The Sustainable Harvest of Wild Populations of Oshá (*Ligusticum porteri*) in Southern Colorado for the Herbal Products Trade

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It is a challenge to both use and conserve wild-harvested medicinal plants, especially when it appears they may be threatened by harvest pressure, and there is often limited biological information available to inform management decisions. Oshá (*Ligusticum porteri*) is an important medicinal plant whose roots are harvested in the southwest USA and Mexico as an herbal remedy to treat flu, sore throat, and other illnesses. We studied population structure, root production, and the ability of oshá to recover from harvest in different environmental contexts at two high-elevation southern Colorado sites with a goal of understanding what a sustainable rate of harvest might be. We experimentally harvested roots of mature oshá plants at four different rates. Results indicate that low rates of harvest allow for stable oshá populations over the short term (3–5 year) at our sites. Due to management interest by the USDA Forest Service, we propose a possible sustainable harvest rate of 50% of mature plants every 10 years. Given variability due to weather and other environmental factors, we recommend that future oshá harvest should be planned and adjusted after careful monitoring.

Key Words: Ethnobotany, Medicinal plant, Policy, Roots, Wild harvest.

Introduction

Oshá (*Ligusticum porteri* J. M. Coult. and Rose) is an important medicinal plant in the southwest USA and NW Mexico whose roots are harvested as an herbal remedy for flu, sore throat, and other illnesses (Kindscher et al. 2013). It has a long history of use by Hispanics and Native Americans in the Southwest, is considered sacred to many tribes, and is of considerable importance by the herbal products trade (American Herbal Pharmacopoeia 2018). As it is not easily cultivated, it is primarily wild-harvested. In 2010, 1942 pounds of roots were reported to be harvested from wild stands (American Herbal Products Association 2012). Based on interviews of harvesters and USDA Forest Service (USFS) officials, most harvest of oshá occurs on high-elevation US National Forest lands, despite no commercial permits issued for its harvest (Myhal 2017; Kindscher, personal communications 2014–2017). Both the USFS and the herbal product industry have interest in developing plans for sustainable rates of harvest of oshá, which requires detailed knowledge of its population dynamics.

The definition of sustainable harvest can be problematic. In 2004, the USFS adopted a definition of the term sustainable that recognized three areas: environment, society, and economy (USFS 2004). All three must be considered when developing a sustainability plan for a particular resource. This definition does not provide quantifiable measures and is much broader than how most scientists would define sustainable harvest or sustainable yield, where usually one needs to look at just an adequate replacement of the harvested resource over time. Currently, there is no agreed upon metric to use for sustainable harvest.

Assessment of sustainable harvest of non-timber forest products is often hindered by limited scientific data (Ticktin and Shackleton 2011; Ticktin et al. 2018). In general, studies of sustainable

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harvest of non-timber forest products are rare, mostly due to lack of knowledge on basic ecology and reproductive biology of harvested species, which can vary widely in response to harvest (Ticktin et al. 2018). The few studies that have been completed typically highlight the fact that species vary widely in response to harvest. Ginseng (*Panax quinquefolius* L.) and goldenseal (*Hydrastis canadensis* L.) populations are significantly threatened by harvest (Mooney and McGraw 2007; Van der Voort et al. 2003) while echinacea (*Echinacea* spp.) resprouts and re-grows more easily, allowing for its sustainable harvest (Kindscher et al. 2008; Kindscher 2016). Overall, perennials for which the roots are the subject of harvest, or trees which are killed by the bark being removed, are most at risk of being overharvested. Due to these concerns of over-harvest, we have been involved in the development of an At-Risk of Over-harvest Tool (Castle et al. 2014), which provides a numeric analysis of species according to the following groups of traits/data: their life history, the effects of harvest, their abundance and range, their habitat, and marketplace demand. Results from studying 40 medicinal plant species indicated that stinging nettle (*Urtica dioica* L.), for which only leaves of this weedy species are harvested was least at risk, whereas lady's slipper orchids (*Cyperpedium* spp.) and sandlewood (*Santalum* spp.) were most at risk. Oshá was in the middle of the range and is moderately at risk of over-harvest.

Until recently, little was known about population structure, root production, or the capacity of oshá to recover from harvest in different environmental contexts. Besides our work (Kindscher et al. 2013, 2017), the only other study related specifically to harvesting populations of oshá is that of Mooney et al. (2015) who found that oshá plants recovered after moderate levels of root harvest based on data collected from 1 m^2 plots. However, root yields and recolonization were not assessed with larger plots or after realistic simulation of wild-harvesting, in which all roots of marketable size are harvested. Our previous work demonstrated that there are large stands of oshá in the Southwest USA and that there is a culturally important documented history of its use (Kindscher et al. 2013; American Herbal Pharmacopeia 2018). Additional results suggested that oshá population structure and root production were significantly influenced by canopy cover, but that plants had a high capacity for post-harvest recolonization under variable light conditions (Kindscher et al. 2017). Our current work examines the long-term population consequences of harvesting oshá at two montane populations. The comparison of these populations will help us address our central questions:

1) Do populations of oshá recover after harvest?
2) What would be a sustainable rate of harvest for oshá?

Methods

In our effort to learn about the population dynamics and sustainability of harvest of oshá, we documented the recovery of oshá populations following harvest for multiple years at two high-elevation sites: Cumbres Pass in the Rio Grande National Forest, and Missionary Ridge in the San Juan National Forest, both located between 3050 and 3150 m (10,000 and 10,500 ft). At both sites, substantial winter precipitation falls as snow. Oshá is found in moist, but moderately well-drained soils, often on north-facing slopes and in habitats similar to where one would possibly find high-elevation aspen (*Populus tremuloides* Michx.). At both sites, we choose large, healthy populations, located in the heart of oshá's geographical range in areas where harvest had been occurring along roadsides. Work began at Cumbres pass in 2012 and at Missionary Ridge in 2014.

At our Cumbres Pass site, located in southern Colorado near the highway mountain pass, west of Antonito, Colorado, we collected population data on a large stand of oshá on either side of a USFS road at 3050 m (10,000 ft). The meadow habitat, located on the uphill side of the road, has greatly reduced canopy cover (17% tree cover) due to contract logging in 1991 (Fig. 1). The population found on the downhill side of the road, referred to as the forest habitat, has not been commercially harvested, and at the time of harvest, in 2012, had 52% tree cover of mixed spruce-fir canopy. Recently, there have been beetle-killed trees, so tree cover at this site could decrease in time (Fig. 2).

In August of 2012 within each habitat type (meadow, forest) at Cumbres Pass, we established two parallel transects spaced 10 m apart. Each transect (approximately 100 m long) consisted of 10 m × 3 m plots ($n = 20$) with a buffer of 2 m between plots, thus establishing 40 plots per habitat type for a total of 80 plots at this site. Both transects were on a north-facing slope of moderate, but somewhat variable, incline (Kindscher et al. 2013).

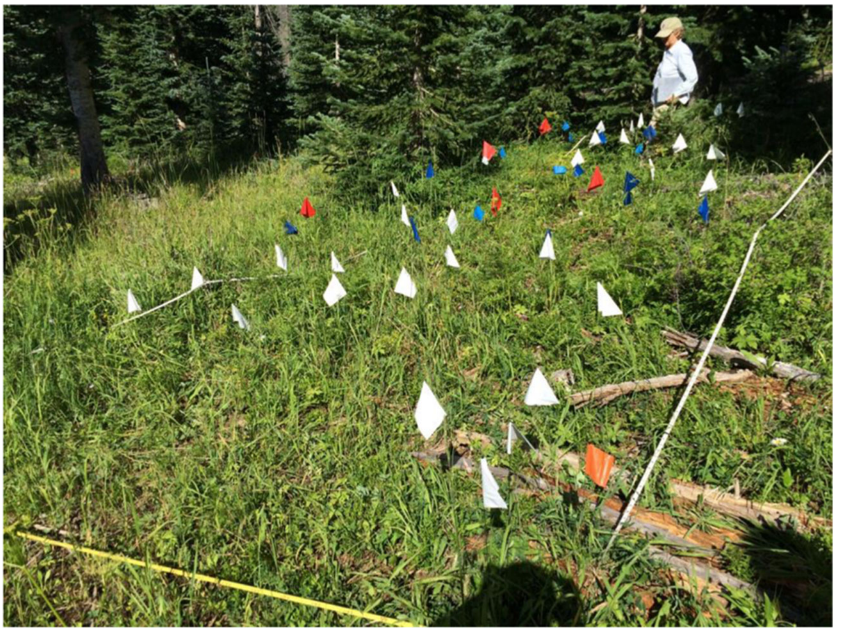

Fig. 1. Cumbres Pass meadow plot in August 2016 at Rio Grande National Forest. Flags show plants and stage classes (different flag colors indicate different stage classes).

In August of 2014, we established an additional 40 plots of the same dimensions about 100 miles west at the Missionary Ridge site, northeast of Durango, Colorado, increasing the total number

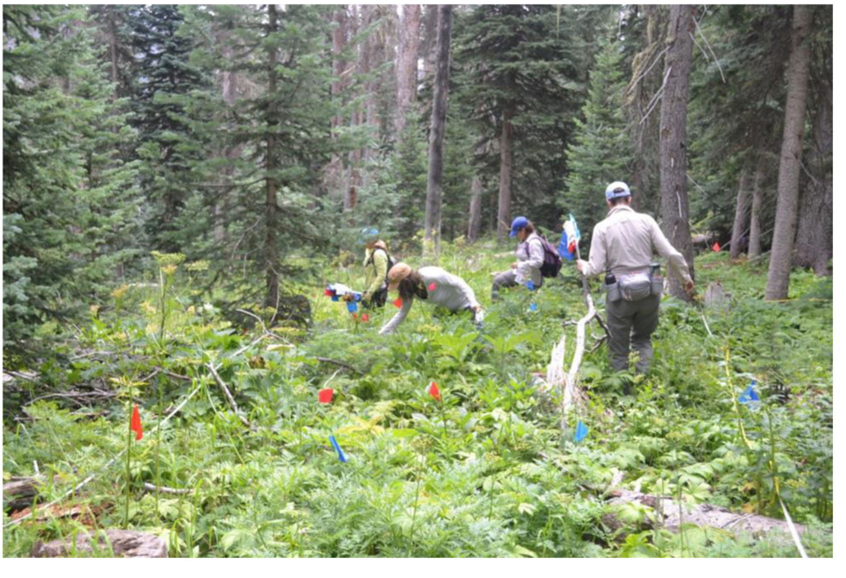

Fig. 2. Cumbres Pass forest plot in August 2016 at Rio Grande National Forest. Crew is marking oshá plants with different colored flags to categorize plants with their stage classes.

of permanently marked plots in the study to 120. The Missionary Ridge site, designated as the burned habitat, was consumed by the historic fire of June 2002, which covered over 71,000 acres and was the fourth largest fire at the time in Colorado history (Durango Herald 2002). Recolonization of trees following the fire has been very limited, and there was no essentially canopy cover above any plot at this site (Fig. 3).

Prior to applying our experimental harvest treatments, we gathered baseline population data. At both sites (Cumbres Pass year 2012; Missionary Ridge year 2014), within each plot, we recorded counts of plants and percent cover (the percentage of the entire plot covered from a bird's eye perspective) for specific stage classes of oshá: seedling, juvenile, vegetative, and reproductive (Table 1). We also recorded the total percent cover of all oshá in each plot (that is the total percent cover of oshá in the plot regardless of its specific stage class), as well as the total number of flowering stalks in each plot (individual plants can vary from 0 to 15 flowering stems, with 2–3 being common for those that do flower). An individual oshá plant can be challenging to discern due to its rhizomatous root system and overlap of vegetative growth. Therefore, we assigned the criteria that the vegetative cover of one individual plant is 50 cm or less in diameter, and that a plant should be considered a separate individual if it is greater than 20 cm away from the edge of another individual's leaf or flowering stem. Although these criteria may be subjective, they were used consistently across plots, and imposing them was necessary to both quantify root production and aboveground variables at a realistic scale of harvest (both the scale of the plants across a large area, and the scale at which they are harvested with shovels), and to mimic the wild harvest that is occurring in the area, where clumps of oshá about 50 cm across are often dug.

In order to determine a sustainable rate of harvest of oshá, we measured the long-term response of these populations to varying rates of harvest pressure. We only harvested mature plants—both Vegetative and Reproductive stage classes. Note that mature plants do not flower every year. We established five different treatments of harvest intensity based on the harvest percentages of mature plants (both vegetation and reproductive classes as large mature plants, which would be harvested, do not flower every year): 0%, 33%, 66%, and 100%, with 10 replicate plots of each harvest intensity per habitat type (meadow, forest, burned). The meadow and forest habitats were located at Cumbres Pass and were harvested in 2012, while the burned habitat was located at Missionary Ridge and was harvested in 2014. This second site was established due to a request from the San Juan National Forest and because we thought we had the capacity to collect data at another site. One of every three mature plants was harvested in the 33% treatment, two of every three mature plants were harvested in the 66% treatment, all mature plants were harvested in the 100% treatment, and no plants were harvested in the 0% treatment, which served as a control. Note that in all treatments, no seedling or juvenile plants were harvested.

Because a minimum of six mature oshá plants was required to differentiate between these treatments (i.e., the problem of harvesting 33% of 2 or 5 plants was most easily solved by only studying plots with larger numbers of plants), some prospective plot locations along each transect with fewer than six mature plants were omitted from the study and included in the buffer between plots. In total, seven plots were excluded at the three sites but added back in as new plots at the end of their respective transects. We met with both USFS personnel and wild harvesters and examined non-experimental harvest pits to ensure that our methods realistically mimicked wild harvest. Harvested plants were preferentially selected based on large size and ease of access (i.e., in open areas, not next to large rocks, logs, or fallen trees). All mature plants were harvested in the 100% harvest treatment regardless of size and ease of access. Every effort was exerted to harvest all roots of marketable size from mature plants, but as will be discussed, root fragments are frequently missed by both our research team and wild harvesters. Soil that was removed by harvesting oshá roots was subsequently replaced in pits in order to simulate practices of larger commercial and more conscientious harvesters.

Statistical Analysis

We analyzed Cumbres Pass harvest treatment data separately from the Missionary Ridge data because the experiments were started in different years. We used repeated measures ANCOVA to determine whether harvest treatments differed for all response variables at each site. Dependent variables were as follows: number and cover of juvenile class; number and cover of vegetative class; number and cover of reproductive class; number of

Fig. 3. Transect and plots at Missionary Ridge in August 2016 at the San Juan National Forest. Pink flags mark plot corners within transects marked with measuring tapes.

flowering stalks; and total oshá cover. Therefore, eight ANCOVAs were run for each of the Cumbres Pass and Missionary Ridge sites, for a total of 16 ANCOVAs. We used the *lme* function in the *nmle* package in R version 3.0.2. For both locations, we took into consideration the counts and cover of oshá plants in plots prior to harvest (2012 for Cumbres Pass and 2014 for Missionary Ridge) in our analysis. We did this because plots had different numbers and covers of oshá for the various classes prior to harvesting. To do this, we included data before harvest (time 0) as a covariate in our statistical models. Data for time 0 was collected immediately before harvest during the year we established the experiment. We returned 1 year later in August and collected data on counts and cover (time 1), and we returned each year thereafter to sample the plots.

In 2017, data were collected for time 5 at the Cumbres sites and time 3 at Missionary Ridge. We analyzed whether harvest treatments differed, whether there were any overall trends across years (time), and whether harvest treatments differed across time (time × harvest treatment interactions). Tukey's post hoc multiple comparison tests were performed when the harvest treatment was significant in the ANCOVA ($P \leq 0.05$) using the *glht* function in the *multcomp* package. For Cumbres Pass, we were also interested in whether the forest and meadow habitats differed. Therefore, we included habitat in the statistical model, but we interpreted any significant differences in habitat conservatively because the habitats were not replicated at the site scale. Percent cover response variables were *logit* transformed, and count variables

TABLE 1. DEFINITIONS OF OSHÁ STAGE CLASSES USED IN THE OSHÁ EXPERIMENT.

Stage class	Definition
Seedling	Plants with cotyledons and plants of comparable size, given that cotyledons senesce
Juvenile	Plants with single- or double-stemmed leaf stalks that were distinctly larger than seedlings
Vegetative	Mature plants that had three or more leaf stalks and obtained a size equivalent to reproductive plants, but were not flowering during the year of observation
Reproductive	Mature plants that displayed inflorescences or evidence that a flowering stalk had formed during the year of observation (if aborted or eaten off)

were $ln + 1$ transformed prior to analyses to improve normality (Warton and Hui 2011). Untransformed means are reported in figures and tables. All analyses were conducted using R version 3.0.2 (R Core Team 2013).

Results

Recovery of oshá populations was evident for some habitats and harvest treatments. In no case did habitat type (forest vs. meadow) impact the outcome of the harvest treatments at Cumbres Pass (all habitat × treatment interactions $P > 0.30$; Table 2). However, habitat type did affect juvenile and vegetative stage classes overall, regardless of treatments (Table 2; Figs. 4 and 5). The number of juveniles at Cumbres Pass was 2.6 times higher in the meadow (with much greater light availability) than in the forest, and this did not vary significantly across time (Table 2; Fig. 4). However, habitat type at Cumbres Pass impacted the cover of juveniles, the number and cover of vegetative plants, and total oshá cover differently over time (Table 2; Figs. 4, 5, and 6). Specifically, the cover of juveniles increased more over time in the meadow than in the forest, such that by 2017 the meadow contained 2.4 times more cover of juveniles than the forest (Fig. 4). Number and cover of vegetative plants also increased more in the meadow over time compared to the forest (1.4 and 1.5 times greater in the meadow, respectively, by 2017) (Table 2, Fig. 5).

Number and cover of vegetative plants were not impacted by harvest treatments at either site, but harvest treatments impacted juveniles differently at Cumbres Pass and Missionary Ridge. Specifically, harvest treatments impacted the number of juveniles at Missionary Ridge but not Cumbres Pass. There were 2.0 times as many juveniles in the 100% harvest treatment compared to controls at Missionary Ridge. Furthermore, juvenile cover differed with treatments over time at Cumbres Pass, but it was not impacted by treatments at Missionary Ridge (Tables 2 and 3; Figs. 4 and 8). Thus, juveniles were conditionally impacted by harvest treatments between the sites. Juvenile numbers also increased in the year immediately after harvest, particularly at Cumbres Pass. These increased numbers were probably representative of resprouts.

The number and cover of reproductive plants, the number of flowering stalks, and the total cover of oshá were all significantly impacted by harvest treatments at both Cumbres Pass and Missionary Ridge (Tables 2 and 3; Figs. 6, 7, and 8). In none of these cases did the difference in treatments change significantly over time (Tables 2 and 3). In all cases, the 100% harvest treatment had significantly lower levels of oshá than the control and the 33% harvest treatment (all tukey's post hoc $P \leq 0.05$) (Tables 2 and 3; Figs. 7 and 8). Specifically, at Cumbres Pass, the number and cover of reproductive plants, the total number of flowering stems (note very large plants can have multiple flowering stalks), and total oshá cover in a plot were 43%, 43%, 55%, and 27% lower, respectively, in the 100% harvest treatment compared to controls (Table 2; Figs. 7 and 8). The number and cover of reproductive plants, the number of flowering stems, and total oshá cover were also 39%, 34%, 45%, and 21% lower, respectively, in the 100% harvest treatment compared to the 33% harvest treatment (Table 2; Figs. 7 and 8). The control treatment, with zero harvest, did not differ from the 33% or 66% harvest treatment at Cumbres Pass for any of these classes (Table 2). Total cover of oshá also differed between habitats across time, such that by the fifth year after harvest (2017), the meadow had 1.7 times more oshá than the forest (Table 2; Fig. 7). At Missionary Ridge, the number and cover of reproductive plants, the number of flowering stems, and total oshá cover were 49%, 57%, 54%, and 49% lower, respectively, in the 100% harvest treatments compared to the controls (Table 3, Fig. 8). The number and cover of reproductive plants, the number of flowering stems, and total oshá cover were also 46%, 49%, 48%, and 39% lower, respectively, in the 100% harvest treatment compared to the 33% harvest treatment (Table 3; Fig. 8). The number and cover of reproductive plants also had less oshá in the 66% harvest treatment compared to controls (Table 3; Fig. 8).

Seeds and seedlings could be important to the regeneration of oshá populations. No seedlings were observed in most plots in most years. Seedlings appeared very rarely, although they are small enough that it is likely we did not observe all that were present. When we did observe seedlings, they seemed to be most common in disturbed areas. But because there were so many zeroes in the seedling data (and so few seedlings in our plots), we were unable to analyze seedling data. When seedling data were added to the juvenile data category, it did not affect the results. In addition, seedlings were observed to grow very slowly and did not appear to reach

TABLE 2. RESULTS (*F STATISTIC; PROBABILITY*) OF REPEATED MEASURES ANCOVA FOR COUNTS AND COVER AT CUMBRES PASS, WITH TUKEY'S POST HOC TESTS (*PROBABILITY*). RESULTS OF TUKEY'S POST HOC TESTS WERE NA IF THE OVERALL HARVEST TREATMENT EFFECT WAS NOT SIGNIFICANT, BECAUSE POST HOC TESTS ARE NOT CONDUCTED IN THAT CASE.

Cumbres Pass counts of plants by stage class					
Source	df	Number of juvenile plants	Number of vegetative plants	Number of reproductive plants	Number of flowering stalks from all plants
Time 0 (before harvest)	1	*25.56 (< 0.01)*	*59.62 (< 0.01)*	*40.40 (< 0.01)*	*50.53 (< 0.01)*
Habitat (Hab) (Block)	1	*47.23 (< 0.01)*	*5.76 (0.02)*	0.06 (0.81)	0.00 (0.97)
Treatment (Trt)	3	0.54 (0.66)	1.22 (0.31)	*6.77 (< 0.01)*	*7.29 (< 0.01)*
Hab × Trt	3	0.57 (0.63)	1.19 (0.32)	0.46 (0.71)	0.38 (0.77)
Error (Plot × Hab × Trt)	71				
Time (T)	4	*23.31 (< 0.01)*	*11.39 (< 0.01)*	*4.19 (< 0.01)*	*8.76 (< 0.01)*
Time 0 × T	4	0.89 (0.47)	0.14 (0.97)	0.53 (0.72)	2.03 (0.09)
Hab × T	4	2.18 (0.07)	*4.91 (< 0.01)*	0.58 (0.70)	0.91 (0.46)
Trt × T	12	1.17 (0.31)	1.05 (0.40)	1.24 (0.25)	0.96 (0.48)
Hab × Trt × T	12	0.56 (0.88)	0.77 (0.68)	0.78 (0.67)	0.70 (0.75)
Error (Plot × Hab × Trt × T)	284				
Post hoc tests					
0–33%		NA	NA	1.00	1.00
0–66%		NA	NA	0.24	0.29
0–100%		NA	NA	*0.02*	*0.03*
33–66%		NA	NA	0.24	0.29
33–100%		NA	NA	*0.02*	*0.03*
66–100%		NA	NA	0.66	0.76
Cumbres Pass percent cover of plants by stage class					
Source	df	Cover of juvenile plants	Cover of vegetative plants	Cover of reproductive plants	Total oshá percent cover
Time 0 (before harvest)	1	2.39 (0.13)	*50.95 (< 0.01)*	*47.01 (< 0.01)*	*87.75 (< 0.01)*
Habitat (Hab) (Block)	1	*29.85 (< 0.01)*	2.87 (0.09)	0.21 (0.65)	2.07 (0.15)
Treatment (Trt)	3	0.76 (0.52)	1.26 (0.30)	*4.67 (< 0.01)*	*4.18 (< 0.01)*
Hab × Trt	3	0.96 (0.42)	0.40 (0.75)	0.29 (0.83)	0.07 (0.98)
Error (Plot × Hab × Trt)	71				
Time (T)	4	*12.58 (< 0.01)*	*48.42 (< 0.01)*	*29.15 (< 0.01)*	*89.67 (< 0.01)*
Time 0 × T	4	1.13 (0.34)	1.33 (0.26)	*8.76 (0.01)*	*2.53 (0.04)*
Hab × T	4	*6.53 (< 0.01)*	*7.92 (< 0.01)*	1.61 (0.17)	*8.09 (< 0.01)*
Trt × T	12	*1.95 (0.03)*	1.13 (0.34)	1.24 (0.26)	1.32 (0.21)
Hab × Trt × T	12	0.60 (0.84)	1.26 (0.24)	1.07 (0.39)	0.81 (0.64)
Error (Plot × Hab × Trt × T)	284				
Post hoc tests					
0–33%		NA	NA	1.00	0.99
0–66%		NA	NA	0.09	0.14
0–100%		NA	NA	*0.04*	*< 0.01*
33–66%		NA	NA	0.08	0.26
33–100%		NA	NA	*0.03*	*0.02*
66–100%		NA	NA	0.98	0.70

Numbers in italics indicate findings are significant at < 0.05

maturity in our multi-year study. Therefore, we decided to exclude seedlings from the analysis.

Overall, there was significant variation across time for all the Cumbres Pass oshá response variables (Table 2; Figs. 4, 5, 6, and 7). Interestingly, total cover of oshá was higher in the meadow at Cumbres Pass in 2017 in all harvest treatments than it was at the beginning of the study (Fig. 7). There was not as much variation across time at Missionary Ridge (Table 3; Fig. 8), but this could be due to the fact that there were fewer sample dates (fewer years of data) to test for this variation.

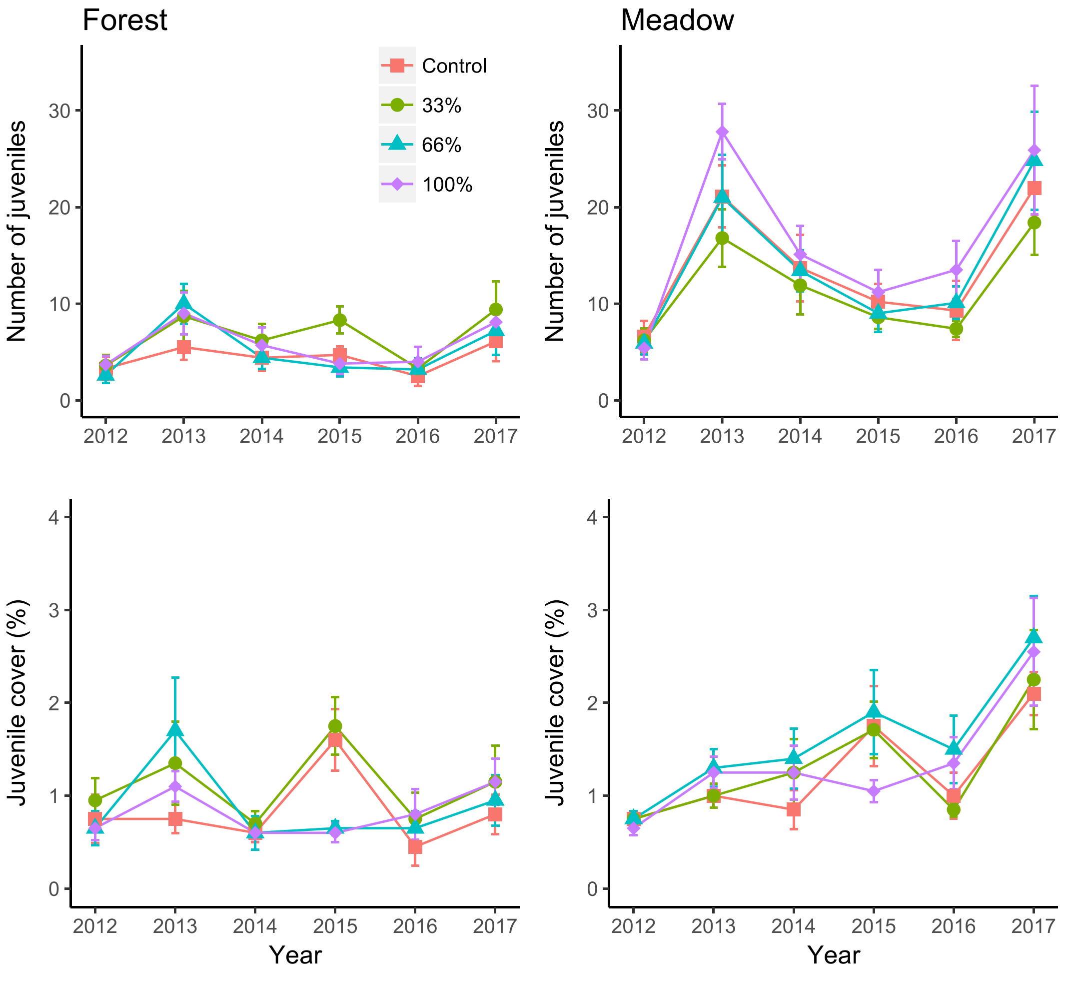

Fig. 4. Means ± standard error bars of number (top panels) and percent cover (bottom panels) of juvenile plants in each harvest treatment over time in the forest (left panels) and meadow (right panels) habitats at Cumbres Pass. Data from 2012 were taken just prior to harvest treatments being implemented that year, and 2013–2016 data were recorded after harvest treatments were implemented. Juveniles were defined as having single- or double-stemmed leaf stalks that were distinctly larger than seedlings.

Discussion

This study indicates that oshá can recover following low levels of harvest (33%), particularly when looking at the % cover of reproductive plants and total oshá cover. Part of this recovery may be driven by resprouting of rhizomes inadvertently left in the ground by harvesters. As documented in previous work (Kindscher et al. 2013), we found that rhizomes and large juvenile plants grew quickly to mature, and flower, where the soil had been disturbed by harvesting. Higher levels of harvest lead to a slower recovery of oshá. Although there was variation in some population responses between Cumbres Pass and Missionary Ridge populations, generalizations and predictions about the impact of harvest intensity on oshá can be drawn.

First, and most importantly, all stage classes of oshá recovered from 33% harvest treatments at both sites by the end of the study, as there was no difference in population measurements between the control and 33% harvest treatments. Missionary Ridge populations recovered after 3 years, and Cumbres Pass populations recovered after 5 years.

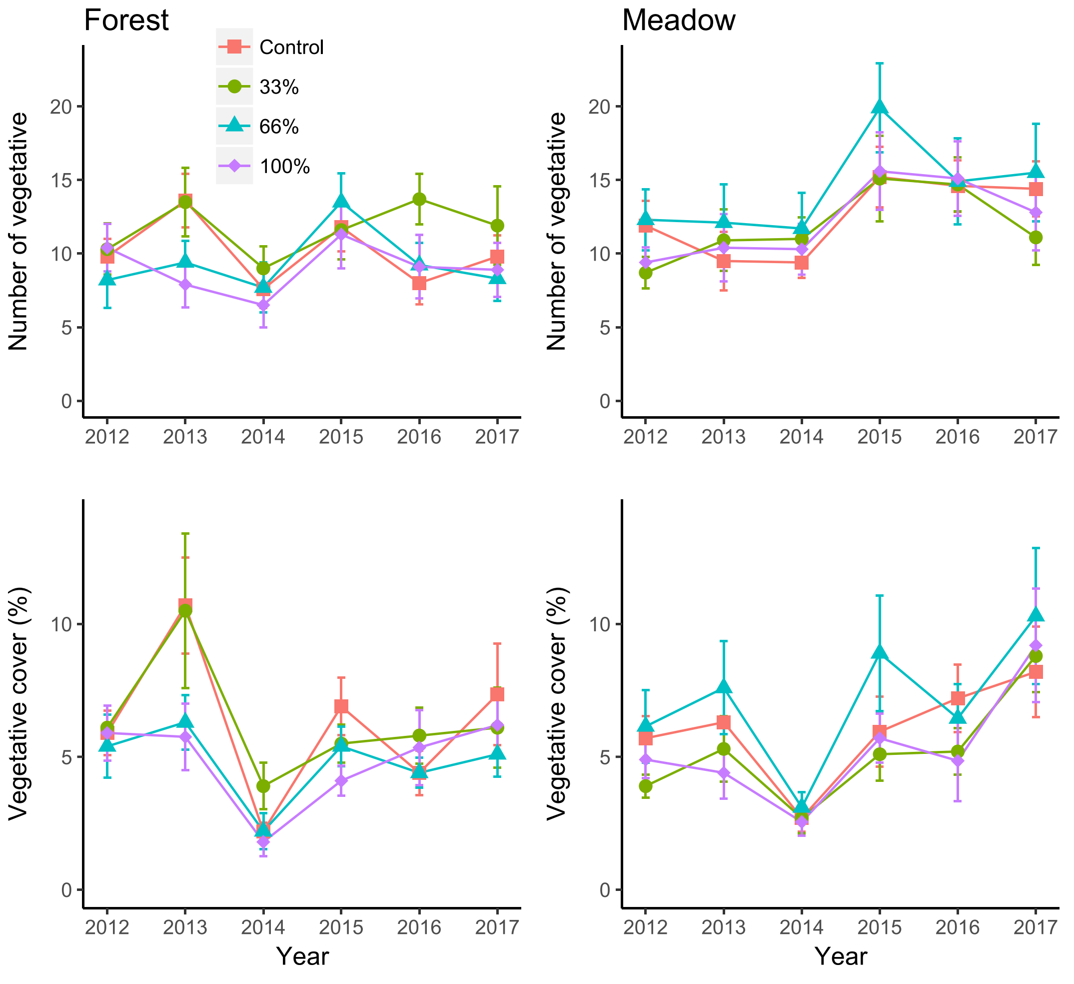

Fig. 5. Means ± standard error bars of number (top panels) and percent cover (bottom panels) of vegetative plants in each harvest treatment over time in the forest (left panels) and meadow (right panels) habitats at Cumbres Pass. Data from 2012 were taken just prior to harvest treatments being implemented that year, and 2013–2016 data were recorded after harvest treatments were implemented. Vegetative plants had three or more leaf stalks and obtained a size equivalent of reproductive plants, but were not flowering during the year of observation.

Second, harvesting 100% of the mature plants in a plot resulted in significantly lower number and cover of reproductive plants, number of flowering stems, and total oshá cover compared to no harvest and 33% harvest of mature plants. This pattern was consistent between both sites. Even 5 years after harvest, the plots receiving the 100% harvest treatment did not recover to pre-harvest levels. Thus, 100% harvest of mature plants should likely be avoided if short-term recovery of aboveground oshá after harvest is a goal.

Differences between Cumbres Pass and Missionary Ridge were seen when looking at the 66% harvest treatment. In particular, the response of number and cover of reproductive plants to the 66% harvest treatment varied between sites. At Cumbres Pass, harvesting up to 66% was not detrimental to the reproductive stage class, as the number and cover of plants was similar to that of the control plots. At Missionary Ridge, however, 66% harvest did reduce number and cover of reproductive plants, compared to the control plots, although it had no effect on the number of flowering stems or total cover of oshá. We only studied the Missionary Ridge population for 3-year post-harvest, and given two more years, the population may recover from

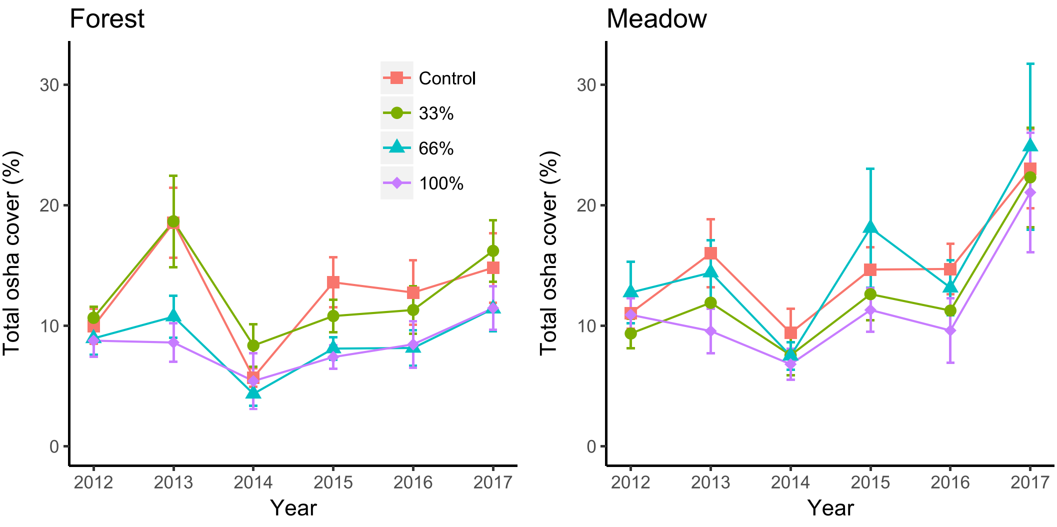

Fig. 6. Means ± standard error bars of total percent cover of all oshá in each harvest treatment over time in the forest (left panel) and meadow (right panel) habitats at Cumbres Pass. Data from 2012 were taken just prior to harvest treatments being implemented that year, and 2013–2016 data were recorded after harvest treatments were implemented.

66% harvest, as was seen in the Cumbres Pass population. These results, however, do raise the question of sustainability of harvesting 66% of the population, and suggests that higher levels of harvest should proceed cautiously.

Vegetative and juvenile plants are interesting, because, through root sprouts, they may be a main driver for population recovery after harvesting. These stage classes exist naturally in stands, but are also common in the disturbances created by harvesting. In fact, soil disturbances created by harvesting may increase the presence and cover of vegetative and juvenile oshá plants, as root fragments resprout (Kindscher, personal observation after destructive examination of root fragments). A similar process is seen with the harvest of goldenseal (Van der Voort et al. 2003), although goldenseal rhizomes are much smaller. In fact, at Missionary Ridge, the 66% and 100% harvest treatment plots contained more juveniles than the control plots. The percent cover of juveniles at Cumbres Pass fluctuated among time between the treatments. Vegetative plants were not affected by harvest treatments at either site. Further studies explicitly examining the effects of disturbance on oshá root regeneration could provide valuable insight into population recovery.

Habitats within Cumbres Pass were not replicated, and thus we cannot draw strong conclusions about the effect of habitat on the recovery of oshá after harvest. However, we did see higher numbers of juvenile and vegetative plants in the disturbed meadow, and the meadow had visually larger and denser stands of plants. Thus, in future work, it may be useful to examine the effect of habitat type (open vs. forest) on population recovery after harvesting.

The significant amount of variation over time at Cumbres Pass for all oshá response variables indicates that factors other than harvest can impact populations. For example, we have observed light to heavy grazing by cattle and some elk, insect damage to foliage and seeds, and chipmunks regularly climb up the flower stalks to eat ripening seeds. Of these, there is some evidence indicating that cattle grazing can negatively impact oshá populations (Julander 1968). Weather would almost certainly be a factor in the variability of oshá populations through time. The reduction in total oshá cover in 2014 at Cumbres Pass, for example, likely could be attributed to low total precipitation from October the previous year through September of that year. During this time period, total precipitation was 56.1 cm, only the third time in 36 years that year precipitation fell below 60 cm, with the average being 91.8 cm (Kindscher et al. 2013). The year of harvest (2012) and the year after harvest (2013) at Cumbres Pass also saw lower than average precipitation at 69.9 and 66.3 cm, respectively. The

TABLE 3. RESULTS (*F; P*) OF REPEATED MEASURES ANCOVA FOR MISSIONARY RIDGE AND TUKEY'S POST HOC TESTS (*P*). RESULTS OF TUKEY'S POST HOC TESTS WERE NA IF THE OVERALL HARVEST TREATMENT EFFECT WAS NOT SIGNIFICANT, BECAUSE POST-HOC TESTS WERE NOT CONDUCTED.

Missionary Ridge counts of plants by stage class					
Source	df	Number of juvenile plants	Number of vegetative plants	Number of reproductive plants	Number of flowering stalks
Time 0	1	*8.94 (< 0.01)*	*10.91 (< 0.01)*	*60.54 (< 0.01)*	*47.31 (< 0.01)*
Treatment (Trt)	3	*5.30 (< 0.01)*	2.50 (0.08)	*7.21 (< 0.01)*	*6.07 (< 0.01)*
Error (Plot × Trt)	35				
Time (T)	2	*4.22 (0.02)*	2.34 (0.10)	*3.95 (0.02)*	2.17 (0.12)
Time 0 × T	2	0.35 (0.71)	0.85 (0.43)	0.43 (0.65)	*5.53 (< 0.01)*
Trt × T	6	0.79 (0.58)	0.64 (0.70)	0.86 (0.53)	1.02 (0.42)
Error (Plot × Trt × T)	70				
Post hoc tests					
0–33%		0.84	NA	0.97	0.97
0–66%		*0.02*	NA	*0.02*	0.15
0–100%		*0.01*	NA	*< 0.01*	*<0.01*
33–66%		0.14	NA	0.07	0.29
33–100%		0.12	NA	*< 0.01*	*< 0.01*
66–100%		1.00	NA	0.86	0.39
Missionary Ridge percent cover of plants by stage class					
Source	df	Cover of juvenile plants	Cover of vegetative plants	Cover of reproductive plants	Total oshá percent cover
Time 0	1	0.62 (0.44)	1.25 (0.27)	*92.80 (< 0.01)*	*87.12 (< 0.01)*
Treatment (Trt)	3	0.46 (0.71)	0.91 (0.44)	*10.03 (< 0.01)*	*7.40 (< 0.01)*
Error (Plot × Trt)	35				
Time (T)	2	0.54 (0.58)	*3.75 (0.03)*	1.07 (0.35)	1.74 (0.20)
Time 0 × T	2	2.16 (0.13)	0.00 (1.00)	*6.73 (< 0.01)*	*11.82 (< 0.01)*
Trt × T	6	1.23 (0.30)	0.56 (0.76)	0.64 (0.70)	0.82 (0.49)
Error (Plot × Trt × T)	70				
Post hoc tests					
0–33%		NA	NA	0.60	0.74
0–66%		NA	NA	*< 0.01*	0.09
0–100%		NA	NA	*< 0.01*	*< 0.01*
33–66%		NA	NA	0.15	0.55
33–100%		NA	NA	*0.01*	*0.05*
66–100%		NA	NA	0.83	0.59

Numbers in italics indicate findings are significant at < 0.05

Drought Severity Index also indicates that the area was in various stages of severe or moderate drought from 2012 through the early part of 2015 (National Drought Mitigation Center 2016). Longer term sampling would further enhance our understanding of the effects of precipitation and other factors on oshá recovery after harvest.

THE LIFE CYCLE OF OSHÁ AND SUSTAINABLE HARVEST PARAMETERS

We were unable to track individual oshá plants through time because it was impossible to know whether sprouts and shoots were growing from rhizomes generated by existing plants, or from rhizome pieces remaining in the soil after harvesting plants. We tried marking plants at the beginning of the experiment at all sites, but abandoned this effort after 2 years of confusing results as it appeared that rhizomes can move "plants" several decimeters, and sometimes in more than one direction, as plants appeared to overlap. Knowing the length of time for an oshá plant to transition from seedling to juvenile, to vegetative, and to a reproductive class would be useful for understanding how populations are responding after harvest. For example, we do not know if the juveniles identified in 1 year remained juveniles the following year. We expect some to become vegetative, or even reproductive. Furthermore, some vegetative and reproductive plants may have died, and we expect that root fragments after harvest may have produced some new juveniles.

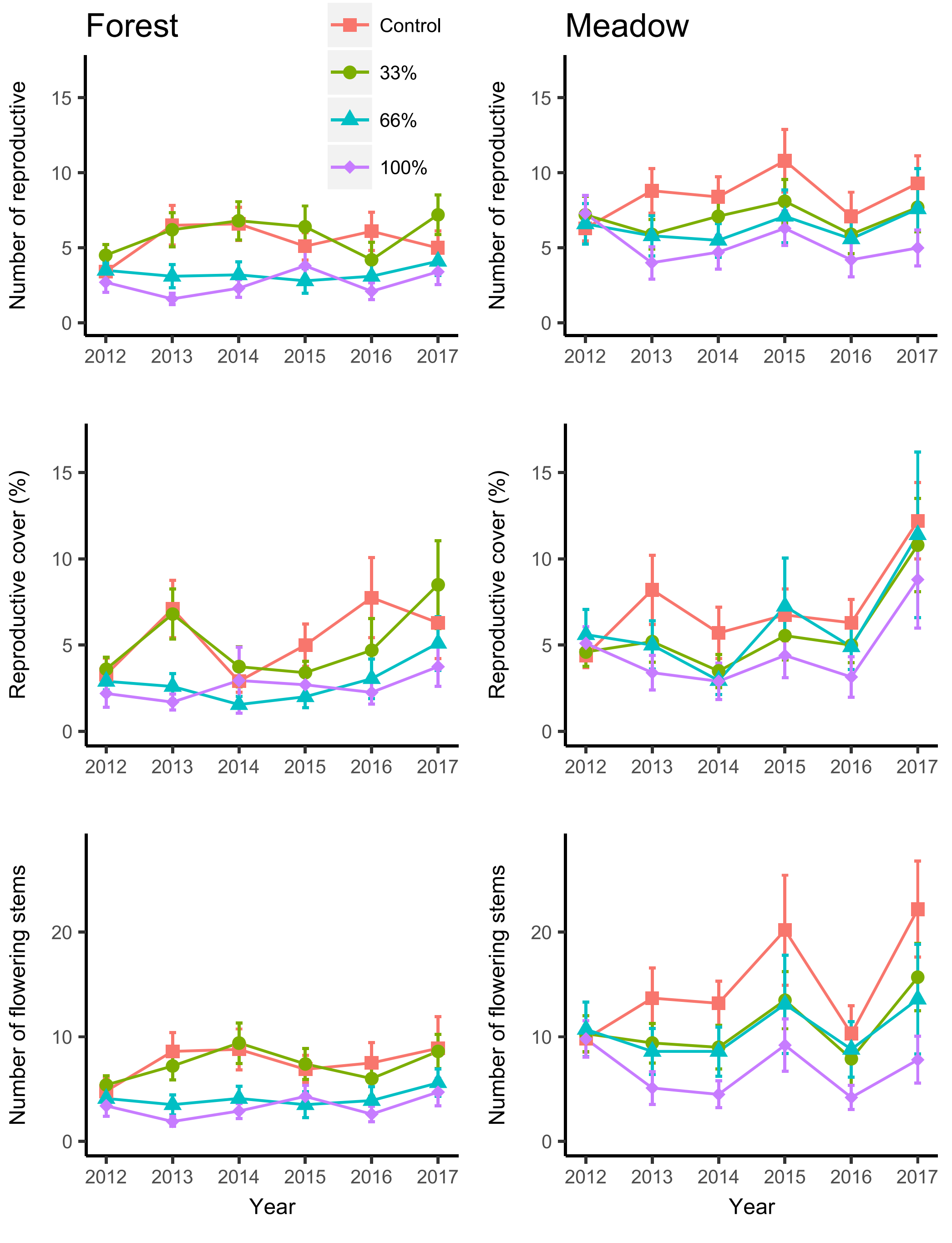

Fig. 7. Means ± standard error bars of number (top panels) and percent cover (middle panels) of reproductive plants, and number of flowering stems (bottom panels) in each harvest treatment over time in the forest (left panels) and meadow (right panels) habitats at Cumbres Pass. Data from 2012 were taken just prior to harvest treatments being implemented that year, and 2013–2016 data were recorded after harvest treatments were implemented. Reproductive plants displayed inflorescences or evidence that a flowering stalk had formed during the year of observation (if aborted or eaten off).

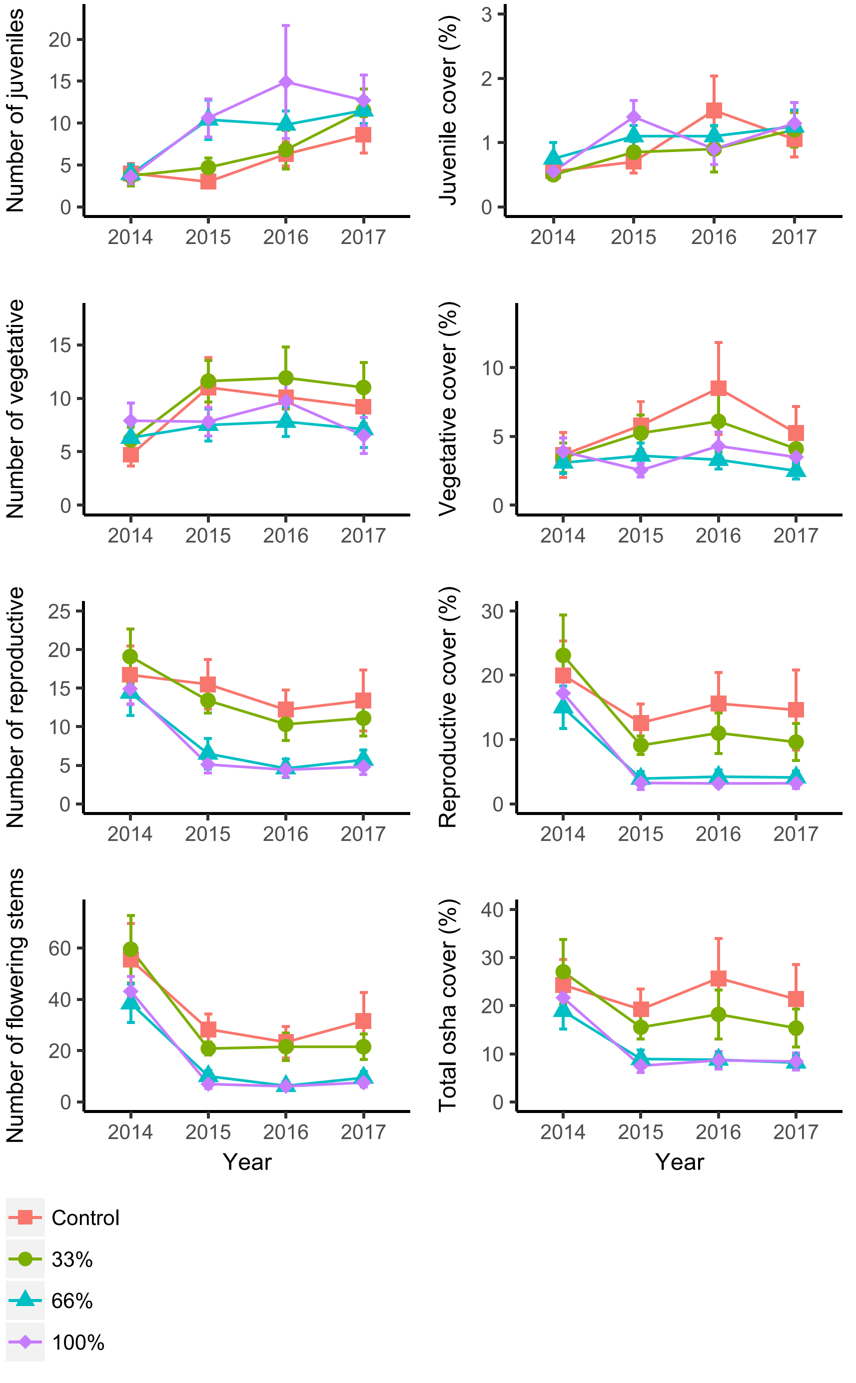

Fig. 8. Means ± standard error bars of all oshá response variables in each harvest treatment over time at Missionary Ridge. Data from 2014 (time 0) were taken just prior to harvest treatments being implemented that year, and 2015–2016 data were recorded after harvest treatments were implemented. Oshá stage classes are defined in Table 1.

Identifying an individual plant is challenging because of its rhizomatous habit; however, this may also be the reason for the apparent resilience of oshá to low levels of harvest. One observation that deserves discussion is that a few plants were observed flowering in the 100% harvested plots 1 year after harvest, indicating that some rhizome pieces that escaped harvest had sufficient root reserves to reproduce. Knowing these specific population dynamics could aid in further understanding the response of oshá to harvest.

Future Research Needs

Additional questions remain with respect to the generality of our results. First, longer term studies will allow us to make better recommendations for the number of years between harvests that would sustain oshá populations. Our current study documents the effects of harvest in the short-term, 5-year post-harvest at Cumbres Pass and 3 years at Missionary Ridge. Longer term results are desirable, especially for the US Forest Service and their interest in long-term sustainability of oshá harvest. We do not know how long it would take for Missionary Ridge populations to recover after harvest, as did the populations at Cumbres Pass. Longer term studies would provide us better information in developing a sustainable harvest plan. Longer term studies would also allow us to examine the effects of weather on the recovery time of oshá populations. For example, if harvest takes place during a drought, for example, as it did in our study at Cumbres Pass, it could take much longer for oshá to regenerate. A more extensive study, examining the effects of harvest across years with varying weather conditions, would be required to confirm this.

Second, we only conducted a single harvest event on our plots. However, harvesters often return to the same population year after year. A longer term study, with multiple harvests and longer term monitoring, would allow a more accurate picture of the effect of harvesting on oshá population recovery times.

Third, the generation of a good population model would help inform and develop protocol for sustainable harvest. In particular, quantifying the transition probabilities between stage classes would be necessary in developing such a model. This model should include examination of the seed stage and how soil disturbances, such as those created by harvesting, influence seed recruitment and root sprouting. Given the difficulty in identifying individual plants, the use of DNA markers would assist in this process.

Fourth, although we studied the aboveground populations of oshá after experimental harvest, we did not collect subsequent data on whether root production was different between the harvest treatments 5- and 3-year post-harvest. Without this data, the assumption must be made that aboveground and belowground dynamics are correlated. We did find that greater aboveground biomass was correlated with greater belowground biomass (root weight) when we conducted our initial harvest (unpublished data). However, whether this relationship changes after one or multiple harvests is not known. The correlation could remain, or it could be altered when roots are broken up during harvest activities and regrow. Only another harvest event would tell us if root production could remain viable as well. That said, in 2017, we re-dug two plants at the Missionary Ridge site and examined them visually, noting that we could see where the previous rhizomes had been cut during harvest 4 years ago. We also observed that not only were the current roots large enough to harvest again, but they had significant weight and size that a harvester would be looking for (Kindscher and Daniel Gagnon, personal observation, August Kindscher et al. 2017).

Finally, understanding differences among populations across the species range will also be important for generating local sustainability plans. For example, oshá populations in the Front Range of Colorado, the eastern edge of the species geographical range, tend to be smaller and have lower plant densities (K. Kindscher, personal observation). This study focuses on large populations at the core of the range.

Conclusion

Overall, it appears that lower levels of harvest (33% or lower) could produce stable populations of oshá over the short term (3–5 years). The USFS is interested in developing and monitoring a long-term sustainable harvest plan for oshá, one that is straight forward, easy to monitor, and does not overly burden staff time. Based upon these needs and the results from this study, our current recommendation is to permit harvest of 50% of mature plants from a population every 10 year. First, we believe that this is a sustainable rate of harvest. At Cumbres Pass, population measures for the 66%

harvest rate were not different than for the 33% and 0% harvest treatment after 5 years. At Missionary Ridge, we did see a similar recovery after 3 years for the 33% harvest treatment, but not for the 66% harvest treatment. Further study would be required to know how this population would recover after 5 years. Mooney et al. (2015) also show some level of recovery of oshá plants after harvest. Second, harvest of 50% of mature plants is easily and logically monitored, and is easy for harvesters to visualize. Third, a 10-year interval between revisits should be a long enough to allow repopulation from rhizome resprouts and seed germination. Harvesters could be given access to a large area or 10 discreet areas, and move from harvest patch to harvest patch each year, using a new area over each of 10 years, before returning to their original harvest location. US Forest Service personnel have suggested at least some populations could be behind locked gates on decommissioned roads, protecting harvesters' patched from those just driving by.

We recognize that our data only span 3 to 5 years, and it is possible that, over this short time frame, root biomass would not recover from harvest. Understanding the effects of harvest on root mass would require additional study. Further, we found variation between our sites in recovery at 66% harvest, and the effects of our recommended 50% harvest were not examined in this study. Given this variation, the limited number of year post-harvest, and lack of data on the recovery of the root systems after harvest, we suggest any policy regarding oshá harvesting should be generated with caution, and actionable steps to monitor oshá after harvesting events should be considered. In all, oshá is fairly unique in its ability to repopulate areas that have been harvested due its consistent ability to grow from root pieces that are inadvertently left in the ground, in contrast to ginseng (Van der Voort et al. 2003) and many other wild–harvested medicinal plant species (Castle et al. 2014).

Finally, for this program of sustainable oshá harvest to be successful, it will need to include input from the harvesters themselves, who (as stated by Ticktin and Shackleton 2011) understand local knowledge and practices, including their drivers and ecological impacts. Considering that environment, society, and economy are all parts of US Forest Service (2004) recognized sustainable harvest, we believe that the proposed permitted harvest, which will include local adaptive management strategies can ultimately be adopted as a sustainable practice.

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