitoring allows evaluation of regional or local variation, because trends in biodiversity are scale dependent (McGill et al., 2015). It can provide baselines for ecosystem-based management, without which poor decision-making and environmental policies can result (Seargeant, Moynahan, & Johnson, 2012; Yaffee, 1997).

The United Nations Convention on Biological Diversity (CBD) provides a global imperative for national biodiversity monitoring. Pereira et al. (2013) formulated Essential Biodiversity Variables (EBVs) suitable for determining progress towards the Aichi Targets of the CBD, set for 2020. The EBV classes include species populations and community composition, which include individual EBVs well suited to repeated measurements at point locations. New Zealand is a global biodiversity hotspot (Myers, Mittermeier, Mittermeier, da Fonseca, & Kent, 2000), with very high endemism. As a signatory to the CBD, New Zealand needs to report progress towards Aichi Targets and it has passed legislation (Environmental Reporting Act 2015) requiring regular environmental reporting, including biodiversity. A single Government agency, the Department of Conservation (DOC), administers 32% of the country's land area, including nearly all its alpine ecosystems and most natural forests (in total 85,522 km^2, Table S1; hereafter 'public land'). The Department needs to report progress towards maintaining and restoring native biodiversity (McGlone, McNutt, Richardson, Bellingham, & Wright, 2020). Regional governments are responsible for enacting policies, rules, and plans to maintain native biodiversity across the rest of New Zealand, including agricultural ecosystems and plantation forests where non-native plants comprise most biomass.

In response to international, national, and regional requirements, DOC began systematic measurement and reporting of biodiversity state and trend across public land in 2011. Reporting is based on ecological integrity, defined in terms of dominance by native species, species representation (occupancy within former or predicted range), ecosystem representation, and resilience to climate change (McGlone et al., 2020). In this paper, we describe the implementation of multiple, integrated measures of EBVs at point locations to meet national and international reporting requirements (e.g. CBD, Montreal Process). The EBVs (within the species populations and community composition EBV classes; Table 1) measure native and non-native vascular plants and birds. They suit New Zealand's national requirements, because conservation management often focuses on maintaining and restoring bird communities and their habitats, and they are consistent with recommended global measures (Herzog & Franklin 2016; Pereira & Cooper 2006; Schmeller et al., 2018). Species populations and community composition of some non-native terrestrial mammals are also measured because they exert strong influences on native flora and fauna (Walker & Bellingham 2011). New Zealand already reports EBVs based on national-scale remote sensing (in the ecosystem structure EBV class; e.g. Cieraad, Walker, Price, & Barringer, 2015) and the data from point locations sampled systematically can supplement and add value to these EBVs by validating interpretation of imagery (Table 1; Pereira et al., 2013). National measurements of EBVs at point locations recognise interrelationships between native and non-native biodiversity (Figure. 1) and are all quantified within weeks of each other at the same permanent sample points. We demonstrate these interrelationships at a national scale, which was impossible before the programme began.

2 | MATERIALS AND METHODS

2.1 | Measuring and reporting EBVs across New Zealand

The main islands of New Zealand (North Island, South Island, Stewart Island, and immediately adjacent islands) extend between 34° 23′ S and 47° 17′ S and comprise 266,256 kmš. Axial mountain ranges extend about 80% of the country's length (up to 3,724 m elevation in the South Island), while volcanic peaks (up to 2,797 m) feature prominently in the North Island. The climate is oceanic temperate (McGlone, Buitenwerf, & Richardson, 2016). Before human settlement, most land below treeline was forested, with alpine grasslands above treeline. Māori settlement (from about 1280) caused deforestation of drier regions, east of the axial ranges (Perry, Wilmshurst, & McGlone, 2014). European settlement from about 1830 deforested the wetter regions and lowlands, and altered the biota by introducing European agricultural grasses, crops, and livestock such that little native vegetation cover now remains in some regions (Walker & Bellingham 2011). Many introduced plants and animals are invasive and have caused substantial, rapid change in native biodiversity. For example non-native predatory

TABLE 1 Essential Biodiversity Variables (EBVs) for which New Zealand's national biodiversity monitoring programme contributes data specifically (X, or other qualifiers) and to which it could potentially contribute data (P; in situ data could supplement EBVs measured primarily by remote sensing), within EBV classes (Pereira et al., 2013). Dashes represent EBV classes or individual EBVs to which no contribution is made. Individual EBVs and their descriptions are from https://geobon.org/ebvs/what-are-ebvs/

EBV class	EBV	Vegetation	Birds	Mammals
Genetic composition		–	–	–
Species populations				
	Species distribution	X	X	X
	Population abundance	X	X	X
	Population structure by age/size class	Trees only	–	–
Species traits		–	–	–
Community composition				
	Taxonomic diversity	X	X	Partial
	Species interactions	P	P	P
Ecosystem structure				
	Ecosystem extent and fragmentation	P, in situ	P, in situ	P, in situ
	Ecosystem composition by functional types	P, in situ	P, in situ	P, in situ
Ecosystem function				
	Disturbance regime	P, in situ	–	–

mammals, as well as human hunting, caused major extinctions in its fauna and non-native ungulates modified many ecosystems (Walker & Bellingham 2011). The naturalised non-native vascular plant flora (1,792 species) is almost as large as the native flora (2,299 species; Brandt et al., 2020). Contemporary pressures on New Zealand's biodiversity are biological invasions, habitat destruction, land-use intensification, and climate change. On public land, 85.7% is predominantly in native vegetation cover (sensu Cieraad et al., 2015), 4.1% predominantly in non-native vegetation cover, and 10.2% is unvegetated (Table S1). Most (62.8%) of the 11.67 million ha in native vegetation cover is administered by DOC; the remainder is mostly privately owned.

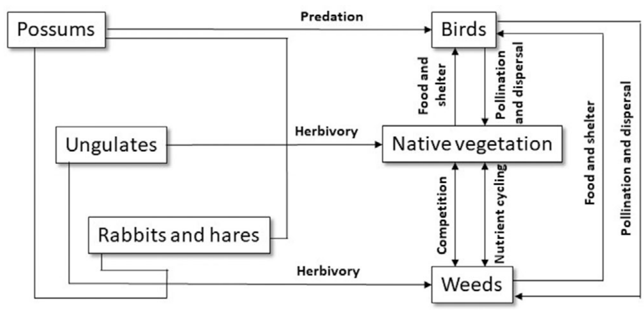

FIGURE 1 Interrelationships among measures of Essential Biodiversity Variables implemented throughout New Zealand

2.2 | Species populations and community composition as EBV classes measured nationally

The EBVs implemented across New Zealand provide data for two of six EBV classes, that is species populations and community composition (Pereira et al., 2013), and provide comprehensive quantification of three individual EBVs for vegetation, birds, and non-native mammals, and of another EBV (population structure) for forest trees (Table 1). Vegetation, birds, and non-native mammals have been of enduring public interest and are major foci for management and restoration (Allen, Bellingham, & Wiser, 2003; Norton, 2009). Effects of biological invasions are a particular focus. Individual EBVs employ widely used methods (Supporting Information S1) but never before combined simultaneously at the same sample points; each have therefore required iterative refinement (e.g. Forsyth et al., 2018a; Gormley et al., 2015). Methods provide data on 15 of 32 non-native mammals, particularly herbivores (Figure 1) and two omnivores (brushtail possums *Trichosurus vulpecula* and pigs *Sus scrofa*). Other non-native mammals, notably rodents and mustelids, have large interannual population fluxes so are unsuited to annual measurements. Integrated measurements of vegetation, birds, and mammals at sample points are a novel aspect of the design that enables interrelationships among them to be determined (Figure 1).

The national programme uses a grid-based, systematic sampling approach centred on a permanently marked 20 m × 20 m vegetation plot, within and about which measures for birds and mammals are conducted to a maximum distance of 200 m from the plot (Figure 2). The grid size (8 km × 8 km) was chosen to achieve a sample size sufficient to produce an unbiased national estimate of the carbon stored in natural forests and shrublands on public and private land with statistical precision of 5% about the mean, as required under the 1992 Kyoto Protocol, and subsequently the United Nations Framework Convention on Climate Change (UNFCCC) and 2015 Paris agreement (Coomes, Allen, Scott, Goulding, & Beets, 2002; Holdaway et al., 2017).

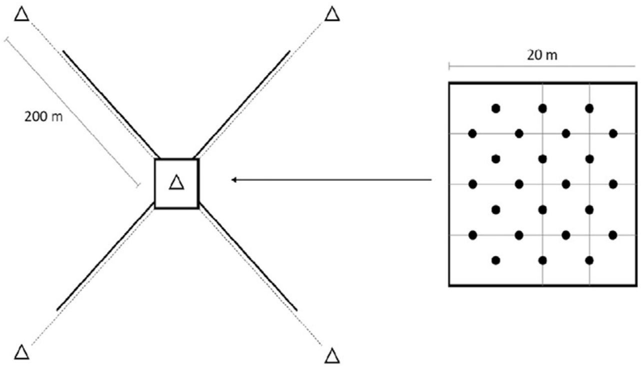

FIGURE 2 Field plot layout for measuring Essential Biodiversity Variables (EBVs) for birds (triangles), vegetation (enlarged square at right), and mammals

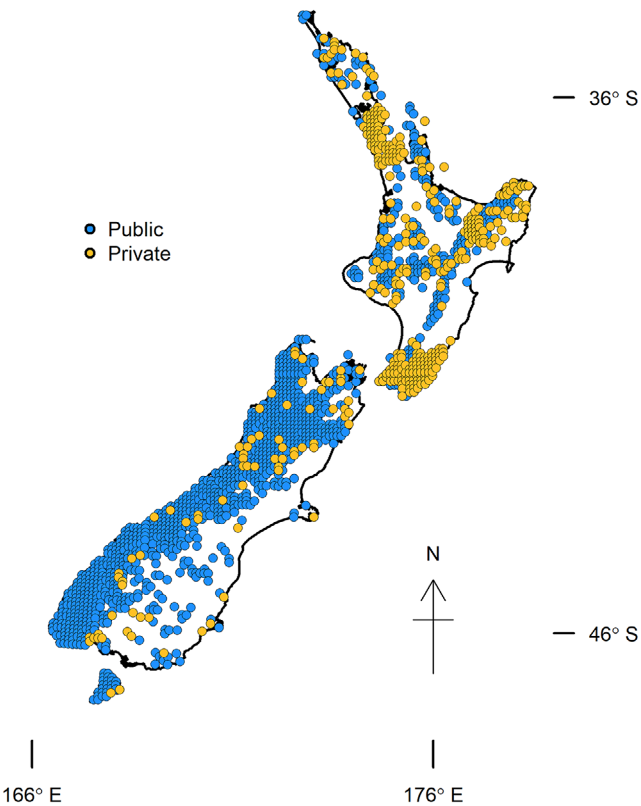

FIGURE 3 Points on public and private land sampled until 2019 on an 8-km grid superimposed across New Zealand

National biodiversity monitoring capitalised on that initiative and, since 2011, the grid-based sampling approach for EBVs has been extended to include all ecosystems (Figure 3). EBVs had not previously been measured in non-woody ecosystems at a national scale, nor had they included non-vascular species. EBVs for birds and mammals were measured previously in watersheds or protected areas (e.g. Elliott, Wilson, Taylor, & Beggs, 2010, Forsyth et al., 2011) but not nationally.

Measurement of vegetation EBVs began in 2001 in forests and shrublands (Table 2), and vegetation in non-forested ecosystems, and EBVs for birds and mammals began in pilot programmes in 2011 and 2012 (160 sample points; Supporting Information S1). A full annual schedule for all EBVs was implemented across all public land (1,346 points; 2013–2017; Table 2), with remeasurement beginning in 2018 (275 points). Measurement of all EBVs across agricultural ecosystems, plantation forests, and urban areas on private land began in 2014 in the southern North Island (Greater Wellington Region) and in 2016 in the northern North Island (Auckland Council) (Table 2; Figure 3).

3 | RESULTS

3.1 | Native birds are most abundant in natural forests and least abundant in non-woody ecosystems

Native bird counts (all species combined) were nearly four times greater per sample point than non-native birds in forests and shrublands on public land in three elevational classes (Figure 4a; mean count per sample point of native birds across all elevational classes = 9.4; of non-native birds = 2.4; analyses assume no differences in detection probabilities between native and non-native birds). Native bird counts were about 2.5 times more abundant in forests and shrublands than in non-woody ecosystems (mean count across all elevational classes = 3.7; Figure 4a). In non-woody ecosystems, there were no differences between counts of native (mean = 3.6) and non-native birds (3.1) at all elevations. Native bird counts (all species combined) exceeded those of non-native birds across all New Zealand's physiognomic forest groups (sensu Wiser, Hurst, Wright, & Allen, 2011), including shrublands (Figure 4b). Non-native bird counts were greater in shrublands than in all forest physiognomic groups (Figure 4b).

3.2 | Some non-native mammals are almost mutually exclusive in their distributions

Non-native mammals (brushtail possums, brown hares (*Lepus europaeus*), European rabbits (*Oryctolagus cuniculus*), and ungulates) occurred on 88% of 823 sample points across public land (Figure 5). The areas invaded by brushtail possums and those by brown hares were almost mutually exclusive (co-occurrence at only 12% of sample points; $\chi^2{}_1 = 19.5$, $p < .001$). Brushtail possums occurred throughout forests and shrublands, across all latitudes, more often below 1,000 m (79% of sample points) than between 1,000 and 1,500 m (64% of sample points; $\chi^2{}_1 = 5.78$, $p = .016$; Figure 5a). They occurred even less frequently in non-woody ecosystems (44% of sample points), where they were 74% less abundant than in forests and shrublands (mean trap catch index = 1.7% ± 0.28 (*SEM*) % vs. 6.5% ± 0.42%; two-sample $t_{811} = 9.43$, $p < .001$). Brown hares occurred mostly in the eastern South Island, seldom in the North Island (12 of 191 sample points there; Figure 5b) and, in contrast to possums, scarcely occurred in forests and shrublands (only 7% of sample points below 1,500 m). Although brown hares occurred in some non-woody ecosystems below 500 m (14% of those sample points), they were much more frequent in them above 500 m (60% of those sample points), including

TABLE 2 Number of plots where each method was applied each year between 2001 and 2018, partitioned between public and private land, and land cover assigned by dominance by native or non-native vegetation (according to Cieraad et al., 2015)

	Vegetation				Birds				Mammals			
	Native land cover		Non-native land cover		Native land cover		Non-native land cover		Native land cover		Non-native land cover	
Year	Public	Private	Public	Private	Public	Private	Public	Private	Public	Private	Public	Private
2001	70	33		4								
2002	140	59	2	15								
2003	229	105	8	22								
2004	198	79	2	24								
2005	250	62	3	24								
2006	14	28		1								
2007												
2008	65	32		3								
2009	136	53	2	15								
2010												
2011	153	64	5	12	66	4			68	4		
2012	328	92	13	28	84		10		85		10	
2013	244	36	10		255	16	12		258	16	12	
2014	259	48	6	16	255	12	6	13	255	12	6	13
2015	258	40	15	17	249	2	15	12	248	2	15	12
2016	242	44	13	15	237	16	12	14	238	15	12	14
2017	268	44	8	22	257	12	8	18	257	12	8	15
2018	262	43	13	28	260	12	13	25	260	12	13	23

alpine ecosystems (maximum 2,030 m). Brown hares were also about eight times more abundant above 500 m (faecal pellet index below 500 m = 0.96 ± 0.73 vs. above 500 m = 7.97 ± 0.99; $t_{176} = 5.60$, $p < .001$).

3.3 | The deforested eastern South Island is heavily invaded by non-native plants, birds, and mammals

The severity of biological invasions by each of non-native plants, birds, and mammals across public land was assessed using a binary classification based on thresholds defined by either management targets (e.g. Warburton & Livingstone 2015) or expert opinion (Bellingham, Cieraad, Gormley, & Richardson, 2015). Thresholds of a high degree of invasion for non-native plants was >25% of cumulative cover; for non-native birds, their species richness exceeded that of native birds; and for non-native mammals when at least one species (or species group for ungulates) exceeded threshold indices of abundance (presence of brushtail possums at >5% of subsample points, and faecal pellet indices exceeded 40 for ungulates, 5 for brown hares, and zero for European rabbits). A combined metric for each sample point was defined as Good (0 points), Reasonable (1 point), Fair (2 points), or Poor (3 points) based on the sum of the three binary classifications (i.e. to be 'Poor', plants, birds, and mammals all exceeded the thresholds for a high degree of invasion). More than 90% of 777 sample points scored either 'Good' or 'Reasonable'. Those scoring 'Good' (43.4%, $n = 337$) were most prevalent in the western South Island and Stewart Island (Figure 6). Only 6.4% ($n = 50$) of points scored 'Fair' and these were scattered nationally, but most prevalent in the northern North Island and deforested regions of the eastern South Island. The 3.2% ($n = 25$) of sample points that scored 'Poor' were in deforested regions of the eastern South Island, particularly the north-east (Figure 6).

4 | DISCUSSION

The approach taken by New Zealand's national biodiversity monitoring programme of measuring multiple EBVs simultaneously has resulted in defensible, objective reporting of the national state of biodiversity and sets in place an infrastructure that can be measured repeatedly to determine trends and interrelationships among EBVs.

4.1 | Implementing a national programme

Seargeant et al. (2012) identified attributes needed to implement long-term biodiversity monitoring. First is leveraging off existing infrastructure. Reporting EBVs throughout New Zealand built on existing

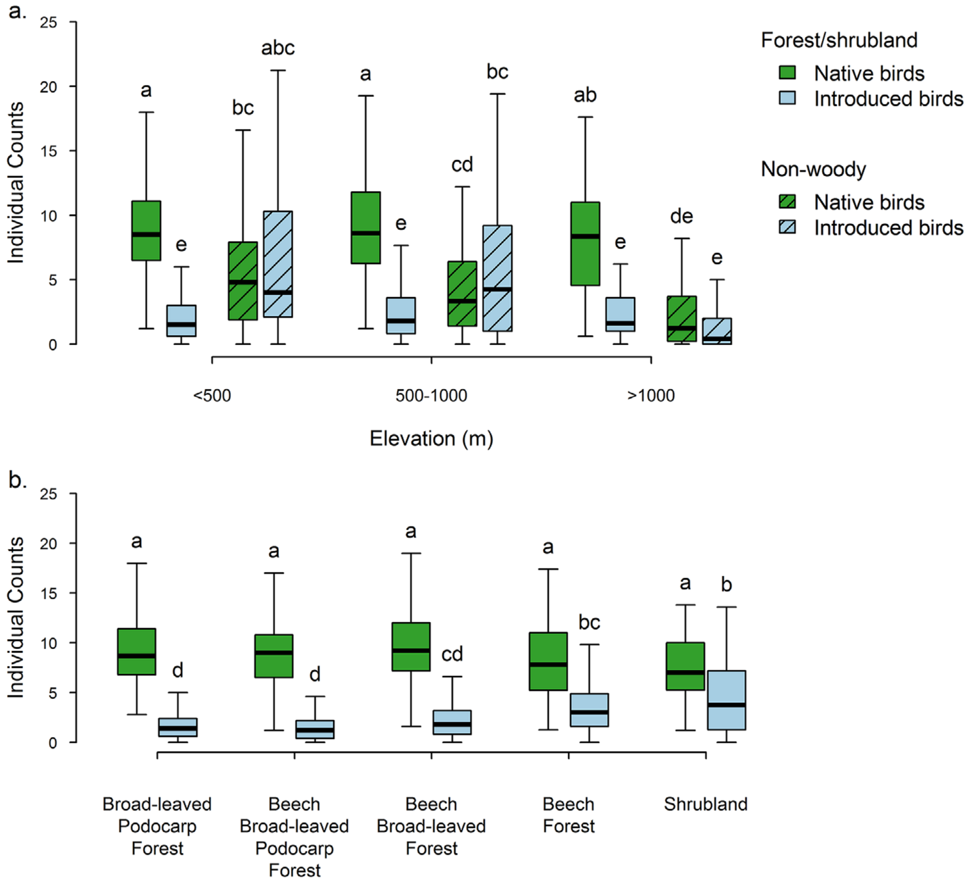

FIGURE 4 Box-and-whisker plots of cumulative counts of all individual native and non-native bird species for 1340 sample points, grouped by (a) forests and shrublands versus non-woody in three elevational classes, and (b) major forest physiognomic groups and shrublands (from Wiser et al., 2011). Counts sharing the same letter are not significantly different at $\alpha = .05$ (Tukey HSD test,). Boxes indicate the 25th and 75th percentiles and the horizontal line indicates the median. The whiskers cover data points no more than 1.5 times the interquartile range from the box

infrastructure for national carbon reporting, using the same permanent plots in natural forests and shrublands (Holdaway et al., 2017) to measure vegetation EBVs (plant species distributions, population abundances, and taxonomic diversity; Table 1) as well as carbon stocks, and the programme uses well-established, existing methods. Mexico's national biodiversity monitoring built upon similar existing national programmes for forests (Garcia-Alaniz et al., 2017). Second, Seargeant et al. (2012) recommended a pilot season, which the programme did, enabling method refinements, and cost and capability evaluations (Supporting Information S1). Third, they recommended regular reporting, and the programme has contributed to DOC's annual reports from its inception (e.g. Bellingham et al., 2015), to the most recent state of environment reports (Ministry for the Environment and Statistics New Zealand, 2015, 2018), and the recent national CBD report. Data from public land are obtainable on request from the New Zealand Department of Conservation and Ministry for the Environment, while data from private land require additional permission from landowners and regional councils.

New Zealand's national programme provides a baseline of measurements at temporal and spatial scales that relate directly to objectives at local management scales, as recommended by Seargeant et al. (2012), and it provides evidence to show local or regional conformity or departure from widespread patterns. For example, control of red deer (*Cervus elaphus scoticus*) was conducted in one forested watershed to determine effects on seedling recruitment, and the local estimates of ungulate density were the same as the median nationally, supporting a view that the effects of control were generalizable (Bellingham et al., 2016). Local management of deer and other ungulates in New Zealand forests has often been predicated on low representation of small stems outside long-established but subjectively placed fenced exclosures compared with those inside. The systematic assessment showed that forests nationally are similar to those 'inside' exclosures (Peltzer et al., 2014), indicating that locally intense effects of ungulate browsing are not generalizable. National data can also provide a rational basis for assigning resources for management, preventing inappropriate diversion of resources to some local sites.

4.2 | Integration of EBVs

The integration of bird and vegetation EBVs from the same sample points demonstrates the importance of forests as habitat for New

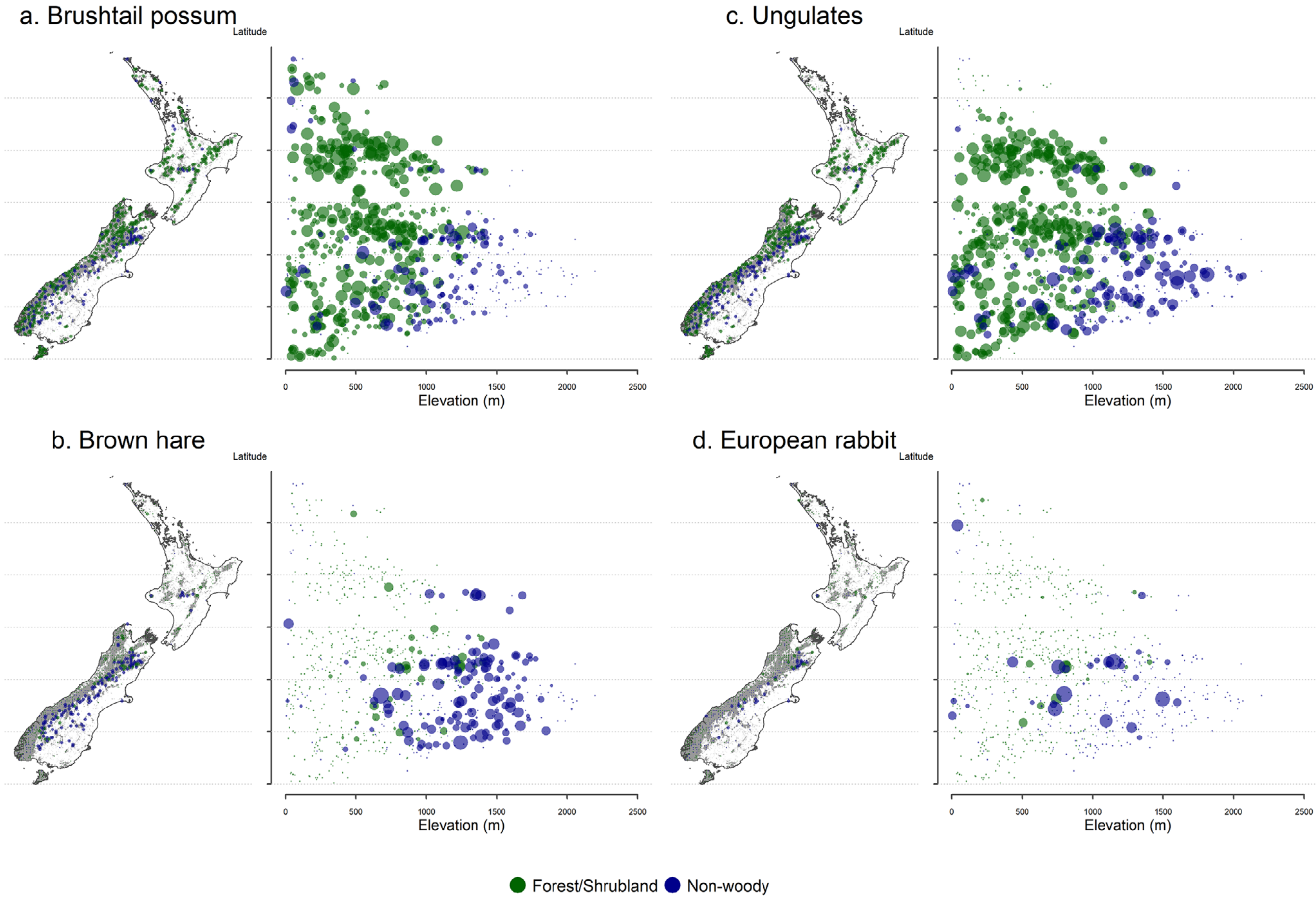

FIGURE 5 Relative abundance of four non-native mammals across 823 sample points by elevation and latitude, ranging from 0 (smallest points) to maximum abundance (largest circles) in woody (green) and non-woody (blue) ecosystems. For possums, circle sizes relate to the mean trap-catch index (possums per 100 trap nights) recorded across four transects. For ungulates, rabbits, and hares, circle sizes relate to the mean pellet count across the four transects. Circle sizes of abundance are not comparable among the four mammal groups

Zealand native birds, and that research is needed to determine why non-native birds sometimes dominate in non-woody ecosystems. Existing national data sources, such as bird species' occurrence in 10 × 10 km cells throughout New Zealand (Robertson, Hyvönen, Fraser, & Pickard, 2007), could not provide this information because most cells contain more than one vegetation type (Dymond, Shepherd, Newsome, & Belliss, 2017), and are therefore unsuitable for linking bird community composition and vegetation habitat. Similarly, the limited co-occurrence of brushtail possums and brown hares (Figure 5) could not be deduced from existing distribution maps (King 2005). National plot-based data will improve precision in species distribution models, enabling them to accommodate the fine-scale differences in climate and habitat essential for forecasting interacting effects of global change.

4.3 | Benefits of national measurement of EBVs

Systematic national sampling is suitable for reporting trends of the common and dominant species that exert the strongest influence on ecosystem processes and underpin provisioning of many ecosystem services (Avolio et al., 2019). Some can become rare rapidly, for example the near-total loss of once-dominant American chestnut (*Castanea dentata*) from eastern North American forests in the early 20th century caused by the non-native pathogen *Cryphonectria parasitica* (Paillet, 2002). Others show gradual, but significant declines, for example 19 abundant North American land bird species each experienced population reductions of >50 million birds over 48 years (Rosenberg et al., 2019), and common plants showed the greatest declines in occurrence over 20 years in Germany (Jansen, Bonn, Bowler, Bruelheide, & Eichenberg, 2020). Repeated national sampling of common species will provide early warning signals to prompt action (Schmeller et al., 2018; Wintle, Runge, & Bekessy, 2010). In New Zealand, unpublished data on bird communities, collected during the National Forest Survey (1940s–1950s; Masters, Holloway, & McKelvey, 1957), show that mohua (*Mohoua ochrocephala*) occurred throughout South Island forests. Had its abundance and occupancy been measured systematically during the 1960s–1990s, its drastic reduction in range, caused mostly by non-native predatory mammals (Dilks, Willans, Pryde, & Fraser, 2003), might have been detected much

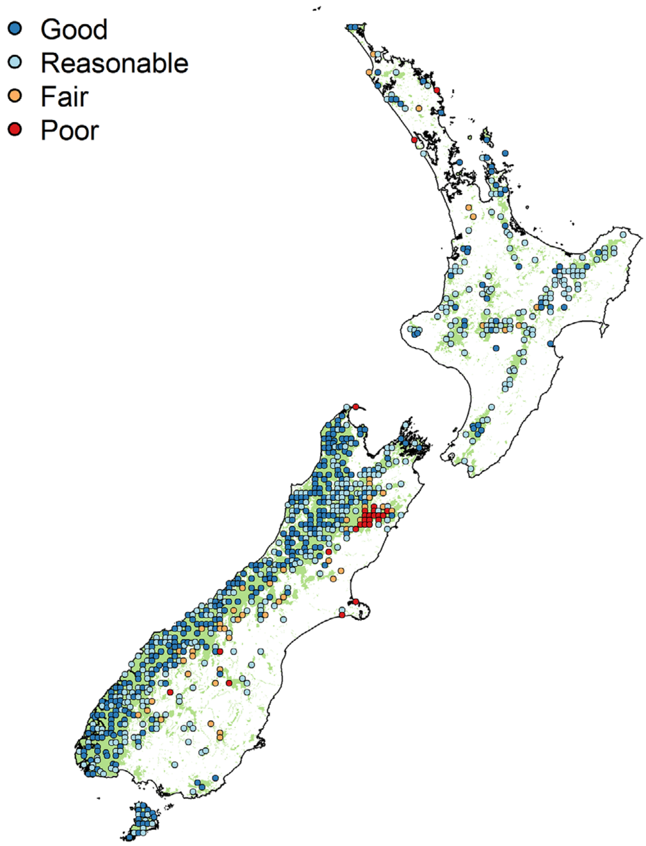

FIGURE 6 Map of an aggregated measure of invasion for 777 sample points by non-native plants, birds, and mammals. The classifications Reasonable, Fair, and Poor represent where 1, 2, and 3 of the taxonomic groups, respectively, exceed their threshold of a high degree of invasions (determined by expert opinion)

earlier. Critically, earlier detection of this trend would have needed to spur management agencies to implement an intervention programme (Lindenmayer, Piggott, & Wintle, 2013) to prevent mohua reaching its current 'nationally vulnerable' status (Robertson et al., 2013).

The Alberta Biodiversity Monitoring Program employs a similar approach to that in New Zealand, measuring vegetation, mammals, and birds across 1,656 sites on a 20-km grid, sampled every 5 years (330–375 sample sites per year; Alberta Biodiversity Monitoring Institute, 2015). Lindenmayer and Likens (2010) bemoaned the lack of questions to guide that Program, but we disagree with this criticism. Because even the best ecologists are poor at anticipating the behaviour of extremely well-studied systems (Doak et al., 2008), questions based on deterministic models can constrain data collection and sampling design (Wintle et al., 2010). Too little is known about many environmental drivers of New Zealand's biodiversity in space and time. For example, distributional limits of many endemic trees and their relative abundances are poorly understood (Lee, 1998) and the distributions of many birds defy simple explanations in terms of habitat suitability or predation pressure (e.g. the patchy distribution of South Island robin (*Petroica australis*); Powlesland, 2013). More generally, we disagree that measuring change in biodiversity requires questions to guide it or hypotheses to test. Governments routinely report trends in GDP, health, crime, and education metrics without hypotheses or questions (McGlone, 2014): these data generate, rather than respond to, questions. Long-term collection of climate data, atmospheric CO_2 concentrations, and precipitation and stream chemistry was driven not by questions, but because the data were seen as fundamental (Lovett et al., 2007; McGlone, 2014): the trends from these data spawned hypotheses and formed the convincing evidence base for global and national policies (Lovett et al., 2007). We believe long-term, systematic collection of biodiversity data is equally fundamental, and that it will similarly generate questions and hypotheses, and form the evidence base needed to set policies to maintain biodiversity (Kidd, Bekessy, & Garrard, 2019), and evaluate their effectiveness (Visconti et al., 2019).

Lindenmayer and Likens (2010) favoured stratifying sample points across the Alberta Biodiversity Monitoring Program according to recent logging history. We argue for measurement of management history, many environmental factors (climate, latitude, lithology, and soil nutrient concentrations; Gardner, 2010), and surrogates for disturbance history (e.g. species composition and ecosystem structure in forests, e.g. Holdaway et al., 2017) to allow post hoc, rather than a priori, stratification (Ramsey, Forsyth, Wright, McKay, & Westbrooke, 2019) because it is often challenging to disentangle management effects from those attributable to natural causes (Peltzer et al., 2014). Such an approach allows documenting and learning from ecological "surprises" (sensu Doak et al., 2008, e.g. unprecedented interactions between climate change and pests and pathogens). The longer the monitoring is maintained, the greater the chance of revealing unprecedented community dynamics (Lindenmayer, Likens, Krebs, & Hobbs, 2010) and detecting effects of infrequent, but ecologically important, events. For example since New Zealand's programme began, the first tropical cyclone in 46 years to disturb western South Island forests occurred in 2014 (Macara, 2015), a M_w 7.8 earthquake in 2016 generated thousands of landslides across the north-eastern South Island (Hamling et al., 2017), and a novel pathogen, myrtle rust (*Austropuccinia psidii*), reached many regions in 2017, infecting some native Myrtaceae species. The national network of sample points allows in situ quantification of the disturbance regime EBV (Table 1), and the data from the other EBVs allow unprecedented quantification of biotic interactions in response to perturbations (e.g. whether myrtle rust effects on fleshy fruited and nectar-bearing Myrtaceae also affect bird species that feed on them).

4.4 | Limitations and relationships to other monitoring initiatives

Systematic national sampling is unsuitable to assess status and trends in uncommon ecosystems (sensu Williams, Wiser, Clarkson, & Stanley, 2007), which will be sampled by few replicates, if at all (Gardner, 2010; Lindenmayer & Likens 2010). Uncommon ecosystems, and the species restricted to them, therefore require their own monitoring systems that encompass their full environmental range. Likewise, local networks can target taxa that are too demanding of expertise to measure nationally (e.g. of invertebrates; Watts, Stringer, Innes, & Monks, 2017), and species with interannual changes in abundance so great that five-yearly measurements are inappropriate (e.g. rodents; Ruscoe, Wilson, McElrea, McElrea, & Richardson, 2004). Local networks that provide intensive sampling in space and time (e.g. Elliott et al., 2010) add interpretive value to national programmes (Jetz et al., 2019), as well as assessing the effectiveness of local management (e.g. Forsyth, Ramsey, Perry, McKay, & Wright, 2018b). The growing contribution of citizen science can also be integrated alongside the national programme (e.g. enhanced prediction of species occupancy; Jetz et al., 2019).

5 | CONCLUSION

New Zealand's national programme is now providing primary data on species populations and community composition throughout the country, which have been hitherto lacking compared with well-surveyed, densely populated countries (e.g. in Europe). The programme's systematic sampling sets it apart from post hoc assembling of data from multiple subjectively placed samples to determine biodiversity status and trend (e.g. Butchart et al., 2010) or from unrepresentative sites (e.g. national monitoring networks that only sample nature reserves, as in China; Xu et al., 2017).

The sustainability of programmes such as New Zealand's is uncertain, in part because of high start-up costs and the lag between implementation and realising benefits, which are most apparent once trends are demonstrated (Watson & Novelly 2004). The national programme currently assesses biodiversity mostly on public land; more emphasis is now needed in private land, which can be achieved through greater regional government participation. The more agencies that are involved (central and regional government, and scientific research agencies), the greater its chances of sustainability (cf. Jackson et al., 2016). This poses challenges in terms of maintenance and sharing of infrastructure (e.g. databases) and coordination of field efforts and capacity building. For now, New Zealand's national reporting of EBVs is a step towards it becoming normalised, in the same manner as its national and international reporting of human health and education statistics.

AUTHORS' CONTRIBUTIONS

Bellingham, Richardson, Gormley, Allen, Forsyth, McKay, MacLeod, van Dam-Bates, and Wright conceived the ideas and designed methodology. Cook, Crisp, McKay, and Wright directed collection of the data. Richardson and Gormley analysed the data. Bellingham and Richardson led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All data used in this study are available in the publicly accessible DataStore: the Manaaki Whenua – Landcare Research Data Repository https://doi.org/10.7931/mvs4-dm96.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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