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Research article

Restoration intensity shapes floristic recovery after forest road decommissioning

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ABSTRACT

Forest roads fragment and degrade ecosystems and many have fallen into disrepair and are underutilized, to address these issues the United States Forest Service is restoring, or "decommissioning," thousands of kilometers of forest roads each year. Despite the prevalence of decommissioning and the importance of vegetation to restoration success, relatively little is known about floristic responses to different forest road decommissioning treatments or subsequent recovery to reference conditions. Over a ten year period, this study assessed floristic cover, diversity, and composition responses to and recovery on forest roads decommissioned using three treatments varying in intensity (abandonment, ripping, recontouring), in Montana, USA. Initially, floristic cover groups were lowest on the recontoured roads, however, they demonstrated the fastest temporal response (e.g. increased litter and vegetative cover). The floristic communities of both active treatments (ripped and recontoured) had more species and were more diverse than the communities of the abandoned (control) treatment. Among the three on-road plant communities, the recontoured treatment was most associated with desirable species, including the native shrubs *Rosa woodsii* and *Spirea betulifolia*, while the abandoned treatment was most associated with two non-native species, *Taraxacum officinale* and *Trifolium repens*. Assessed using a restoration index, recovery to reference conditions was limited in all treatments, however, the recontoured treatment had a positive restoration trajectory in seven of eight metrics and was the best recovered treatment. Community composition on the recontoured treatment had more native species than the other treatments, and was moving toward, though still substantially different from, reference communities. These findings demonstrate that restoration of forest roads benefit from active restoration methods and, while forest road recontouring facilitates floristic recovery in the first decade after decommissioning, full recovery will likely take years to decades longer.

1. Introduction

Ecological restoration has demonstrable benefits for humanity (Benayas et al., 2009; Bradbury et al., 2021) and restoring degraded forests is a global priority (Lindenmayer, 2019; Nunez-Mir et al., 2015). Forest roads facilitate transportation, recreation and tourism, and resource extraction, however, while providing these services, they degrade catchments, destroy and fragment critical habitat (Boston, 2016), alter plant communities and facilitate the introduction and spread of invasive plant species (Haider et al., 2018; Larson et al., 2021; Rew et al., 2018). In a step towards conserving forest biodiversity and restoring degraded forest habitats, managers are working to remove and restore, or "decommission", forest roads (Apodaca et al., 2018). In the United States, thousands of kilometers of forest roads are decommissioned each year (Switalski et al., 2014), however, there is a relative dearth of information regarding the success of different road decommissioning treatments.

Road decommissioning is when a roadbed undergoes a physical treatment to stabilize and restore the disturbed area to a more natural state; it seeks to restore forest aquatic and terrestrial ecosystems by reducing erosion and runoff, connecting and restoring vital habitat, enhancing ecosystem biodiversity, and facilitating vital belowground processes (Apodaca et al., 2018). Decommissioning treatments can be passive – natural regeneration after the removal of disturbance – or active – practices that seek to accelerate recovery of a site – and both use methods that differ in effort, cost, and amount of soil/ecosystem disturbance. Passive abandonment is the decommissioning treatment that has the lowest effort, cost, and intensity and is accomplished when

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road access is blocked with gates, or boulders and course woody debris (Switalski et al., 2004). Ripping/subsoiling the forest roadbed is the most common active decommissioning treatment and has an intermediate amount of effort, cost, and intensity (Switalski et al., 2004). Road recontouring uses heavy machinery to obliterate the roadbed and restore natural topography and is the treatment that has the highest amount of effort, cost, and is the most intense (Foltz et al., 2007).

Vegetation stabilizes soil, increases infiltration, and reduces runoff and erosion (Liu et al., 2018), and is an important sign of initial recovery after restoration (Ruiz-Jaen and Aide, 2005). Once established, floristic community attributes (i.e. structure, diversity, community composition) are vital to ecosystem functioning (Cardinale et al., 2012). For example, structure of forest vegetation (often assessed as percent cover) informs multitrophic habitat suitability (Hingee et al., 2022; López-Bedoya et al., 2022; Schneider et al., 2021). Diverse plant communities provide ecosystems with many benefits and services, such as higher productivity, resistance to invasions, decrease in fungal and viral infections, and increased nutrient cycling (Cardinale et al., 2012) and biodiversity is associated with ecological functions and services after ecological restoration (Benayas et al., 2009). Restoring plant communities without regard for composition may compromise the benefits of restoration. For example, the use of non-native plant species during restoration may increase immediate productivity and reduce erosion but can decrease native cover and lead to non-native invasions of surrounding areas (Cao et al., 2009; Rydgren et al., 2016).

The importance of floristic attributes to ecosystems makes them commonly used metrics to assess restoration success (Gann et al., 2019; Gatica-Saavedra et al., 2017; Wortley et al., 2013). Successful restoration projects will approach adjacent undisturbed reference conditions in form and function (Bullock et al., 2011; Gann et al., 2019), and be characterized by native assemblages with low levels of non-native species (Gann et al., 2019; Hallett et al., 2013). Reference sites used for comparison should be physically close to restored sites and assessments should be temporally close to account for natural yearly variation (Suding, 2011). Restoration indices that directly compare restored communities with adjacent reference communities through time are metrics that can be used to evaluate success (Marchand et al., 2021; Sinclair et al., 2018).

Floristic recovery after road decommissioning has not been well researched. Road decommissioning studies have primarily assessed cover groups and functional group recovery. Initially after treatment, road recontouring often results in substantially reduced vegetation and elevated bare ground (Foltz et al., 2007; Lloyd et al., 2013), but can have faster recovery of vegetative productivity, including later successional functional groups (i.e., trees and shrubs), than passive regeneration on abandoned roads (Lloyd et al., 2013; St-Pierre et al., 2021). Road decommissioning is often accompanied by planting or seeding and multiple studies have found higher tree and shrub recovery after combining road ripping or recontouring with active planting (Kolka and Smidt, 2004; Lacerte et al., 2021; Tarvainen and Tolvanen, 2016), although without planting active measures have not proven significantly better than natural regeneration (Lacerte et al., 2021). To our knowledge, studies have yet to assess multiple aspects (abundance, diversity, community composition) of floristic recovery after road decommissioning. Nor have any studies compared floristic recovery across a restoration intensity spectrum (passive abandonment – road obliteration) and used a restoration index to compare restored communities with adjacent communities through time.

The aim of this study was to fill this gap in knowledge by quantifying floristic recovery on forest roads decommissioned using three treatments (abandonment, ripping, and recontouring) with varying intensity over the first 10 years post-treatment. The specific research questions were: (1) How have cover groups (total vegetation, native species, tree + shrub, bare ground + rock (bare ground hereafter), litter, non-native species), floristic diversity (native species richness, Simpson's diversity index), and community composition changed 10 years post-treatment and how do they compare between treatments? (2) Using adjacent reference conditions, how have cover groups, floristic diversity, and community composition of the three decommissioning treatments recovered over the course of the study?

2. Materials and methods

2.1. Study site

In the Gallatin National Forest near Bozeman, MT (45.6770° N, 111.0429° W; Supplementary Fig. 1a) the United States Forest Service decommissioned nine single vehicle width forest road segments in 2010 (Supplementary Fig. 1b). The segments were split into three sites with three road segments in each. The road segments were historically used for resource extraction (i.e., logging), although as logging decreased in the area over the last ~50 years they have primarily been used for recreation (e.g., driving, mountain biking, camping) and the entire area undisturbed for the benefit of wildlife and flora. All segments were characterized by similar surrounding temperate forest communities, aspect (north, northwest), and elevations (ranging between 1945 m and 2262 m). The surrounding forest communities were largely comprised of *Pseudotsuga menziesii* in the tree layer, most common understory graminoids were *Carex geyeri* and *Calamagrostis rubescens*, while common forbs and shrubs were *Eurybia conspicua*, *Fragaria virginiana*, *Spirea betulifolia, Symphoricarpos albus,* and *Rosa woodsii* (Supplementary Table 1). The study area (Supplementary Fig. 1) has a continental climate with warm summers and cold winters; between 1979 and 2019 the mean annual temperature was 4 °C and the mean annual precipitation was 734 mm (Abatzoglou, 2013). The soils are in the Alfisol and Inceptisol orders, with the dominant classification being Mollic Cryoboralfs (Soil Survey Staff, 2022).

2.2. Road decommissioning treatments

The three segments at each site were treated with one of the three most common decommissioning treatments (abandoning, ripping, recontouring) in the region. The abandoned treatment prevented vehicle access using large boulders and/or coarse woody debris and functioned as a control for the natural/passive recovery on forest roads. The ripping treatment was accomplished by a small bulldozer with hydraulically operated steel chisels, aimed to reach a depth of 0.2 m – 0.45 m below the soil surface. The recontouring treatment used an excavator to exhume sidecast fill materials discarded in the road building process and establish stable hillslopes where the forest roads previously ran. The abandoned and ripped decommissioning treatments had similar slopes but the recontoured slopes were steeper. Once the active treatments were completed in early August 2010, a seed mix (Supplementary Table 2) was broadcast across each segment. The soil was not prepared (e.g., fertilization, liming) beyond the physical soil preparation of the active treatments.

2.3. Experimental design and field measurements

In 2011, one year after decommissioning, seven on-road plots (0.25 m^2) were randomly located along the extent of each road segment. In each plot, aerial percent cover of bare ground, litter, and the vegetative community recorded to the species level was taken. Assessments took place in August, when peak biomass of the plant communities occurred at the sites. The plots were marked and re-sampled in 2012, 2013, 2014, and 2020. In 2012, and each subsequent sampling year, the study was expanded to include six off-road reference plots per road segment located 15 m off-road in the surrounding forest communities. The same aerial percent cover assessments were taken in the reference plots.

2.4. Statistical analysis

For each cover group (total vegetation, native species, non-native species, tree + shrub, bare ground, litter) separate linear mixed effects models were created ("lmer" in the R-package "lmerTest"; Kuznetsova et al., 2017). For native species richness, a generalized linear mixed effects model with a Poisson distribution was used ("glmer" in the R-package "lme4'; Bates et al., 2015). From the species cover data, Simpson's diversity index was calculated using the R-Package "vegan" (Oksanen et al., 2019), which was analyzed using a generalized linear mixed effects model with a Beta distribution ("glmmTMB" in the R-package "glmmTMB"; Brooks et al., 2017). For each model, road decommissioning treatment, time (numeric), and the interaction between the two were fixed effects, while repeated measures were considered using segment-plot nested in site as a random effect. If the interaction between treatment and time was insignificant it was removed, and the additive model used. For important temporal comparisons, Tukey pairwise comparisons of the treatments' estimated marginal means in each year of the study were compared using the R-package "emmeans" (Lenth, 2020).

Community composition was compared using a Bray-Curtis community dissimilarity matrix created using the "vegan" R-package (Oksanen et al., 2019). Permutational multivariate analysis of variance ("adonis" in the R-package "vegan") using the dissimilarity matrix compared road communities of each treatment and the on- and off-road communities. In addition, we compared communities using the same Bray-Curtis dissimilarity matrix by implementing a Kruskal non-metric multidimensional scaling ordination (NMDS) ("metaMDS" in the R-package "vegan"; Oksanen et al., 2019). To assess how species' were associated with communities, the 'scores' of all species were correlated with the first two NMDS axes using the 'envfit' function in the R-package "vegan" (Oksanen et al., 2019).

To assess recovery to reference conditions of each treatment for cover groups and floristic diversity, a restoration index was calculated using a log response ratio (LnRR) for each metric, where LnRR = ln (*restored/reference*) and a LnRR = 0 indicates no difference between restored and reference sites (Marchand et al., 2021; Sinclair et al., 2018). For desirable variables that are likely higher in reference conditions (e.g., total and native cover) a LnRR <0 is expected and increases towards 0 with recovery. For less desirable variables that are likely higher in restored sites (e.g., bare ground, non-native cover) a LnRR >0 is expected and progresses downward to 0. The LnRR for each metric was analyzed using linear mixed effects models with decommissioning treatment, year (numeric), and the interaction between the two as fixed effects, and segment-plot nested in site as a random effect. To determine if the LnRR differed from reference conditions (LnRR = 0), the estimated marginal means were tested against the default of zero using a reference grid and the "test" function of the R-package "emmeans" (Lenth, 2020). Tukey pairwise comparisons of the treatments' estimated marginal means in each year of the study were compared using the R-package "emmeans" (Lenth, 2020).

For all linear mixed effects models, the assumption of normality was assessed and cover values for total vegetation, native species, tree + shrub, litter, non-native species were natural log transformed. Homoscedasticity was assessed and ensured using a visual assessment of the residuals. The linear mixed effects model differences between the explanatory variables and response variables assessed at the $P < 0.05$ level were calculated from F statistics of type III sum of squares based on Satterthwaite's approximations of degrees of freedom. The generalized linear mixed effects models were not over-dispersed as overdispersion was assessed by calculating the sum of squared Pearson residuals and comparing it to the residual degrees of freedom and differences between explanatory variables and response variables at the $P < 0.05$ level were calculated from a type III Wald chi-square test from the R-package "car" (Fox and Weisberg, 2019).

All statistics and graphics were performed and produced in the statistical software R, version 4.0.5 (R Core Team, 2021), graphics were produced using R-packages "ggplot2" (Wickham, 2016), and "cowplot" (Wilke, 2019) packages.

3. Results

3.1. On-road cover and diversity

One year after decommissioning, percent cover of total vegetation was lowest on recontoured roads (Fig. 1a), which differed from the ripped ($P = 0.006$; Fig. 1b) and abandoned treatments ($P = 0.002$; Fig. 1c). Total vegetation increased with time in the recontoured ($P < 0.001$) and ripped treatments ($P = 0.005$). There was also a significant interaction between time and treatment ($P < 0.001$), indicating a difference in rate of increase, and by the third year post-treatment there were no differences in total vegetation among the treatments. Initially, native cover was low but increased with time in all treatments ($P < 0.001$), however, the rate differed among treatments ($P = 0.009$) and 10 years post-treatment the recontoured treatment (Fig. 1a) had significantly more native cover than the ripped ($P = 0.043$; Fig. 1b) and abandoned treatments ($P = 0.001$; Fig. 1c). Non-native cover differed among treatments ($P = 0.002$) with the recontoured treatment (Fig. 1a) having significantly less cover than both the ripped ($P = 0.003$; Fig. 1b) and abandoned treatments ($P = 0.017$; Fig. 1c). Tree and shrub cover was initially low in all treatments but increased in the recontoured ($P < 0.001$) and ripped treatments ($P = 0.035$). There was a difference in rate of recruitment among treatments ($P = 0.050$) and from the third year until the end of the study the recontoured treatment had significantly more tree and shrub cover than the ripped and abandoned treatments, and, even after 10 years, ripped and abandoned levels did not differ (Fig. 1a, b, c).

Bare ground was substantially higher in both the recontoured and ripped treatments until the fourth-year post-treatment, and although it decreased in all three treatments over time ($P < 0.001$), the rate of decrease differed between treatments ($P < 0.001$), and by 10 years post-treatment there were no differences among treatments (Fig. 1a, b, c). Litter was substantially lower the first year after decommissioning in both the recontoured and ripped treatments compared with the abandoned treatment ($P = 0.001$, $P = 0.030$, respectively; Fig. 1a, b, c). However, in contrast to bare ground it increased in all treatments over time ($P < 0.001$), with the rate of increase differing among treatments ($P = 0.014$), and by 10 years post-treatment there were no differences among the treatments.

Overall, 114 species were observed on the treated roads: 80 in recontoured (Supplementary Table 3), 79 in ripped (Supplementary Table 4) and 68 in abandoned (Supplementary Table 5). Native richness differed between treatments ($P < 0.001$), it demonstrated a significant increase in the recontoured treatment through time ($P < 0.001$), and 10 years post-treatment the recontoured treatment had more native species per plot (7.5 ± 3.03) than both the ripped (5.6 ± 2.52; $P = 0.053$) and abandoned treatments (4.4 ± 2.64; $P < 0.001$; Fig. 2a). Simpson's alpha diversity index varied among treatments ($P < 0.001$) and increased through time ($P < 0.001$). However, over the course of the study, Simpson's diversity index did not differ between the recontoured and ripped, while the abandoned treatment was lowest in every year (Fig. 2b). (For a complete list of significant cover and diversity pairwise comparisons among treatments in each year reference Supplementary Table 6).

3.2. On-road community composition

Results of the permutational multivariate analysis of variance using Bray-Curtis distance matrix demonstrated that treatment ($P = 0.001$), year ($P = 0.001$), and the interaction between the two ($P = 0.001$) affected plant communities. Non-native species' *Taraxacum officinale* and *Trifolium repens* were most associated with the abandoned road

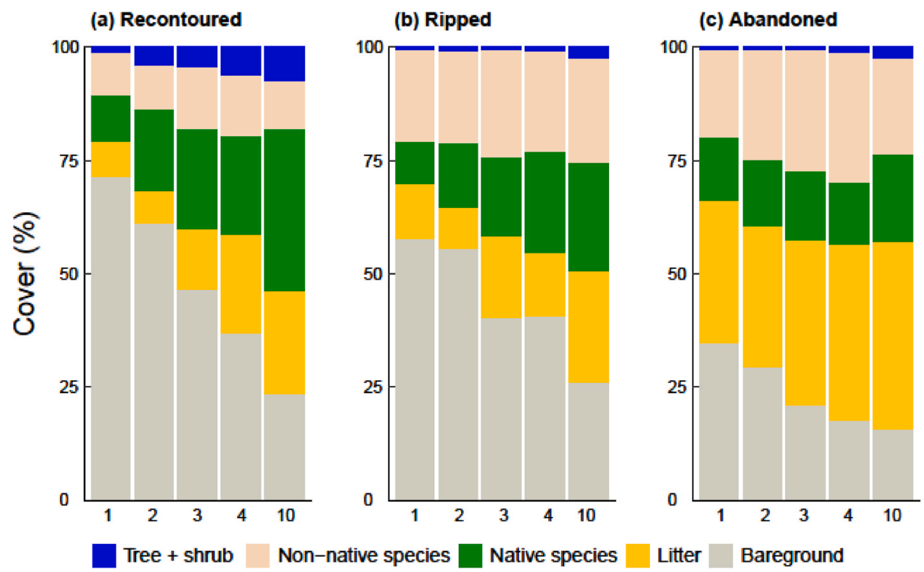

Fig. 1. Cover groups over time in the **(a)** recontoured, **(b)** ripped, **(c)** abandoned treatments. The X axis represents years post-treatment: 1–4 (2011–2014), and 10 (2020). Total vegetation is the sum of non-native species (tan) and native species (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

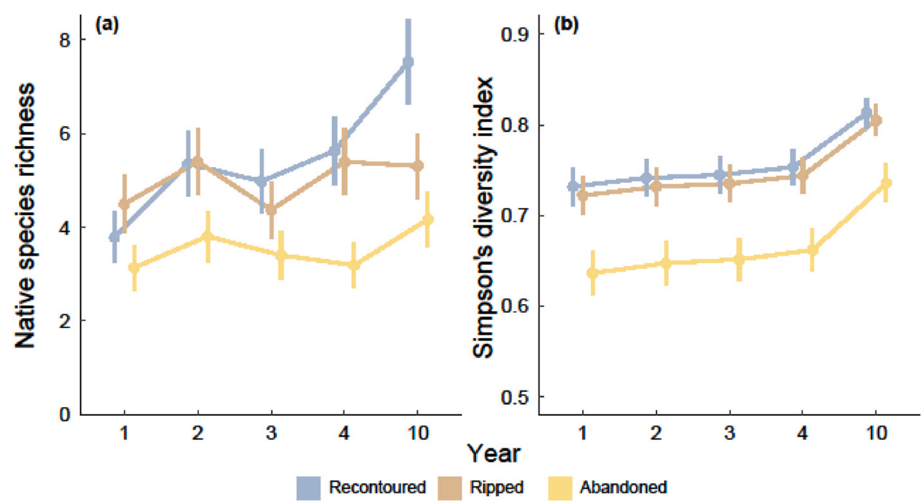

Fig. 2. (a) Native species richness and (b) Simpson's diversity index for each decommissioning treatment over time. The X axis represents years post-treatment: 1–4 (2011–2014), and 10 (2020). Means (±SE) are back transformed estimated marginal means from linear mixed effects models.

treatments, whereas the native species' *Spiraea betulifolia, Rosa woodsii,* and *Arnica cordifolia* were most associated with the active restoration treatments (Fig. 3).

3.3. Recovery of cover groups and floristic diversity

The restoration index (LnRR) measures how restored treatments differ from adjacent reference vegetation. Total vegetation restoration index was lowest in the recontoured treatment two years after intervention, however it increased through time ($P < 0.001$) and by 10 years post-treatment there were no differences among treatments and recontoured levels did not differ from reference conditions (Fig. 4a). Native species LnRR increased through time in the recontoured ($P < 0.001$) and abandoned treatments ($P = 0.007$), and there was an interaction between time and treatment ($P = 0.025$). After 10 years, the recontoured treatment native LnRR was significantly higher than the abandoned treatment (0.005; Fig. 4b), and there was a trend that it was higher than the ripped treatment ($P = 0.06$), but no treatment recovered to reference levels. Tree + shrub LnRR was low in all treatments in all years of the study, although 10 years post-treatment, recovery was higher in the recontoured treatment compared with the abandoned treatment ($P = 0.053$; Fig. 4c) but again differed from references levels. Litter LnRR differed among treatments ($P < 0.001$), though it increased temporally across all treatments ($P < 0.001$), with all three treatments resembling reference conditions four and 10 years post-treatment (Fig. 4d). Bare ground recovery progressed toward reference conditions in all treatments, with the recontoured (−0.208) having the highest rate of change compared with both ripped (−0.090; $P = 0.013$) and abandoned treatments (−0.076; $P = 0.006$), however, the abandoned treatment met reference conditions after three years (Fig. 4e). Throughout the study, non-native LnRR remained higher in all treatments compared with reference levels (Fig. 4f); however, the treatments differed ($P = 0.001$) and there was an interaction between time and treatment ($P = 0.001$), with non-native LnRR in the recontoured treatment increasing through time (0.049; $P = 0.034$), while the ripped (−0.066; $P = 0.004$) and abandoned (−0.047; $P = 0.040$) treatments decreased toward the reference levels (Fig. 4f). Native richness recovery was affected by treatment ($P < 0.001$) and was initially highest in the active treatments.

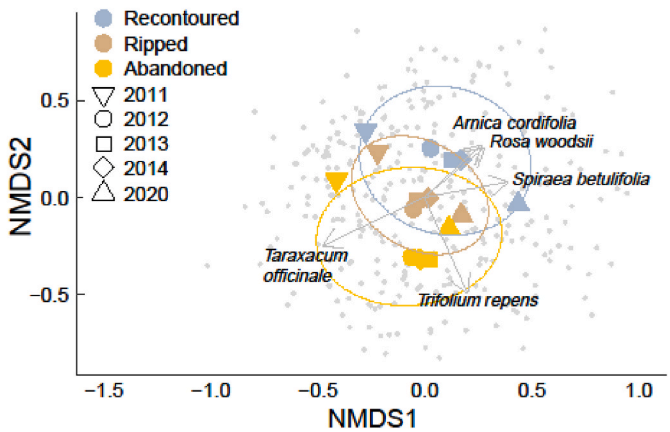

Fig. 3. Plant community non-metric multidimensional scaling ordination for the three decommissioning treatments through time, based on a Bray-Curtis dissimilarity matrix (k = 6, stress = 0.12), and the five species most correlated with the first two axes of the ordination.

The recontoured ($P < 0.001$) and abandoned ($P < 0.001$) native richness LnRR increased through time and 10 years post-treatment it was higher in the recontoured treatment compared with both other treatments and there was almost no difference with reference levels ($P = 0.0540$; Fig. 4g). Finally, in all years, the Simpson's diversity index LnRR for the two active treatments did not differ from reference conditions and substantially increased in the abandoned treatment ($P < 0.001$), such that 10 years post-treatment none of the treatments differed from reference conditions (Fig. 4h).

3.4. Restored and reference community composition

Results of the permutational multivariate analysis of variance between restored and reference communities demonstrated differences between communities ($P < 0.001$) and among years ($P < 0.001$). Non-native species' *T. officinale* and *Phleum pratense* were most associated with the restored communities and the native species *Vaccinium scoparium*, *Eurybia conspicua,* and *S. betulifolia* were the species most correlated with the off-road reference sites (Fig. 5).

4. Discussion

Floristic attributes (structure, diversity, and community composition) are closely tied with restoration success (Furey and Tilman, 2021; Gatica-Saavedra et al., 2017; Ruiz-Jaen and Aide, 2005; Wortley et al., 2013). Using these attributes, this study addressed the two types of variation in restoration success - differences between restored ecosystems and recovery assessed against reference levels (Brudvig et al., 2017) - and provided a thorough assessment of floristic recovery following forest road decommissioning treatments that differed in intensity. Consistent with previous forest restoration studies, differences were found between restoration methods, time since intervention was an important factor shaping recovery, and temporal recovery to reference levels of individual floristic metrics varied significantly in each treatment (Crouzeilles et al., 2016).

4.1. Floristic differences among decommissioning treatments

As expected and consistent with previous findings, active road decommissioning, especially the intense road recontour, resulted in low vegetation, low litter, and high bare ground immediately following intervention (Foltz et al., 2007; Lloyd et al., 2013; Tarvainen and Tolvanen, 2016). Active decommissioning treatments are designed to reduce soil compaction, which is the largest impediment to vegetation establishment (Archuleta and Baxter, 2008; St-Pierre et al., 2021). It was expected and consistent with previous studies that total vegetative growth – and concurrent increase in litter and decrease in bare ground – increased faster on active treatments compared with passive revegetation on abandoned roads (Lloyd et al., 2013; St-Pierre et al., 2021; Tarvainen and Tolvanen, 2016). Slightly unexpected was the faster rate of re-growth on the recontoured roads compared with the ripped roads. Ripping forest roads is designed to improve infiltration, reduce erosion, and promote vegetation establishment (Archuleta and Baxter, 2008), however its benefits for soil structure may only be marginal and temporary (Luce, 1997). This limited benefit may be due to ripping roads in summer (as was the case in our study) when it is logistically easier but when dry soil limits the depth to which the tines can reach. Belowground recovery has been higher following recontouring compared with both ripped roads (Kolka and Smidt, 2004) and abandoned roads (Lloyd et al., 2013), and it is likely that the recontouring treatment facilitated higher belowground recovery compared with the other treatments, resulting in faster vegetative re-growth.

One of the primary goals of restoration is the absence of threats to the ecosystem (e.g., contamination, invasive species; Gann et al., 2019). Limiting non-native species on restored sites is crucial because non-native dominated communities can be difficult/impossible to recover from without further intervention (Suding and Hobbs, 2009). Soil disturbance, particularly at higher intensity or frequency, is closely associated with non-native species (Jauni et al., 2015) and, high propagule pressure from seeding non-native species within mixes, can result in high non-native cover preventing native seed establishment and cause decommissioned roads to become exotic meadows (Glabek, 2005). However, lower non-native propagule pressure in unseeded road decommissioning treatments has resulted in lowered invasion levels after active decommissioning treatments (Bradley, 1997; Grant et al., 2011). Interestingly, the treatment with the most soil disturbance, the recontoured treatment, had lower non-native cover compared with the lower intensity abandoned and ripped treatments. Pre-existing seed banks and naturally occurring establishment shape abandoned road communities. However, they can also shape ripped road communities if remnant vegetation remains after treatment (Grant et al., 2011). In contrast, the vegetation on backfilled sites (such as recontouring) are shaped by the make-up of backfilling material and likely hold more native species (Gentili et al., 2020) than previous road seed banks. The seed mix used for this study only had two fertile non-native species so, consistent with previous studies, non-native propagule pressure from the seed bank (legacy of the former roadbed) is the likely mechanism behind the observed difference in non-native species cover between the recontoured and the other treatments.

Passive regeneration of forest overstory can be slow and usually follows graminoid and forb growth (Arroyo-Rodríguez et al., 2017; Benayas et al., 2008; Dhar et al., 2020), and regeneration on abandoned forest roads has proven no different (Lloyd et al., 2013). Initial growth (up to six years) after ripping/de-compacting forest roads without direct tree/shrub planting has been shown to follow the typical process of natural succession, with herbaceous species dominating plant communities, and trees and shrubs being no different or less abundant than on abandoned roads (Lacerte et al., 2021; Tarvainen and Tolvanen, 2016). This was consistent with the results of our study, which demonstrated no difference between tree and shrub recruitment between the ripped and abandoned roads even after 10 years. Consistent with other studies, the natural recruitment of trees and shrubs in our study was more rapid on the recontoured roads compared with ripped (Kolka and Smidt, 2004) and abandoned (Lloyd et al., 2013) roads. Suitable microsites are essential for successful tree (Castro et al., 2021) and shrub (Davies et al., 2020) establishment during restoration and our ripped and abandoned treatments likely experienced microsite limitation due to remnant soil compaction. In comparison, recontouring more thoroughly broke up the compacted forest roads while reshaping the landscape to re-establish hillslope connectivity, which likely created more microsites for tree and shrub establishment.

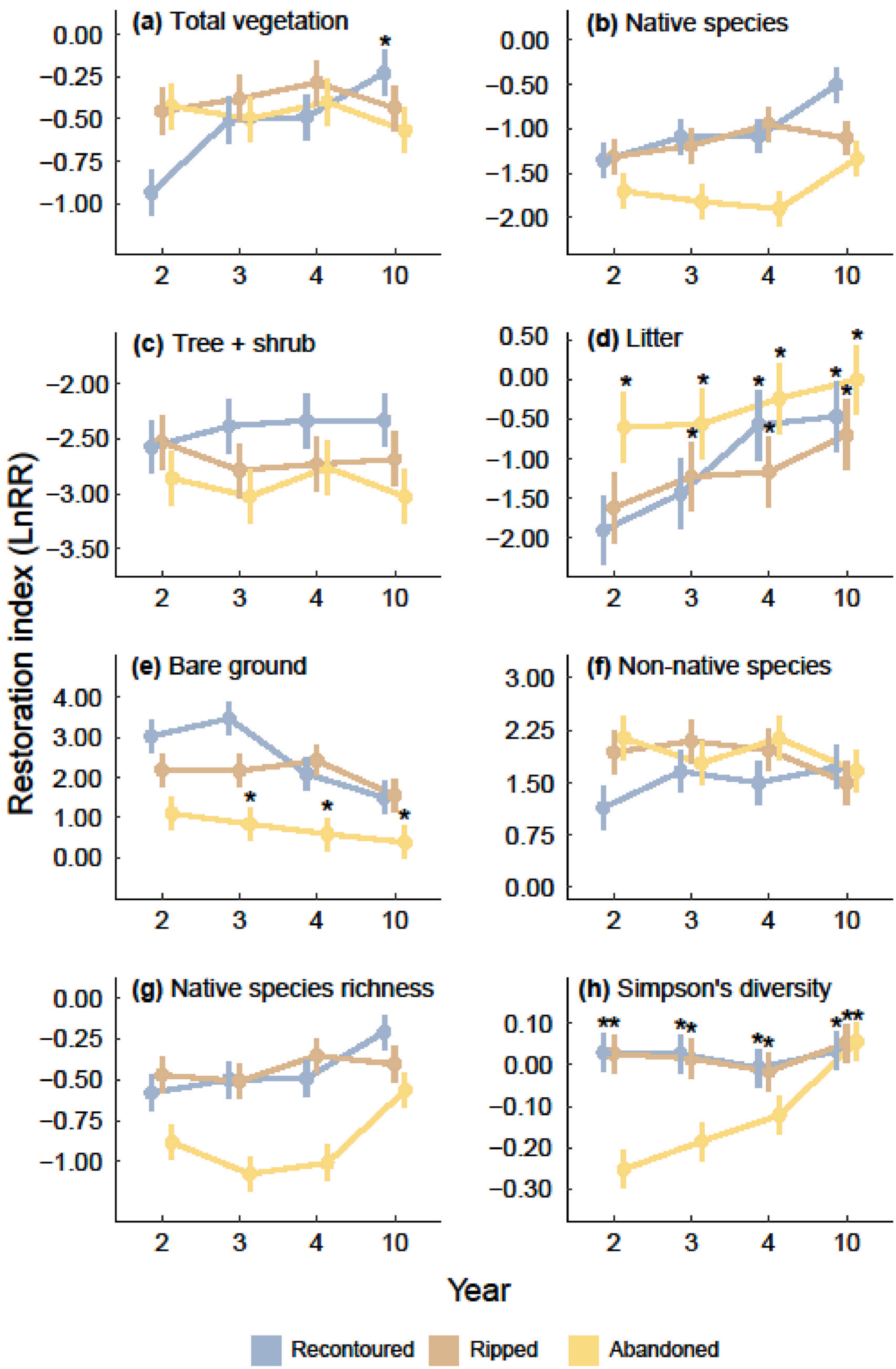

Fig. 4. Restoration index (LnRR) for **(a)** total vegetation, **(b)** native species, **(c)** tree + shrub, **(d)** litter, **(e)** bare ground, **(f)** non-native species, and **(g)** native species richness, and (h) Simpson's diversity index. Means are the estimated marginal means (±SE) for each treatment 2–4 (2012–2014) and 10 (2020) years post-treatment. A value of zero represents reference conditions, LnRR <0 indicates the reference is higher than restored and is expected for attributes recovering upward toward reference conditions (e.g., total vegetation). A LnRR >0 indicates the restored has higher values than the reference and is expected for those attributes where target reference levels are low (i.e., bare ground, non-native species). * denotes mean values do not differ from reference conditions.

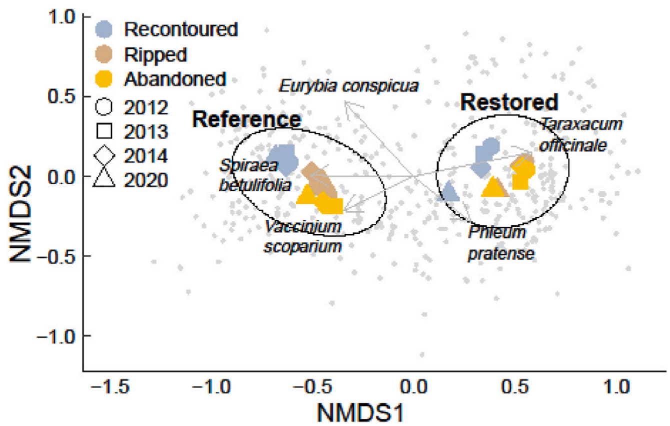

Fig. 5. Plant community non-metric multidimensional scaling ordination for restored and reference sites for each decommissioning treatment through time, based on a Bray-Curtis dissimilarity matrix (k = 6, stress = 0.11), and the five species most correlated with the first two axes of the ordination.

Diversity, native species richness, and community composition have not previously been compared between road decommissioning treatments and this study demonstrated higher values on active treatments, especially the recontoured treatment. The higher richness and diversity was expected as seeding after restoration, especially on active restoration that includes disturbance, often has higher diversity and richness than natural regeneration (Freitag et al., 2021). While both active treatments were substantially and immediately more diverse than abandoned roads, 10 years post-treatment the recontoured treatment had more native species than the other treatments and its plant communities were more closely associated with native species, including the desirable shrubs *R. woodsii* and *S. betulifolia*. These differences were likely driven by the previously mentioned mechanisms of belowground recovery, seed sources from the seedbank of the fill material, as well as seed rain from adjacent vegetation, and availability of microsites.

4.2. Recovery to reference levels

Floristic recovery to reference levels after three road decommissioning treatments varying in intensity demonstrated a range of recovery trajectories across the different metrics over the first decade post-treatment. This was expected and the findings consistent with the hierarchy of predictability theory in restoration, which states recovery of structure, production, and richness/taxonomic diversity are more predictable and faster than composition and similarity (Brudvig et al., 2017; Laughlin et al., 2017). In our study, the abiotic structure attributes litter and bare ground, as well as vegetation production and Simpson's diversity index, were the attributes to recover to reference levels by year 10 in at least one treatment, and species richness was very close to demonstrating no difference with reference levels in the recontoured treatment. All of these metrics display species functional redundancy, they do not consider the specific identity when calculated (Brudvig et al., 2017). In contrast, measures where all species are not functionally redundant (nativity, tree + shrub) were not close to reference levels and the highly specific measure of community similarity based on species composition was substantially dissimilar. Overall, the results of this study agree with Brudvig et al.'s (2017) theory that asserts recovery of structure, production, and richness/taxonomic diversity are more predictable and faster than composition and similarity.

Comparing recovery after three forest road decommissioning methods differing in intensity, the treatment with the highest intensity (recontour) was the most recovered treatment compared with reference levels. This treatment was the closest to reference levels or demonstrated no difference with reference levels in seven of eight response variables and had the closest association with native species compared with the ripped and abandoned treatments. This finding contrasts with recent meta-analyses which have concluded that passive restoration is equally as effective as active restoration (Crouzeilles et al., 2017; Jones et al., 2018; Meli et al., 2017). While these studies analyzed multiple variables across hundreds of studies world-wide in response to a variety of disturbance types, one acknowledged shortcoming was the lack of studies assessing recovery after restoration practices varying in intensity following the same disturbance at paired sites (Atkinson and Bonser, 2020; Jones et al., 2018). This study addressed this shortcoming and, as the level of restorative intervention required depends on disturbance and site degradation (Atkinson and Bonser, 2020; Prach et al., 2019), it should be concluded that the ecological impacts of forest road use are severe enough to require high intensity restorative intervention.

Recontouring costs four to six times as much ripping/subsoiling or abandoning (Shouse et al., 2001; Smidt and Kelka, 2001) and previous studies have concluded that ripping is the preferred economic choice (Kolka and Smidt, 2004). In their study, Kolka and Smidt (2004) based this conclusion off cost, and intermediate (between abandonment and recontour) recovery of tree seedling growth after the second growing season post-treatment. Our ripped treatment only demonstrated a positive recovery trajectory after 10 years in three of eight recovery metrics (litter, bare ground, non-native cover). This stagnation begs the question whether the ripped roads will ever fully recover. Poor recovery on the ripped site may be related to the less-than-ideal implementation of the treatment in the summer, however, this is likely typical in many regions, so these results are likely representative. In contrast, recontouring is more likely to be correctly implemented due to the equipment used and, regardless of the efficacy of implementation, the nature of the recontoured treatment obliterates soil compaction more thoroughly and to a greater depth than road ripping. While the abandoned treatment demonstrated positive temporal trends in six of eight metrics, it was still the least recovered in four of the metrics (demonstrating very low recovery and lacking a positive trajectory in total vegetation and tree + shrub recruitment) and it was the treatment with communities most associated with non-native species. The high initial costs of road recontouring may be made up if the other treatments fail to recover and require further intervention.

5. Conclusion

In the first study to thoroughly assess floristic recovery following road decommissioning, demonstrable differences were found between road recontouring, ripping, and abandonment, and in their recovery to reference levels. This study demonstrated that the restoration of forest roads benefits from active restoration methods and road recontouring should be used over less active treatments. The plant communities of the recontoured roads had consistently higher floristic responses compared with the other treatments, were associated with desirable native shrub species (*R. woodsii, S. betulifolia*), and demonstrated positive temporal trends such that they will likely recover to reference levels given adequate time. However, after 10 years, recontouring only demonstrated full recovery in coarse species redundant metrics and, while more associated with native species than the other two treatments, its community composition was moving toward though still substantially different from reference communities. Based off these findings, it should be concluded that considerable recovery after forest road decommissioning can be made in 10 years, especially with the recontouring treatment, but full recovery will likely take years if not decades longer.

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Author contributions

Christian Larson: Conceptualization, methodology, formal analysis, investigation, data curation, writing – original draft. **Lisa Rew:** Conceptualization, methodology, investigation, resources, writing – review & editing, supervision, funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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