

# Plant Functional Diversity - Cover

While each plant functions differently in an ecosystem context, the degrees of dissimilarity which exist between all species are unequal, allowing them to form natural groups. This observation has given rise to the notion of *Plant Functional Types*, shared attributes which unite similar species, and which bind how they affect ecosystems. Plant functional types are often the easiest form of vegetation data to measure, hence great amounts of work have been conducted on how they affect ecosystem function.

In Western Colorado, four plant functional types are often used to evaluate rangeland conditions. These forms are: Trees, Shrubs, Grasses, and Forbs (or herbs), and each has been linked to affecting rangelands in multiple ways; theoretically their distributions and abundances are driven by variations in soil moisture throughout horizons (O. Sala et al. (1997)). Accordingly, in nearly all instances a mix of each of these groups, less trees, is best to maintain ecosystem services on BLM Land. In the UFO which features extensive Pinon-Juniper Woodlands, trees when present, are included in this mix on ecological sites where they represent the climax vegetation community.

Semi-arid lands which are utilized as rangelands across the world are experiencing several common issues relating to shifts in the composition of their plant functional types (Archer & Predick (2014), Eldridge et al. (2016), Maestre et al. (2016), Diaz et al. (2007), Dalgleish et al. (2010)). Namely, decreases in grasses whilst increases in woody species are occurring, and a decrease in the cover and number of species of perennial forbs while annual forbs increase (Diaz et al. (2007), West & Yorks (2006)). In certain areas, the increases - or encroachment of - woody species may be split into encroachment of trees, and the transition to a shrub state in ecological sites which do not support trees.

The current increases in shrub cover relative to the cover of the herbaceous components of vegetation are problematic for a variety of reasons. The increase in trees within mixed grass-shrubland sites may decrease water available to grasses, forbs, and shrubs which favors non-native annual grasses (McIver et al. (2022)), as domestic livestock and wildlife depend on palatable grasses, forbs, and shrubs these decrease the ability of our lands to support either. Increases in shrubs at the expense of perennial grasses and forbs may increase the severity of site level drought (Wilson et al. (2018)), further shrubs and trees may foster higher severity fires. Increases in shrubs decrease soil stability, allowing increased erosion, increasing ‘dust on snow’, and poor air quality (Munson et al. (2011)). Decreases in perennial grass may reduce competition with non-native annuals from overtaking sites Sheley & James (2010), Corbin & D’Antonio (2004), and a diversity of grass species may be the most effective prevention (Belnap & Sherrod (2008)). A decrease in forbs adversely affect wildlife both directly and indirectly, by decreasing the quality of habitats for species such as the Gunnison Sage-Grouse (Pennington et al. (2016)).

## Methods

Numerous inconsistencies exist between what the USDA Plants database species list classifies a shrub, sub-shrub, or forb relative to how ecological sites classify them into functional groups. These inconsistencies are permeated into the Colorado state species list utilized by AIM to calculate the plant functional group cover summaries. To appropriately compare conditions on the ground to ecological sites or ecological site groups we had to reassign certain plant species to the appropriate functional group.

Very good agreement existed between our species reclassification summaries and TerrAdat plant functional group summaries (Figure 1), however outliers existed within the shrub and forb functional groups. Species outliers from Figure 1 were manually investigated for their functional classification in Ecological Sites and were reassigned. A total of 1760 site functional group pairs were utilized for this process. By the end of the process 1485 of these pairs had identical values when rounded to 1 decimal point (a tenth of a percent), of the remaining 275 records, 120 had less than a one percent difference in cover, and 166 were less than a 1.5%

difference. By the end of the process the Pearson correlation coefficient for trees ( $n = 269$ ,  $r = 0.99999$ ) and grass ( $n = 400$ ,  $r = 0.99971$ ) indicated the values were essentially identical, and most likely diverged merely according to rounding during internal computations. We further added the groups of Sedges (Cyperaceae), and Rushes (Juncaceae), into our calculations of grass cover. This is important as they are included in Interpreting Indicators of Rangeland Health (IIRH), and hence the ESD cover estimates, and are likely to be included in the ESG estimates. They are likely to make a notable difference in higher elevations sites, Mixed-Mountain Shrub & Aspen, where Elk Sedge (*Carex geyeri*) may be abundant.

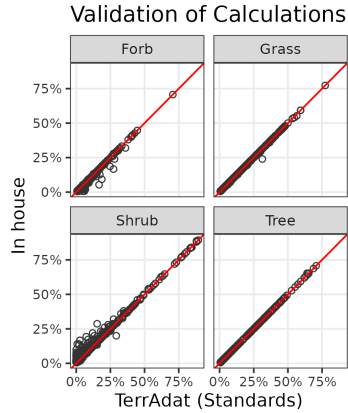


Figure 1: Comparison of calculations

The difference between the remaining functional groups was greater due to whether a species was considered in one group or the other. For Forbs and Shrubs there was a consistent discrepancy regarding a single abundant species, *Gutierrezia sarothrae* (Broom Snakeweed). Based on a review of ESD's, most authors considered this a sub-dominant shrub, a group which is combined into their estimates for Shrub Cover. Accordingly, we utilized this assessment of *Gutierrezia sarothrae* and included it as a shrub in our recalculations. As a result, we have a slightly larger discrepancy between our estimates and the TerrAdat estimate of shrub cover ( $n = 436$ ,  $r = 0.99189$ ). Since many ecological sites also consider succulents, specifically the genus *Opuntia*, a shrub in their shrub cover estimates we also included it in our calculations of Shrub cover. This also leads to a discrepancy associated with estimates of forb cover ( $n = 380$ ,  $r = 0.99542$ ). However, a greater number of values diverge between the TerrAdat summary of cover and our reclassified summaries, of the 275 records which diverge by  $> 0.1\%$  cover, 188 of them are associated with Shrubs, and the correlation here is much lower at  $r = 0.97911$ . We were unable to match up the functional groups from these two sources beyond this point.

## Results & Discussion

### Forb Cover

Benchmark forb cover is generally low across all Ecological Sites in the study area, with a maximum expected cover at any site of 15% and the median of all mean values across all sites 5.5%. In general these estimates focus on perennial species, as after they germinate nearly all species will produce above ground biomass every year of their lives. Compared to annual forbs, which may not be apparent in drier years - and remain as seeds, and are known to have considerable variation in there year to year abundances as a response to precipitation.

Across all BLM land which is not managed as an NCA, WSA, or ACEC, the estimate of the total amount of land which is achieving benchmarks is 32% (LCB = 27%, UCB = 37.1%), similar to the estimates for all ACEC-WSA areas 27.1%, and the Dominguez-Escalante NCA 28.3%. Results for the Gunnison Gorge are

much lower, none of the 19 sampled sites were meeting benchmarks, indicating none of the land is. That roughly only 1/3 of all BLM administered land is meeting these objectives was unexpected.

While nearly all plants produce less above-ground biomass during drought, the largest reduction in forb cover may be due to natural and climate induced mortality of individuals and the lack of recruitment of perennial forbs from the soil seed bank which replenishes local populations (Eziz et al. (2017), Casper (1996) Munson et al. (2022)). In other words, many individual plants are dying, and new individuals are not being recruited from seed during the prolonged drought. The establishment of both long and short lived forbs seems hampered during drought periods, and it may take several years after the cessation of a drought for the cover of perennial forbs to return to pre-drought conditions (Anderson & Inouye (2001)).

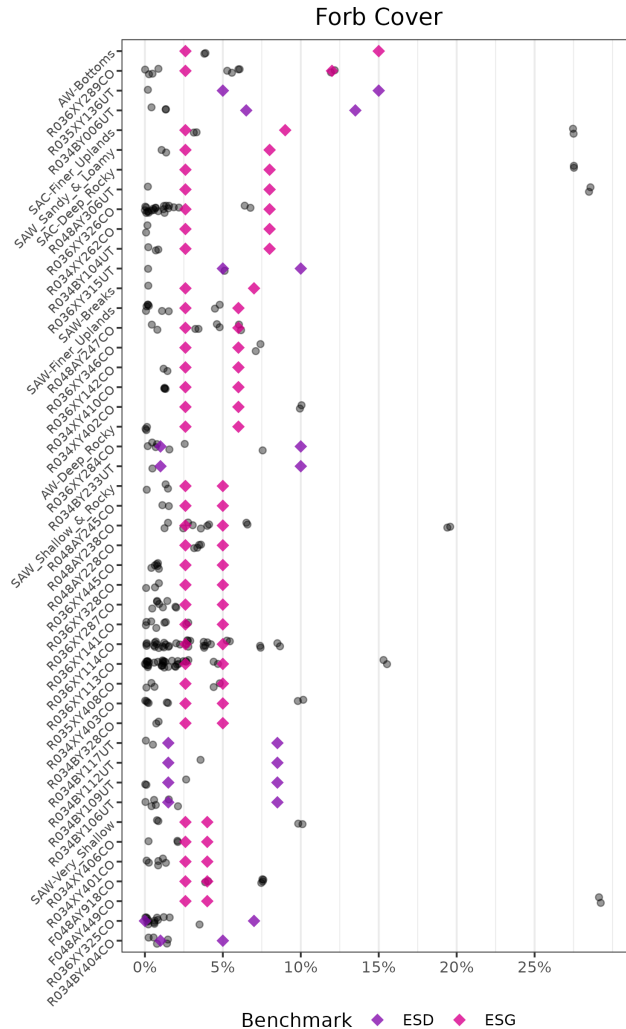


Figure 2: Benchmarks and Observed Values

It is probable that short lived perennial forbs, which generally only live a total of 2-4 years past their germination (Dalglish et al. (2010)), have widely decreased in areas during the drought (Torang et al. (2010), Anderson & Inouye (2001)). Many long-lived perennial forbs seem to generally persist for one to two decades (but up to four are noted), and once established (i.e. they reach reproductive maturity) are able to survive disturbances, such as drought (Treshow & Harper (1974), Lauenroth & Adler (2008), Morris et al. (2008)). However, given the duration of the current drought, and the merely episodic periods of normal moisture (Section 6) it is possible many of the long lived perennials have suffered non-drought induced mortality. Because of these conditions forbs have not recruited individuals from the seed bank. Recovery of the above ground cover of both forms of perennial forbs may require periods of from 2-5 years, or more, in mesic habitats (Anderson & Inouye (2001)) and longer in xeric habitats (Figure 2).

Areas in the field office which may be the most affected by forb declines may be those ecological sites with inherently lower water holding capacity; such as those with skeletal soils, high clay content, and shallow depths to bedrock, e.g. Salt Desert and considerable portions of Pinyon-Juniper Woodland. Soil depth can be a highly influential factor on survival of perennial forbs during times of drought (Davison et al. (2010), Nicole et al. (2011)). Accordingly, ecological sites supporting Wyoming Big-Sage, e.g. Gunnison Sage-Grouse habitat, are less affected due to greater soil depth and higher water holding capacity. When a lack of forbs is observed at these sites, is likely to be stemming from issues other than drought.

Aspects regarding the nature of perennial forbs are discussed further in section 12, but given the timing of sampling relative to the drought (Section 6), these results are not surprising. A more worrisome metric would relate to the species composition of forbs which are present at plots, rather than collective cover of them during periods of drought. This is because forbs have been shown to recover after droughts, granted they are initially present in the soil seed bank, partially because they have seeds which tend to have strong longevity, and partially because most species can produce some seed even under adverse conditions (LaForgia et al. (2018), Loydi & Collins (2021)). If these forbs are even present patchily throughout an area, than

it appears secondary dispersal (e.g. movement of seeds by an animal) of their seeds will allow a number of them to reach suitable micro-sites for possible reestablishment of individuals and then a population under climatically favorable conditions (Olano et al. (2012)).

## Woody Plant Encroachment

The cover of woody plants, both shrubs and trees, is observed to be at the upper end or beyond the reference benchmark values for cover at nearly all Ecological Sites (Figure 3 & 4). Greater cover of woody plants relative to reference condition is a common occurrence in nearly all arid and semi-arid rangelands globally (Bestelmeyer et al. (2018), Archer et al. (2017)). While some disagreement over the exact mechanistic causes of increases in woody plant cover exist in the literature, commonly attributed causal factors include: 1) An altered fire-cycle, 2) increasing atmospheric CO<sub>2</sub>, 3) improper grazing by livestock (Bestelmeyer et al. (2018)). These initial drivers may lead to feedback loops enforced by changes to soil fertility which cause the shrub and or tree-encroached status of these sites to perpetuate (Bestelmeyer et al. (2018)).

Drought and insect induced mortality in Sagebrush and Pinyon-Juniper woodland ecological sites have been locally apparent in the field office, and across the Southwest, over the last 20+ years (Gaylord et al. (2013), Floyd et al. (2009)). Where mortality has occurred it threatens to create conditions which allow for high severity wildfire or diminished ecological function (Baker & Shinneman (2004)). While the species of shrubs and trees which grow in semi-arid lands are considered less responsive to droughts than forbs and grasses, due to depths which many of their roots are able to reach to draw soil moisture, drought predisposes them to insect induced mortality and die back (Gaylord et al. (2013), Winkler et al. (2019)). Shrubs and trees are considerably longer lived than either forbs and grasses, and recruitment of these species are limited during dry periods, the effects of background mortality on plant cover is likely to have only marginal effects at the time scales over which the current drought is occurring, and current reductions are likely to be the direct results of drought (Shinneman & Baker (2009)).

Areas with dense stands of similarly aged trees are likely to experience high mortality due to a lack of self thinning processes and the competition between densely colonizing trees for limited water (Baker & Shinneman (2004)). These dense stands are often times the result of historic vegetation treatments, or other severe disturbances which led to a very large cohort of shrub and trees species germinating and attempting to develop simultaneously. Given the high density of these individuals and the long time which it takes for them to decompose, if a source of ignition occurs these areas are likely to allow fires to spread rapidly and burn 'hot'. Conditions which lead to wildfire's which are difficult to manage.

We suspect that ecological sites which are being encroached upon by Pinon-Junipers, will have more mortality than those sites, which have them as the climax vegetation. It has been observed that their encroachment more commonly occurs at the lower elevation sage-brush sites, than mixed-mountain sites. Since the sage-brush habitat is generally closer to human habitations, and important for sage-grouse, these areas represent those which funding and management efforts can be focused towards. Further, as few of the sage-brush species resprout, fires can have longer lasting impacts there than in several other areas.

## Shrub Cover

Across all BLM land which is not managed as an NCA, WSA, or ACEC, the estimate of the total amount of land which is achieving benchmarks is 52.9% (LCB = 47.1%, UCB = 58.7%), similar to the estimate for the Gunnison Gorge NCA 55.7%. Both the ACEC-WSA areas 66.5%, and the Dominguez-Escalante NCA 66.8%, had higher estimates of land meeting benchmarks, and the confidence intervals slightly overlapped the goal of having 80% of these lands being within the realm of natural variability, for this particular indicator. Accordingly overall, between one half and two thirds of all BLM lands were meeting this benchmark.



## Tree Cover

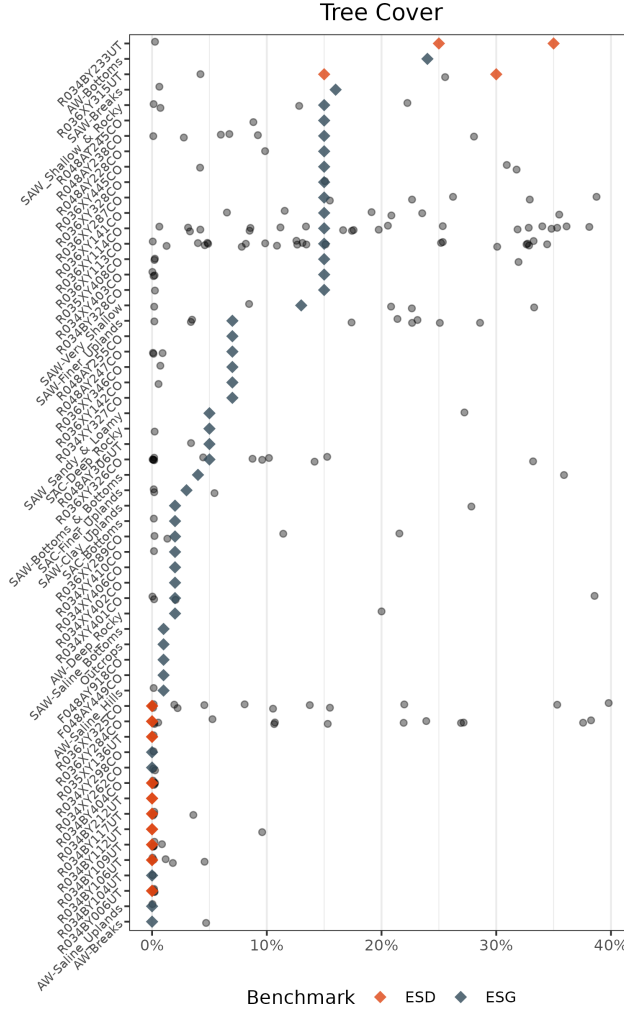


Figure 4: Benchmarks and Observed Values

Across all BLM land which is not managed as an NCA, WSA, or ACEC, the estimate of the total amount of land which is achieving benchmarks is 44.1% (LCB = 38.5%, UCB = 49.8%), similar to the estimate for the Dominguez-Escalante NCA 43.8%. Both the ACEC-WSA areas 56.7%, and the Dominguez-Escalante NCA 62.2%, had higher estimates of land meeting benchmarks, and for the Gunnison Gorge the confidence intervals slightly overlapped the goal of having 80% of these lands being within the realm of natural variability, for this particular indicator.

The same general observations, trends, expectations, and reasoning behind an increase in tree cover is shared as discussed in the shrub section. Mortality of portions of trees is expected less on trees than shrubs.

Many historical Pinyon-Juniper vegetation treatments, were conducted throughout the study area (Pilliod et al. (2017)). However, akin to a great proportion of other such treatments globally, where the goal was to increase big game and livestock habitat, most of these were marginally effective (Ding & Eldridge (2022)). This is likely due to the potential of those ecological sites not including a mixed grass-shrubland more desirable for livestock use.

Currently three trajectories for Pinyon-Juniper cover exists in the study area. The **first** is the re-growth of Pinyon-Juniper on sites which were historically treated, and cannot support mixed grass-shrublands, and which are being allowed to naturally re-vegetate. The **second** is that a lack of certain disturbances, e.g. fire, at certain Ecological Sites is resulting in increases in Pinyon-Juniper as natural process of *succession*, i.e. these are parts of the landscape where the climax vegetation commu-

nity is PJ, but which via management may be kept in a grass-shrub condition. The **third** trajectory is that Pinon-Juniper are encroaching into ecological sites where trees are not expected due to the absence of naturally occurring processes, and are starting to promote their own expansions via feedback loops. In areas such as this multiple functionalities of the land are reduced, and are sites where vegetation treatments are highly desirable from a variety of ecosystem services perspectives (Yahdjian et al. (2015)), and which are capable of regaining ground for wildlife and livestock usage (Anadon et al. (2014), Archer et al. (2017), Morford et al. (2022)).

The higher cover of trees than expected throughout the study area identifies ecological sites which vegetation treatments which involve tree removal can be implemented. Due to the effects of woody encroachment on the production of species which are used as forage by livestock, removals of low percentages of woody species at select ecological sites might have strong effects with minimal effort. Prioritization of sites where treatments will offer the most ecosystem services, such as the most productive sites in terms of forage production, and areas with species of wildlife which are susceptible to higher predation via tree encroachment.



## Perennial Grass Cover

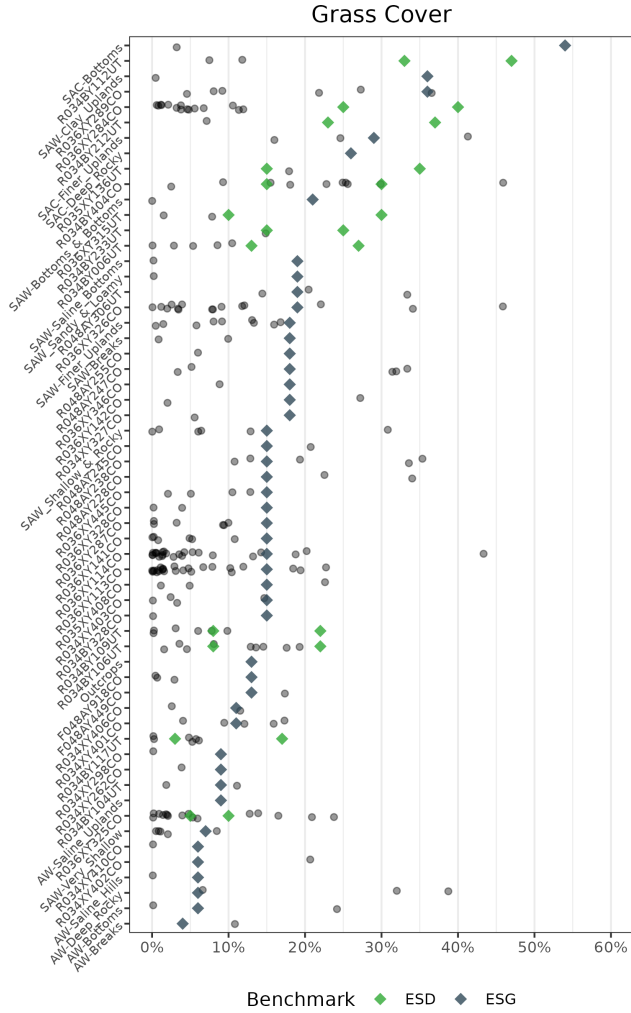


Figure 5: Benchmarks and Observed Values

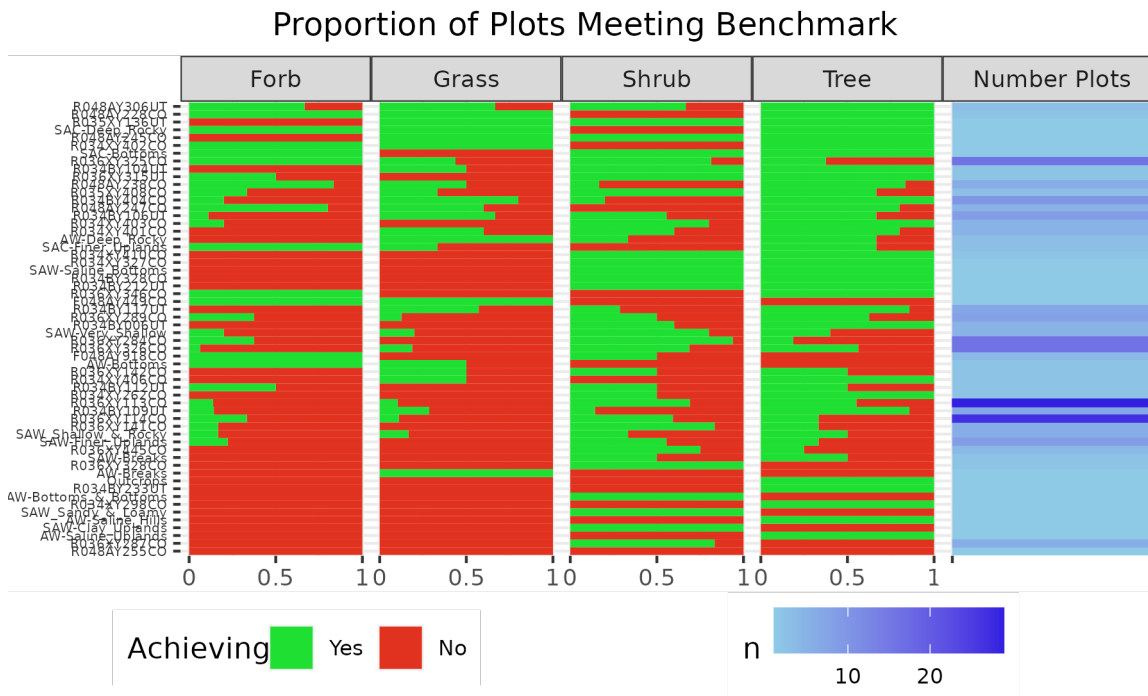
Across all BLM land which is not managed as an NCA, WSA, or ACEC, the estimate of the total amount of land which is achieving benchmarks is 15.8% (LCB = 11.7%, UCB = 19.8%). Results for the other areas, were comparable, but quite as low, with Dominguez-Escalante NCA 24.7%. The ACEC-WSA areas 21.7%, and the Dominguez-Escalante NCA 25.3%. No confidence estimates for the amount of areas meeting benchmarks came close to meeting management objectives.

It is difficult to determine the extent to which grasses of the Colorado Plateau will reduce their above ground growth in response to drought. Various studies have found that grass production decreases during drought, and during periods of highly variable precipitation, however the extent of reductions are variable (Gherardi & Sala (2015), Staver et al. (2019), Munson et al. (2022)). While other studies show that the amount of biomass produced by grasses is quite resilient to drought (Byrne et al. (2017)), and that moisture limitation reductions in grass growth are largely buffered by legacy effects (in this case, a single normal year of precipitation, e.g. 2018, can offset the next few years of dryness and *vice versa*; **SECTION XX**) (O. E. Sala et al. (2012), Reichmann et al. (2013)). More recent studies on the Colorado Plateau have shown reduced growth of C4 grasses, partially due to variability in Monsoons, and C3 grasses via reduced cool season precipitation (Munson et al. (2022), Hoover et al. (2021)). However, given the distinctive growth forms of grasses (i.e. generally columnar), it is unlikely that their cover would be found to be much lower via the methods employed by AIM, unless high levels of mortality occurred.

Compared to perennial forb duration perennial grasses in general appear to live for considerably longer, many from 4-7 decades (Lauenroth & Adler (2008), Treshow & Harper (1974)) but many of the grasses in the sampling areas may only persist 1-1.5 decades. Many clonal (in particular rhizomatous & stoloniferous) grass species, such as some species of *Bouteloua* appear much less likely to undergo mortality of the whole plant (De Witte & Stocklin (2010)) relative to bunch-grasses (but see Winkler et al. (2019)). Mortality due to drought is expected to reduce cover measurements of grasses more than reductions in above ground biomass. While grasses tend to have deeper roots than forbs, soil textures and depths (Chamrad & Box (1965), Griffin & Hoffmann (2012)) still mediate drought effects. A manipulative experiment which sought to determine the effect of drought on five grass species in the Colorado Plateau observed mortality of roughly 25% of all individuals under the ambient treatment (similar conditions to what the UFO experienced), largely attributed to Indian Rice Grass (*Achnatherum hymenoides*), tracked in ambient conditions over the time period 2011-2018 (Winkler et al. (2019)).

Similar to forbs, we expect little to none recruitment of new grass individuals from the soil seed bank. However suspect it is unlikely that has considerably high a proportion of the members of this functional group would have died off over this period, independent of drought induced mortality (Morris et al. (2008),

Winkler et al. (2019)) as perennial forbs, and given their average rooting depths relative to forbs should be more drought tolerant (O. Sala et al. (1997)). Accordingly we expect estimates of grass cover to be at the lowest end of the benchmarks.



Few clear trends emerge regarding which Ecological Sites are failing to meet certain benchmarks, and the relationships between the functional diversity benchmarks which they are not meeting. It is evident that few plots in few Ecological Sites are meeting either forb or grass cover benchmarks, and the only Ecological Sites which appear notably different here are those with only a single plot which was sampled in them. In general most ecological sites were achieving benchmark goals for shrub and tree cover, with the few exceptions being ecological sites which lacked replicates. This illustrating a notion that woody encroachment is not a large issue in the area of analysis, but rather that the loss of non-woody species within the remaining inter-spatial areas is concerning.

Each individual Ecological Site, or Ecological Group, varies in the proportion of all plots located in them which are within reference condition. Once a greater number of replicate plots are sampled per Ecological Site (see Figure XX, panel 5 (*right most*)), and combined with digitized management records, these data may form an approach towards understanding the resilience of different Ecological Sites in the UFO to management actions. The Ecological Sites are arranged via descending order of the total proportion of vegetation types and plots which are achieving benchmarks. These results currently largely reflect the



Results by management areas in general do not differ greatly. From a broad perspective, roughly a quarter of lands in the field office is meeting standards for forb or grass cover, except for the Gunnison Gorge National Conservation Area which has no land meeting objectives for forb cover (Table 1). While there were relatively few plots sampled in the Gunnison Gorge NCA, **XX**, all plots sampled failed to achieve minimum benchmark cover values a result that is unlikely to be due to chance, as is reflected by the Areas of Critical Environmental Concern (Table 1). No areas are meeting the benchmarks for Tree cover either, although most management areas have roughly one half of their land achieving. This indicates the need to explore tree thinning, or removal, operations in certain areas, as funding permits and needs require, to benefit wildlife via modification of habitat or to decrease the threats of wildfires to adjacent human population base (Baker & Shinneman (2004), Shinneman & Baker (2009)). Given the historic reductions in fire cycle this is an issue which requires a great many decades before coming back into resolution, but given the current awareness of the problem, management actions are now underway which will do so. Roughly half to two-thirds of land are achieving shrub cover objectives, and two areas have confidence intervals which do (51.4- 66.5% -81.7), of very nearly (54- 66.8% -79.5), include the land cover targets. On the whole, the results taken together indicate that the study area is failing to meet metrics for plant functional diversity, with only areas 2 having confidence intervals which even overlap the management objectives. However, the perennial grass functional group presents the most serious concern. The median estimate of land within any area meeting objectives for cover of perennial grasses is 23.2%, across the entirety of the field office the estimate of lands meeting objectives for grasses is a low 15.8%, the <sup>2nd</sup> lowest proportion of land out of all benchmarks and areas.

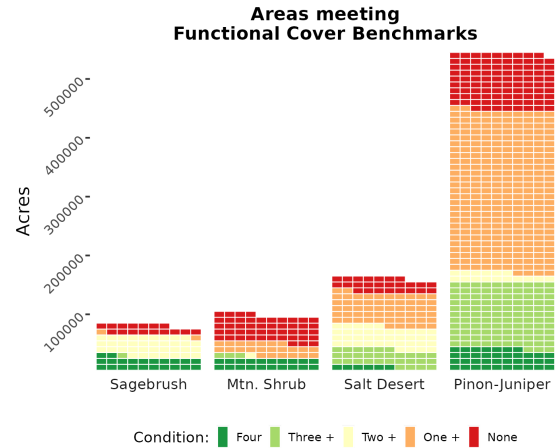


Figure 7: Total area of each stratum and the overall status of benchmarks

Table 1: Land Meeting Benchmarks by Administrative Unit

Goal	Management	Plots	Group	% Land Meeting
80%	ACEC-WSA	12	Forb	(15.5-) 27.1% (-38.7)
			Grass	(10.5-) 21.7% (-32.9)
			Shrub	(51.4-) 66.5% (-81.7)
			Tree	(38.3-) 56.7% (-75.1)
	DE-NCA	35	Forb	(15.1-) 28.3% (-41.5)
			Grass	(14-) 24.7% (-35.5)
			Shrub	(54-) 66.8% (-79.5)
			Tree	(31.6-) 43.8% (-56)
	GG-NCA	19	Forb	(0-) 0% (-0)
			Grass	(12.2-) 25.3% (-38.5)
			Shrub	(37.4-) 55.7% (-74)
			Tree	(42.6-) 62.2% (-81.7)
70%	SampleFrame	200	Forb	(27-) 32% (-37.1)
			Grass	(11.7-) 15.8% (-19.8)
			Shrub	(47.1-) 52.9% (-58.7)
			Tree	(38.5-) 44.1% (-49.8)

## References

- Ackerman, T. L. (1979). Germination and survival of perennial plant species in the mojave desert. *The Southwestern Naturalist*, 399–408.
- Anadon, J. D., Sala, O. E., Turner, B., & Bennett, E. M. (2014). Effect of woody-plant encroachment on livestock production in north and south america. *Proceedings of the National Academy of Sciences*, 111(35), 12948–12953.
- Anderson, J. E., & Inouye, R. S. (2001). Landscape-scale changes in plant species abundance and biodiversity of a sagebrush steppe over 45 years. *Ecological Monographs*, 71(4), 531–556.
- Archer, S. R., Andersen, E. M., Predick, K. I., Schwinning, S., Steidl, R. J., & Woods, S. R. (2017). Woody plant encroachment: Causes and consequences. In D. D. Briske (Ed.), *Rangeland systems: Processes, management and challenges* (pp. 25–84). Springer International Publishing. [https://doi.org/10.1007/978-3-319-46709-2\\_2](https://doi.org/10.1007/978-3-319-46709-2_2)
- Archer, S. R., & Predick, K. I. (2014). An ecosystem services perspective on brush management: Research priorities for competing land-use objectives. *Journal of Ecology*, 102(6), 1394–1407.
- Baker, W. L., & Shinneman, D. J. (2004). Fire and restoration of pinon–juniper woodlands in the western united states: A review. *Forest Ecology and Management*, 189(1-3), 1–21.
- Belnap, J., & Sherrod, S. K. (2008). Soil amendment effects on the exotic annual grass *bromus tectorum* l. And facilitation of its growth by the native perennial grass *hilaria jamesii* (torr.) benth. In *Herbaceous plant ecology* (pp. 345–357). Springer.
- Bestelmeyer, B. T., Peters, D. P., Archer, S. R., Browning, D. M., Okin, G. S., Schooley, R. L., & Webb, N. P. (2018). The grassland–shrubland regime shift in the southwestern united states: Misconceptions and their implications for management. *BioScience*, 68(9), 678–690.
- Blaisdell, J. P., & Holmgren, R. C. (1984). *Managing Intermountain rangelands - salt-desert shrub ranges*. U.S. Department of Agriculture, Forest Service, Intermountain Forest; Range Experiment Station. <https://doi.org/10.2737/int-gtr-163>
- Byrne, K. M., Adler, P. B., & Lauenroth, W. K. (2017). Contrasting effects of precipitation manipulations in two great plains plant communities. *Journal of Vegetation Science*, 28(2), 238–249.
- Casper, B. B. (1996). Demographic consequences of drought in the herbaceous perennial *cryptantha flava*: Effects of density, associations with shrubs, and plant size. *Oecologia*, 106(2), 144–152.
- Chamrad, A. D., & Box, T. W. (1965). Drought-associated mortality of range grasses in south texas. *Ecology*, 46(6),

- Corbin, J. D., & D'Antonio, C. M. (2004). Competition between native perennial and exotic annual grasses: Implications for an historical invasion. *Ecology*, 85(5), 1273–1283.
- Corlett, R. T., & Westcott, D. A. (2013). Will plant movements keep up with climate change? *Trends in Ecology & Evolution*, 28(8), 482–488.
- Dalgleish, H. J., Koons, D. N., & Adler, P. B. (2010). Can life-history traits predict the response of forb populations to changes in climate variability? *Journal of Ecology*, 98(1), 209–217.
- Davison, R., Jacquemyn, H., Adriaens, D., Honnay, O., De Kroon, H., & Tuljapurkar, S. (2010). Demographic effects of extreme weather events on a short-lived calcareous grassland species: Stochastic life table response experiments. *Journal of Ecology*, 98(2), 255–267.
- De Witte, L. C., & Stocklin, J. (2010). Longevity of clonal plants: Why it matters and how to measure it. *Annals of Botany*, 106(6), 859–870.
- Diaz, S., Lavorel, S., McIntyre, S., Falczuk, V., Casanoves, F., Milchunas, D. G., Skarpe, C., Rusch, G., Sternberg, M., Noy-Meir, I., et al. (2007). Plant trait responses to grazing—a global synthesis. *Global Change Biology*, 13(2), 313–341.
- Ding, J., & Eldridge, D. (2022). The success of woody plant removal depends on encroachment stage and plant traits. *Nature Plants*, 1–10.
- Eldridge, D. J., Poore, A. G., Ruiz-Colmenero, M., Letnic, M., & Soliveres, S. (2016). Ecosystem structure, function, and composition in rangelands are negatively affected by livestock grazing. *Ecological Applications*, 26(4), 1273–1283.
- Eziz, A., Yan, Z., Tian, D., Han, W., Tang, Z., & Fang, J. (2017). Drought effect on plant biomass allocation: A meta-analysis. *Ecology and Evolution*, 7(24), 11002–11010.
- Floyd, M. L., Clifford, M., Cobb, N. S., Hanna, D., Delph, R., Ford, P., & Turner, D. (2009). Relationship of stand characteristics to drought-induced mortality in three southwestern piñon-juniper woodlands. *Ecological Applications*, 19(5), 1223–1230.
- Gaylord, M. L., Kolb, T. E., Pockman, W. T., Plaut, J. A., Yezpez, E. A., Macalady, A. K., Pangle, R. E., & McDowell, N. G. (2013). Drought predisposes piñon-juniper woodlands to insect attacks and mortality. *New Phytologist*, 198(2), 567–578.
- Gherardi, L. A., & Sala, O. E. (2015). Enhanced precipitation variability decreases grass-and increases shrub-productivity. *Proceedings of the National Academy of Sciences*, 112(41), 12735–12740.
- Griffin, P. C., & Hoffmann, A. A. (2012). Mortality of Australian alpine grasses (poa spp.) After drought: Species differences and ecological patterns. *Journal of Plant Ecology*, 5(2), 121–133.
- Hoover, D. L., Pfennigwerth, A. A., & Duniway, M. C. (2021). Drought resistance and resilience: The role of soil moisture–plant interactions and legacies in a dryland ecosystem. *Journal of Ecology*, 109(9), 3280–3294.
- Jonas, J. L., Grant-Hoffman, M. N., & Paschke, M. W. (2018). Restoration of north american salt deserts: A look at the past and suggestions for the future. *Ecological Restoration*, 36(3), 177–194.
- LaForgia, M. L., Spasojevic, M. J., Case, E. J., Latimer, A. M., & Harrison, S. P. (2018). Seed banks of native forbs, but not exotic grasses, increase during extreme drought. *Ecology*, 99(4), 896–903.
- Lauenroth, W. K., & Adler, P. B. (2008). Demography of perennial grassland plants: Survival, life expectancy and life span. *Journal of Ecology*, 96(5), 1023–1032.
- Loarie, S. R., Duffy, P. B., Hamilton, H., Asner, G. P., Field, C. B., & Ackerly, D. D. (2009). The velocity of climate change. *Nature*, 462(7276), 1052–1055.
- Loydi, A., & Collins, S. L. (2021). Extreme drought has limited effects on soil seed bank composition in desert grasslands. *Journal of Vegetation Science*, 32(5), e13089.
- Maestre, F. T., Eldridge, D. J., Soliveres, S., Kefi, S., Delgado-Baquerizo, M., Bowker, M. A., Garcia-Palacios, P., Gaitan, J., Gallardo, A., Lazaro, R., et al. (2016). Structure and functioning of dryland ecosystems in a changing world. *Annual Review of Ecology, Evolution, and Systematics*, 47, 215.
- McIver, J., Grace, J. B., & Roundy, B. (2022). Pion and juniper tree removal increases available soil water, driving understory response in a sage-steppe ecosystem. *Ecosphere*, 13(11), e4279.
- Meyer, S. E., & Pendleton, B. K. (2005). Factors affecting seed germination and seedling establishment of a long-lived desert shrub (coleogyne ramosissima: rosaceae). *Plant Ecology*, 178, 171–187.
- Morford, S. L., Allred, B. W., Twidwell, D., Jones, M. O., Maestas, J. D., Roberts, C. P., & Naugle, D. E. (2022). Herbaceous production lost to tree encroachment in United States rangelands. *Journal of Applied Ecology*, 59(12), 2971–2982.
- Morris, W. F., Pfister, C. A., Tuljapurkar, S., Haridas, C. V., Boggs, C. L., Boyce, M. S., Bruna, E. M., Church, D. R., Coulson, T., Doak, D. F., et al. (2008). Longevity can buffer plant and animal populations against changing climatic variability. *Ecology*, 89(1), 19–25.
- Munson, S. M., Belnap, J., & Okin, G. S. (2011). Responses of wind erosion to climate-induced vegetation changes on the Colorado plateau. *Proceedings of the National Academy of Sciences*, 108(10), 3854–3859.

- Munson, S. M., Bradford, J. B., Butterfield, B. J., & Gremer, J. R. (2022). Primary production responses to extreme changes in north american monsoon precipitation vary by elevation and plant functional composition through time. *Journal of Ecology*, 110(9), 2232–2245.
- Nicole, F., Dahlgren, J. P., Vivat, A., Till-Bottraud, I., & Ehrlen, J. (2011). Interdependent effects of habitat quality and climate on population growth of an endangered plant. *Journal of Ecology*, 99(5), 1211–1218.
- Olano, J., Caballero, I., & Escudero, A. (2012). Soil seed bank recovery occurs more rapidly than expected in semi-arid mediterranean gypsum vegetation. *Annals of Botany*, 109(1), 299–307.
- Pennington, V. E., Schlaepfer, D. R., Beck, J. L., Bradford, J. B., Palmquist, K. A., & Lauenroth, W. K. (2016). Sagebrush, greater sage-grouse, and the occurrence and importance of forbs. *Western North American Naturalist*, 76(3), 298–312.
- Pilliod, D. S., Welty, J. L., & Toevs, G. R. (2017). Seventy-five years of vegetation treatments on public rangelands in the great basin of north america. *Rangelands*, 39(1), 1–9.
- Reichmann, L. G., Sala, O. E., & Peters, D. P. (2013). Precipitation legacies in desert grassland primary production occur through previous-year tiller density. *Ecology*, 94(2), 435–443.
- Sala, O. E., Gherardi, L. A., Reichmann, L., Jobbagy, E., & Peters, D. (2012). Legacies of precipitation fluctuations on primary production: Theory and data synthesis. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 367(1606), 3135–3144.
- Sala, O., Lauenroth, W., & Golluscio, R. (1997). 11 plant functional types in temperate semi-arid regions. *Plant Functional Types: Their Relevance to Ecosystem Properties and Global Change*, 1, 217.
- Sheley, R. L., & James, J. (2010). Resistance of native plant functional groups to invasion by medusahead (*taeniatherum caput-medusae*). *Invasive Plant Science and Management*, 3(3), 294–300.
- Shinneman, D. J., & Baker, W. L. (2009). Historical fire and multidecadal drought as context for pinon–juniper woodland restoration in western colorado. *Ecological Applications*, 19(5), 1231–1245.
- Staver, A. C., Wigley-Coetsee, C., & Botha, J. (2019). Grazer movements exacerbate grass declines during drought in an african savanna. *Journal of Ecology*, 107(3), 1482–1491.
- Torang, P., Ehrlen, J., & Aagren, J. (2010). Linking environmental and demographic data to predict future population viability of a perennial herb. *Oecologia*, 163(1), 99–109.
- Treshow, M., & Harper, K. (1974). Longevity of perennial forbs and grasses. *Oikos*, 93–96.
- West, N. E., & Yorks, T. P. (2006). Long-term interactions of climate, productivity, species richness, and growth form in relictual sagebrush steppe plant communities. *Western North American Naturalist*, 66(4), 502–526.
- Wilson, S. D., Schlaepfer, D., Bradford, J., Lauenroth, W., Duniway, M., Hall, S., Jamiyansharav, K., Jia, G., Lkhagva, A., Munson, S., et al. (2018). Functional group, biomass, and climate change effects on ecological drought in semiarid grasslands. *Journal of Geophysical Research: Biogeosciences*, 123(3), 1072–1085.
- Winkler, D. E., Belnap, J., Hoover, D., Reed, S. C., & Duniway, M. C. (2019). Shrub persistence and increased grass mortality in response to drought in dryland systems. *Global Change Biology*, 25(9), 3121–3135.
- Yahdjian, L., Sala, O. E., & Havstad, K. M. (2015). Rangeland ecosystem services: Shifting focus from supply to reconciling supply and demand. *Frontiers in Ecology and the Environment*, 13(1), 44–51.