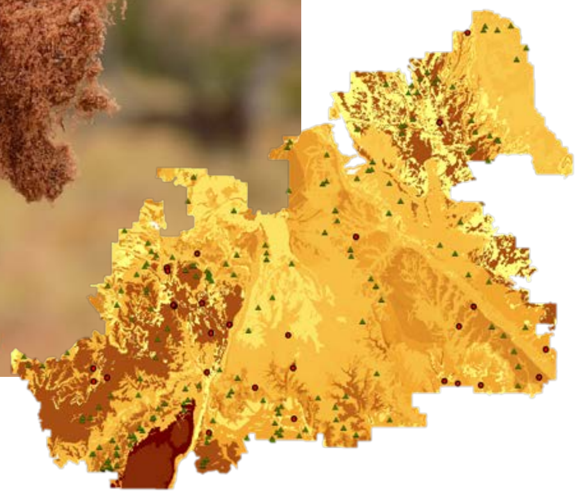
Grand Staircase-Escalante National Monument Biocrust Survey 2014-2015
Grand Canyon Trust



ABSTRACT

From 2014-2015, Grand Canyon Trust staff, interns, student groups and volunteers, with assistance from Western Watersheds and Great Old Broads for Wilderness staff completed a broad-scale survey of biological soil crust (biocrust) conditions throughout the Grand Staircase-Escalante National Monument. The survey chose a 200-site subset of the 507 rangeland health assessment sites established by the Bureau of Land Management (BLM) in 2000 based on these sites' high (>20%) crust cover potential and high susceptibility to erosion. These criteria were meant to identify the most biocrust-dependent ecosystems in the Monument. Of the 200 sites selected, 176 were assessed and 24 were generally inaccessible to the surveyors. The survey used a step-point transect to determine ground cover. It distinguished lightly pigmented (early successional) cyanobacteria-dominated crusts, darkly pigmented (mid-successional) cyanobacteria-dominated crusts, and moss and lichen (later successional) crusts at 153 sites. At an additional 23 sites, the study conflated dark and light cyanobacteria-dominated crusts. These sets were separated for analysis. The 153-site set was compared both to the crust cover measured by the 2000-2003 rangeland health survey and to the Bowker, et al. (2006) model, which predicts potential mid- and late-successional (dark cyanobacteria, moss and lichen) crust cover on the Monument. Analysis using Fisher's exact test found no significant difference in distribution of mid- to late-successional crust cover values from 2000-2003 to 2014-2015 (p=0.184). However, Student's t-test showed mean mid- to late-successional crust cover did significantly decrease between 2000-2003 and 2014-2015 (p=0.017). Both surveys recorded mid- and late-successional crust cover that was significantly (p<0.001) below crust cover potential predicted by the Bowker, et al. (2006) model. Light cyanobacteria crusts were absent from 17% of sites; and at 80% of sites occupied less than 50% of the available habitat at the site. Transects in pastures that were ungrazed for 15 years showed, on average, higher light cyanobacteria-dominated crust coverage than transects in grazed pastures. At an overwhelming number of sites, biocrust development is being arrested at a light cyanobacteria-dominated (i.e., early) successional stage if biocrust is present at all. Moss and lichen crusts are particularly absent and were not present along the transect at a majority of sites.

INTRODUCTION

The Grand Canyon Trust ("Trust") is a regional conservation organization focused on the Colorado Plateau. The Trust's mission is "to protect and restore the Colorado Plateau–its spectacular landscapes, flowing rivers, clean air, diversity of plants and animals, and areas of beauty and solitude." For two years, the Trust has collaborated with the Bureau of Land Management (BLM), partner non-governmental organizations, scientists and volunteers to conduct an extensive biocrust survey throughout the Grand Staircase-Escalante National Monument ("Monument"). During 2014-15, the survey measured abundance of light cyanobacteria-dominated crusts, dark cyanobacteria-dominated crusts, moss, and lichen at 176 transects throughout the Monument. This report compares results of the survey to the soil crust potential model (dark cyanobacteria-dominated, moss, and lichen) created by Bowker, et al. (2006) to ascertain the degree to which biocrust is reaching its predicted potential on the Monument.

PURPOSE

The survey aims to provide a broad-scale assessment of the condition of biocrust on the Monument. The survey focuses on sites that have both a high crust potential (≥20% cover) and a high vulnerability to erosion. The survey is also intended to provide a comparison to the Rangeland Health (RLH) assessment completed by the Bureau of Land Management (BLM) between 2000 and 2003, four years after the establishment of the Monument. New scientific research regarding biocrusts has appeared since 2003 regarding the impacts of global warming on biocrusts, the value of biocrusts in preventing erosion and fostering native species, and the ecological succession and resiliency of biocrust communities. Ultimately, the Trust asks that information gathered in this survey be used to inform how the BLM manages livestock grazing on the Monument to protect the valuable ecological services that biocrusts provide.

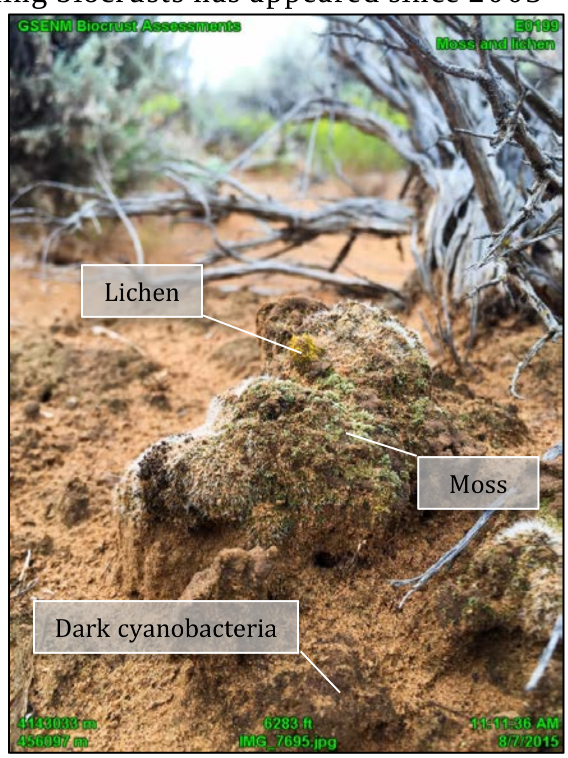


Fig. 1: Moss, lichen and dark cyanobacteria-dominated crust protected under shrub.

BACKGROUND

What are biocrusts?

Biocrusts are complex and highly-specialized communities of organisms which have evolved to live in and on top of the soils of arid and semi-arid environments where competition from vascular plants is reduced. Cyanobacteria, mosses, and lichens are major components of most biocrusts. These components form a successional series beginning with filamentous cyanobacteria (in particular, *Microcoleus* spp.) which provide preliminary soil stabilization and structure upon which other species of pigmented (i.e., "dark") cyanobacteria, mosses and lichens can develop (Belnap and Gardner 1993). Crusts that are primarily composed of filamentous cyanobacteria (which are only lightly pigmented) are referred to as light cyanobacteria-dominated crusts. Although an early-successional stage, these crust communities provide substantial aggregation of the soil, which strengthens soil against erosion (Belnap and Gillette 1997). Once colonies of large filamentous cyanobacteria are active and in place, single-celled cyanobacteria (e.g., *Nostoc, Scytonema,* and *Tolypothrix)* appear and begin colonizing the soil. These cyanobacteria produce several pigments responsible for the darkening of the crust. Scytonemin is the main pigment providing protection from damaging ultraviolet radiation. These pigments give soils a darker, blackish cast. Biocrusts with visible pigmentation are categorized as dark cyanobacteria-dominated crusts. Once formed, these crusts provide a substrate for the late-successional biocrust components, lichens and mosses, to thrive.

Four basic biocrust morphologies exist: smooth, rugose, rolling and pinnacled. Pinnacled crusts, which can grow up to 15 cm tall and have up to 40% crust and lichen cover, dominate cool deserts like those of the Colorado Plateau. The pinnacled structure helps increase residence time of water on the soil surface and, in the case of moss-dominated crusts, increases water infiltration (Loope and Gifford 1972; Brotherson and Rushforth 1983).

A range of soil functional types exist in the Monument and these substrates vary in their crust potential. Generally, soils of the Monument can support moderate to high levels of crust cover. An exception are fine bentonitic soils, like those derived from the Mancos and Tropic shale formations, which have very low crust potential due to their high shrink-swell capability (Bowker, et al. 2006). Gypsiferous soils, like those derived from particular rock members such as the Paria River member (Carmel formation), Shnabkaib member (Moenkopi formation), and Paradox formation are often observed to have highly developed biocrust communities (Bowker, et al. 2006). Most of the Monument is predicted to have 20%-70% mid- to late-successional crust cover (Bowker et al. 2006).

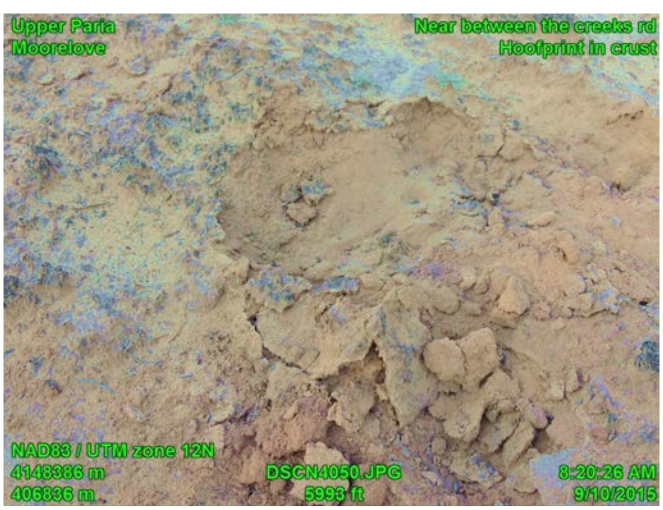


Fig. 2: Disturbed dark cyanobacteria-dominated biocrust

Biocrusts perform a variety of vital ecological functions on the Colorado Plateau including not only stabilization of soils (Mazor, et al. 1996) and facilitation of water infiltration (Loope and Gifford 1972; Brotherson and Rushforth 1983), but also nitrogen and carbon fixation (Belnap 1996; Eldridge and Greene 1994, Housman et al. 2006). Biocrusts promote carbon sequestration in soils via photosynthesis and nitrogen via nitrogen fixation. Lichens (on the Colorado Plateau, particularly *Collema* spp.) and mosses are capable of higher conversion rates of these elements than light cyanobacteria-dominated crusts (Belnap 1995; Housman et al. 2006).

Though only metabolically active when wet, a developed biocrust's impact during these hydration periods is profound, with primary production comparable to a continuous leaf covering the surface of the desert (Lange 2003). Intact biocrusts, even when inactive, act as a soil shield and help prevent the production of dust from wind erosion (Belnap and Gillette 1997). Airborne dust has been shown to cause earlier melting of snowpack in the Rocky Mountains, which could result in less available water for the Colorado River Basin (Painter, et al. 2007).

While remarkably resistant to water and wind erosion, biocrusts are quite vulnerable to compaction and shear stress imparted by vehicles, as well as human and ungulate trampling. Since mosses and lichens are more vulnerable to these stressors, trampling tends to push crusts to an earlier successional stage dominated by light cyanobacteria (Belnap, et al. 2003). Disturbance during dry periods, when biocrusts are inactive and brittle, is more destructive than during wet periods (Belnap, et al. 2001). There is also evidence that grazing when the ground is frozen decreases the impact of trampling on biocrust cover (Memmot, et al. 1998; Harper and Marble 1989).

Climate and Crusts

The planet's climate is undergoing a period of rapid warming due to emissions of greenhouse gases (IPCC 2014). The southwestern US is poised to be drastically impacted by global warming in two primary ways: temperature increase and altered precipitation patterns. In the Southwest, the past 50 years have been hotter on average than the preceding 600 (Garfin, et al. 2013). Depending on the rate of greenhouse gas emissions over the coming decades, climate models predict an increase of 1-4˚F between 2021 and 2050 and between 2-9˚F by 2099 (Garfin, et al. 2013). Changes in precipitation patterns are more difficult to predict, but models generally agree that spring precipitation will decrease and that extreme winter precipitation will increase (Garfin, et al. 2013).

Recent research shows that global warming-related impacts (e.g., increased short duration precipitation events) will have negative impacts on biocrust communities. Ferrenberg, et al. (2015) have demonstrated that the impacts of experimental global warming were surprisingly similar to

Fig. 3: Storm approaching on Nipple Bench, Grand Staircase-Escalante National Monument.

the effects of physical disturbance. In their study, warming of 2-4° C, well within predictions if emissions remain at their current levels, caused mortality of late successional moss and lichen organisms and increased dominance by cyanobacteria over a period of ten years. In addition, simulated short duration, high-intensity summer rainfall caused rapid die-off of moss. Ferrenberg, et al. (2015) state, “This shift toward an early successional state has critical implications for ecosystem processes and functioning, as early successional biocrusts fix less carbon and nitrogen and lose more carbon and nitrogen via leaching.” The same holds true whether the shift is caused by physical or climatic disturbance

BIOCRUSTS AND THE GRAND STAIRCASE-ESCALANTE NATIONAL MONUMENT

Management direction

The proclamation establishing the Grand Staircase-Escalante National Monument states, “Fragile cryptobiotic [biological soil] crusts... play a critical role throughout the monument, stabilizing the highly erodible desert soils and providing nutrients to plants” (Clinton, 1996).

The *Monument Management Plan* adopted in 2000 elaborates, “Biological soil crusts... play an important ecological role in the Monument in the functioning of soil stability and erosion, atmospheric nitrogen fixation, nutrient contributions to plants, soil-plant-water relations, seedling germination, and plant growth” (BLM 2000). A main objective in the *Management Plan* is to “manage uses to prevent damage to soil resources and to ensure that the health and distribution of fragile biological soil crusts is [sic] maintained or improved.” To reach that objective, the management plan specifies, “The BLM will apply procedures to protect soils from accelerated or unnatural erosion in any ground-disturbing activity” (BLM 2000) and “...Prior to any ground disturbing activity, the potential effects on biological soil crusts will be considered and steps will be taken to avoid impacts on their function, health and distribution” (BLM 2000).

Management context for the survey

The Monument is currently developing a Livestock Grazing Management Plan Amendment (“grazing amendment”; BLM 2013). The grazing amendment will provide direction on how to harmonize BLM management of cattle grazing in the Monument with protection of the monument objects enumerated in the Monument Proclamation (e.g., soil crusts). Ultimately, the grazing amendment will make decisions regarding cattle grazing practices throughout the Monument.

The BLM *Analysis of Management Situation* (AMS), released in July 2015 is an outline of resource concerns to be addressed in the upcoming Environmental Impact Statement (EIS) analysis of grazing amendment alternatives. The AMS, in addition to citing the importance of biocrusts in managing healthy desert ecosystems on the Monument, notes that, “Comparisons of observed crust distribution with potential distribution can serve as a surrogate for reference condition” (BLM 2015). In the spirit of that recommendation, this study takes a close look at the current status of biocrusts throughout the Monument. This survey is a complement to the study completed between 2000 and 2003 (Miller 2008), which was based on the BLM's Interpreting Indicators of Rangeland Health (Pellant, et al. 1999) The survey uses the step-point transect protocol to gauge biocrust cover throughout the Monument and compares observed cover values to the Bowker, et al. (2006) model of biocrust potential. This is the predictive model specifically cited in the AMS (BLM 2015, p. 75).

This survey adds one important element to the rangeland health assessment protocol by recording the presence of light cyanobacteria-dominated crusts. The RLH protocol required recording of only dark cyanobacteria, moss, and lichen presence.

After citing the ecological benefits of biocrusts, the AMS claims that because "soil crusts may take decades to recover from disturbance…they are not good short-term indicators of the appropriateness of current management actions" (BLM 2015, p. 76).

Light cyanobacteria-dominated crusts are resilient to physical disturbance and can recover from disturbance over a period of 0-3 years (Belnap, et al. 2001). Therefore, presence and cover of light cyanobacteria-dominated crusts can be an effective short-term indicator of the consequences of management actions, including management of cattle grazing. Absence of light cyanobacteria-dominated crust where late-successional stage crusts are predicted indicates a contemporary and deleterious impact.

METHODS

Table 1: Selected attributes of 2000-2003 and 2014-2015 biocrust surveys

Survey	Year	Number of sites	Recorded light cyanobacteria-dominated crusts?	Conflated light and dark cyanobacteria crusts?	Recorded lichen and moss?
Miller RLH Study	2000-2003	507	No	No	Yes
Trust General Survey	2014-2015	153	Yes	No	Yes
Whitman Survey	2014	23	Yes	Yes	Yes

Miller Rangeland Health Study

Between 2000 and 2003, the BLM coordinated a broad-scale survey of biotic, hydric, and soil health throughout all Monument allotments and pastures. The survey included assessments in all soil types within a pasture that cumulatively made up at least 75% of the pasture area (Miller 2008). The survey assessed soil/site stability, hydrologic function and biotic integrity at each of 507 sites. Sites were rated by the degree to which they departed, if at all, from reference conditions (none to slight, slight to moderate, moderate, moderate to extreme, extreme). The integrity of biological soil crusts was relevant to all three assessment categories (i.e., soil/site stability, hydrologic function, and biological integrity).

Data on ground cover (including biocrusts) and canopy cover were gathered by a step-point transect. The study found that seeded areas on sagebrush-dominated, fine-loamy soils (Upland and Semidesert Loam) had the highest frequency of low health ratings for all three categories. These same fine-loamy soils are areas of high potential for biological soil crust. The study found a steep decline in biological soil crust cover between sites rated “none to slight” and “slight to moderate” for all three attributes of rangeland health, indicating the sensitivity of well-developed biocrusts to disturbance (Miller 2008). Miller suggests that the loss of biocrusts played a role in the poor rangeland health measures associated with fine-loamy sagebrush sites.

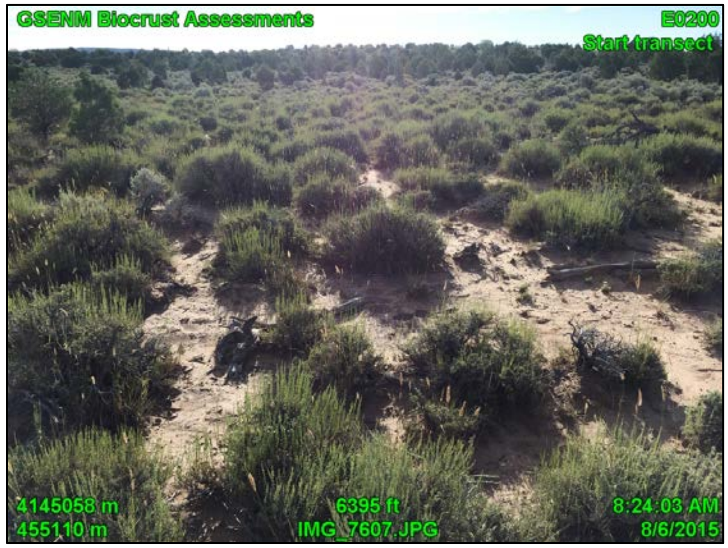


Fig. 4: ***Artemesia novaria*** **seeding with bare interspace**

Development of the Bowker, et al. (2006) Predictive Model

In order to develop a predictive model of biological soil crust on the Monument, Bowker, et al. (2006) first categorized a variety of soil types within the Monument to sample. The sampling was guided by the categorization of precipitation (≤20, 20-30, and ≥30 cm/yr), soil type (bentonitic fine soil, calcareous sandy soils, and non-calcareous sandy soil), and preliminary observations and literature (Rajvanshi, et al. 1998). Using these factors, the study created eight mutually-exclusive soil functional types: bentonitic fine soil, calcareous sandy soils, non-calcareous sandy soils, gypsiferous soils, siliceous sandstone, non-bentonitic fine soils, Kaiparowits-derived soils, and limestone soils. All possible combinations of functional soil type by precipitation category were sampled and replicated at 114 sites. These sites were sampled by 300 point step-point transects in areas of low to no livestock impact. Step-point transects were used to record abundance of moss, lichen, light or heavy litter, light or dark cyanobacteria-dominated crust, surface rock, exposed bedrock, shrub or annual canopies, vagrant lichens, and shrub or annual stems. Fourteen sites were randomly selected for evaluating the predictive power of the model. The remaining 100 sites were classified and analyzed using regression trees (CART; De’ath and Fabricius 2000) to build the model. Compared to the evaluative set of 14 sites, the model performed very well on moss (R^2=0.55), lichen (R^2=0.64) and lichen+moss+dark cyanobacteria-dominated (R^2=0.64) crust predictions. Light cyanobacteria-dominated predictions did not correlate well with the evaluative sites (R^2=0.22). Therefore, light cyanobacteria observations in this survey could not be compared to cover predicted by the Bowker, et al. model. Bowker, et al. (2006) cautioned that the field data for building the model was collected during the dry season (summer) of dry years, including an extreme drought year (2003), so model predictions are likely on the lower end of true potential cover.

2014-2015 Field Survey

To compare the actual cover of biocrust on the Monument to the cover predicted by the Bowker, et al. model as well as to the cover recorded in the 2000-2003 RLH assessment, the Grand Canyon Trust selected a subset of 200 of the 507 RLH sites to revisit. The RLH sites had been located to provide a representative transect of primary ecological sites within each pasture on the Monument (Miller 2008). The 200-site subset was selected based on susceptibility to wind and water erosion[1] and percent cover of mid- to late- successional biocrust predicted from the Bowker, et al. model (>20%). The survey prioritized these sites because they showed both high potential for biocrust and high vulnerability to erosion. Of the 200 sites selected for inclusion in the study, 176 were visited during 2014-15 (Fig. 6).

Fig. 5: Grand Canyon Trust researchers reading a transect

The surveys repeated the step-point transect method used both in the 2000-2003 survey (method from Coulloudon, et al. 1999) and the Bowker, et al. survey. Most transect sites included at least 100 points with transects 100-200 meters long (depending on the length of the recorder's stride). The 2000-2003 survey recorded only start points for transects, and thus transect direction could not be replicated. In 2014-2015 a random number was generated to pick an impartial direction for the transect from the original start point recorded in the 2000-2003 survey. To stay within a single ecological site description (ESD), a recorder would, if necessary, turn the transect clockwise from the randomly generated direction until s/he found a line that appeared to stay within the starting ESD. If a recorder encountered a significant vegetation or soil boundary while reading the transect, s/he would turn around (i.e., 180˚) and run a parallel transect approximately 20 meters from the original transect, and continue reading until 100 points were reached. At each point, ground cover was recorded as litter, rock/gravel, bare ground, standing dead vegetation, light cyanobacteria-dominated crust, dark cyanobacteria-dominated crust, moss or lichen. Light cyanobacteria-dominated crust was counted if bacterial filaments were both visible and aggregating the soil surface into a cohesive unit. Vegetation type is an

[1] Susceptibility to water erosion was determined by a K-factor. Only sites where K>0.15 were included. Wind erosion susceptibility was determined by which Wind Erodibility Group (NRCS 2015) defined the site. Only sites within the top 4 WEGs were included.

imperfect predictor of soil functional type. For example, biocrusts respond more strongly to the level of calcium carbonate ($CaCO_3$) in soil than vegetation (Bowker, et al. 2006). Nevertheless, the Trust used vegetation type to keep transect data collection consistent with the 2000-2003 RLH data. Vegetation type was the easiest visual cue to keep data collectors running transects in a relatively homogenous ecotype.

One exception to the method was a set of 23 sites completed by a group of Whitman College students in 2014, which counted light and dark cyanobacteria-dominated crust as a single category. This group also counted any visible presence of bacterial filaments as biological soil crust, not just light cyanobacteria that had developed to the point of aggregating the soil surface. This set of transects was analyzed separately from the remaining 153 sites except where otherwise noted.

To compare with Bowker's model, the absolute hits were converted to a percent cover of available habitat calculated by the following formula:

> *Percent cover of available habitat = [(dark cyanobacteria-dominated crust hit + moss hit + lichen hit)/*
> *(dark cyanobacteria-dominated crust hit + moss hit + lichen hit + light cyanobacteria-dominated crust hit + bare ground hit)] x 100*

The above percentage was compared to the mid- to late-successional crust cover percentage predicted by the Bowker, et al. model to create a percent of predicted cover by the following formula.

> *Percent of predicted mid- to late-successional biocrust cover = [(Percent cover of available habitat)/(predicted dark cyanobacteria percent cover + predicted moss percent cover + predicted lichen percent cover)] x 100*

For the 2014-15 survey, light cyanobacteria-dominated crust (i.e., early successional crust) percent cover of available habitat was calculated by the following formula

> *Light cyanobacteria percent cover of available habitat = (light cyanobacteria hits)/(light cyanobacteria hits + bare ground hits)*

Statistical Analysis

Fisher's exact test and Student's T-test were used to analyze whether the 2000-2003 and 2014-2015 surveys differed significantly from each other and whether the two surveys differed significantly from the Bowker, et al. model predictions.

To analyze differences in distributions between surveys, sites were grouped into six categories based on their percent of predicted mid- to late-successional crust values (0-10%, 11-25%, 26-50%, 50-75%, 75-100%, and >100%). Fisher's exact test was used to determine whether the number of sites contained in each category for the two surveys differed significantly from each other.

To determine whether the distribution of observed values between the two surveys differed significantly from the Bowker, et al. model, sites were grouped into five categories based on the percent cover of available habitat mid- to late- successional crusts (0-10%, 25-50%, 50-75%, 75-100%). Fisher's exact test was used to determine whether the number of sites in each category of a particular survey differed significantly from the expected crust occupancy predicted by the Bowker, et al. model.

Fisher's exact test was also used to test whether the methodological differences between the 2014-2015 general survey and the Whitman survey led to different distributions in observed crust percent of available habitat.

To combine data collected in the Whitman survey and the general survey, a combined moss and lichen measure was generated for all 176 sites. The same was done for the corresponding 176 sites in the 2000-2003 survey. This value was compared to a predicted value for combined moss and lichen from Bowker, et al. (2006).

Student's T-test was used to compare the mean percent cover of available habitat of mid- to late-successional biocrust between the 2000-2003 survey and 2014-2015 general survey. T-tests were also performed to determine whether mean percent cover of available habitat significantly departed from the predicted mean.

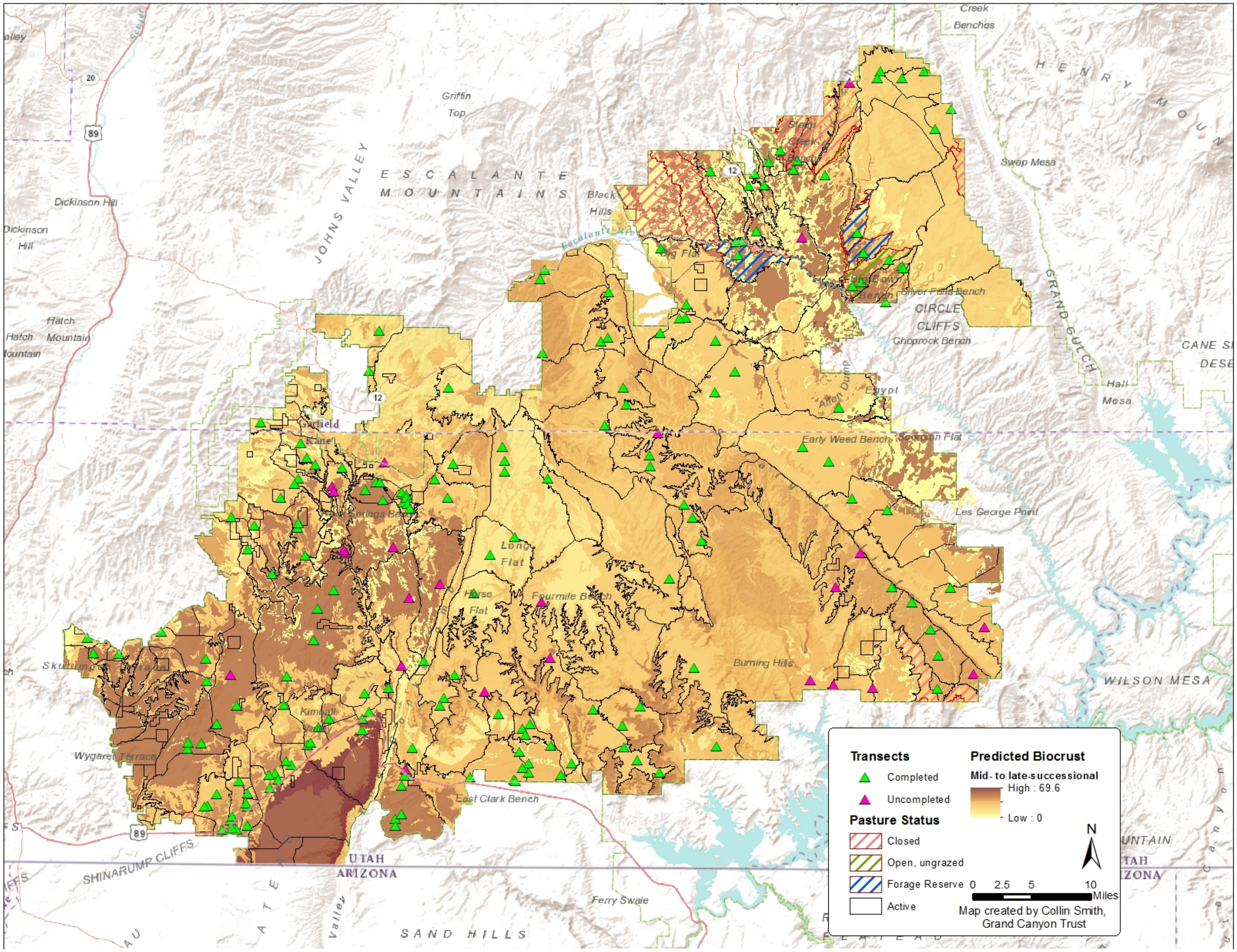


Fig. 6: Predicted cover of mid- and late-successional biocrust from Bowker, et al. (2006); and completed and uncompleted transects, 2014-2015.

RESULTS

Note: Figures in the results section use abbreviations for light cyanobacteria-dominated crust (L), dark cyanobacteria-dominated crust (D), moss (M), and lichen (Li) for clarity. References to 2000-2003 only include the 153 (or 176 when specified) sites repeated in 2014-15.

Of the 153 sites that distinguished light and dark cyanobacteria-dominated crusts, 140 (92%) fell below predicted potential values in 2014-2015 and 135 (88%) fell below predicted potential in the 2000-2003 survey (Fig. 7). Fisher's exact test showed the difference in distribution between the two surveys to be non-significant (p=0.498).

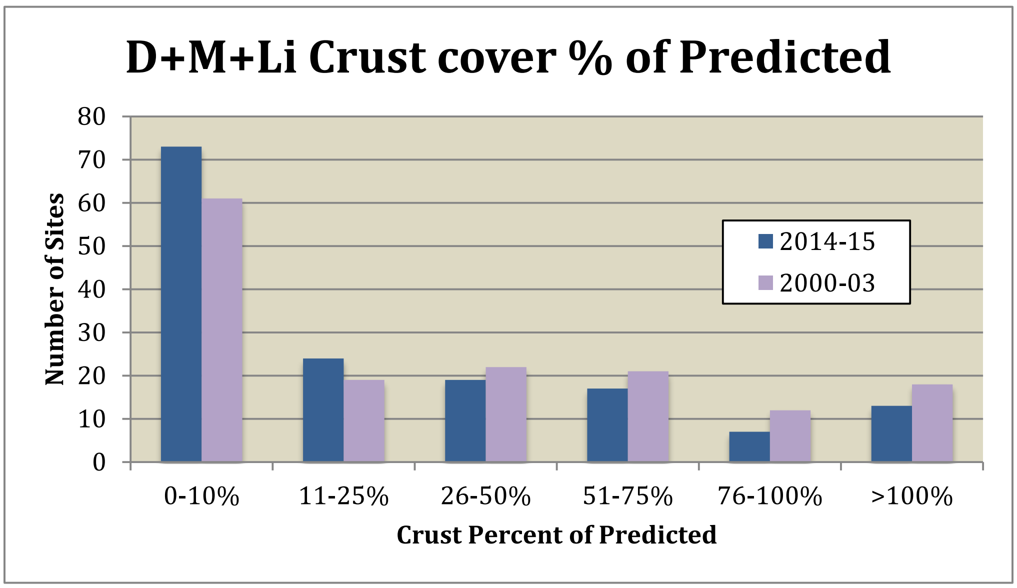


Fig. 7: Comparison of 2000-2003 D+M+Li percent of Bowker, et al. predicted cover with 2014-2015. N=153 for both datasets.

While the Bowker, et al. model predicts crust percent cover of available habitat as a relatively symmetric distribution around 50% for the 153 sites read in 2014-15, field surveys show a distribution strongly skewed right, with most sites clustering below 25% cover (Fig. 8). Fisher's exact test shows the differences in distribution between both the predicted and 2014-15 survey and the predicted and 2000-2003 survey are significant (p<.001 for both). The difference in distribution of 2000-2003 and 2014-2015 % cover of available habitat was not significant (p=0.184). In 2014-15, 47 (31%) sites predicted to support at least 20% mid- to late-successional biocrust cover recorded zero dark cyanobacteria crust, moss or lichen. In 2000-2003, 53 (35%) sites recorded zero dark cyanobacteria crust, moss or lichen.

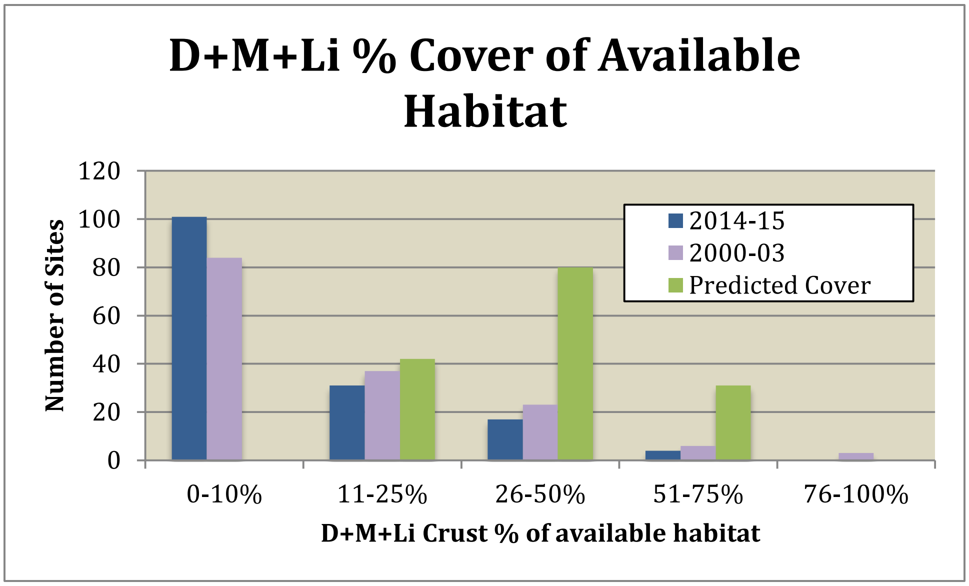


Fig. 8: Comparison of D+M+Li crust habitat occupancy for 2000-03 RLH survey, 2014-2015 survey and Bowker (2006) predicted occupancy. N=153 for both

P-values for Student's T-test analysis of mean % cover of available habitat for mid- to late-successional crust are shown below. Differences between predicted and observed mean % cover of available habitat were highly significant (p<.001) for both 2014-15 and 2000-2003 surveys. Mean % cover of available habitat in 2014-2015 (10.3%) was significantly (p=.017) lower than mean % cover of available habitat in 2000-2003 (14.8%) at the alpha=.05 level.

Table 2: Mean and p-values for Student's T-test comparison of mean % cover of available habitat between 2000-2003, 2014-2015 and predicted data sets.

	2014-2015	**2000-2003**	**Predicted**
Mean	10.3%	14.8%	35.2%
2014-2015 T-test	–	0.017	1.11E-47
2000-2003 T-test	0.017	–	2.08E-25

In 2014-15, light cyanobacteria crust was recorded in addition to dark cyanobacteria crust, moss, and lichen. Again the distribution for percent cover of available habitat is skewed right. Twenty-six sites recorded no light cyanobacteria-dominated crust (Fig. 9).

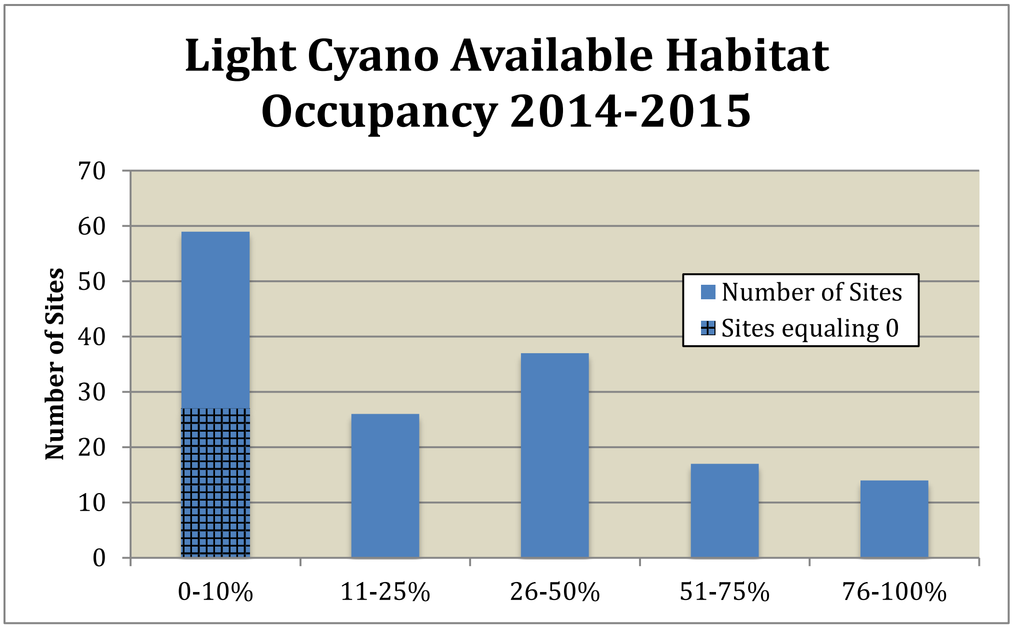


Fig. 9: Light Cyanobacteria-dominated crust measured in 2014-2015 (n=153). Sites with zero light cyanobacteria-dominated crust hits shown in crosshatch.

To compare biocrust recordings from the Whitman College survey with the 2014-2015 survey, dark and light cyanobacteria-dominated crust hits were combined for a light-and-dark percent cover of available habitat. The Whitman College data regarding cyanobacteria-dominated crusts cannot be compared to data from the 2000-2003 survey, which did not record light cyanobacteria-dominated crusts, or the Bowker, et al. model, which did not predict light cyanobacteria-dominated crust occupancy.

Figure 10 shows a significantly higher ($p<0.001$) percent cover of available habitat when including light cyanobacteria filaments that have not yet strongly aggregated the soil surface.

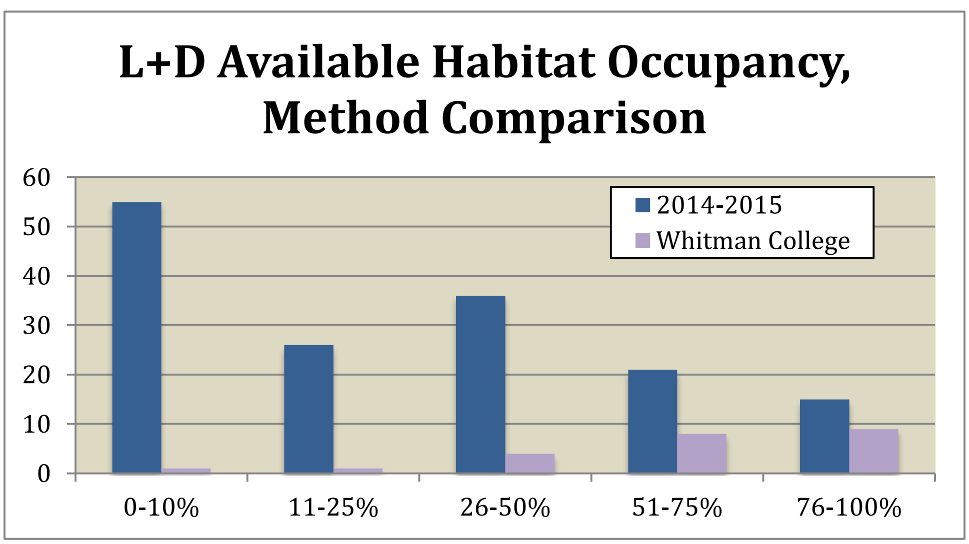


Fig. 10: Difference in combined light and dark cyanobacteria-dominated crust scores for Whitman College 2014 survey (N=23) and the 2014-15 general survey (N=153).

The general survey and Whitman College data can be combined for moss and lichen sampling, since the sampling method for these categories was identical. The sites can be compared to the Bowker, et al. predicted moss and lichen percent cover of available habitat data. Since both predicted and observed cover for moss and lichen are small, this study combined the two categories. Moss and lichen were often not intercepted in site transects (Fig. 11). Fisher's exact test found the difference in these distributions significant ($p<.001$). A T-test comparing mean moss and lichen % cover of available habitat was also significant ($p=0.005$).

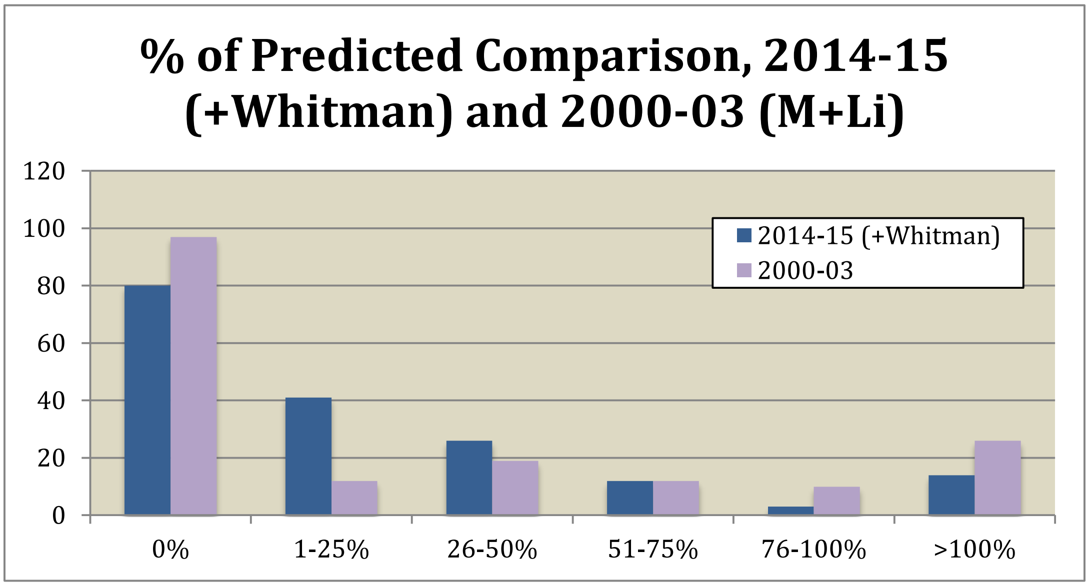


Fig. 11: Comparison of late-successional crust (moss and lichen) percent of predicted between 2014-2015 (including Whitman College data) and 2000-2003, N=176.

Table 3: Mean moss and lichen percent cover of available habitat comparison, 2000-2003 to 2014-2015

	2014-2015 M+Li % cover of available habitat	**2000-2003 M+Li % cover of available habitat**
Mean	3.9%	6.6%
Standard Deviation	6.3%	10.8%
Student's T-test	0.005	

Ten of the 176 included in the survey were located in areas that were not within an active grazing allotment. Four sites were in closed allotments or closed portions of allotments (E0690, E5049, E0658, E0655), three fell in forage reserves, which can be occasionally grazed (E0676, E1600, E054), and three in open allotments not grazed since 2000 (E0669, E0670, E0672). Four transects were completed in the Whitman survey and cannot be compared for light cyanobacteria alone. Detailed information of the remaining six transects within the general survey are shown below in Table 4.

Table 4: Selected site attributes for transects occurring in ungrazed pastures.

Site ID	Allotment	Pasture	Grazing status (years since last graszed)	2014-15 % of Predicted (D+M+Li)	2000-2003 % of Predicted (D+M+Li)	Predicted crust %	2014-15 Light Cyano CAH*	% Bare ground (absolute)	Notes
E0669	Big Bowns Bench	Horse Spring	Open, ungrazed (15)	0%	0%	52%	21%	63%	Sandy, rolling dunes. Biocrust functionally absent but do occupy some areas protected by shrubs
E0670	Big Bowns Bench	Horse Pasture	Open, ungrazed (15)	9%	3%	52%	2%	63%	Sandy, dominated by Indian ricegrass, sand sage. Biocrust patches present but occasional.
E0672	Big Bowns Bench	Horse Pasture	Open, ungrazed (15)	29%	11%	25%	31%	33%	Rocky ridgetop with pinyon-juniper and shrubs. A few patches of dark cyano present but erosion is evident.
E0676	Deer Creek	Wolverine	Forage Reserve (?)	88%	79%	52%	80%	4%	Native grasses dominate. Erosion light. Sandy soil but crust is near-continuous. Little lichen present
E0690	Deer Creek	Cottonwood	Closed (16)	18%	48%	52%	90%	3%	Elevated bench in creek bottom. Dominated by light cyanobacteria and sagebrush with native and non-native grasses (e.g. grama, Indian ricegrass, cheatgrass). Patches of late successional crusts common.
E1600	Little Bowns Bench		Forage Reserve (?)	34%	53%	52%	47%	21%	Juniper and grass (e.g. sandhill muhly, Indian ricegrass) dominant. Signs of historic cattle usage (Russian thistle, dried out cattle feces under juniper). Lots of loose sand.
Ungrazed Average (N=6)			–	30%	32%	–	45%	31%	
Grazed Average (N=147)			–	30%	46%	–	27%	32%	

* Cover of available habitat (CAH) : (Light cyano hits)/(Light cyano hits + Bare ground hits)

DISCUSSION

The results of the 2000-2003 RLH survey and the 2014-2015 survey are similar (Figs. 7-8). Both distributions are strongly skewed right with very few sites (13 in 2014-2015 and 18 in 2000-2003) reaching or exceeding the potential predicted by the Bowker, et al. model. The distributions are statistically similar, although mean % cover of available habitat was significantly lower in 2014-2015 (Table 2). Crust darkness occurs on a continuum (Belnap, et al. 2008), It is possible that since the 2014-2015 study distinguished and recorded light and dark cyanobacteria-dominated crusts, some points that would have been labeled dark cyanobacteria-dominated crust in 2000-2003 were categorized as light cyanobacteria-dominated crust in 2014-15. This may have led the 2014-2015 study to report slightly lower dark cyanobacteria-dominated crust cover overall. The decrease might also be attributed to factors beyond methodological differences. Mean moss and lichen cover (a component of the mid- to late-successional crust cover) also significantly decreased from 2000-2003 to 2014-2015 (Table 3). The decrease mirrors an overall decrease in net primary productivity (as measured by normalized difference vegetation index NDVI) on the Monument during the period of 1986-2011 (Hoglander, et al. 2014). The inability of 2014-2015 researchers to replicate the unrecorded 2000-2003 transect directions increases random variation and makes quantitative comparisons at the individual site level beyond the scope of this report.

Regardless of small methodological differences, biological soil crust cover is far below potential at a majority of sites (Fig. 7) across the Monument. The number and wide geographic range of sites included in the survey indicate that biocrust cover and diversity is systemically below potential across the Monument.

The paucity of biocrust at most sites suggests that those sites suffer from accelerated erosion (Belnap and Gardner 1993), impaired carbon and nitrogen fixation (Housman, et al. 2006), and diminished plant nutrient availability (Belnap and Harper 1995). Signs of surface flow and excessive erosion (e.g., headcuts, incising and gullying) were documented on many sites and are evident in previous sagebrush treatments.

Later-successional biocrusts (i.e., mosses and lichens), which are particularly sensitive to physical disturbance (Belnap, et al. 2001) are especially rare in the survey (Fig. 11). One-hundred and twenty-one of 176 sites (69%) were below 25% of their predicted late-successional (moss+lichen) cover. In the survey, mosses and lichens were most typically observed in protected areas underneath shrubs, near the edges of cliffs or slickrock, or in other areas cattle rarely access (e.g., persistent pinyon-juniper woodlands).

While mid- and late-successional stage biocrusts with moss, lichen and dark cyanobacteria are clearly underrepresented on the Monument, the picture for light cyanobacteria-dominated crusts is mixed. In the general 2014-2015 survey (which only measured light cyanobacteria-dominated crusts if they strongly aggregated the soil surface), light cyanobacteria-dominated crusts occupied less than 25% of their available habitat at a majority of sites (Fig. 9). However, in the 23 sites which recorded light cyanobacteria-dominated presence if *Microcoleus* filaments were visible with a hand lens, aggregate light + dark crust percentages were much higher. While the 153 sites in the general survey clustered below 50% cover, the 23 sites from the Whitman College survey clustered above 50% cover, with crust at nine sites occupying 75-100% of available habitat. The discrepancy between these two datasets suggests that while functional cyanobacteria-dominated crusts were not recorded at every site, the building blocks of a crust system, *Microcoleus* filaments, are typically present at high rates. It would be inaccurate to assume that because crusts are not present at a site, that crusts could not develop, given greater relief from trampling. Aggregation of soil driven by cyanobacteria could likely occur in a relatively short period of time (0-3 years with adequate rainfall)

Though not to the degree late successional biocrusts do, light cyanobacteria-dominated crusts help guard against wind erosion (Belnap and Gillette 1997) and provide some soil nutrients (Belnap 1996, Housman et al. 2006).

Active allotments cover 96.4% of the Monument (deRoulhac 2013*a*) and cattle exclosures are rare (deRoulhac 2013*b*). Ten of the 176 transects in this survey were in closed allotments, forage reserves or otherwise livestock-free allotments. Livestock grazing has been absent or significantly reduced for at least 15 years in these pastures. Six of those transects were in the general 2014-2015 survey. On average, in 2014-15, the sites in grazed and ungrazed pastures had similar mid- and late-successional crust percent of predicted (Table 3). However, light cyanobacteria percent cover of available habitat, on average, was 19% higher than in the ungrazed sites. This follows the expected trend in biocrust recovery, with light cyanobacteria-dominated crusts recolonizing more quickly than dark cyanobacteria, moss, or lichen after disturbance (Belnap et al. 2001). Light cyanobacteria-dominated crust recovery appears to be capable of occurring on the order of years, not decades.

The Trust will soon produce an appendix to this report with individual site reports (see Appendix A for an example of such a site report).

A difficulty in analyzing individual sites is the lack of comprehensive information regarding the various treatments and seedings that have occurred on the Monument. Treatments can have severe implications for crust abundance and the ecological services that crusts provide (Miller 2008). The Monument is currently compiling information regarding vegetation treatments and seedings completed on the Monument (personal communication, Monument Manager Cynthia Staszak) and the Trust intends to incorporate that information in the site summaries as well as future analysis of the 2014-2015 survey data.

IMPLICATIONS FOR GRAZING MANAGEMENT

The findings of this broad-scale survey of biological soil crust throughout the Monument lead to several implications for development of the upcoming grazing plan amendment.

1) **Light cyanobacteria-dominated crusts are a crucial indicator of current grazing management.**

This survey provides evidence that contradicts the BLM *Analysis of Management Situation* claim that since "soil crusts may take decades to recover from disturbance… they are not good short-term indicators of the appropriateness of current management actions." (BLM 2015).

Given that lightly pigmented, early successional cyanobacteria-dominated crusts can recover relatively quickly (on the order of years, not decades) and that they also perform important ecosystem functions (Housman et al. 2006), the total lack or minimal presence of light cyanobacteria on Monument sites predicted to support at least 20% mid- or late-successional crusts is a strong indicator that **current** management actions are either eliminating or greatly diminishing a range of ecological benefits including soil stability, water retention, carbon and nitrogen fixation, as well as the foundation for later successional crusts.

Light cyanobacteria are simple and quick to observe given proper training. A helpful tool in this analysis is the "level of darkness" classification created by Belnap, et al. (2008).

2) **Recovery of biocrusts in the Monument will require more protection.**

Biocrusts are currently far below their predicted potential on the Monument. This study only surveyed sites predicted to have significant (>20%) mid- to late-successional biocrust cover, yet almost a third of such sites recorded zero mid- to late-successional soil crusts. Ninety-two percent of sites in the general survey fell below their predicted potential, and 96 sites (64%) fell below 25% of their predicted potential.

The presence and diversity of biocrusts provide valuable information regarding the functional status of an ecosystem. If an ecosystem is in a low-functioning state (e.g., if soil is eroding due to compromised crust), it suggests that more of the same management is inappropriate. The greatest potential for recovery of biocrusts that the BLM can provide in the Monument is relief from trampling by cattle and human foot or vehicular trampling. This is true whether damage was done last week or last year. Given that cattle trampling is the most ubiquitous form of trampling within the Monument, the grazing amendment provides the greatest opportunity for generating biocrust recovery in the Monument.

3) **More ungrazed reference areas are necessary to understand how biocrusts are performing in response to global warming or improved grazing management.**

Ferrenberg, et al. (2015) provide a disturbing look into the future of biocrusts. The impacts of warming and altered precipitation on biocrusts are similar to, and cumulative with, physical disturbance. Both stressors move crusts towards an earlier successional stage dominated by light cyanobacteria-dominated crusts at the expense of lichens and mosses. The Monument has the opportunity to designate more and larger ungrazed areas to help distinguish the impacts of global warming from physical disturbance and to assess the future of and best management options for biocrusts in the Monument.

Similarly, large. ungrazed reference areas allow for comparison of improved, innovative, and/or experimental grazing methods with ungrazed areas on any of a number of measures.

The current ungrazed areas of the Monument (concentrated in the remote northeast corner, in, and on the benches above, the Escalante River corridor) represent only a small set of the possible climate, soil, crust and vegetation interactions present over the whole Monument. In order to provide information relevant to livestock grazing on all major soils and vegetation types on the Monument, the network of ungrazed areas must be significantly increased, maintained, and monitored over decades.

4) **The Monument should encourage further research on biocrust development, function, and rehabilitation.**

The first sentence of the Monument Proclamation (Clinton 1996) notes the value of the Monument for scientific research:

> *The Grand Staircase-Escalante National Monument's vast and austere landscape embraces a spectacular array of scientific and historic resources.*

Biocrusts are one of the valuable scientific resources referenced in the Proclamation. The variety of soils, climate and vegetation communities on the Monument provides unparalleled opportunities to study biocrusts on the Colorado Plateau. Research into crust succession after physical disturbance, a critical area of study in the Intermountain West, would be a particularly apt use of the Monument. In particular, the Monument offers a large area of diverse soils in which the transitions from early to more developed light cyanobacteria-dominated soils to later successional biocrusts could be studied.

Promising research into assisted crust rehabilitation using inoculation with mosses along with other soil stabilization and nutrient augmentation techniques is currently being pursued (Bowker 2007). This research would benefit from protected field areas to develop and test new methodologies (Bowker et al., 2012).

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Appendix A Sample GSENM Biocrust Site Summary

<table>
<tr><th>Site Number</th><th colspan="2">Allotment</th><th>Pasture</th><th colspan="2">Ecological Site Description</th><th>Date</th></tr>
<tr><td>E1600</td><td colspan="2">Little Bowns Bench</td><td>N/A</td><td colspan="2">Semidesert steep shallow loam PJ</td><td>9/23/15</td></tr>
<tr><th colspan="2">Category</th><th>Light Cyano</th><th>Dark Cyano</th><th>Moss</th><th>Lichen</th><th>Bare Soil</th></tr>
<tr><td colspan="2">% Absolute Cover[2]</td><td>27%</td><td>12%</td><td>0%</td><td>0%</td><td>30%</td></tr>
<tr><td>Crust Percent[3] 2003</td><td>27.6 (53.2)[4]</td><td colspan="5" rowspan="3">Notes
Juniper and grass dominated. Pinyon present in low amounts. Signs of historic cattle usage (Russian thistle patches, large piles of dried feces under juniper).Lots of cactus present. Bare soil was often loose sand. Ground was a combination of sand, crust, and desert pavement. No signs of significant erosion.</td></tr>
<tr><td>Crust Percent 2015</td><td>20.0 (38.5)</td></tr>
<tr><td>Crust Percent Predicted</td><td>51.9</td></tr>
</table>

Fig. 1) Transect start, representative of site

Fig. 2) Transect end

Fig. 3) Dark cyano crust in cactus

Fig. 4) Russian thistle patch

2 % Absolute cover= (total category hits)/(total number of transect points), indicates percent of survey area occupied by a particular crust category.

3 Crust percent= (total crust hits)/(total crust hits + total bare soil hits), indicates percent of available crust habitat actually occupied by crust

4 () denotes percent of predicted potential