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Research article

Use of density-impact functions to inform and improve the environmental outcomes of feral horse management

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The available science often demonstrates the need for feral horse population control but not the degree of control required to achieve environmental conservation objectives. To better manage the influence of feral horses, we must first understand the relationship between feral horse density and environmental impact. We recorded vegetation and soil disturbance, and the sign of potential causes of this impact in two parts of the Australian Alps, the Bogong high plains (BHP) and the Eastern Victorian Alps (EVA). We calculated density-impact functions to assist managers with determining feral horse density targets for control programmes. Minimal sign of feral horse impact was detected on the BHP, with no impact of feral horses observed along 99% of the length of transects. In contrast, impacts assigned to feral horses were significantly higher in the EVA, where a larger, higher-density population of feral horses existed. However, greater than 83% of the walked transect length was still undisturbed by feral horses in the EVA. We detected a threshold of horse impact at ~ 250 horse faecal piles per ha. Above this threshold, a slight increase in horse density resulted in a disproportionately large increase in impact. In this context, a relatively small population control effort may substantially reduce direct horse impact. But where horse densities exist below this threshold, considerably more expense and control effort (resulting from the difficulties related to control at low density) is likely to make very little difference to an already low level of direct impact. The combined impacts associated with the sign of deer, feral pigs, fire and humans were large compared to that of feral horses. Management of feral horses to reduce their direct impact is unlikely to be beneficial without complementary management to reduce the effects of these other agents of impact.

Keywords: brumby, density-impact, environmental impact, *Equus caballus*, mustang, overgrazing, wildlife management

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Introduction

Effective management of feral horses *Equus caballus* and their environmental impact is challenging due to complex ecological and socio-political issues (Beever et al. 2019, Scasta et al. 2020, Boyce et al. 2021). Terminology complicates the situation further. For instance, the term 'feral' is shunned by some sections of the community because it is considered derogatory, or an undesirable synonym of 'pest' (ITRG 2016, SAP 2020). Others are content with 'pest horse' or 'invasive species' and are sensitive to potential barriers to population control, such as suggestions that feral horses may be beneficial to some economic, environmental or social value. Some use 'free-ranging' or 'wild', but we prefer the term 'feral' because it is accurate given that feral horses are derived from domestic horses. Feral horses have evolved through three phases of selective pressure: the first before domestication, the second requiring adaptation to a domestic state, and the third phase requiring adaptation to living wild, independent of humans once more (Berman 1991). The meaning of the term impact has also become distorted due to the emotion involved and is now commonly believed to imply damaging influences (Driscoll et al. 2019b) when this is often not the case. Here we defined the impact of feral horses to be any change that occurs because of feral horses, whether detrimental, neutral or beneficial.

Eldridge et al. (2020) analysed data from 78 studies across five continents and reported that the impacts of feral horses reduced 'the status of ecosystem characteristics that are important for sustaining all living organisms' (Eldridge et al. 2020) by 13% overall. The magnitude of this decline increased with increases in the density or frequency of use of an area by horses. The direct impact from grazing and trampling of vegetation and soil further increased soil erosion and reduced plant biomass and litter cover (Eldridge et al. 2020). The evidence presented by these studies supports an increased effort to control or remove feral horses, where necessary, to achieve some lower level of environmental impact (TWS 2011, Worboys et al. 2018, Driscoll et al. 2019b, Schoenecker et al. 2021). In contrast, feral horses have been positive and instrumental in the management of vegetation in European conservation reserves (Duncan 1992, Menard et al. 2002, Nuñez et al. 2016) by maintaining short lawns within a matrix of tall grass areas, which promotes plant and animal diversity, thereby increasing the abundance of food for endangered rabbits, waterfowl and seed-eating bird species (Fleurance et al. 2011, Fleurance et al. 2012). Grazing by feral horses or other introduced ungulates can facilitate some native ungulate species in North America (Berger 1986) and macropods in Australia (Newsome 1971). Coprophagous insects or predatory beetles benefit from horses in Europe (Fleurance et al. 2012). Increased insect abundance near dung also provides food for lizards or amphibians (Duncan 1992). These ecological benefits of horses may be associated with returning ecosystem structure or function to the period prior to the disappearance of mega-fauna (Freeland 1990). This could include reduced fuel for wildfire (Rule et al. 2012) or increased plant species and structural diversity (Duncan 1992, Wild and Poll 2012). Evidence that horses can have both damaging and beneficial impacts means there is no one simple message to bring community groups together to support feral horse management. Detailed, careful, scientific monitoring conducted in a way that attracts community support is required to guide sensible and effectual feral horse management, such as was demonstrated in central Australia over 30 years ago (Berman 1991, Dobbie et al. 1993, Nuñez et al. 2016, Braysher 2017).

In New Zealand and the United States of America (USA), feral horses were protected by laws enacted due to fear that these culturally valuable horses would be lost (Rogers 1991, National Research Council 2013). Horse numbers have increased since their protection, putting ecosystems at risk and requiring ongoing management to restrict population growth. The intention in the USA is to keep feral horse populations at 'appropriate management levels' to achieve a 'thriving natural ecological balance and prevent rangeland deterioration with minimal management' (National Research Council 2013). Native wildlife benefits in places where feral horse populations have been maintained at or below appropriate management levels, but feral horse numbers have commonly increased above the intended levels (Coates et al. 2021).

In Australia and Argentina, feral horses have generally been considered invasive species managed to minimise adverse environmental impacts (Nuñez et al. 2016, Scorolli 2018), though this policy position is not unanimous. In the New South Wales section of the Australian Alps (Kosciuszko National Park) the cultural heritage value of feral horses has been explicitly acknowledged since the passing of the Kosciuszko Feral Horse Heritage Bill (2018), where feral horses are to be protected without compromising other values of the national park. While there are highly variable impacts of feral horses on ecosystems worldwide (Monsarrat et al. 2020) and management goals vary considerably, one common theme that could unite the various viewpoints is to maintain horse densities at levels where their ecological damage is minimised and their ecological and cultural benefits are maximised. To achieve this balance it is essential to know how vegetation and ecosystem functioning varies with feral horse density (Dobbie et al. 1993, Walters and Hallam 1993, Dawson 2009, National Research Council 2013), but this area of research has received very little attention (Berman and Jarman 1988, Berman 1991, Beever and Herrick 2006).

Successful management requires selecting a threshold level of population control or density of feral horses, below which their impact is acceptable to the agency responsible and the community, based on scientific measurement of beneficial and detrimental impact. This threshold level could be zero horses in some cases, but removing all horses (local eradication) is rarely achieved and it may or may not be the most desirable goal (Bomford and O'Brien 1995). Feral horses often inhabit remote and rugged areas where it is extremely difficult to locate and remove every individual. Community groups often oppose eradication, and agencies responsible rarely have the resources to overcome the logistical and technical difficulties of achieving eradication. Control methods may also be inadequate, and the required perseverance can be lacking for a very long and challenging process (Matthews et al. 2001, Berman 2013). The high cost of eradication, including continued work to maintain the area free of horses, must be weighed against the cost of ongoing management of a sustainable population that retains its heritage, aesthetic and ecological value. A plan to 'do nothing' with feral horse populations is likely to be unsatisfactory since, without management, feral horses tend to increase to high abundances where food becomes limiting (Dobbie et al. 1993, Dawson and Hone 2012, Zabek et al. 2016b, Scorolli 2021). Where this occurs, horse density will almost certainly be higher than the threshold for acceptable environmental impact. There will also be unacceptable horse welfare impacts as horses suffer prolonged deterioration and death due to lack of food or water (Berman and Jarman 1987, Berman 1991). If eradication is not a viable option and doing nothing is unacceptable, then a target density somewhere in between must be determined (Braysher 1993, Dobbie et al. 1993).

Density-impact functions, such as the relationship between the density of feral horses and the reduced viability of populations of threatened species, can help determine the minimum intensity of control required to reach a target level of impact (Braysher 1993, Hone 1994, Choquenot and Parkes 2001, Hone 2007, Norbury et al. 2015, Braysher 2017). When feral horse density coincides with a maximum acceptable conservation impact, a threshold can be set for imposing control. When feral horse density exceeds this threshold, conservation impacts will be unacceptable, and horse control will be required. Where feral horse density is below the threshold, further control will incur some opportunity cost (for example, the loss of the chance to control deer or feral pigs due to resources wasted by continuing to manage horses with no benefit achieved) and is not recommended (Choquenot et al. 1997, Choquenot and Parkes 2001).

Feral horse management is particularly controversial in the Australian Alps, which is considered home for not only horse people and feral horses but also a range of vulnerable or endangered native animals endemic to this uniquely moist and higher-altitude part of Australia (Carr and Turner 1959a, Calaby and Wimbush 1964, Costin et al. 2000, Green and Osborne 2003). Consequently, there is considerable conflict between stakeholder groups, with the extremes holding very inflexible ideologies, and reciprocal mistrust of Government agencies, community groups, and scientists (ITRG 2016, SAP 2020), as is the case in many other parts of the world (Boyce et al. 2021). Science is essential for informing Government policy and the public to help ensure sensible, successful, and acceptable management of feral horses (Berman 2012). Community engagement and involvement of community groups in research and management have been recommended and shown to improve the acceptance of scientific findings and management approaches (Dobbie et al. 1993, Berman 2013, Scasta et al. 2020, Berman 2021).

Feral horses were established in the Australian Alps by the 1830s, but reports of potential environmental issues did not appear until the 1950's (Costin 1954). It was then almost another 40 years before feral horse impacts were first examined scientifically (Dyring 1990). There has been a recent rapid increase in scientific activity in the Australian Alps (Driscoll et al. 2019a). The hard hooves, grazing, and trampling of feral horses are assumed to cause damage because these large, introduced ungulates did not evolve with the Australian vegetation, soil and water (Wimbush and Costin 1979, Dyring 1990, Lawrence 1995, McDougall 2007, Department of the Environment 2015, Cherubin et al. 2019, Foster and Scheele 2019, Robertson et al. 2019, Schulz et al. 2019). Exclusion plots and sampling at sites with or without feral horses demonstrate their direct impacts, such as selective removal of vegetation by grazing or trampling, exposure and compaction of soil, and deposition of dung (Dyring 1990, Wild and Poll 2012, Williams et al. 2014, Robertson et al. 2019). These studies recorded the direct impact of horses, but how this impact varies with horse density has not been reliably quantified. Consequently, existing studies provide very little guidance for managers seeking to define targets for feral horse density or monitor changes resulting from management actions.

In this study, we aimed to 1) measure the direct environmental impact of feral horses in two separate parts of the area occupied by feral horses in the Victorian part of the Australian Alps, one with low and the other with higher feral horse density, 2) compare impact associated with the sign of feral horses, with impact associated with the sign of other potential agents of impact such as deer *Rusa unicolor*, *Dama dama*, feral pigs *Sus scrofa*, fire, and humans 3) and derive density-impact functions using faecal pile density as an index of feral horse density. Our overall goal was to identify any threshold of feral horse density that stakeholders could use to inform more collaborative management of feral horse environmental effects. We further suggest ways to improve the measurement of the environmental effects of feral horses and other potential agents of impact.

Material and methods

Study area – general

The mountainous area known as the Australian Alps includes the southeastern part of New South Wales (predominantly Kosciuszko National Park) and the northeastern part of Victoria (predominantly the Australian Alpine National Park). In March 2020 and again in February–March 2021, we visited sites in the Victorian part of the Australian Alps (sites were within 11 km of latitude −36.91302°, longitude 147.30136° and within 40 km of latitude −36.92271°, longitude 148.09149°; Fig. 1). In the Victorian part of the Australian Alps, two separate areas occupied by feral horses, about 50 km apart, are known locally as the Bogong high plains (BHP) and the Eastern Victorian Alps (EVA). These areas, respectively, have different feral horse densities of 0.8 and 1.72 feral horses km^{-2}, different population sizes of ~

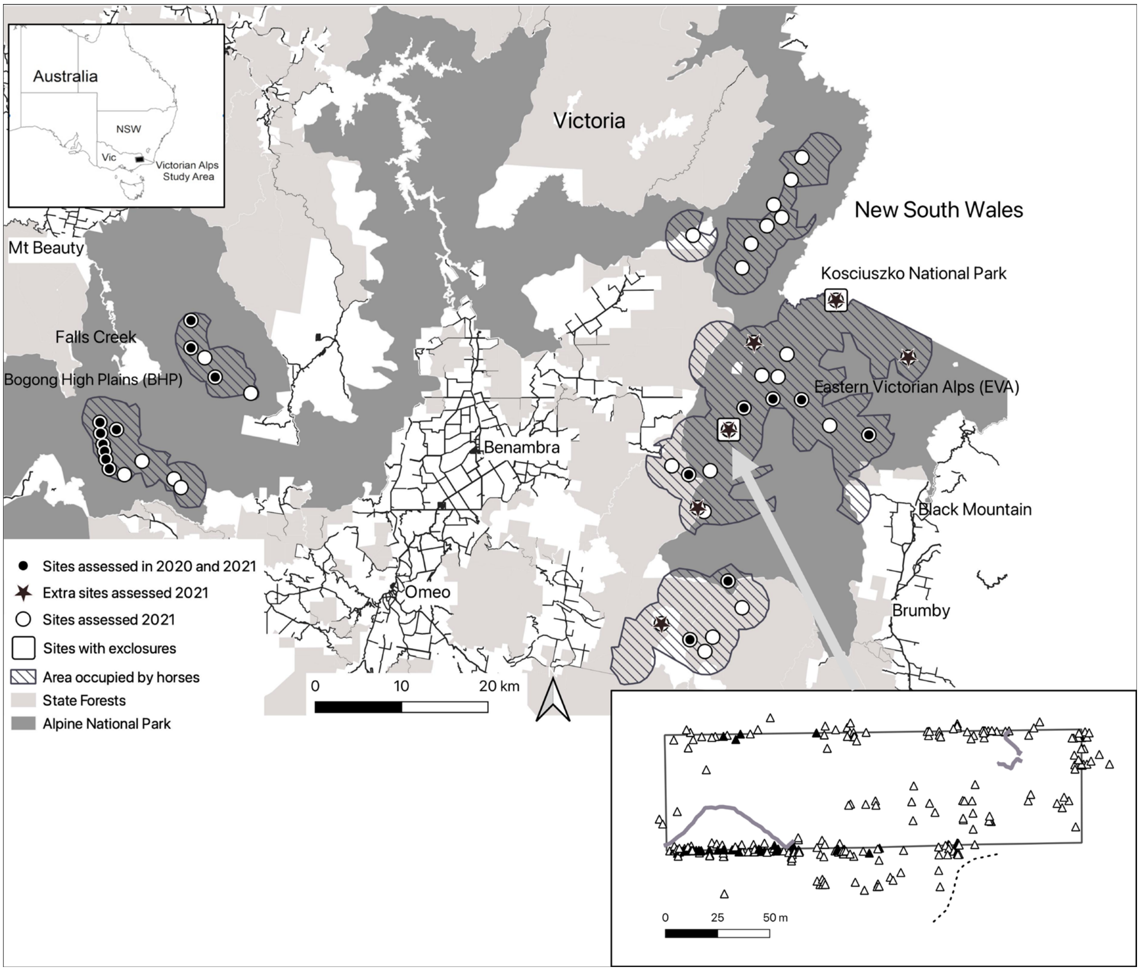

Figure 1. The location of sites visited by us in March 2020 and February–March 2021 in the Victorian part of the Australian Alps (Australian Alpine National Park and State Forests) to measure the environmental impact associated with feral horses. Sites with streams present in alpine treeless drainage line vegetation type, were visited in the two separate parts of the area occupied by feral horses in the Victorian Alps, the Bogong High Plains (BHP) and the Eastern Victorian Alps (EVA). The area occupied by feral horses (hashed) within three kilometres of the entire set of sites established in 2012 (Robinson et al. 2019). Horse occupation confirmation was based on aerial survey (Cairns 2019) in the EVA and ground surveys (Tolsma and Shannon, 2018, Robertson et al. 2019) on the BHP. An example site map shows the 500 m rectangular Site-transect (thin black line), 50 m Streambank-transect (dashed line), animal paths (thick grey lines), horse faecal piles (open triangles) and deer pellet groups (black triangles). Work conducted in 2020 allowed development of methods suitable for the full study in 2021.

100 and ~ 3200 and different rates of increase of < 1.2 and 12.2% per year (Curran 2018, Cairns 2019, Dawson and Miller 2008, Parks Victoria 2017). The management objective on the BHP is eradication, whereas the intention is for feral horses to remain in the EVA, requiring ongoing population control (Parks Victoria 2017, Cairns 2019).

Both areas have a long history of pastoralism involving seasonal grazing by cattle, sheep, and horses (Cabena 1980, Crabb 2003). The EVA was the first area in the Australian Alps where horses were abandoned and allowed to become feral in 1843 (Dyring 1990). Cattle and horses were the main introduced grazing animals in the BHP and the EVA, with horses being the most numerous (Carr and Turner 1959a). For example, Osbourne Young mustered (rounded up) 1500 horses off the BHP in one season in the 1880s for sale as Waler horses (Butler G and Associates 1996), indicative of the relatively large numbers of horses that were there at that time. Breeding and sale of horses for the remount trade was an important economic enterprise during this period, particularly on the BHP. Stocking rates for sheep, cattle and horses were very high, particularly during the droughts of 1884/1885, 1902/1903 and 1914/1915, with sheep numbers reaching at least 40 000 and cattle peaking at over 25 000 in the whole of the Victorian part of the Australian Alps (Cabena 1980). In 1935 there were 6500 cattle on the BHP. However, in the 1950s, sheep and cattle were progressively reduced until all grazing licences were withdrawn from the Australian Alpine National Park in 2005 (Williams et al. 2006). The present population of ~ 3400 feral horses and ~ 3200 cattle (Victorian Department of Energy Environment and Climate Action) represent the few (compared to historical numbers) feral or domestic ungulates remaining in the area. The Australian Alpine National Park is now primarily managed for conservation and recreation. In contrast, the State Forests surrounding it are used for native timber production, with some cattle grazing continuing (Forests Licences and Permits Regulations 2019 Victoria).

Other introduced grazing or browsing species present on the BHP and in the EVA during the study period included sambar *R. unicolor* and fallow *D. dama* deer. There were potentially over 7000 deer in the EVA during our study (Cairns 2019), assuming the reported rate of increase continued. No survey data were available to estimate the number of deer on the BHP. Still, ground survey results suggest the deer density was similar on the BHP to the EVA. Unknown numbers of European rabbits *Oryctolagus cuniculus*, European hares *Lepus europaeus* and feral pigs *S. scrofa* were also present. Native grazing and browsing animals on both BHP and in the EVA include the common wombat *Vombatus ursinus*, red-necked wallaby *Macropus rufogriseus*, swamp wallaby *Wallabia bicolor*, and eastern grey kangaroo *Macropus giganteus*.

The elevations of the study areas ranged from 900 to 1800 m a.s.l. A significant snow cover can last for a few weeks at elevations from 1200 to 1400 m and persist for up to four months of the year (usually June–September) on the highest peaks (Whetton et al. 1996). A mix of open native tussock grassland dominated by *Poa* spp. and heathland *Epacris serpyllifolia* occurred above 1700 m on the BHP. At lower elevations between 1100 and 1700 m, there were patches of open native grassland, heathland and snow gum *Eucalyptus pauciflora* woodland. The snow gum woodland understory was dominated by native grass (*Poa* spp.) or low shrubs *Grevillea australis*, *Hovea montana*, *Leucopogon hookeri*, *Orites lancifolia*, *Bossiaea foliosa* and *Ozothamnus hookeri*. The lower altitude sites of the EVA, between 900 and 1400 m, were predominantly in tall Alpine ash *Eucalyptus delegatensis* open forest with tiny (1–5% of the area) patches of open riparian habitat dominated by *Sphagnum* spp., shrubs *Epacris paludosa*, grass (*Poa* spp.) or *Carex* spp.

The Bogong high plains

The area occupied by feral horses on the BHP was around 132 km^2 (Fig. 1). In this area, there were 90 horses in 2001 (Dawson 2005) and 80–100 horses in 2008 (Dawson and Miller 2008, Parks Victoria 2017). This population appears to have been relatively stable, suppressed by ongoing trapping and removal, with the most recent estimate of 109 horses determined by an aerial survey in 2018 (Curran 2018), shortly before our study commenced. The area occupied by horses is from 1400 to 1800 m a.s.l., with minimum temperatures as low as −9°C in the winter and as high as 30°C in the summer (Falls Creek, Commonwealth of Australia 2021, Bureau of Meteorology). The mean annual rainfall for the year prior to our study for our sites on the BHP was 1499 mm (Interpolated data from the Queensland Government Department of Environment and Science (DES) and the Commonwealth of Australia 2021, Bureau of Meteorology).

The Eastern Victorian alps

The area occupied by feral horses in the EVA is around 1906 km^2. In the EVA, aerial survey indicated that there were approximately 655 horses in 2005 (Dawson et al. 2006) and 3282 horses in 2019 (Cairns 2019), shortly before the commencement of our study. This population had increased within the surveyed area by 15% per year from 2014 to 2019 despite trapping and removal operations (Cairns 2019, Parks Victoria 2017). Our surveys focused on a sub-section of the area occupied by feral horses of around 720 km^2 (Fig. 1) within 3 km of the monitoring sites established by Robertson et al. (2019). This area is between 900 m and 1700 m a.s.l., with minimum temperatures as low as −6°C in the winter and as high as 38°C in the summer (Black Mountain, Commonwealth of Australia 2021, Bureau of Meteorology). At higher altitudes, the temperature was probably more similar to the BHP, but no meteorological stations were closer to these areas. The mean annual rainfall for the year prior to our study for our sites in the EVA was 1018 mm (Interpolated data from the Queensland Government Department of Environment and Science (DES) and the Commonwealth of Australia 2021, Bureau of Meteorology).

Monitoring sites

We established a total of 47 monitoring sites to measure the density and effects of feral horses in the two areas (BHP and EVA) occupied by feral horses in the Victorian portion of the Australian Alps (Fig. 1). All sites were selected within the same vegetation classification (Alpine treeless drainage lines) described by Robertson et al. (2019). No site was all grassland (meadow) or all forest. All sites had a mix of open grassland, heathland or open woodland. A total of 16 sites were on the BHP, and 31 sites were in the EVA. Thirty-three of our 47 sites were a systematically selected (process described below) subsample of a set of study sites established in 2012. These sites were originally randomly selected for the Australian Alps-wide study of the impact of feral horses on treeless alpine drainage lines (Robertson et al. 2019); we refer to these here as Rob-sites (Table 1). There were 8 Rob-sites on the BHP and 25 in the EVA. To increase the number of sites on the BHP, we selected six more existing sites. These sites were originally established in 2017 to study the environmental impact of feral horses (Tolsma and Shannon 2018), and we refer to these here as TS-sites (Table 1). The Rob-sites and TS-sites were selected, independent of the density of feral horses. We monitored the previously studied Rob-sites and TS-sites for comparative purposes. We do not report the outcomes of those comparisons here because they are outside the scope of our objectives, but in summary, we observed little change or difference in horse impact at these sites between 2012/2017 and the time we undertook our surveys in 2020 and 2021. The Rob-sites and TS-sites were used here to compare the two regions (BHP and

Table 1. Description four types of sites visited in February–March 2021 in the Victorian part of the Australian Alps (Australian Alpine National Park and surrounding State Forests) to measure the environmental impact associated with feral horses on the Bogong High Plains (BHP) and in the Eastern Victorian Alps (EVA).

Selection	Site types (number of sites)	Description
Selected independent of feral horse density and used for comparison between BHP and EVA	Rob-sites (33)	Randomly selected in 2012 for the Australian Alps-wide study of the impact of feral horses on alpine treeless drainage lines (Robertson et al. 2019)
	TS-sites (8)	Originally established in 2017 to study the environmental impact of feral horses on the BHP (Tolsma and Shannon 2018).
Selected because of suspected or known high horse activity to populate the upper part of the density-impact curve	Extra-sites (4)	Selected by us in areas with evidence suggesting high horse activity (reports of or observation of horses, an abundance of horse faecal piles and hoof prints)
	Exclusion-sites (2)	At the location of exclosures built in 1999 to demonstrate the impact of feral horses (Theile and Prober 1999)

EVA) because these sites were selected within the area occupied by feral horses independent of observed feral horse activity levels. We selected our remaining six sites by targeting areas with evidence suggesting high horse activity (reports of or observation of horses and abundance of faecal piles and hoof prints etc.) to ensure a wide range of horse densities were available for plotting the relationships between impact and density (as per our objectives, described above). In exploratory analyses not reported here, when we plotted the faecal pile density against impact, there was a clump of 16 sites with very low faecal pile density and only one with substantially higher faecal pile density. A straight line was the best fit for these data and identification of a meaningful density-impact relationship was difficult. With only randomly selected sites like these, we would have required many more such sites to determine the shape of the density-impact function at the upper level of the curve where faecal pile densities are high, but this was not possible in the time available nor necessary for our purpose. Sites with relatively high horse activity or horse density or faecal pile density are easy to identify as you drive or walk through the Australian Alps; horses are seen, and the high densities of hoof prints, faecal piles, and paths are obvious. However, our non-random selection meant that these six sites were not included in analyses comparing the BHP and the EVA because they would have exaggerated the difference between these regions. Four of these remaining six sites are therefore referred to here as Extra-sites (Table 1). The other two sites were at the location of exclosures built in 1999 (Theile and Prober 1999) and are referred to here as Exclusion-sites. Four small (30 × 10 m) horse-proof exclosures were present at each Exclusion site (Table 1). Our surveys were conducted outside the exclosures in areas fully accessible to feral horses. These Exclusion-sites were an excellent reference for the present study showing the extremes of the density-impact relationship. We expected a considerable difference between the randomly selected sites (Rob-sites, TS-sites) and the subjectively selected sites (Extra-sites and Exclusion-sites) for horse faecal density and impact of horses.

No other exclosures established to measure the impact of horses were present in the area. There is one other area near an Extra-site where grazing was excluded in the State Forest. This fence was established to protect rare plants from cattle. Another set of exclosures was established outside of our study area in Kosciuszko National Park. These are mentioned in our discussion. Other long-term exclosures were established on the BHP to measure the impact of cattle (Carr and Turner 1959b), but these are outside the area occupied by feral horses.

To define the geographical extent of our study area, a three-kilometre buffer area from the complete set of Rob-sites was overlayed on the area occupied by feral horses determined by aerial survey (Parks Victoria 2017, Cairns 2019) in the EVA. Aerial and ground surveys on the BHP were used to define the area occupied by feral horses there (Dawson 2005, Tolsma and Shannon 2018, Robertson et al. 2019). We selected the sub-sample from the full set of Rob-sites so that the sites we monitored were 0.5–3.0 km apart and spread as evenly as possible across the full extent of our study area. We had limited access to wilderness areas in the northeastern and eastern parts of the EVA, so a lower density of sites was selected there. Still, our observations indicate that the sites visited adequately represented the feral horse density for alpine treeless drainage lines in these wilderness areas.

Field visits

Pilot study

A subset of 10 sites were visited on the BHP and six in the EVA between 13 March 2020 and 23 March 2020. Bush fires delayed the commencement of fieldwork, and COVID-19 border closures and travel restrictions caused an early end to fieldwork in 2020. Consequently, this field visit was relegated to a pilot study (Fig. 1), and the 2020 data were not included in the results presented here.

Complete survey

All 16 sites were visited (see below for methods) on the BHP and all 31 were visited in the EVA from 19 February 2021 to 24 March 2021.

Monitoring method selection

We based our methods on those developed for feral horse impact assessment in the Australian Alps (Robertson et al. 2019) adapted from the Ephemeral Drainage Line Assessment method (Tongway and Ludwig 2011). Exploratory analyses of data collected during our pilot study indicated that the categorical scoring system used by Robertson could only identify large differences between areas in impact, so we developed a more sensitive method using continuous measures described in the present paper. We used both the Robertson categorical scoring system as well as our continuous scoring system at all sites, but only data from the continuous scoring system are reported here. The Robertson method involves scoring a site by viewing a 20 × 50 m plot and giving scores from 1–5 for various impact variables while for our method we walked along 50 m of stream bank and 500 m through the site recording the number of metres with observed impact and the number of metres with no observed impact. The observer needed to identify vegetation changes caused by horses, such as grass that had been grazed, and the presence of horse faeces or hoof prints. While doing this, the observer recorded signs of other introduced and native wildlife and humans. In other words, we recorded the presence or absence of impact for every metre walked through the site, which is akin to quantifying what an observant bushwalker, park ranger, or horseback rider would see as they move through the site.

Impact of feral horses, deer, feral pigs, rabbits, hare, cattle, fire and humans

Trampling and grazing

Evidence of trampling, and grazing was recorded where there was vegetation broken, bent or trodden into the ground, soil disturbed by hooves or feet or animals rolling/wallowing or vehicles, bitten grass leaves indicated by being square at the top and shorter than pointed leaves of the same grass species, and grass pulled out of the ground.

Potential causes of impact

For each record of grazing or trampling, the potential agent(s) of impact was/were allocated by identifying sign (e.g. foot/hoof prints, faeces, wheel tracks etc.) of the presence of feral or domestic horses, deer, feral pigs, rabbits, hare, cattle or humans observed along the same section of transect. Single or multiple potential causes were assigned to records with no attempt to quantify the relative contribution. Human sign consisted of vehicle paths, wheel tracks or footprints.

Fire impact

Blackened, dead vegetation and bare ground with charcoal and ashes indicated fire occurrence. Nine out of 47 sites surveyed for our study were burnt during the 2019/2020 bushfires.

Streambank-transect

At each site, we surveyed a 50 m section of stream (Fig. 1). The start of each 50 m section was located at the closest point on the nearest stream (drainage line) to the published random point (Robertson et al. 2019), site point (Tolsma et al. 2018) or the additional site waypoints selected by us. The streambank-transect was along both banks parallel to and 1 m from the water or 1 m from the centre of a dry drainage line. The length in metres of transect passing over evidence of trampling or grazing was recorded along with evidence of species (horse, deer, feral pig, rabbit, hare, cattle or human) presence or fire associated with the impact. Since both banks were included, 100 m of stream-bank-transect was surveyed for evidence of grazing or trampling and animal signs at each site.

Site-transects, faecal density and impact

We established and walked along each Site-transect quantifying faeces and evidence of grazing or trampling (Fig. 1). Observations started at each site point, located by GPS, and the observer (Berman) walked along a rectangular transect 200 m east, 50 m north, 200 m west, then 50 m south, ending back at the site point (total 500 m). The number and location of horse, deer, rabbit, hare, cattle or feral pig faecal piles were recorded. For each location where faecal piles were observed, the perpendicular distance from the transect to the pile's centre was recorded to determine density using Distance Sampling (Buckland et al. 1993). The location of both stallion piles (stud piles or dung piles) and individual faecal deposits was recorded as the location of feral horse faecal piles. Stallion piles are multiple faecal deposits on top of each other created by stallions marking their presence. Any faecal pile with more than one faecal deposit was recorded as a stallion pile. The age and size of the pellets distinguished the different faecal deposits on a stallion pile. The number of faecal pellets was counted in stallion piles and in individual faecal deposits to allow estimation of the number of individual faecal deposit equivalents in stallion piles. The mean number of faecal pellets in individual faecal deposits was also counted. We counted the pellets that were not decayed and could still be identified as horse faecal pellets in stallion piles and in individual deposits. If faecal material was too decayed to be identifiable as horse faeces it was not recorded. So we counted the same thing for stallion piles as we did for individual faecal deposits. Stallions eat in the same place with the mares and young they accompany, so their diet should not vary much from other horses. Horse faecal pile density was calculated as the density of faecal pile locations (individual faecal deposits and stallion piles) with no correction for the number of individual defections in stallion piles. Presenting faecal pile density without determining the number of individual faecal deposits in a stallion pile allows others to more easily compare their faecal pile density estimates with ours without the requirement to count individual pellets or weigh faeces. Only if someone wishes to convert faecal pile density to actual horse density is it advisable to follow the methods described to count pellets. Conversions from horse faecal pile density to horse density were based on the number of individual horse faecal deposits, including those in stallion piles. We converted horse faecal pile density to horse density using a 426 day decay rate and eight defecations per day (Linklater et al. 2001, Zabek 2015a, Zabek et al. 2016a).

We also obtained horse faecal pile densities for 20 sites in the EVA surveyed in 2018 by Cherubin et al. (2019) and converted these to horse densities for comparison with our results. Cherubin's sites were in the same area we surveyed in the EVA. They were a sub-sample of the Robertson sites, just like ours were. Some sites were possibly the same as ours, but we could not obtain the actual location of Cherubin's sites. We converted deer faecal pellet group density to deer density using a 71 day decay rate (Davis and Coulson 2016) and 12 defecations per day (Ratcliffe 1987, Nugent et al. 1997, Mayle et al. 1999, Forsyth 2005).

The number of metres of the Site-transect passing over evidence of grazing or trampling and the sign of potential agents of impact was recorded. If a path (large animal trail) was observed crossing the Site-transect, it was mapped using a GPS by walking along its entire length within the area bounded by the 500 m rectangular Site-transect. All paths within the rectangular Site-transect were mapped at each site and were photographed at the points where they crossed the Site-transect, their average width was estimated, and the animal tracks or faeces present on the path were recorded. We recorded that a path had been used by a species based on the presence of their faeces or foot/hoof prints, or wheel tracks. For example, a 50 m section of GPS-mapped path where both horse and deer hoof prints were detected would be assigned to both horses and deer. Assigning a section of path to a species meant that there was evidence that that section of path had been used by that species within the period that animal tracks or faeces remained visible.

Density-impact functions

Feral horse faecal pile density (as a surrogate of horse density) and impact (evidence of grazing or trampling where there was sign of feral horses) data collected at all 47 sites were used to determine density-impact functions for feral horses. Three impact measures: 1) metres of impact along Site-transects, 2) metres of impact along Streambank-transects and 3) the area of path impact at sites – were plotted against horse faecal pile density to determine the strength and characteristics of their relationships. We selected candidate functions after viewing the plots of impact versus faecal pile density. Candidates included the Gompertz (Tjørve and Tjørve 2017), Logistic and Linear functions. Unlike the Logistic function, the Gompertz function is not symmetric around the inflection point.

Statistical analyses

Data were analysed using the R (www.r-project.org) statistical computing environment (ver. 4.1.0). The density of horse and deer faecal piles and the probabilities of detection were determined using the Distance Sampling analysis in the Rdistance package ver. 2.1.3 (www.r-project.org). We conducted t-tests to see if there was a difference between the EVA and BHP in mean feral horse faecal pile density and the mean number of metres with evidence of grazing or trampling associated with the sign of feral horses (Rob-sites and TS-sites data). To see if the mean faecal pile density were different between the four site types, we conducted one-way ANOVAs. Subsequent Tukey multiple comparison post hoc tests were conducted for the significant ANOVA. Density-impact curves were fitted, and the best model was selected based on Akaike's information criterion (AICc) for small samples (Akaike 1998).

Results

Horse faeces and impact

Horse faeces (dung) was detected at 12 out of 16 sites (75%) on the BHP and 24 out of 26 sites (92%) in the EVA. Evidence of feral horse grazing or trampling was detected at all sites where horse faeces was detected (Fig. 2). Horse faecal pile density was lower on the BHP than in the EVA ($t = 3.85$, $df = 41$, $p < 0.01$; Fig. 2, Table 2), and there were substantial differences between Exclusion-sites/Extra-sites and Rob-sites/TS-sites ($F_{(3, 43)} = 56.75$, $p < 0.01$; Fig. 3). The probability of detection of a horse faecal pile was 0.30, and the effective strip width was 3.03 m, as determined by Distance Line Transect analysis. The mean length of sections of Site-transects ($t = 3.15$, $df = 41$, $p < 0.01$) and Streambank transects ($t = 3.05$, $df = 41$, $p < 0.01$) with evidence of grazing or trampling was lower on the BHP than in the EVA (Table 3).

Horse density

Site horse densities in the BHP and the EVA are shown in Table 3 for Rob-sites and TS-sites. The mean we calculated for 20 sites surveyed in 2018 by Cherubin et al. (2019) in the EVA was 43.20 horses per km^2. This horse density was significantly higher than the mean for our Rob-sites (7.18 horses per km^2) in 2021 ($t = -5.42$, $df = 44$, $p < 0.01$) but not statistically different to our Extra-sites (16.52 horses per km^2) or our Exclusion-sites (58.53 horses per km^2). Approximately 72% of locations recorded with horse faeces had individual faecal deposits, and 28% had stallion piles (equivalent to 3.7 individual faecal deposits per stallion pile).

Horse density-impact function

The evidence of grazing and trampling along the Site-transects was very low (< 2% of transects) until density reached around 200–250 feral horse faecal piles per ha. Evidence of grazing and trampling then increased rapidly as feral horse faecal pile density increased (Fig. 4). No BHP site had more than 1% of the Site-transects with evidence of horse grazing/trampling. Only 24% of all sites and 17% of randomly selected sites across the BHP and the EVA had more than 2% of the Site-transects with evidence of feral horse grazing/trampling. Once feral horse faecal pile density was above 250 faecal piles per ha, the grazing and trampling sign became much more obvious. The sites with the highest impact were the Exclusion-sites first established by Theile and Prober in 1999, where we found faecal pile density to be exceptionally high (> 1000 faecal piles per ha).

The relationship between stream bank evidence of feral horse impact and faecal pile density had a greater spread of points, but below 250 faecal piles per ha the sign was still relatively low (Fig. 4b).

The relationships for both impacts, Site-impact and Streambank-impact with horse faecal pile density, fitted best to the Gompertz function (Table 4). Gompertz function is:

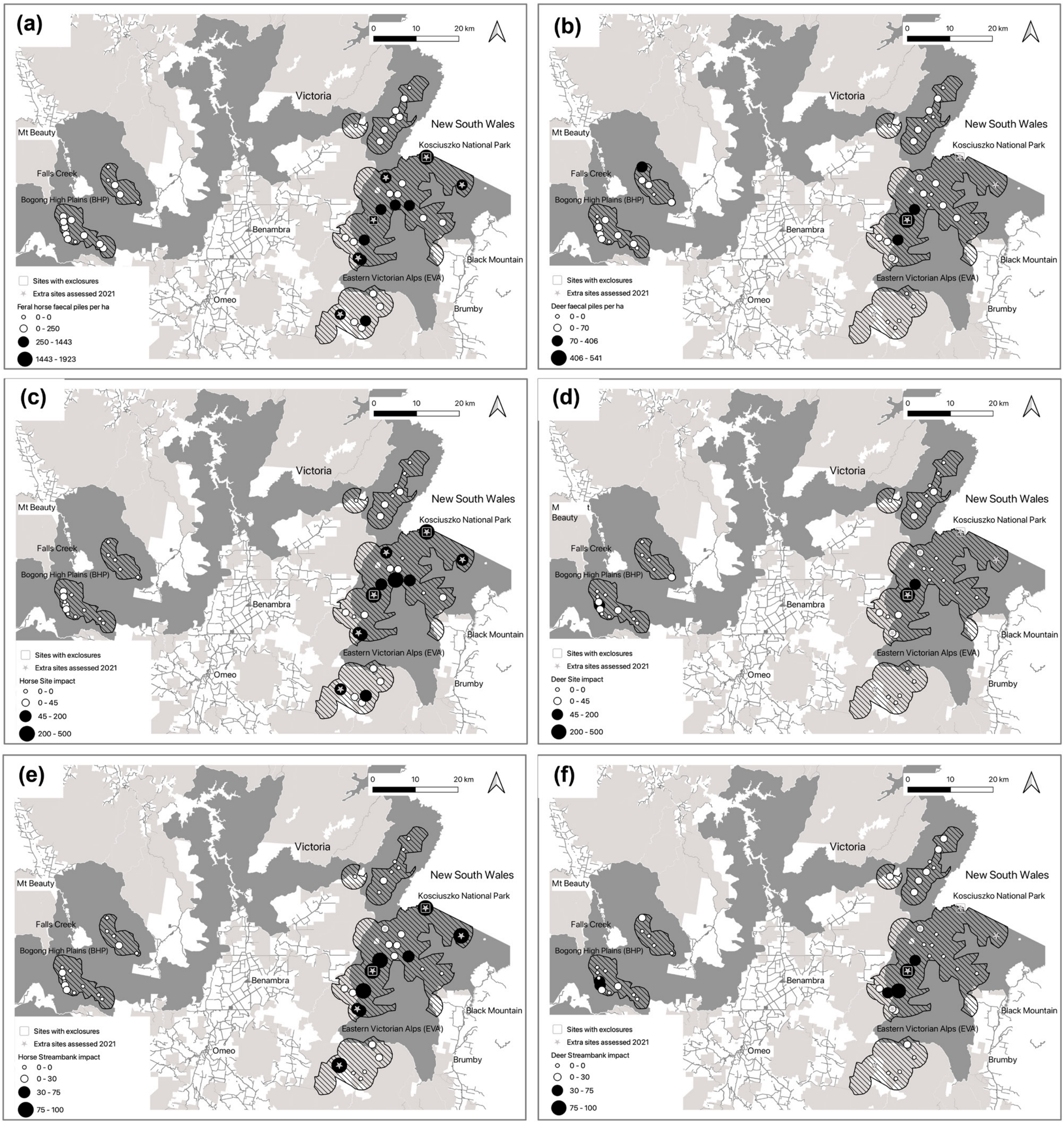

Figure 2. Maps of (a) feral horse and (b) deer faecal pile density, (c) feral horse and (d) deer grazing and trampling evidence along Site-transects, (e) feral horse and (f) deer grazing and trampling evidence along Streambank transects at sites visited by us in February–March 2021 in the Victorian part of the Australian Alps (Australian Alpine National Park – dark grey and surrounding State Forests – light grey). Shown is the area occupied by feral horses (hashed) within three kilometres of the entire set of sites established in 2012 (Robinson et al. 2019) on the Bogong High Plains (BHP) and in the Eastern Victorian Alps (EVA).

$$y = c + (d - c) \times \exp(-\exp[b \times (x - e)])$$

where $b = -0.003$, $c = -12.172$, $d = 100.944$, $e = 266.311$ for Site impact and $b = -0.003$, $c = -2.494$, $d = 527.079$, $e = 576.257$ for Streambank impact.

Deer faecal piles

BHP and the EVA did not differ significantly in deer faecal pile density (Table 2). Deer faecal piles were detected at 11 out of 16 (42%) sites on the BHP and 13 out of 26 (50%) sites in the EVA. We found the probability of detecting deer

Table 2. Horse and deer faecal piles counted along Site-transects, converted to density by Distance sampling. Animal density of horses and deer were calculated using faecal decay rates and defecation rates. Data from Extra-sites and Exclusion-sites were not included because they were selected based on the presence of very high feral horse activity. Includes data from 42 sites visited in February–March 2021 in the Victorian part of the Australian Alps (Australian Alpine National Park and surrounding State Forests) to measure the environmental impact associated with feral horses on the Bogong High Plains (BHP) and in the Eastern Victorian Alps (EVA).

	Region	Faecal piles in 500 m ± SE	Faecal pile density (groups/ha) ± SE	Animal density (animals/km²) ± SE	Sites (n)
Horse	BHP	4.06 ± 1.19	17.11 ± 5.64	0.64 ± 0.31	16
	EVA	36.54 ± 9.58	191.22 ± 51.44	7.18 ± 1.93	26
Deer	BHP	1.69 ± 0.60	21.24 ± 7.60	3.02 ± 1.08	16
	EVA	3.58 ± 1.71	45.02 ± 21.54	6.39 ± 3.06	26

faecal piles was 0.13, and the effective strip width was 1.30 m according to Distance Line Transect analysis.

Deer density

Site deer densities are shown in Table 2 for Rob-sites and TS-sites on the BHP and in the EVA. Deer density estimates ranged from 0 to 13.96 deer per km^2 on the BHP and 0–60.01 deer per km^2 in the EVA.

Evidence of deer grazing/trampling

The mean lengths of transect sections with evidence of deer grazing or trampling for the BHP and the EVA were not statistically different (Table 3). On the BHP, evidence of deer grazing/trampling was detected at 7 out of 16 randomly selected sites (44%). Evidence of deer grazing/trampling in the EVA was detected at 14 out of 26 randomly selected sites (54%).

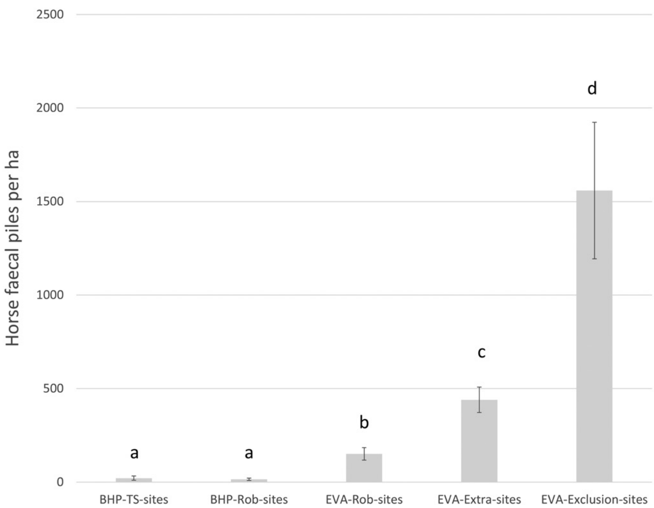

Figure 3. Comparison of feral horse faecal pile density at site types visited by us in February–March 2021 in the Victorian part of the Australian Alps (Australian Alpine National Park and surrounding State Forests) to measure the environmental impact associated with feral horses. Mean ± SE horse faecal pile density for the different site types on the Bogong High Plains (BHP) and in the Eastern Victorian Alps (EVA) are shown with significant differences determine by ANOVA and the Tukey post hoc test indicated by different letters a, b, c and d. TS-Sites were established and surveyed in 2017 by Tolsma and Shannon (2018). Rob-sites were established and surveyed in 2012 by Robertson et al. (2019) on the BHP and in the EVA. Extra sites were established by us in 2021in the EVA to increase the sample size of sites with high levels of horse activity to better determine the shape of the density-impact function at high feral horse density. Exclusion-sites were first established in 1999 to demonstrate the difference between small, fenced areas and areas heavily grazed by horses (Theile and Prober 1999). Our surveys were conducted outside the fenced plots in areas fully accessible to feral horses.

Animal paths

There was no significant relationship between the area of paths with horse tracks and the density of horse faecal piles at a site (Fig. 4c). Table 3 shows the mean area of the site that was path with horse sign and or deer sign. Excluding sites where no paths were detected, 0.19 and 0.21% of the area were impacted by paths on the BHP and in the EVA, respectively. Paths with horse hoof prints or horse faeces were detected at 6 out of 16 (38%) sites on the BHP and 15 out of 26 (58%) sites in the EVA. On the BHP, a total length of 570.98 m of path was recorded at the six sites with paths. The mean width of paths was 19.46 cm, covering a total area of 111.10 m^2 (0.07%) within the total of 160 000 m^2 for 16 sites bounded by the Site-transects (each site 200 × 50 m) on the BHP. In the EVA, a total length of 1992.52 m of path was recorded at the 15 sites with paths. The mean width of paths was 16.46 cm covering a total area of 338.62.10 m^2 (0.13%) within the total of 260 000 m^2 for 26 sites bounded by the Site-transects (each site 200 × 50 m) in the EVA.

Paths with deer hoof prints or faecal piles were detected at 10 out of 47 (21%) sites. There were 0.21 and 0.18% of the area impacted by paths with deer prints or faeces present on the BHP and in the EVA, respectively, at sites with paths detected.

For the total area of all paths where evidence of recent use was recorded, 78% of the area of path had sign of human use, 13% feral horse use, 4% deer use, 3% cattle use and 1% feral pig use. Paths leading to wombat burrows were observed at two sites in the EVA but no sign of wombats was detected on these paths.

Other impact agents

Figure 5 shows the proportion of impact associated with the sign of horses to be small compared to the combined impact of deer, feral pigs, rabbits, hare, cattle, fire and humans along both the Site-transects and Streambank-transects at sites on both the BHP and in the EVA. No feral pig diggings or faeces were seen on the BHP. Out of 31 sites in the EVA, feral pig diggings were detected at seven (23%) sites (3.01/500 m ± 1.54 SE) and pig faeces was recorded at five sites. No rabbit

Table 3. Horse and deer impact along Site-transects, Streambank transects and paths excluding Extra-sites and Exclusion-sites because they were selected based on the presence of very high feral horse activity. Includes data from 42 sites visited in February–March 2021 in the Victorian part of the Australian Alps (Australian Alpine National Park and surrounding State Forests) to measure the environmental impact associated with feral horses on the Bogong High Plains (BHP) and in the Eastern Victorian Alps (EVA).

	Region	Site impact m in 500m ± SE (% of transect)	Stream bank impact m in 100m ± SE (% of transect)	Path impact m^2 in 10 000 m^2 (% of area)	Sites (n)
Horse	BHP	0.75 ± 0.35 (0.15%)	0.69 ± 0.44 (0.69%)	9.10 ± 5.32 (0.09%)	16
	EVA	49.46 ± 20.93 (9.89%)	17.11 ± 6.05 (17.12%)	15.03 ± 3.53 (0.15%)	26
Deer	BHP	5.94 ± 3.30 (1.19%)	6.75 ± 3.52 (6.75%)	2.68± 2.02 (0.03%)	16
	EVA	16.08 ± 11.78 (3.22%)	13.08 ± 5.26 (13.08%)	4.51 ± 2.24 (0.05%)	26

faecal pellets were detected on the BHP. Rabbit faecal pellets were recorded at seven sites (17.94 pellets/500 m ± 12.72 SE) in the EVA. Evidence of rabbit grazing or soil disturbance was detected along a mean of 0.42/500 m ± 0.24 SE at Rob/TS-sites and 9.20/500 m ± 9.20 SE at Exclusion/Extra-sites in the EVA. No evidence of rabbit grazing or soil disturbance was detected in the BHP or along Streambank transects in the EVA. Off-transect, we observed rabbit warrens and the bare ground around warrens presumably created by rabbits. Hare pellets were recorded at six sites on the BHP but at no sites in the EVA. Evidence of hare grazing or soil disturbance was detected along a mean of 2.19/500 m ± 2.19 SE at random sites on the BHP. No evidence of hare grazing or soil disturbance was detected on the EVA or along Streambank transects on the BHP. Cattle sign was detected at four sites out of 31 (13%) sites. All sites with cattle sign were in the State Forest in the southern section of the EVA. Evidence of cattle grazing or trampling was detected along a mean of 6.96/500 m ± 4.67 SE at Rob-sites and 58.33/500 m ± 58.33 SE at Exclusion/Extra-sites in the EVA. No cattle sign was detected on the BHP or in the National Park in the EVA.

Fire impact was present at one of the sixteen (6%) sites surveyed on the BHP and at six of the 31 (19%) sites in the EVA. Two sites out of 16 (13%) had the impact of humans, including vehicle and bush walking tracks on the BHP. Four sites out of 26 (15%) had human impact in the EVA. Evidence of human disturbance was detected along a mean of 0.44/500 m ± 0.33 SE of Site-transect on the BHP and 8.13/500 m ± 6.39 SE in the EVA and a mean of 6.37/100 m ± 6.34 SE of Streambank-transect on the BHP and 0.24/100 m ± 0.24 SE in the EVA Rob-sites and TS-sites. Native macropods probably contributed to grazing and browsing, but we detected no sign along transects associated with these species. We observed wombat burrows off-transect at one site out of 16 on the BHP and six sites out of 31 in the EVA. Evidence of wombat grazing or trampling, or soil disturbance was detected along a mean of 0.29/500 m ± 0.19 SE of Site-transect but not along Streambank-transects in the EVA. There was no evidence of wombat disturbance along transects or off-transects in the BHP.

Discussion

Understanding the role and extent of feral horse impacts is important for ensuring that the best and most agreeable management outcomes are reached. Understanding density impact functions can assist this, but had not been previously attempted for horses in the Australian Alps. We detected and measured the magnitude of difference in direct feral horse impact between two separate parts (the BHP and EVA) of the area occupied by feral horses in the Victorian part of the Australian Alps. As expected, the lowest impact associated with feral horses was on the BHP, where the lowest feral horse density had been determined by aerial survey (Worboys et al. 2018, Cairns 2019) and by our feral horse density derived from faecal pile density (Fig. 2, Table 2). But contrary to assertions made in earlier studies (Tolsma et al. 2018), almost all (>99%) of the area we surveyed by walked transect on the BHP had no detectable evidence of grazing or trampling associated with the presence of horses (Fig. 5, Table 3). Even in the EVA, where feral horse faecal pile density and impact were significantly higher than the BHP, the vast majority of the area surveyed (> 82%) had no evidence of grazing or trampling associated with the presence of feral horses (Fig. 5, Table 3). Previous studies concluded that there was high feral horse impact on the BHP based on the proportion of sites they surveyed with impact detected (i.e. presence of any sign of horse faeces, hoof prints, stream bank, soil or vegetation disturbance), although estimates of the proportion of the area at each site with horse impact were not reported (Tolsma et al. 2018). Instead, they emphasised the high proportion of sites (57%) surveyed with at least some sign of horses having been detected there, meaning that a site with one horse faecal pile or one deer pellet was considered to have an equal impact to sites with many horse faecal piles or deer pellets. Results like those of Tolsma et al. (2018) therefore confirmed horses had been present, but they provided little information about the degree of impact at sites or the extent of impact throughout the BHP, particularly considering that sites were selected because they were 'known, or suspected, to be utilised by feral horses' (Tolsma et al. 2018). Like the previous researchers whose sites we resurveyed, we conducted our work within the known distribution of feral horses. Consequently, we also found the proportion of sites with at least some horse impact to be high (75% on the BHP and 92% in the EVA). But a 'high proportion of sites with horses present' says nothing about the level of horse impact at those sites, and is also not particularly noteworthy given that sites were initially selected because of horse presence. Thus, although the proportion of sites with sign of horses was understandably high given sampling efforts focused on areas with known horse presence, the proportion of those sampled areas with actual horse impact was extremely low (< 1%) on the BHP and low (< 18%) in the EVA (Table 3, Fig. 5).

Interestingly, the proportion of the area travelled by horses on paths did not differ between the BHP and the EVA

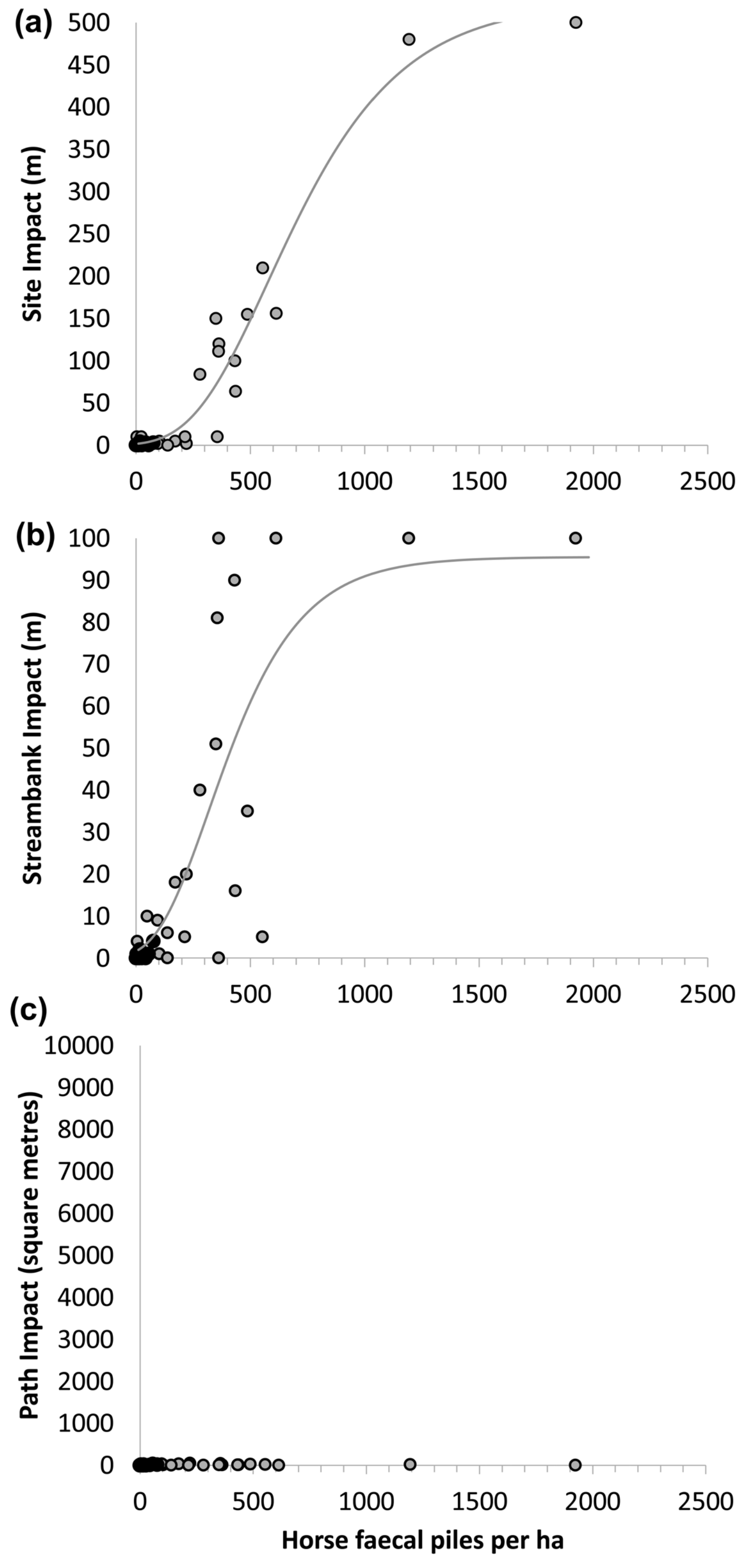

Figure 4. Density/impact relationships for all sites visited by us in February–March 2021 in the Victorian part of the Australian Alps (Australian Alpine National Park and surrounding State Forests) to measure the environmental impact associated with feral horses. (a) Relationship between grazing and trampling impact along Site-transects on the Bogong High Plains (BHP, black dots) and in the Eastern Victorian Alps (EVA, grey dots). (b) Relationship between grazing and trampling impact along Stream bank-transects on the BHP (black dots) and in the EVA (grey dots). (c) Area of path impact within the Site-transect area on the BHP (black dots) and in the EVA (grey dots).

Table 4. Ranking according to AICc (Akaike's information criterion for small samples) of density-impact functions for horse faecal pile density and impact recorded along Site-transects and Streambank transects. Includes data from all 47 sites visited in February–March 2021 in the Victorian part of the Australian Alps (Australian Alpine National Park and surrounding State Forests) to measure the environmental impact associated with feral horses on the Bogong High Plains (BHP) and in the Eastern Victorian Alps (EVA).

	AICc	
Functions	Site impact	Stream bank impact
Gompertz	438.9	416.7
Logistic	442.8	418.4
Linear	468.6	424.2

despite different horse densities (Table 1, 2). These paths are the most visually obvious impact of horses and were a major focus of previous work (Dyring 1990). Paths are created and/or maintained by horses and other animals repeatedly travelling over the same routes, compacting the soil and damaging or removing the vegetation under their feet. Paths running along drainage lines can disturb stream banks and stream flow (Kauffman and Krueger 1984, Hope et al. 2012). While we observed examples of what appears to be severe impact where paths crossed streams (gully erosion and churned-up mud), these were very isolated in the broader landscape given that the actual area of impact on soil and vegetation found in our study was only around 0.2% of the area surveyed at sites where paths were even detected at all. Dyring (1990) also recorded 0.2% of the area of one of her sites subjected to path impact. This small area of impact does not appear to vary with horse density (Fig. 4c), so removing or managing horse populations is unlikely to change the proportion of the area affected by this type of impact. Multiple animal species, including native animals like wombats, or introduced animals like deer, will use and maintain the paths even with reduced feral horse use, so some, if not all, these paths are likely to remain even if horses are removed.

Density-impact functions for Site and Streambank grazing and trampling demonstrate the rarity of sites with very high feral horse density and impact (Fig. 4). The lower part of the curve for feral horse faecal pile density and site impact is relatively flat; then, as faecal pile density increases, the curve rises steeply at around 250 horse faecal piles per hectare before flattening again and approaching an asymptote above 1000–1500 faecal piles per hectare as the impact is detected along 100% of the transect. We found that below the threshold of ~250 horse faecal piles per ha, or 9 horses per km^2, increases in faecal pile density resulted in very small increases in evidence of feral horse grazing/trampling (Fig. 4). This is particularly so for Site impact (Fig. 4a), with a relatively rapid increase at low densities for Streambank impact (Fig. 4b). Below this threshold, greater than 97% of the length of site transect and 90% of the stream bank transect had no evidence of feral horse grazing or trampling detected. However, a small increase in faecal pile density above this threshold resulted in a disproportionately large increase in evidence of feral horse grazing/trampling detected. At the sites above the threshold (17% of randomly selected sites), a small population control effort targeting 17% of the area (instead of the entire area occupied by horses) and costing relatively little, may significantly reduce evidence of feral horse grazing/trampling. Below the threshold where horse density is low, and the cost of removal of horses is most likely high (Choquenot et al. 1999), a considerable expense will be incurred in attempts to reduce an already low level of direct impact (Hone 1994, Choquenot and Parkes 2001, Hone 2007, Norbury et al. 2015). Hence, the most efficient way to reach an acceptable level of direct feral horse impact is to target areas with the highest feral horse density for population control, identified here as areas with densities along alpine treeless drainage lines above 250 faecal piles per ha or 9 feral horses per km^2. However, we caution that the threshold determined here may only apply to the current study area and also may not even apply during drier or wetter periods or if the abundance of other species changes. Monitoring needs to be designed to determine site-specific thresholds and to allow re-evaluation of any threshold as conditions change.

We also found the combined impact associated with the sign of deer, feral pigs, humans, and fire to be large compared to the impact associated with the sign of feral horses alone, particularly on the BHP (Fig. 5). Horse sign was associated with no more than 4% of the impact on the BHP and less than 34% of the impact in the EVA (Fig. 5). Comparing impact potential as we did, where the impact is recorded on a transect line, should minimise differences in impact detectability between the various potential agents of impact. Searching rectangular strip transects or sample areas so that impact or sign is recorded at various distances from the observer may also increase the chance of differences in impact detectability between the various potential agents of impact. Detection probability can be determined using Distance Sampling (Buckland et al. 1993), and we found horse faecal piles to be more easily detected than deer faecal pellets. Horse hoof prints are also larger and, therefore, most likely more easily observable at a distance than deer or pig prints. Without searching carefully along a line, if any bias exists, then the proportion of horse impact recorded will be exaggerated compared to those of deer and pigs. Previous authors either excluded the impact of agents other than horses statistically (Robertson et al. 2019) or assumed that the contribution of other agents was insignificant because the sign of horses was much more obvious (Tolsma et al. 2018, Robertson et al. 2019), without considering differences in detectability. Yet these and other similar published studies (Cherubin et al. 2019, Eldridge et al. 2019, Schulz et al. 2019) have lead others to conclude that there is 'unequivocal evidence that feral horses are the single largest cause of widespread environmental degradation throughout their range in the alpine parks' (Driscoll et al. 2019b). This view is clearly inconsistent with data that does account for sampling bias and detectability (Table 2–4, Fig. 2–5) and with the findings of a recent study in Kosciuszko National Park, adjacent to our study site (Hartley et al. 2022). These results show clearly that in spite of deer and feral pig control and management of fire and human activity (Parks Victoria 2016, GSBMPWG

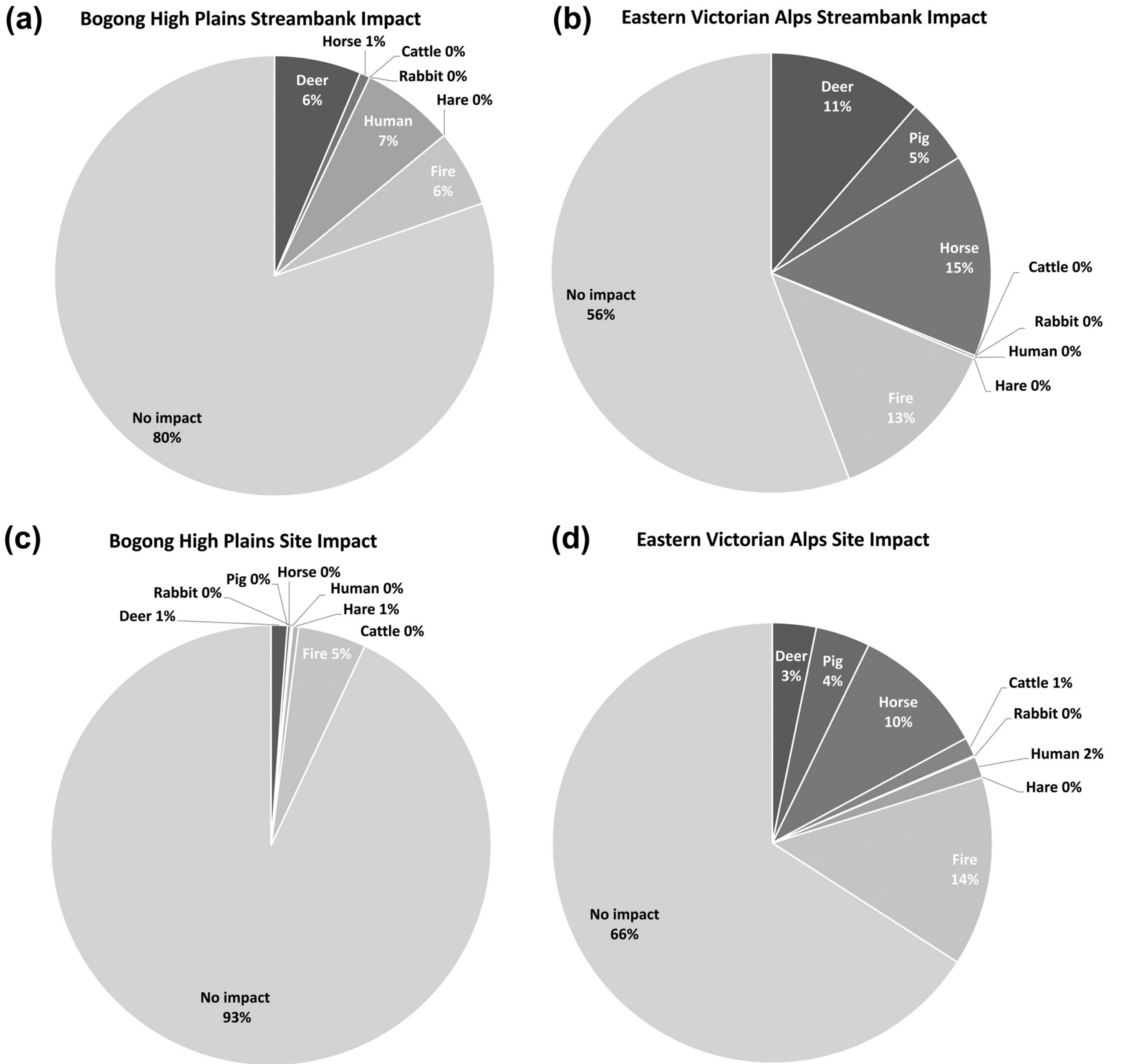

Figure 5. Percentage of impact associated with sign of horses, deer, pig, rabbit, hare, cattle, fire and humans at sites visited by us in February–March 2021 in the Victorian part of the Australian Alps (Australian Alpine National Park and surrounding State Forests) to measure the environmental impact associated with feral horses. Impact and sign of potential causes were recorded along the 500 m Site-transects and 100 m Stream bank-transects on the Bogong High Plains (BHP) and in the Eastern Victorian Alps (EVA). Data from Extra-sites and Exclusion-sites were excluded because these sites were selected because of their known/observed high horse activity. (A) Site impact on the BHP, (B) Site impact in the EVA, (C) Stream bank impact on the BHP and (D) Streambank impact in the EVA .

2020, Comte et al. 2022), these combined impacts far exceed those impacts associated with the sign of feral horses. This does not mean the management of feral horses is unnecessary, but it does mean that 1) feral horses may not be the most important environmental threat and 2) the management of feral horses alone may result in very little reduction in overall environmental impact if these other important factors are not also managed (Braysher 2017).

A study of the impacts of feral horses on threatened native species found horse impacts and faecal piles at 19 out of 20 sites (95%), whereas only seven sites (35%) had evidence of deer (Cherubin et al. 2019). Unlike previous researchers in the Australian Alps, Cherubin et al. (2019) quantified deer faecal piles in the same way as horse faecal piles. Cherubin et al. (2019) also determined decay/disappearance rate for horse faecal piles. But unfortunately, they did not do this for deer faecal pellets and neither was the difference between the detection probability of horse faecal piles and deer faecal piles considered. Hence, they could not compare the level of activity or impact of horses and deer, cautioning that 'we cannot entirely separate the impacts of horses from other species' (Cherubin et al. 2019, Supplementary information). This statement is also true for our study. Another study in Kosciuszko National Park compared deer faecal pile and horse faecal pile densities to determine relative impacts, finding more horse faecal piles than deer faecal piles, whereas camera traps suggested the activity of deer was far greater than that of horses (Ward-Jones et al. 2019). These authors preferred the results of the faecal pile comparison over the camera trap findings because the camera traps were in place for a relatively short period. Short survey periods are a problem for reliably interpreting camera trap data (Meek et al. 2012) but faecal pile indices are also notoriously unreliable when they have not been calibrated to densities with proper measurement of defection rates and decay rates (Allen 2012, Le Pla et al. 2022). Inadequate quantification of the impact or activity of other species, coupled with failure to consider differences in faecal decay/disappearance rate or detection probability, mean that previous assertions about the negative environmental impacts of horses in the Australian Alps are highly likely to be overestimated compared to the impact of other animals, such as deer.

We also found it difficult to disentangle the impact of wild or feral horses from the impacts of domestic horses frequently brought into the study area for recreational purposes, which was likely to have also influenced earlier studies but was not mentioned (Robertson et al. 2019). Likewise, we further found it extremely difficult to disentangle the stream bank impact attributable to deer, horses, or feral pigs given that they all drink, wallow, or cross streams in the same places. In addition to differences in detectability, deer faecal piles can decay more rapidly than horse faecal piles (Linklater et al. 2001, Zabek 2015a, Davis and Coulson 2016). Horse density also varied considerably depending on how and where sites were selected (Fig. 3). Results from the exclusion plot studies that commenced in 1999 (Wild and Poll 2012) are extremely valuable in demonstrating the difference between very high and zero feral horse density. However, such results cannot be extrapolated to all areas of the Australian Alps because those sites only represented extreme horse densities, and not the otherwise normal densities found across almost all other areas of the Victorian Alps (Fig. 2, 3).

The preceding information leads to the observation that 1) unbiased site selection, 2) consideration of detection probability and 3) decay or disappearance rate for horse and deer faecal piles and impact, are each important for reliably comparing density and impacts between species, places, and times. Clearly defining the variable extent and level of impact of feral horses separate to other factors is essential for resolving stakeholder disputes, prioritising management actions, and measuring the success of management. This is not easy and is rarely attempted for horses or deer (Davis et al. 2016), but it is possible.

In our study, to improve comparisons of the relative activity of feral horses and deer, we converted faecal density to animal density using faecal decay/disappearance rate and defecation rate. By doing this, we found that the mean density of horses and deer (number of animals present in a defined area in a 24 h period) along treeless drainage lines in the EVA were very similar (Table 2). This is consistent with aerial survey results indicating feral horse and deer density were similar in 2019 in the EVA (Cairns 2019). The mean horse density for 20 sites surveyed in 2018 by Cherubin et al. (2019) was not significantly different to our Extra-sites or the Exclusion-sites, which were significantly higher than the mean for the randomly selected Rob-sites in our study (Fig. 3). Our Extra-sites and Exclusion-sites were deliberately chosen because they were expected to have high horse activity. Findings from studies where sites are selected in this way (Dyring 1990, Theile and Prober 1999) and subsequent conclusions derived from them (Driscoll et al. 2019b) are not representative of the entire Australian Alps but are relevant only to specific sites with exceptionally high horse activity. In our study, the highest horse density estimate was 60 horses per km^2 at Cowombat Flat (Exclusion-site), and the second highest was 41 horses per km^2 at Native Cat Flat (Exclusion-site). These densities were comparable with densities (46 horses per km^2) determined in the late 1980s at a site studied by Dyring (1990) in Kosciusko National Park, and are exceptionally high compared to the mean determined by us for randomly selected sites in the EVA (Table 2; 8 horses per km^2). In our study at Native Cat Flat where the highest deer faecal pile density was recorded, there were 60 deer per km^2 compared to 41 horses per km^2 based on our faecal pile counts. This is one of the sites where exclusion-fenced plots built in 1999 are commonly used to demonstrate the impact of feral horses (Wild and Poll 2012, Williams et al. 2014) with no consideration of the high relative impact of deer activity at the same site. Our actual horse and deer density estimates from faecal pile density relied on defecation and decay/disappearance rates determined elsewhere. Decay rates can change with the amount of rainfall (Zabek 2015b), so ideally, decay/disappearance rates need to be derived for this location in the period prior to surveys.

With the ultimate goal of threatened fauna conservation in mind, further research is also required to confirm the nature of the relationship between feral horse density or direct impact and threatened fauna behaviour, abundance, or trends. More studies similar to Cherubin et al. (2019) and Schulz et al. (2019) are required over a larger range of feral horse densities, for longer periods and with active manipulation of horse density. The work done on sage-grouse *Centrocercus urophasianus* in the USA which supports the objective of maintaining feral horse density below an 'appropriate management level' (Coates et al. 2021), is a good example of the type of work that is required in the Australian Alps. Nevertheless, this and other previous studies are basically correlative. Finding that the abundance of native species is negatively associated with feral horse activity or density (Schulz et al. 2019, Coates et al. 2021) might well mean that feral horse impact has influenced the native species. Still, such a correlation could also be a result of differences in habitat suitability or preference, independent of feral horse activity or density. Incorporating detailed studies of threatened fauna in planned adaptive management experiments with randomly selected areas for treatment (changing the density of feral horses) would provide the inferential strength of evidence required. More detailed studies of native species at our sites, coupled with an increased number of sites representing other habitats and random manipulation of feral horse density, may allow improved measurement of both direct and indirect horse impact. Identification of ecologically significant, positive, neutral, or negative impacts would then be possible, and with this, the ideal targets for managing feral horse density may be determined.

For the first time in the Australian Alps, our work shows how evidence of the direct impact of feral horses on soil and vegetation varies with feral horse density over the range from very low to very high horse density. If the level of direct impact relates to the level of threat to vulnerable native species, soil, vegetation or water, then our work will guide managers attempting to minimise this threat. Previous studies have reported correlations between horse abundance or impact and vegetation structure (Cherubin et al. 2019), abundance or occurrence of endangered species (Schulz et al. 2019), and abundance of ant nests and soil penetrability (Beever and Herrick 2006), but compared to our study, these earlier reports were based on a limited range of feral horse activity levels and/or were categorised into a small number of classes of horse impact. In our study, grazing and trampling impact correlated with the density of horses, which means feral horse impact should be manageable by changing horse density. However, an exception to this is the impact along paths. This impact appears to reach a maximum at very low horse density and did not increase thereafter with increasing horse density. We also measured the relative extent of evidence of grazing, trampling and vegetation disturbance associated with the sign of deer, feral pigs, fire and humans showing that removal of horse impacts alone could prevent only a small proportion of potentially damaging impact. We are hopeful that we have provided valuable suggestions that will improve the measurement of the environmental impact of feral horses in a way that guides effective and acceptable management.

Management implications

Reduction in direct horse impact can be most efficiently achieved by targeting those few sites where horse impact is highest. Where horse density is low, and the cost of removal of horses is high, a considerable expense will be incurred to reduce an already low level of direct impact. Incorporating experimental monitoring into management will ensure that any unexpected, undesirable consequences of removing horses are detected and the expected benefits of management are measured. Instead of attempting to remove as many horses as possible, a better approach to reducing horse impacts would be to establish an evidence-based target density and then reduce and maintain horse populations at or below that level.

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Author contributions

David McKenzie Berman: Conceptualization; Methodology; Formal anaylsis; Investigation; Data curation; Funding acquisition (equal); Project administration (equal); Writing original draft; Writing – review and editing; Visualization. **Jill Pickering**: Conceptualization (supporting); Funding acquisition (equal); Project administration (supporting); Resources (supporting); Writing – review and editing (supporting). **Deane Smith**: Conceptualization (supporting); Data curation (supporting); Investigation (supporting); Writing – review and editing (supporting). **Benjamin L. Allen**: Conceptualization (supporting); Writing – review and editing (supporting); Visualization (supporting); Validation.

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