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Status and Trends in Upland Vegetation and Soils at Capitol Reef National Park, 2009–2018

(Revised with Cost Estimate)

Natural Resource Report NPS/NCPN/NRR—2020/2183



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ON THE COVER

Upland vegetation and soils monitoring crew with globemallow, Capitol Reef National Park, June 2015. NPS/Amy Washuta.

Status and Trends in Upland Vegetation and Soils at Capitol Reef National Park, 2009–2018

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Prepared by
Dana L. Witwicki
Northern Colorado Plateau Network
National Park Service
P.O. Box 848
Moab, UT 84532

Editing and Design
Alice Wondrak Biel
Northern Colorado Plateau Network
National Park Service
P.O. Box 848
Moab, UT 84532

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Executive Summary

When Capitol Reef National Park (NP) was established in 1971, there were 19 active grazing allotments in the park. By the 1990s, all but two of these grazing permits were retired. Through long-term monitoring, resource managers at Capitol Reef NP are interested to identify impacts of recent livestock grazing on grasslands and track plant and soil recovery after grazing has ceased. The Northern Colorado Plateau Network (NCPN) has monitored the ecological health of vegetation and soils in grasslands in the northern part of Capitol Reef NP for more than 10 years. This report uses grassland data collected at the park from 2009 to 2018 to explore the following questions:

1. What is the current status of upland vegetation and soils (vegetation and surface cover, shrub density, exotic plant frequency, soil stability, and gaps) in Capitol Reef NP grasslands, and how has that status changed from 2009 to 2018? How do status and trends in grassland condition differ by grassland type and livestock grazing history?
2. Which climate conditions are most influential in Capitol Reef NP grasslands? How did they affect upland vegetation and soils from 2009 to 2018?

Three livestock-grazing allotments in the northern part of the park, with different grazing histories, were selected for long-term monitoring: Hartnet, grazed until May 2018, the last year of monitoring data included in this report; Cathedral, where ~80% of animal unit months (AUMs) were retired in 1989, and the rest retired in 1999; and Rock Springs, retired in 1989. Two groups of grassland ecological sites were monitored: deep grasslands and rocky grasslands. Each has different soil and geomorphic properties, as well as some differences in the dominant perennial grass and shrub species present.

We combined ecological-site groups and grazing history to obtain three sampling strata:

1. Deep grasslands in the combined retired Cathedral and Rock Springs allotments (Cathedral/Rock Springs deep grasslands),
2. Deep grasslands in the grazed Hartnet allotment (Hartnet deep grasslands), and
3. Rocky grasslands in the grazed Hartnet allotment (Hartnet rocky grasslands).

Rocky grasslands were not sampled in the Cathedral and Rock Springs allotments because there was only a very small amount present.

In the Cathedral and Rock Springs allotments, deep grasslands retired from livestock grazing were generally in good condition, with trends that were stable or improving. The allotments had low invasion by exotic annual plant species and good recovery from past grazing based on limited historical data.

In actively grazed areas of the Hartnet allotment, conditions of cool-season grasses and soils were in relatively poor condition. The Hartnet deep grasslands had lower soil stability and some evidence of lower cool-season grass cover, lower biological soil crust cover, higher bare-soil cover, and larger gaps between plant canopies than the allotments retired from grazing, though the evidence was not particularly strong. Perennial grasses, especially cool-season grasses, showed declining trends (i.e., declining resource condition). Average to above-average precipitation in later years of monitoring (2013–2016) kept changes in grass cover less negative than would be predicted under long-term mean precipitation conditions from 2009 to 2018. Soil conditions showed some improvement over the 10 years of monitoring, but the current condition of these indicators suggests there is still a moderate-to-high potential for wind and water erosion.

In the Hartnet rocky grasslands, vegetation cover declined from 2009 to 2018 for all analyzed indicators, and was lower during the drought conditions of 2018 than in any of the other years monitored. Soils in the rocky grasslands had low cover of biological soil crust and bare soil, but were still in relatively good condition because a high cover of rocks protects them from trampling and wind erosion. In areas with exposed soils, biological soil crust cover and soil stability increased from 2009 to 2018.

Comparisons of historical vegetation data with recent soil conditions in the grazed Hartnet allotment appeared to show some recovery from past livestock grazing. The soil conditions monitored (soil stability, biological soil crust, and bare-soil cover) improved in all three allotments from 2009 to 2018.

Seasonal precipitation was an important influence on vegetation cover, especially for perennial grasses. The influence of previous-year monsoon precipitation (July–September) on perennial-grass cover was twice as strong as that of cool-season precipitation (October–April) just prior to monitoring. The exceptionally large monsoons of 2013 substantially increased cover of both cool- and warm-season perennial grasses during the following spring. Grass cover was lowest in 2009 and 2018, following periods of drought. The last year of monitoring, 2018, was the driest water year and cool season during the 10 years of monitoring, following an average monsoon season in 2017. Cool-season precipitation was related to the frequency of exotic-plant species detected. High amounts of exotics were detected in 2011, after a particularly wet cool season. Soil conditions (soil stability, biological soil crust, and bare-soil cover) improved in wetter years, which was related to cool-season precipitation for all soil metrics. Soil stability was similarly influenced by both cool-season and monsoon precipitation.

Current conditions and trends are summarized in Table E1. In the table:

- **Current values** are based on modeled data for 2018 for all measures.
- **Change in status** is the change in an indicator from the first to last year of monitoring, driven in part by variations in cool-season and/or monsoon precipitation during the years monitored (i.e., change in status reflects actual changes in an indicator on the ground).
- **Trend** is the long-term change in an indicator, evaluated at the mean of model covariates, such as cool-season and/or previous-year monsoon precipitation.
- Conditions, change in status, and trends were based on modeled data from 2009 to 2018 for all data except exotic-plant frequency, which used modeled data from 2011 to 2018. “Change in Status” is from a version of the model that used the actual values of the covariates each year. “Trend” is from a version of the model that includes the covariates at their means. When condition/trend differed from change in status, this indicates that cool-season and/or previous-monsoon precipitation were important in driving short-term changes in the indicator. When condition/trend differed little from change in status, this suggests that an underlying cause of the trend was not included in the model.
- **Rationale for Condition/Trend:** Vegetation in the Cathedral/Rock Springs deep grasslands was generally stable, with increases in warm-season grass cover. The allotments had low invasion by exotic annual plant species and good recovery from past grazing based on limited historical data. In Hartnet deep grasslands, cool-season grass cover was very low, which may be due to both livestock-grazing pressure and warming conditions that did not favor cool-season grasses. Frequency of exotics was somewhat high, which has been shown to be related to livestock disturbance. Hartnet rocky grasslands had fairly low invasion by exotic-plant species, but grass and

shrub cover were decreasing and particularly susceptible to declines during drought in this soil type.

Soils in the Cathedral/Rock Springs deep grasslands were in moderately good condition and continued to improve, but recovery from trampling disturbances is a slow process. Many areas of the Hartnet deep grasslands had soils trampled by livestock and in relatively poor condition, but wetter-than-average years likely contributed to some improvement in soil conditions. Soils in rocky grasslands had somewhat lower stability and biological soil crust (BSC) cover, but the surface was well protected by high cover of rocks that limited bare soil, prevented erosion, and limited the surface area where BSCs could form.

Table E1. Summary of conditions for grasslands in Capitol Reef National Park with different grazing histories and grassland types.

		Cathedral/Rock Springs deep grasslands (retired)			Hartnet deep grasslands (grazed)			Hartnet rocky grasslands (grazed)		
Vital sign	**Indicator**	**Current mean (95% CI)[A]**	**Change in status**	**Condition/ Trend[B]**	**Current mean (95% CI)[A]**	**Change in status**	**Condition/ Trend[B]**	**Current mean (95% CI)[A]**	**Change in status**	**Condition/ Trend[B]**
Upland plant communities	Total cover	10.6% (5.2–18.0)	+2.3%	⇔	7.0% (3.2–14.1%)	+0.4%	⇩	6.6% (3.5–10.1%)	-2.9%	⇩
	Perennial-grass cover	6.5% (2.7–11.9)	+1.8%	⇔	2.9% (0.7–7.6%)	+0.02%	⇩	2.1% (0.7–4.3%)	-1.5%	⇩
	Cool-season grass cover	2.1% (0.3–6.0)	+0.1%	⇔	0.6% (0.2–1.4%)	-0.2%	⇩	0.8% (0.1–2.5%)	-0.2%	⇩
	Warm-season grass cover	4.1% (1.4–8.7)	+1.8%	⇧	2.6% (0.3–8.0%)	+0.5%	⇔	1.3% (0.4–3.3%)	-1.0%	⇩
	Shrub cover	2.6% (0.8–6.8)	-0.4%	⇩	2.3% (0.6–6.2%)	-0.5%	⇩	2.7% (0.8–5.7%)	-2.2%	⇩
	Shrub density	3,716 shrubs/ha (540–10,730)	+465 shrubs/ha	⇔	7,016 shrubs/ha (575–44653)	+1,170 shrubs/ha	⇔	10,408 shrubs/ha (2,813–26,025)	+1,870 shrubs/ha	⇧
	Frequency of exotic species	0.1% (0–0.7)	-23.7%	⇧	9.4% (0–85.4%)	-41.5%	⇧	3.1% (0–33.4%)	-10.3%	⇔
Soil stability	Biological soil crust cover	12.0% (0.03–39.5)	+9.7%	⇧	1.5% (0–9.1%)	+0.8%	⇧	2.0% (0–8.1%)	+1.2%	⇧
	Bare-soil cover	0.6% (0–4.0)	-5.4%	⇧	1.9% (0–7.5%)	-7.9%	⇧	0.3% (0–1.5%)	-1.4%	⇧
	Soil-stability rating	5.0 (3.9–5.9)	+2.1	⇧	3.1 (1.5–4.5)	+0.7	⇧	4.0 (2.8–5.2)	+1.4	⇧
	Canopy-gap size	74 cm (31–152)	-37 cm	⇧	145 cm (45–294)	-106 cm	⇧	102 cm (42–199)	-41 cm	⇧

[A]CI = credible interval

[B]Green ● indicates the indicator was in good condition. Yellow ● indicates condition that warrants moderate concern. Red ● indicates condition that warrants significant concern. An upward arrow means the condition is improving. A sideways arrow means the condition is unchanging. A downward arrow means the condition is deteriorating. Note that decreasing frequency of exotic species, bare-soil cover, and canopy-gap sizes are considered improving trends. A dashed line means confidence is low. A solid line means confidence is medium. No conditions were reported with high confidence due to the relatively short dataset (≤10 years), wide credible intervals, and limited historical data. There are few reference conditions available in the arid west due to widespread historical livestock grazing. Condition colors will become more informed with additional years of monitoring data and may change as more information is gathered. Because the purpose of this report was to inform management, condition colors were included based on the literature and the author's professional judgment. The rationale for resource condition (see previous page) explains these delineations.

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1 Introduction

Grasslands are an important ecological system throughout the world because of the nutrition they provide to native and domestic grazing animals. In semiarid regions like the Colorado Plateau, where native vegetation tends to be sparse, grasses are an especially important source of nutrition. Protecting grasslands is a high priority for park managers at Capitol Reef National Park (NP), who are responsible for preserving natural resources for the enjoyment, education, and inspiration of park visitors while maintaining historical livestock grazing within parts of the park.

Semiarid grasslands on the northern Colorado Plateau occur on benches, hillslopes, and valley bottoms with deep sandy or loamy soils. They are characterized by native perennial bunchgrasses, including cool-season (C3) grasses, such as Indian ricegrass (*Stipa hymenoides*) and needle and thread (*Stipa comata*), and warm-season (C4) grasses, such as galleta (*Hilaria jamesii*), dropseeds (*Sporobolus* species), and blue grama (*Bouteloua gracilis*). Semiarid grasslands also typically contain salt-desert shrubs, such as fourwing saltbush (*Atriplex canescens*), shadscale (*Atriplex confertifolia*), winterfat (*Krascheninnikovia lanata*), and greasewood (*Sarcobatus vermiculatus*). In these grasslands, biological soil crusts—communities of cyanobacteria, algae, microfungi, mosses, and lichens that occur on the upper few millimeters of the soil surface—play an important role in cycling nutrients and holding soils in place.

Although cool- and warm-season grasses co-occur in semiarid grasslands of the northern Colorado Plateau, their growing seasons differ in some notable ways. Cool-season grasses grow in cooler months, primarily in spring and early summer, and secondarily in fall, when moisture is available (Comstock and Ehleringer 1992). Warm-season grasses initiate growth somewhat later in the spring, and then primarily grow throughout late summer, when moisture from summer monsoons is available (Comstock and Ehleringer 1992). Having a balance of cool- and warm-season grasses is important to land managers on the Colorado Plateau because livestock tend to preferentially utilize nutritionally rich, cool-season grasses (Hart et al. 1993). In semiarid grasslands with a mix of perennial cool- and warm-season grasses, livestock grazing decreases biomass (Irisarri et al. 2016), cover (Manley et al. 1997), and tiller densities (Hart et al. 1993) of cool-season grasses. On the Colorado Plateau, this effect is additionally amplified when winter livestock grazing overlaps the early-spring growing season of cool-season grasses but coincides little with the growing season of warm-season grasses.

Semiarid grasslands in Capitol Reef NP generally contain a high percentage of native plant species, but when the soil surface is disturbed, they are susceptible to invasion by cheatgrass (*Bromus tectorum*), Russian thistle (*Salsola* species), and other exotic annual plants. Repeated or extreme disturbances can transition grasslands to a state where these exotic annuals dominate and native perennial grasses can no longer persist. Herbivory and trampling by native and domestic grazers can also cause shifts in vegetation composition (Harris et al. 2003) and ecological states (Miller et al. 2011). The risk of this occurring is especially high during droughts, when the need for forage is high and plants are not able to produce as much biomass. Drought and herbivory can also increase the size of gaps between plant canopies, which increases the risk of wind erosion (Okin 2008). Trampling increases bare soil and reduces the cover and structural complexity of biological soil crusts, decreasing their ability to hold soils in place (Belnap and Eldridge 2003).

The Southwest is getting warmer (Garfin et al. 2014). Because higher temperatures increase the amount of water that evaporates from the soil, droughts are becoming more frequent and more severe (Cook et al. 2015; Seager et al. 2007). This causes additional water stress for upland vegetation; regional land managers are particularly concerned about how grasses will repond to this increasing drought stress. Cool- and warm-season grasses in the region rely on getting water during particular times of the year to survive (Gremer et al. 2015; Witwicki

et al. 2016), and there is uncertainty about how the amount and seasonality of precipitation events is expected to change in the future (Garfin et al. 2014). Grasslands at Capitol Reef NP are currently co-dominated by both cool- and warm-season perennial grasses. Shifts in the seasonality of precipitation could change the composition of these grasslands.

In 2009, the Northern Colorado Plateau Network (NCPN) began collecting long-term monitoring data on grasslands in Capitol Reef NP to help provide park managers with knowledge of ecological status and trends for use in informed decisionmaking. The effort is part of NCPN's upland vegetation and soils monitoring protocol (Witwicki et al. 2017), whose goals are to determine long-term trends in vegetation, soil stability, and hydrologic function; and understand of the stressors and processes driving these changes.

1.1 Purpose and scope

Resource managers at Capitol Reef NP were most interested in identifying impacts of current livestock grazing on grasslands and tracking plant and soil recovery after grazing had ceased. The purpose of this report is to use grasslands data collected at Capitol Reef NP from 2009 to 2018 to explore the following questions:

1. What is the current status of upland vegetation and soils in Capitol Reef NP grasslands, and how has that status changed from 2009 to 2018? How do status and trends in grassland condition differ by grassland type and livestock-grazing history? The specific indicators examined in this report are:
    - Vegetation cover (total plant, perennial grass, cool and warm season grass, and shrub),
    - Shrub density,
    - Exotic-plant frequency,
    - Surface cover (biological soil crust and bare soil),
    - Soil stability, and
    - Canopy-gap size.
2. Which climate conditions are most influential in Capitol Reef NP grasslands? How did they affect upland vegetation and soils from 2009 to 2018?

The 10 years of data analyzed in this report are recognized as a relatively short period for trend analysis (based on a power analysis of pilot monitoring data; Witwicki et al. 2017, Appendix B), and interannual variability in temperature and precipitation will have a great influence on the trends reported in this study. This report is useful, however, as a status check of the program and as an early look at trends in areas of the park with different grassland types and grazing histories. Grazing on the Hartnet allotment ceased in May 2018. However, the data summarized in this report only include years when the Hartnet allotment was actively grazed by livestock (2009–2018), which is an intuitive point in time to examine these questions. These data will also be useful in better understanding how these grasslands might change as drought intensifies in the future.

1.2 Study area

Capitol Reef NP protects 97,895 hectares (241,903 ac) within southern Utah (Figure 1-1). Elevations range from 1,183 meters (3,881 ft) around Halls Creek, in the park's southern tip, to 2,731 meters (8,960 ft) on the side of Thousand Lakes Mountain, in the north. The park's topography is defined by the Waterpocket Fold, which exposes many layers of geology and breaks the landscape into canyons, valleys, ridges, mesa tops, and monoliths. The varied topography and range of elevations support a variety of upland plant communities, including grasslands, blackbrush, sagebrush, salt-desert shrublands, pinyon-juniper woodlands, and ponderosa-pine and Douglas-fir forests. Semiarid grasslands occur throughout the park, in valleys with deep alluvial and eolian soils and on rocky slopes and benches.

Temperatures range from a mean January low of -8.6°C (16.5°F) to a mean July high of 31.7°C (89.1°C). Mean annual precipitation is 239 millimeters (9.4 in), which tends to be evenly distributed throughout the year, with

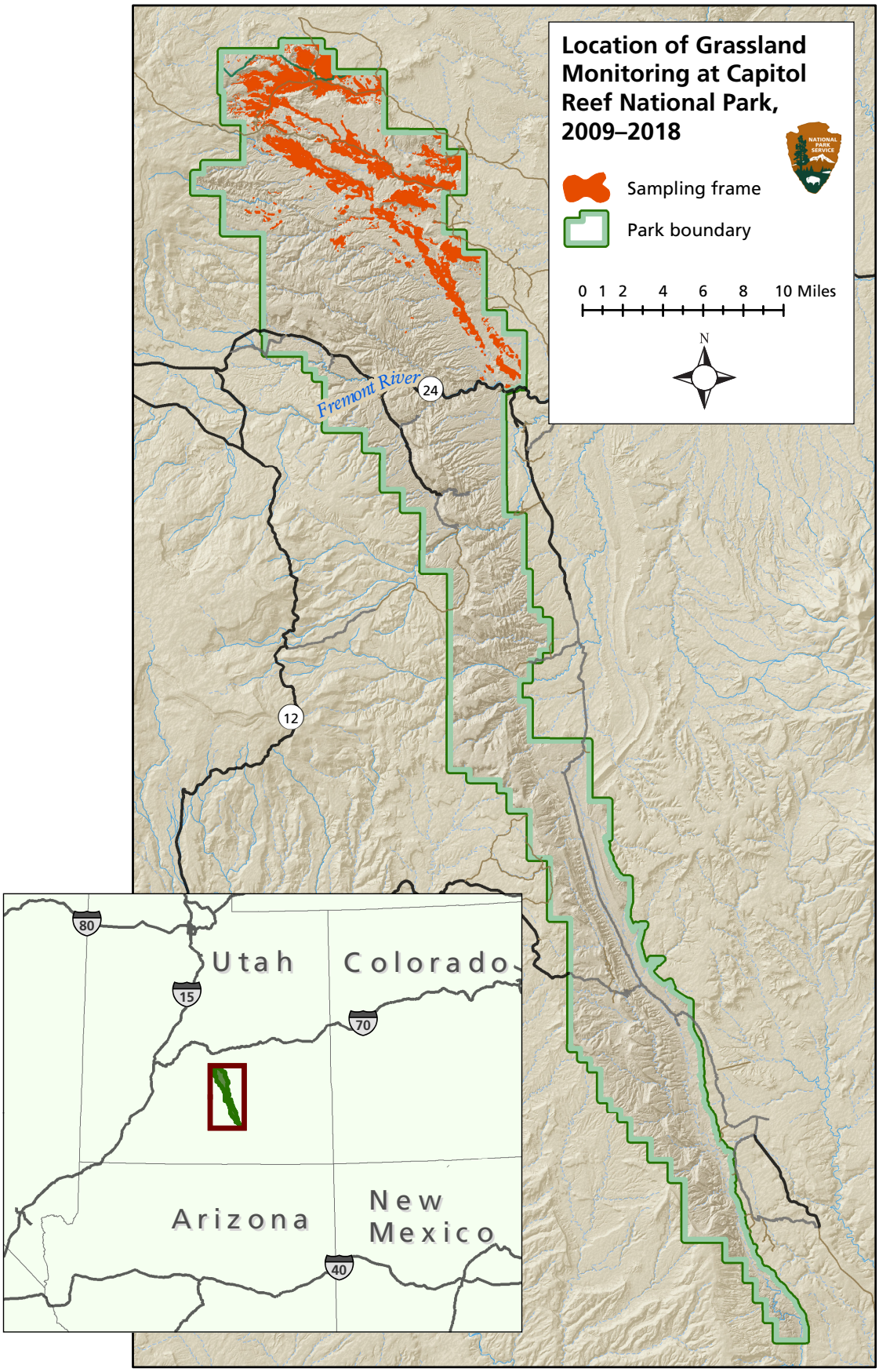


Figure 1-1. Overview of grasslands monitored at Capitol Reef National Park.

the exception that June is consistently the driest month and spring and late summer can be wetter. Much of the precipitation in July through September is attributable to the North American Monsoon (hereafter, "monsoon"), but the amount of precipitation from this source can vary greatly from year to year because Capitol Reef NP is situated at the monsoon's northernmost distribution (Schwinning et al. 2008).

Capitol Reef NP provides important habitat to a number of threatened and endangered plant species the park is responsible for monitoring and protecting (Fertig et al. 2009). Although monitoring rare-plant populations is outside the scope of the NCPN upland vegetation and soils protocol, Wright's fishhook cactus (*Sclerocactus wrightiae*), Winkler's pincushion cactus (*Pediocactus winkleri*), and Last Chance townsendia (*Townsendia aprica*) can occur in areas of the park monitored by the network, including areas used by livestock.

When Capitol Reef NP was established in 1971, there were 19 active grazing allotments in the park. Grazing privileges were extended to heirs of the permit holders. By the 1990s, all but two of these grazing permits were retired. The Hartnet allotment, in the northern part of the park, was grazed by cattle annually from mid-October through the end of May, until its retirement on May 1, 2018. In the central part of the park, the Sandy 3 allotment (not monitored by the NCPN) continues to be grazed by cattle from November through April.

Following conversations with park managers, the NCPN focused its monitoring effort on three grazing allotments in the northern part of the park. These allotments include areas that were actively grazed (during the years of monitoring included in this report) and previously grazed:

- Hartnet, grazed until May 2018,
- Cathedral, where ~80% of animal unit months (AUMs) were retired in 1989 and the rest retired in 1999; and
- Rock Springs, retired in 1989.

Collectively, these allotments comprise about 36% (35,159 ha) of the park area.

Records on the intensity of livestock grazing within the Cathedral and Rock Springs allotments are somewhat incomplete. What the park has gathered from its records is that the Rock Springs allotment had 185–193 AUMs permitted in the park each year from 1971 until livestock grazing in this allotment inside park boundaries ceased in 1989. The Cathedral allotment had a maximum of ~300–500 AUMs permitted for cattle grazing each year from 1971 to 1989; after that, only 43–78 AUMs were permitted each year until 1999. AUMs provide a measure of grazing intensity; "an AUM is defined as one cow or one cow and calf grazing for one month (30.4 days), consuming 26 pounds of dry forage per day" (Fisk and Borthwick 2016).

Records of the actual number of AUMs used by permittees each year are even less complete. The season of use in the Cathedral allotment was reported as mid-November through May (McEwen 1999), but it is unclear if earlier grazing followed this same schedule. Livestock grazing appears to have been retired from the Temple of the Sun and Moon section of the Cathedral allotment in 1989 (McEwen 1999). In the Hartnet allotment, the park allowed a maximum of 1,141 AUMs each year. Records of actual AUMs utilized each year were generally not available.

While regrettable, this paucity of information is not a source of concern relative to the results reported in this document. NCPN uplands monitoring was intended as a way to look at grazing recovery over time and to compare these allotments with the grazed Hartnet allotment—so although it would be preferable to have more historical data from before the Cathedral and Rock Springs allotments were retired, those data were not required for the analysis done here.

2 Methods

Grasslands were sampled in three selected allotments in the northern part of Capitol Reef NP (Table 2-1). Ecological-site descriptions from the Natural Resources Conservation Service (Mayne 2004) describe plant species and soil properties in these grasslands, and how species and site conditions can change with disturbances, such as overgrazing (Table 2-2). Grasslands were classified by ecological site, lumped into two groups: deep grasslands and rocky grasslands (Table 2-2 and Figure 2-1), and mapped as explicitly as possible (Garman et al. 2010). Deep and rocky grasslands had different soil and geomorphic properties, and there were some differences in the dominant perennial grass and shrub species present (Table 2-2).

We combined ecological-site groups and grazing history to obtain three strata sampled for upland monitoring at Capitol Reef NP:

1. Deep grasslands in the combined ungrazed Cathedral and Rock Springs allotments (hereafter, "Cathedral/Rock Springs deep grasslands"),
2. Deep grasslands in the grazed Hartnet allotment (i.e., actively grazed until May 2018, the last year of monitoring data included in this report; hereafter, "Hartnet deep grasslands"), and
3. Rocky grasslands in the grazed Hartnet allotment (hereafter, "Hartnet rocky grasslands") (see Table 2-1).

Deep grasslands in the two retired allotments were combined in the sampling design because most of the grazing in the Cathedral allotment was retired at the same time the Rock Springs allotment was retired, and ecological conditions were similar in both allotments. Rocky grasslands were not sampled in the Cathedral and Rock Springs allotments because only a very small amount was present.

Our monitoring covered 20–30 years post-grazing in the Rock Springs allotment, 10–20 years since all grazing ceased in the Cathedral allotment (and 20–30 years since the ~80% reduction in AUMs), and the last 10 years of grazing in the Hartnet allotment. In the grazed Hartnet allotment, we assumed that livestock used deep grasslands more than rocky grasslands. Deep grasslands are located in valley bottoms, closer to water sources. Much of the rocky grasslands are located on steep hillslopes, where it is difficult to walk, or mesa tops above these slopes (Fisk and Borthwick 2016). The Bureau of Land Management (McEwen 1999) reported similar patterns of use in the Cathedral allotment. Field observations by Capitol Reef NP and NCPN staff also support these relative differences in livestock use between the grassland types.

A probability-based survey design (Theobald et al. 2007) was used to select 180 sampling plots (60 in each stratum; Figure 2-2). Beginning in 2010, a total of 48 plots were monitored each year (16 in each stratum), according to a five-year repeating revisit schedule (Witwicki et al. 2017, appendices A and B). One-third of the plots were visited in two consecutive years to better understand

Table 2-1. Livestock grazing allotments monitored in this project, Capitol Reef National Park.

Allotment name	Year retired[A]	Grassland type	Stratum for upland monitoring
Cathedral	1989 (~80% AUMs) 1999 (~20% AUMs)	Deep grasslands	Cathedral/Rock Springs deep grasslands
Hartnet	2018 (May)	Deep and rocky grasslands	Hartnet deep grasslands, Hartnet rocky grasslands
Rock Springs	1989	Deep grasslands	Cathedral/Rock Springs deep grasslands

[A]AUMs = animal unit months

Table 2-2. Grassland types and ecological sites monitored at Capitol Reef National Park.

Grassland type	Ecological-site name and number[A]	Soil properties	Geologic properties	Vegetative properties	Disturbance-mediated alternative states
Deep grasslands	Semidesert Alkali Sandy Loam (Alkali Sacaton), 035XY201UT	Deep alkali sandy loams on dissected alluvial fans	Alluvium and eolian deposits from mixed sedimentary rocks	Dominated by alkali sacaton, greasewood, Indian ricegrass, and shadscale	Decreased bunchgrass and increased snakeweed, rabbitbrush, and prickly pear. Cheatgrass and Russian thistle may invade.
	Semidesert Sand (Fourwing Saltbush), 035XY212UT	Deep sands on dunes and sand sheets	Eolian deposits derived from sandstone	Dominated by Indian ricegrass, fourwing saltbush, and Mormon tea	Decreased bunchgrass and saltbush and increased snakeweed, prickly pear, juniper, and sand sage. Russian thistle may invade.
	Semidesert Sandy Loam (Fourwing Saltbush), 035XY215UT	Deep sandy loams on mesas and valleys	Alluvium and eolian deposits derived mainly from sandstone	Dominated by Indian ricegrass, needle and thread, fourwing saltbush, and Mormon tea	Decreased bunchgrass and increased snakeweed, Mormon tea, and pricklypear. Cheatgrass and Russian thistle may invade.
Rocky grasslands	Semidesert Stony Loam (Shadscale), 035XY242UT	Deep stony loams on tops of structural benches and valley sides	Alluvium and colluvium derived from sandstone and shale	Dominated by galleta, shadscale, Torrey's jointfir, Bigelow's sagebrush, winterfat, and Indian ricegrass	Decreased Indian ricegrass, Torrey's jointfir, and Bigelow's sagebrush and increased galleta, shadscale, and snakeweed. Cheatgrass and juniper may invade.
	Semidesert Very Steep Stony Loam (Salina Wildrye), 035XY260UT	Deep stony loams on steep remnant hillsides	Basalt glacial outwash over sandstone and shale residuum	Dominated by Indian ricegrass, shadscale, Torrey's jointfir, Bigelow's sagebrush, and Salina wildrye	Decreased Indian ricegrass, Torrey's jointfir, and Bigelow's sagebrush and increased galleta, snakeweed, and juniper. Cheatgrass and halogeton may invade.

[A]Ecological sites are from a 2004 Capitol Reef National Park interim soil survey (Mayne 2004). An updated soil survey was published for the park in 2014 (NRCS and NPS 2014), but plots have not yet been reclassified to match the soils and ecological sites in this newer version.



Figure 2-1. Examples of grassland types monitored in Capitol Reef National Park: deep grassland (left) and rocky grassland (right).

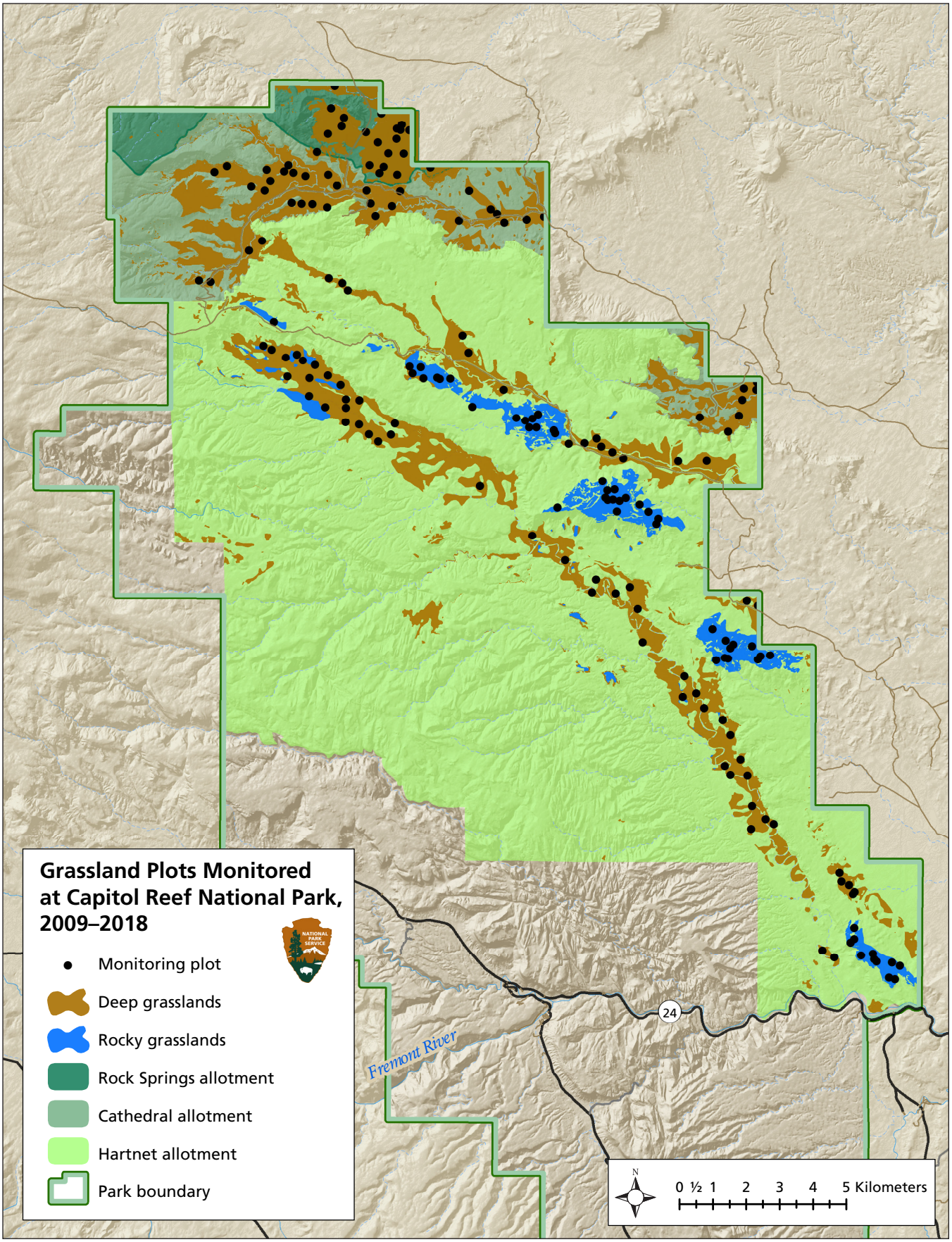


Figure 2-2. Grassland plots monitored at Capitol Reef National Park, 2009–2018.

interannual variability. The remaining plots were visited only once in the five-year period. From 2007 to 2009, sixty-one plots were sampled in a pilot monitoring effort to refine the sampling design and field methods. Due to changes in seasonal timing of sampling and field methods used to collect cover data, only the 2009 data were included in this report. From 2009 to 2018, all plots were sampled in May or June, except a few plots visited on the last three days of April 2009. The last period of monitoring included in this report (May–June 2018) occurred just after cattle were removed from the Hartnet allotment for the very last time, on May 1, 2018. This provides an intuitive cut-off point for comparing and reporting on the actively and previously grazed allotments where the NCPN monitors grasslands.

2.1 Vegetation and soil measurements

Field methods for NCPN upland monitoring (Witwicki et al. 2017) are based largely on rangeland-monitoring procedures recommended by Herrick and colleagues (2005). Each plot has three parallel, 50-meter transects spaced 25 meters apart (Figure 2-3). Transects run across the slope and are permanently marked by rebar at the endpoints. To minimize impacts to biological soil crusts, crew members walk in washes or on rocks or litter whenever possible. When soil crusts are impossible to avoid, crew members step in the same disturbed locations.

A point-intercept method is used to record percent cover of plant species and ground-cover attributes at 0.5-meter intervals along each transect (see Figure 2-3). Since 2011, frequency of exotic species has been recorded using 1 × 1-meter quadrats placed every five meters along each transect. Density of shrubs by species and height class is recorded in a one-meter belt. Canopy-gap measures are acquired along each of the transects using a line-intercept method to record all gaps 20 centimeters or greater. Six soil-surface samples are taken along each transect to assess soil-aggregate stability.

2.2 Analysis

2.2.1 Data summaries

2.2.1.1 Vegetation and soils data

Quality assurance and quality control (QA/QC) procedures were performed for all vegetation and soils data, as outlined by Witwicki and others (2017). These procedures included domain-checking in data-entry, checks for missing values, and logic checks.

For all measurements in the Bayesian trend analysis, data were summarized by transect. Percent cover of live vegetation by lifeform (total, perennial grass, warm-season peren-

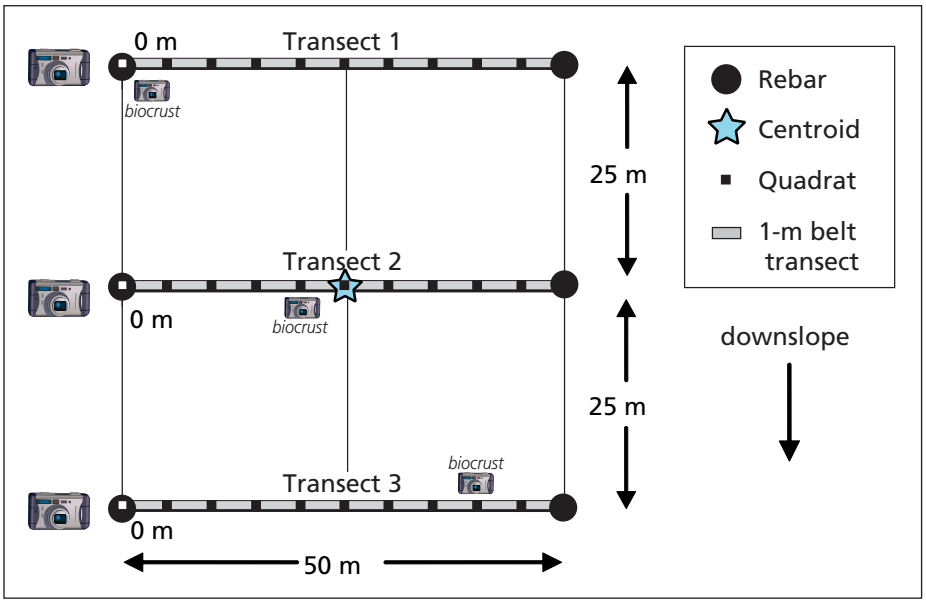


Figure 2-3. Locations of transects and monitoring measurements at grassland plots, including 1-m² quadrats for sampling frequency of exotics and one-meter belt transects for measuring shrubs. Soil stability is also collected at six randomized locations along each transect. Repeat photos are taken of each transect (larger camera symbols show transect photo locations) and of the soil surface on each transect (smaller camera symbols labelled "biocrust" show soil surface photo locations).

nial grass, cool-season perennial grass, and shrub) and surface features (biological soil crust and bare soil) was calculated from point-intercept data. Live cover included photosynthetic and live woody tissue. Cover of cyanobacteria, moss, and lichen at the soil surface was summed and analyzed as biological soil crust. Bare soil was defined as loose soil at the surface.

Exotic frequency was calculated as the percent of 1-m^2 quadrats where an exotic species was detected. Shrub density was calculated from counts of individual shrubs collected in the one-meter belt using all size classes combined.

To help deal with gaps of ≥20 centimeters that could be erroneously omitted from the data because <20 centimeters of the gap overlapped the end of the transect, 20 centimeters were removed from the ends of each transect (i.e., transects started at 20 cm and ended at 4,980 cm for the analysis).

All data summaries and figures were created in R 3.5.1 (R Core Team 2019). Data were summarized using the dplyr package (Wickham et al. 2018). Figures were created with ggplot2 (Wickham 2016).

2.2.1.2 Climate data

We obtained climate data from Daymet (Thornton et al. 2018) for the one-kilometer pixel that coincided with the center of each plot. To visually assess wet and dry periods throughout the duration of sampling, precipitation data were relativized as the difference from the long-term mean (1981–2018) for each plot. We then plotted percentiles of the historical precipitation distribution (1981–2018) for annual (i.e., water year = October of preceding year through following September) and seasonal measures of precipitation, and delineated the following categories similar to Knapp and others (2015): extremely dry (<10^{th} percentile) and extremely wet (>90^{th} percentile). For the summer monsoon, we summed precipitation in July through September. For the cool season, we summed precipitation in October through April. We also summarized precipitation by cool season plus previous year's monsoon to better understand wet and dry conditions before our annual sampling in May and June.

2.2.2 Trend models

We used Bayesian hierarchical modeling to analyze our data and determine status and trends for each stratum (see Appendix A for background on the Bayesian data analysis). One strength of this approach is the ability to handle data that are not normally distributed, which are the majority of our upland monitoring data. As such, each data type has a separate model appropriate for its distribution (see Table A-1 in the appendix). Point-intercept cover data and exotic-frequency data were modeled using a beta binomial or zero-inflated beta binomial likelihood. Shrub density was modeled using a negative binomial likelihood. Soil stability was modeled using a ordinal latent normal likelihood, and canopy gaps were modeled using a log-normal likelihood (Table A-1). In these sets of models, all priors were vague, mostly due to a lack of comparable data available in the literature and because pilot data were often not useful due to differences in methods. For all models except canopy-gap size, we held the slope constant among sites and allowed the intercept to vary among sites. For the canopy-gap model, we allowed both the slope and the intercept to vary among sites.

All Bayesian analyses were run in R 3.5.1 (R Core Team 2019), using JAGS (Plummer 2003) as the Markov Chain Monte Carlo (MCMC) sampler. For each model, we used three chains with a burn-in and number of iterations that varied by model (see Table A1 in the Appendix). All models were checked for convergence using the Gelman-Rubin diagnostic (Gelman and Rubin 1992).

In the results, we report the means of the posterior distribution and the corresponding 95% Bayesian credible intervals. These intervals can be interpreted as a 95% confidence that the true value of the mean of the indicator falls within the lower and upper values for the interval. We used Bayes p values to evaluate model fit. All of our models used for inference had p-values within the acceptable range (see Appendix A for more details).

2.2.3 Covariates

We included climate covariates known to be important to vegetation and soils on the northern Colorado Plateau in the models. It is generally accepted that cool-season precipitation tends to be important to cool-season (C3) grasses, and that summer-monsoon precipitation tends to be important to warm-season (C4) grasses (Sage et al. 1999). Analysis of NCPN grasslands, including those at Capitol Reef NP, indicated that early-spring and previous-monsoon precipitation were correlated with higher spring cover of warm-season perennial grasses (Witwicki et al. 2016), and that climate conditions can influence vegetation production for a year or more (Thoma et al. 2016). In addition, biological soil crusts have net carbon gain only for brief periods in the winter and early spring, suggesting that wet periods in the cool season, when the crusts are not frozen, are most important for growth (Darrouzet-Nardi et al. 2015). Thus, we selected cool-season precipitation (October through April) and the previous year's monsoon precipitation (July through September) to include as covariates in the models.

Because sampling occurs annually in May and June, we were also concerned that a cool, moist spring could delay growth of plant species in the grasslands and make our monitoring data less comparable from year to year. To account for this, we included an additional covariate of cumulative growing-degree days (GDD) from January through April. Growing-degree days are the daily sum of heat accumulation, which is related to plant productivity and phenology (Wang et al. 2003).

Climate data from Daymet (Thornton et al. 2018) were summarized for covariates in the trend models. Precipitation data were summed into annual totals of cool-season and monsoon precipitation in the year prior to sampling. Growing-degree days were summed from January to April and included in models where a late or early spring might affect the response (e.g., grass cover). Cumulative growing-degree days were calculated following McMaster and Wilhelm (1997),

$$cumGDD_{monthly} = \sum_{1}^{d} \frac{T_{max} + T_{min}}{2} - T_{base}$$

where $cumGDD_{monthly}$ is the cumulative GDD over a single month, d is the number of days in a month, T_{max} is the maximum temperature on a given day, T_{min} is the minimum temperature on a given day, and T_{base} = 4.4°C, the temperature below which grasses' physiological activity ceases (Wang 1960).

Climate covariates (cool-season precipitation, previous-monsoon precipitation, and cumulative GDD) were centered and standardized so relative effects of coefficients could be directly compared in the models. All three covariates were included in all of the vegetation-cover trend models, based on their ecological importance outlined above. Covariates for the other models were determined using available ecological information and, in some cases, the lowest posterior predictive loss. Table 3-2 (see next chapter) includes the final covariates selected for each model, and their coefficients. We presented covariate coefficients to provide information about the relative magnitude of their effects within each model. Though some covariates had nominal direction (their credible intervals contained 0), they still improved the model, and so were retained.

2.2.4 Modeling annual status

To model annual status of each indicator, actual values of covariates (cool-season and/or monsoon precipitation) were used to create a figure that expressed the year-to-year variation of the indicator due to the covariate(s). When cumulative GDD was included in the model, this was held at its mean across all years of sampling, because we wanted to account for differences in cumulative GDD among years. The annual-status figures used data from all plots sampled in all years of monitoring. We reported status as the model-predicted mean of an indicator for each year using this version of the model, focusing especially on 2018, the last year of results in this report. Values within the 95% credible intervals should also be consid-

ered as possible values for the mean when evaluating these results. The status for other years was also used to examine indicator responses to climate. These figures highlight shorter-term trends caused by cool-season and/or monsoon precipitation.

2.2.5 Comparing conditions in grazed and ungrazed allotments

To compare conditions in our strata, especially between grazed and ungrazed deep grasslands, we observed the distribution of the difference between each pair of strata (e.g., grazed Hartnet vs. ungrazed CRS deep grasslands, Hartnet deep vs. rocky grasslands) each year. Initially, we looked for 95% credible intervals of the difference that did not contain zero, which would indicate strong evidence that the strata were, in fact, different. When this method proved to be too stringent, we quantified the probability that the strata were different by reporting the probability of the difference not including zero for any probabilities 80% or greater.

2.2.6 Modeling trend

In this report, we define trend as "the directional change in an indicator over time, apart from year-to-year, stochastic variation that is caused by changes in weather, observers, instrumentation, disturbances, or other short-term influences on status" (Hobbs et al. in prep). To model trend of each indicator, smooth-trend figures were created using data from all possible sites in the survey design (i.e., any possible location a plot could have been placed in the sampling frame of the survey design). In these models, we used the model-predicted mean of the response at the mean of each covariate, which removes the year-to-year effects of covariates on the indicator so the resulting trend represents the change over time that would be predicted to occur under average conditions (e.g., change per year per mean monsoon precipitation). Relevant nuisance variables (e.g., differences in observers or year-to-year differences in sampling date or cumulative GDD that might affect the model outcome but are not drivers of ecological change) were also accounted for using this approach.

When a smooth trend appeared to differ from the change in status over the period of monitoring (i.e., using the version of the model with actual covariate values), this indicated that cool-season and/or previous-monsoon precipitation was important in driving short-term changes in the indicator. For example, a climatic covariate such as monsoon precipitation, which varies throughout the monitoring period, might be a large source of variation in perennial-grass cover and the reason for a change in status over the monitoring period. After setting monsoon precipitation at its mean in the model, there may be no trend, providing evidence that year-to-year differences in monsoon precipitation are responsible for short-term variation in perennial grass cover, but not the long-term trend. Of course, the fact that a covariate is largely responsible for shorter-term changes in status over the period of monitoring is in itself useful information—especially as the climate changes and patterns in temperature and precipitation continue to change. When the direction of the change/trend differed little between the two versions of a model, this suggested that an underlying cause not included in the model was driving the observed changes/trends.

2.2.7 Determining significant trends

To determine if an indicator was trending up, down, or remaining constant, we observed the distribution of the change in response per year (i.e., the time slope in the model, or β_1). We concluded there was no trend if the 95% credible interval of the change in response contained zero. If the distribution centered on a value greater than zero with little overlap with zero (i.e., the 95% credible interval did not include 0), we concluded the trend was increasing. Similarly, if the distribution centered on a value less than zero with little overlap with zero (i.e., the 95% credible interval did not include 0), we concluded the trend was decreasing. Credible intervals also expressed our uncertainty about the true value of the trend.

3 Results

3.1 Climate

Multiple droughts occurred during the 10 years of our study, and higher temperatures tended to occur during these periods of drought (Figure 3-1). The driest water years occurred during the first and last years of our monitoring (2009 and 2018), and also in 2008 (Figure 3-1; Figure 3-2A, D). Cool-season precipitation tended to be average or lower than average in most years when compared to the period of record between 1981 and 2018 (Figure 3-2B).

The year 2011 was extremely wet (Figure 3-1), with high monsoon and cool-season precipitation (Figure 3-2B, C). From 2011 to 2016, monsoon precipitation was wetter than the average from 1981 to 2018 (Figure 3-2C). Precipitation was extremely high during the 2013 and 2014 monsoons, especially during the first half of September 2013, when 130 millimeters (5.1 in) of rain fell—more than half the park's mean annual precipitation (Capitol Reef Coop Climate Station 2019).

3.2 Bayesian data analysis

3.2.1 Status of Capitol Reef NP grasslands (2009–2018)

3.2.1.1 Comparison of grassland types and grazing histories

The last year of monitoring, 2018, was also the driest water year and cool season during our 10 years of monitoring, following an average monsoon season in 2017 (Figure 3-2). These are the most recent data on the condition of park resources, and despite the dry conditions, we used them to compare grassland types that have different grazing histories. All types of vegetation cover were lower in 2018 than in most other years monitored (Figure 3-3).

Overall, there were many similarities in the monitored vegetation indicators among the three strata (Table 3-1, Figure 3-3). Shrub cover was similar in all three strata (Table

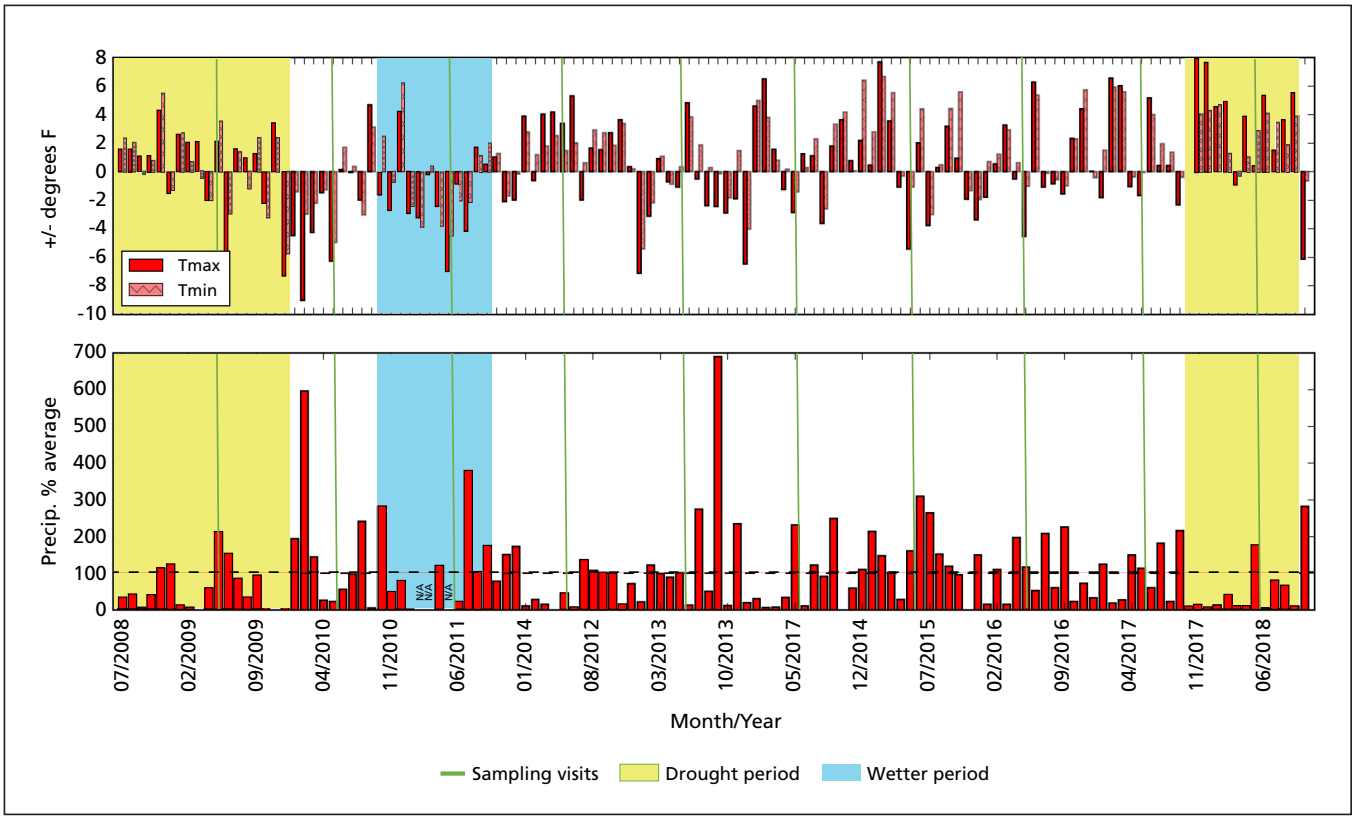


Figure 3-1. Departures from the 30-year average (1981–2010) for minimum temperature, maximum temperature, and precipitation from July 2008 (start of monsoon season the year before NCPN monitoring) to October 2018 (start of 2019 water year) at the Capitol Reef National Park COOP climate station (Station ID #421171). Any month missing more than three days of precipitation or five days of temperature values was marked as N/A.

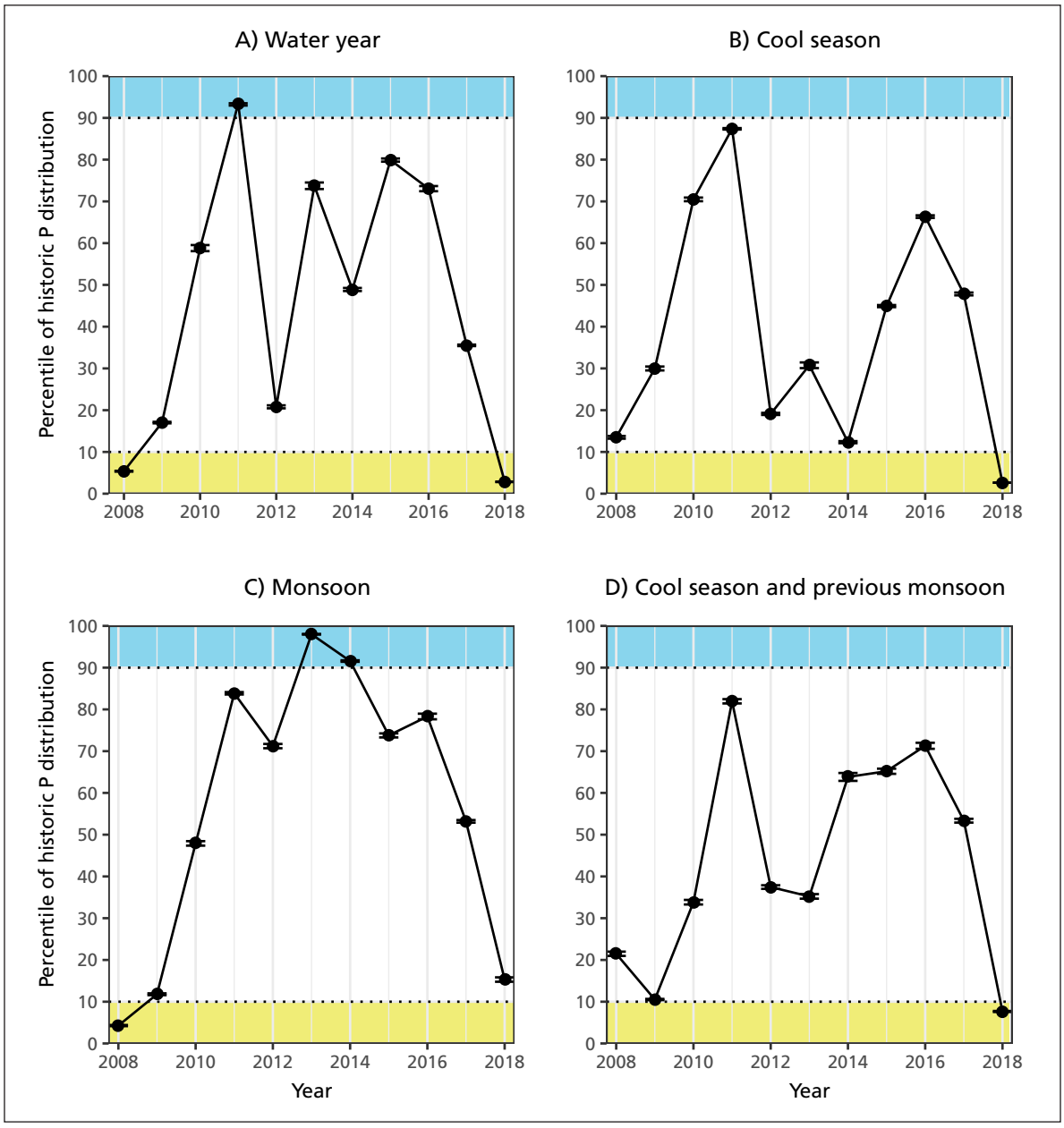


Figure 3-2. Annual and seasonal precipitation summaries for water years 2009–2018 for upland monitoring plots at Capitol Reef National Park. Values are percentiles of historical precipitation (P) distribution (1981–2018) for (A) water year (October of preceding year through following September), (B) cool season (October through April), (C) monsoon (July through September), and (D) cool season and previous monsoon (July of preceding year through following April). Error bars are standard errors. Values >90th percentile (blue shading) are considered extremely wet. Values <10th percentile (yellow shading) are considered extremely dry.

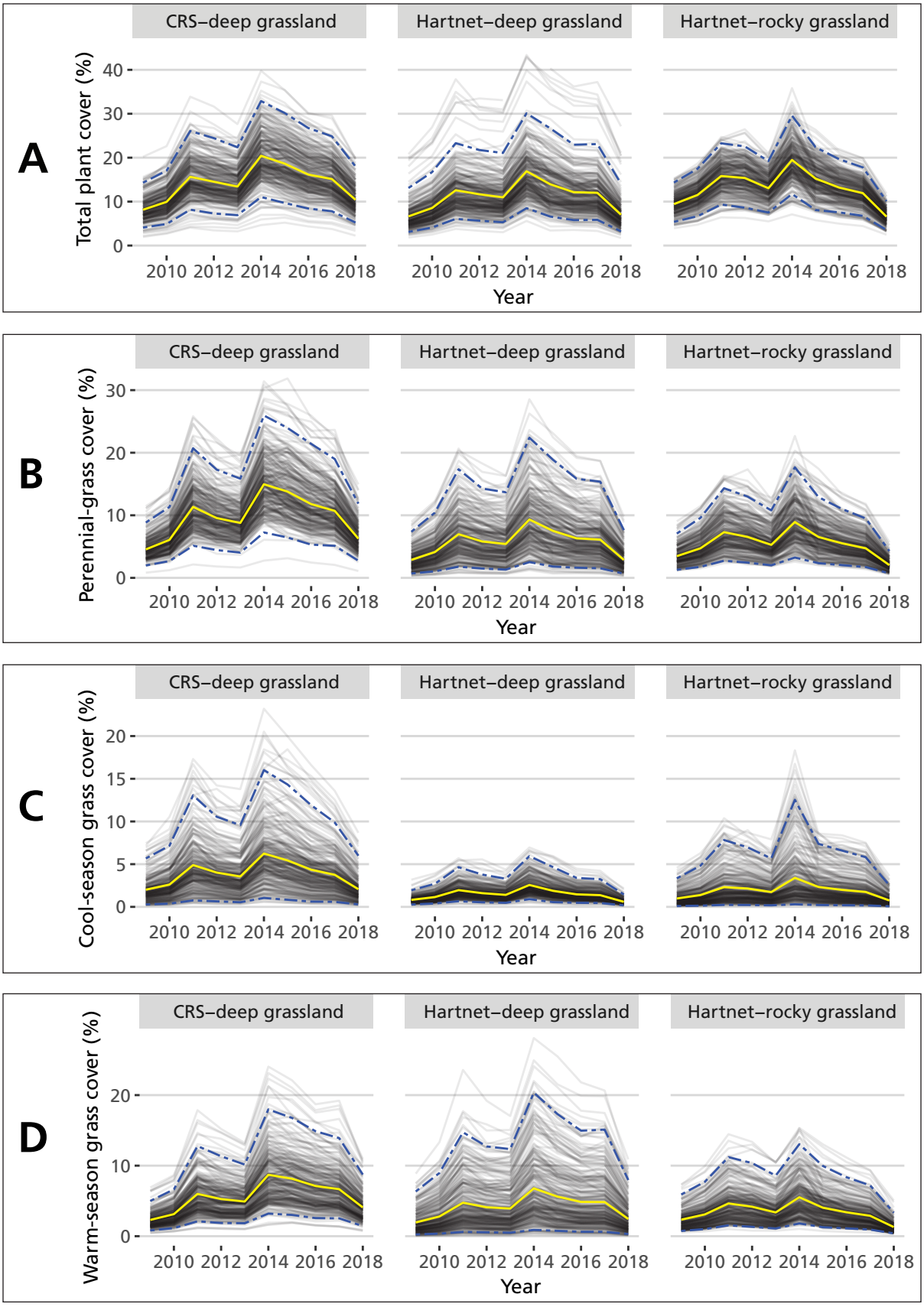


Figure 3-3A–D. Posterior predicted means (solid yellow lines) and 95% credible intervals (gray dashed lines) for annual status of total plant cover, perennial-grass cover, cool-season grass cover, and warm-season grass cover in each stratum, Capitol Reef National Park, 2009–2018. Draws of means (solid gray lines) express probability of different means; the darker the area, the more certain we are that the means fall in those areas. CRS = Cathedral/Rock Springs.

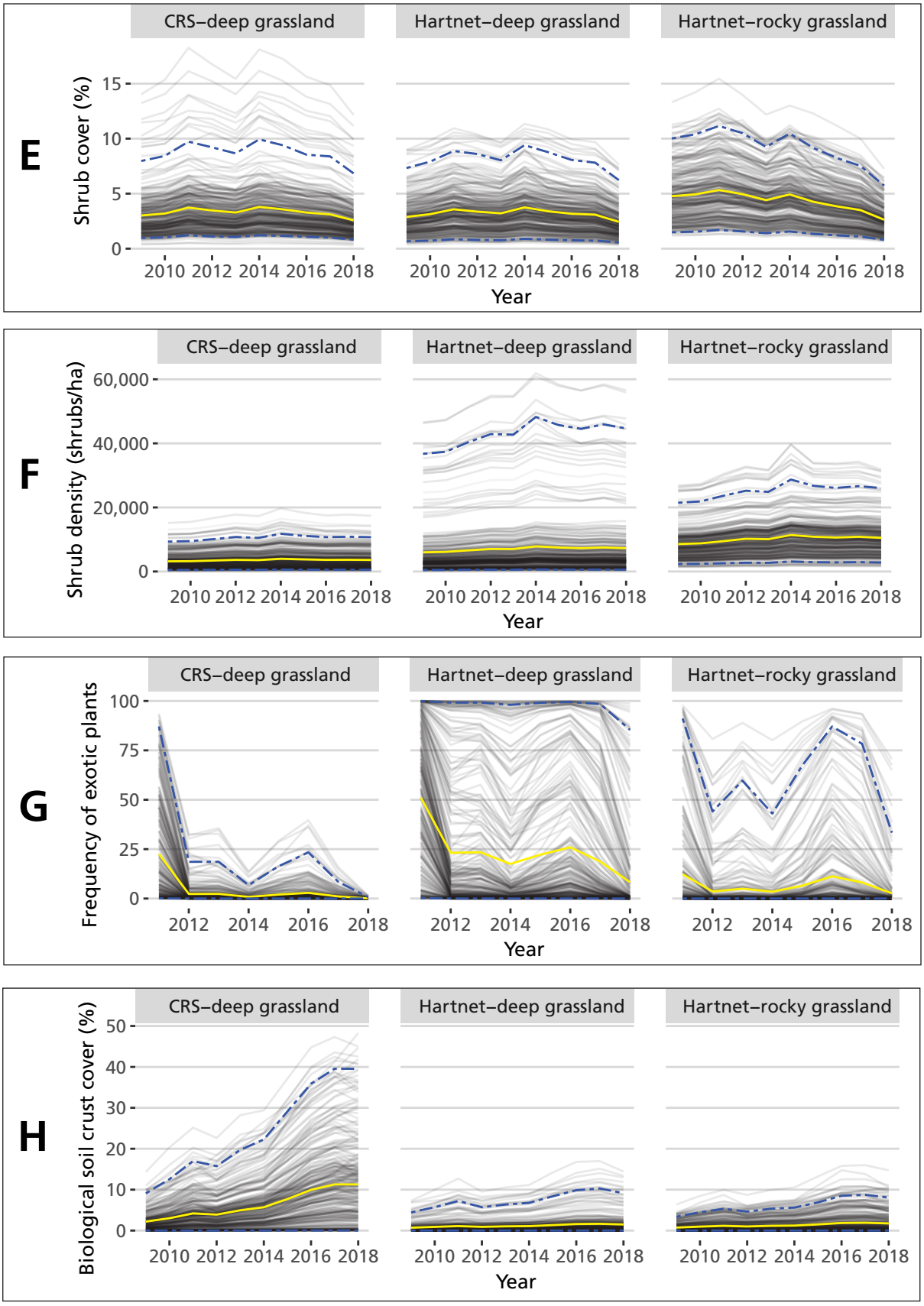


Figure 3-3E–H. Posterior predicted means (solid yellow lines) and 95% credible intervals (gray dashed lines) for annual status of shrub cover, shrub density, frequency of exotic plants, and biological soil crust cover in each stratum, Capitol Reef National Park, 2009–2018. Draws of means (solid gray lines) express probability of different means; the darker the area, the more certain we are that the means fall in those areas. CRS = Cathedral/Rock Springs.

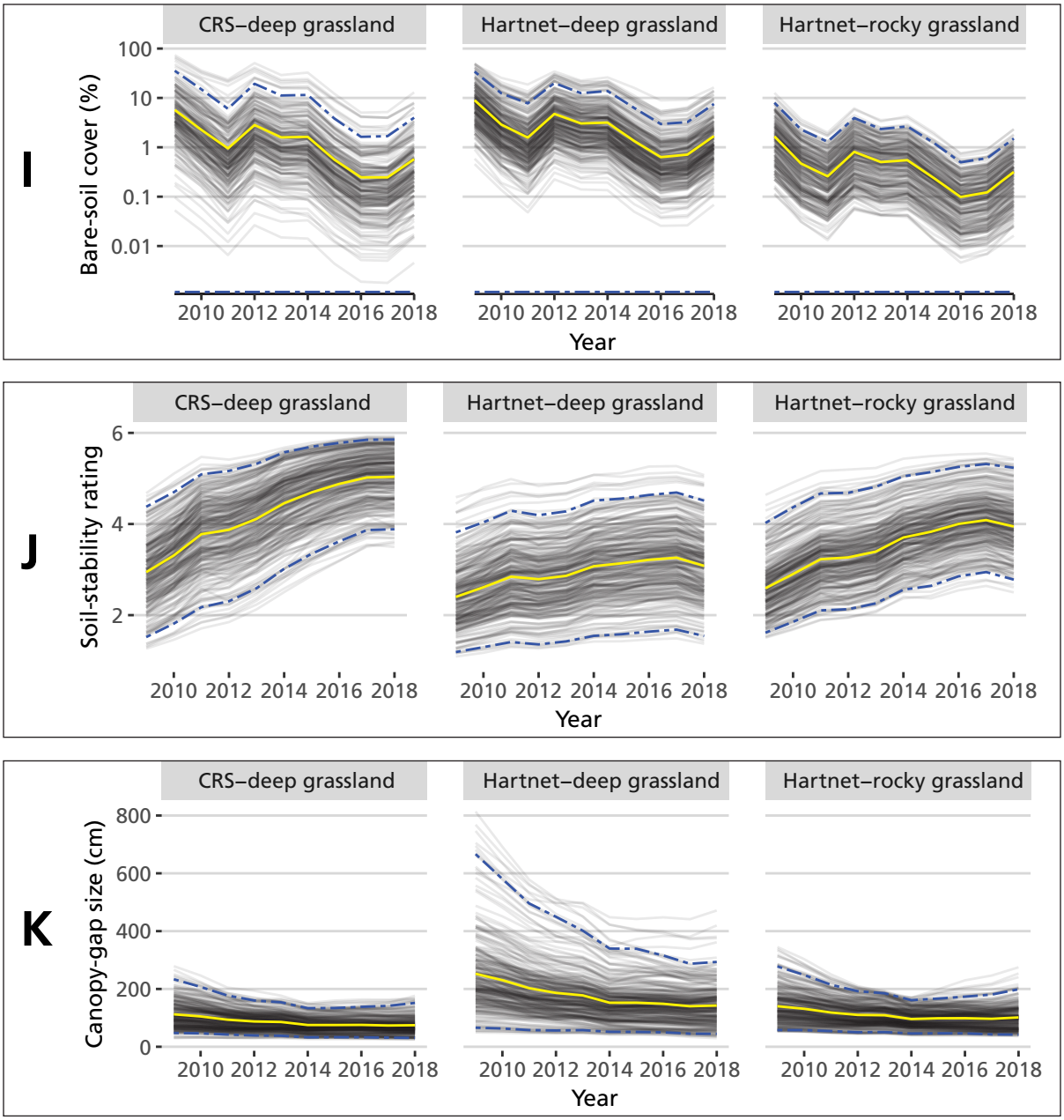


Figure 3-3I–K. Posterior predicted means (solid yellow lines) and 95% credible intervals (gray dashed lines) for annual status of bare-soil cover, soil stability, and canopy-gap size in each stratum, Capitol Reef National Park, 2009–2018. Draws of means (solid gray lines) express probability of different means; the darker the area, the more certain we are that the means fall in those areas. Bare-soil cover is displayed on a log scale to show more detail at low numbers. CRS = Cathedral/ Rock Springs.

Table 3-1. Change in mean status, and current (2018) mean and 95% credible interval (CI) of status in 2018 for each indicator and stratum, Capitol Reef National Park, 2009–2018.

Indicator	Stratum	Change in status over all years of monitoring[A]	2018 status (95% CI)
Total cover	Cathedral/Rock Springs deep grasslands	+2.3%	**10.6% (5.2 to 18.0)[B]**
	Hartnet deep grasslands	+0.4%	**7.0% (3.2 to 14.1)[B]**
	Hartnet rocky grasslands	-2.9%	6.6% (3.5 to 10.1)
Perennial-grass cover	Cathedral/Rock Springs deep grasslands	+1.8%	**6.5% (2.7 to 11.9)[B]**
	Hartnet deep grasslands	+0.02%	**2.9% (0.7 to 7.6)[B]**
	Hartnet rocky grasslands	-1.5%	2.1% (0.7 to 4.3)
Cool-season perennial grass cover	Cathedral/Rock Springs deep grasslands	+0.1%	**2.1% (0.3 to 6.0)[B]**
	Hartnet deep grasslands	-0.2%	**0.6% (0.2 to 1.4)[B]**
	Hartnet rocky grasslands	-0.2%	0.8% (0.1 to 2.5)
Warm-season perennial grass cover	Cathedral/Rock Springs deep grasslands	+1.8%	4.1% (1.4 to 8.7)
	Hartnet deep grasslands	+0.5%	2.6% (0.3 to 8.0)
	Hartnet rocky grasslands	-1.0%	1.3% (0.4 to 3.3)
Shrub cover	Cathedral/Rock Springs deep grasslands	-0.4%	2.6% (0.8 to 6.8)
	Hartnet deep grasslands	-0.5%	2.3% (0.6 to 6.2)
	Hartnet rocky grasslands	-2.2%	2.7% (0.8 to 5.7)
Shrub density	Cathedral/Rock Springs deep grasslands	+464.6 shrubs/ha	3,716 shrubs/ha (540 to 10,730)
	Hartnet deep grasslands	+1,169.8 shrubs/ha	7,016 shrubs/ha (575 to 44,653)
	Hartnet rocky grasslands	+1,870.3 shrubs/ha	10,408 shrubs/ha (2,813 to 26,025)
Frequency of exotic plants	Cathedral/Rock Springs deep grasslands	-23.7%	0.1% (0 to 0.7)
	Hartnet deep grasslands	-41.5%	9.4% (0 to 85.4)
	Hartnet rocky grasslands	-10.3%	3.1% (0 to 33.4)
Biological soil crust cover	Cathedral/Rock Springs deep grasslands	+9.7%	**12.0% (0.03 to 39.5)[B]**
	Hartnet deep grasslands	+0.8%	**1.5% (0 to 9.1)[B]**
	Hartnet rocky grasslands	+1.2%	2.0% (0 to 8.1)
Bare-soil cover	Cathedral/Rock Springs deep grasslands	-5.4%	**0.6% (0 to 4.0)[B]**
	Hartnet deep grasslands	-7.9%	**1.9% (0 to 7.5)[B]**
	Hartnet rocky grasslands	-1.4%	0.3% (0 to 1.5)
Soil-stability rating	Cathedral/Rock Springs deep grasslands	+2.1	**5.0 (3.9 to 5.9)[B]**
	Hartnet deep grasslands	+0.7	**3.1 (1.5 to 4.5)[B]**
	Hartnet rocky grasslands	+1.4	4.0 (2.8 to 5.2)
Canopy-gap size	Cathedral/Rock Springs deep grasslands	-37 cm	**74 cm (31 to 152)[B]**
	Hartnet deep grasslands	-106 cm	**145 cm (45 to 294)[B]**
	Hartnet rocky grasslands	-41 cm	102 cm (42 to 199)

[A]Change in status from 2009 to 2018 for all indicators except frequency of exotic species, which is from 2011 to 2018. Change in status is the change in an indicator from the first to last year of monitoring, driven in part by variations in cool-season and/or monsoon precipitation during the years monitored (i.e., change in status reflects actual changes in an indicator on the ground).
[B]Indicates there was at least 80% probability that the values differed between the Cathedral/Rock Springs and Hartnet deep grasslands (also in bold red text).

3-1, Figure 3-3E). We did not find evidence that shrub density differed between the grazed and ungrazed deep grasslands; the 95% credible interval was especially wide for Hartnet deep grasslands (Table 3-1, Figure 3-3F).

There was some evidence that grass cover differed by grazing history, but it was not particularly strong. We found an 89% probability that native perennial-grass cover was higher in deep grasslands in the ungrazed Cathedral/Rock Springs (CRS) allotment than in deep grasslands in the grazed Hartnet allotment (6.5% and 2.9% mean cover, respectively; Table 3-1, Figure 3-3B). Similarly, we found an 89% probability that cool-season grass cover was higher in the ungrazed than in the grazed deep grasslands (2.1% and 0.6% mean cover, respectively; Table 3-1, Figure 3-3C). Warm-season grass cover was more similar between the grazed and ungrazed deep grasslands (Table 3-1, Figure 3-3D). Perennial-grass cover, including both warm- and cool-season grass cover, was particularly low in the Hartnet rocky grasslands, especially compared to the CRS deep grasslands (Table 3-1, Figure 3-3B, C, D).

The frequency of exotic-plant species had much overlap among the three strata, but there were some notable patterns. At CRS deep grasslands, exotic frequency was low in most years (except during the wettest year, 2011; Figure 3-3G). At the Hartnet deep grasslands, the credible interval was very wide in all years (from 0% to nearly 100% exotic frequency), reflecting the wide range of invasion by exotic species within the Hartnet deep grassland plots (i.e., very low at some plots and very high at others). Mean exotic frequency in the Hartnet rocky grasslands tended to be low, but the credible interval was also wide, overlapping possible values of the mean for the other two strata.

Six species of exotic plants were detected at monitoring plots. Most exotic-plant detections in the CRS deep grasslands were Russian thistle, but halogeton (*Halogeton glomeratus*) and salsify (*Tragopogon dubius*) were also detected. Exotic plants detected in the Hartnet deep grasslands consisted primarily of the annual species, cheatgrass, Russian thistle, halogeton, and African mustard (*Malcolmia africana*). However, tamarisk (*Tamarix* species) was also detected. Russian thistle and cheatgrass were the most common species detected in the Hartnet rocky grasslands, but halogeton and salsify were also present. Plots were sampled in May through June each year, meaning the data could be missing exotic-plant species that germinate later in the season (i.e., after sampling occurs).

Soil stability differed by grazing history, with the greatest differences between the grazed and ungrazed deep grasslands (5.0 and 3.1, respectively; Table 3-1, Figure 3-3J). We also found evidence (though it was not particularly strong) that biological soil crust (BSC), bare-soil cover, and canopy-gap size differed by grazing history. We found an 85% probability that BSC cover was higher in deep grasslands in the ungrazed CRS allotment than in the grazed Hartnet allotment (12.0% and 1.5% mean cover, respectively; Table 3-1, Figure 3-3H). Similarly, we found an 81% probability that bare-soil cover was higher in the grazed than the ungrazed deep grasslands (1.9% and 0.6% mean cover, respectively; Table 3-1, Figure 3-3I). Hartnet rocky grasslands had low cover of both BSCs and bare soil (2.0% and 0.3%, respectively) because much of the soil surface was covered by rocks (Mayne 2004). We also found an 82% probability that canopy-gap size was smaller in deep grasslands in the ungrazed CRS allotment than in the grazed Hartnet allotment (74 cm and 145 cm mean gap size, respectively; Table 3-1, Figure 3-3K).

3.2.1.2 Influence of climate on vegetation and soils

Across all grassland types and grazing histories, plant cover fluctuated from year to year with cool-season and previous-monsoon precipitation (see Figure 3-3A). The year-to-year variation was especially pronounced for grasses (native perennial grasses, including cool-season and warm-season grasses); it was smaller for shrubs. The effect of previous-monsoon precipitation on vegetation cover was twice as strong as the effect of cool-season precipitation (Table 3-2). The effect of cumulative growing-degree days

Table 3-2. Direction, mean, and 95% credible interval (CI) of covariate effects included in trend models for each indicator, Capitol Reef National Park, 2009–2018.

Indicator	Covariates[A]	Direction of covariate effect[B]	Covariate coefficient mean (95% CI)
Total cover	Cool-season P	positive	0.16 (0.12 to 0.20)
	Monsoon P	positive	0.36 (0.33 to 0.40)
	Cumulative GDD	negative	-0.06 (-0.12 to -0.02)
Perennial grass cover	Cool-season P	positive	0.23 (0.16 to 0.29)
	Monsoon P	positive	0.44 (0.40 to 0.49)
	Cumulative GDD	minimal	-0.04 (-0.11 to 0.03)
Cool-season perennial grass cover	Cool-season P	positive	0.22 (0.13 to 0.31)
	Monsoon P	positive	0.47 (0.40 to 0.54)
	Cumulative GDD	minimal	-0.03 (-0.13 to 0.07)
Warm-season perennial grass cover	Cool-season P	positive	0.21 (0.14 to 0.29)
	Monsoon P	positive	0.42 (0.37 to 0.48)
	Cumulative GDD	minimal	-0.08 (-0.17 to 0.01)
Shrub cover	Cool-season P	positive	0.06 (0.0003 to 0.13)
	Monsoon P	positive	0.13 (0.08 to 0.17)
	Cumulative GDD	positive	0.11 (0.04 to 0.18)
Shrub density	Monsoon P	positive	0.06 (0.03 to 0.09)
Frequency of exotic plants	Cool-season P	positive	1.22 (0.85 to 1.59)
Biological soil crust cover	Cool-season P	minimal	0.12 (-0.01 to 0.25)
Bare-soil cover	Cool-season P	negative	-0.66 (-0.82 to -0.50)
Soil-stability rating	Cool-season P	positive	0.18 (0.06 to 0.30)
	Monsoon P	positive	0.20 (0.11 to 0.29)
Canopy-gap size	Cool-season P	minimal	-0.01 (-0.02 to 0.01)
	Monsoon P	negative	-0.06 (-0.08 to -0.04)

[A]P = precipitation; GDD = growing degree days.
[B]Covariates with significant positive (+) or negative (-) effects had 95% CIs that did not include 0. "Minimal" indicates a covariate had nominal direction (i.e., the credible interval contained 0) but improved the model and was retained.

was small in all of the models except for shrub cover, where it was similar to the effect of previous-monsoon precipitation.

Shrub density varied little from year to year with climate (see Figure 3-3F). However, monsoon precipitation had a small but significant effect and was therefore included in the model (see Table 3-2).

Grass cover generally increased from 2009 to 2011, decreased from 2011 to 2013, increased again from 2013 to 2014, and then decreased from 2014 to 2018 (see Figure 3-3A). Mean total live cover in the drought years of 2009 and 2018 was about half as much as in 2014, the year with the highest cover (6.6–10.6% mean total live cover by stratum in 2009 and 2018 vs. 16.7–20.6% mean total live cover by stratum in 2014).

Frequency of exotic-plant species, which were primarily exotic annuals, varied with cool-season precipitation in all strata (see Table 3-2). Exotic frequency was highest in all strata in 2011, the first year this indicator was sampled (23.8% in CRS deep grasslands, 51.0% in Hartnet deep grasslands, and 13.4% in Hartnet rocky grasslands; see Figure 3-3G), after the wettest October-through-April of the monitoring period (see Figure 3-2B). Exotic frequency decreased the following year. In deep grasslands, exotic-plant frequency did not change much from 2012 to 2018, other than a notable decrease in the Hartnet deep grasslands during the drought conditions in 2018 (19.6% in 2017 and 9.4% in 2018).

Precipitation influenced all of the soil indicators. Cool-season precipitation decreased mean bare-soil cover, while both cool-season and previous-monsoon precipitation increased soil stability (see Table 3-2). Mean soil stability increased in all strata during non-drought years (i.e., all years except 2012 and 2018; see Figure 3-3J). At the CRS deep grasslands, increases in mean BSC cover were notable after wetter years (e.g., 2010–2011, 2013–2016; see Figure 3-3H), although cool-season precipitation only had a minimal positive effect in the model (see Table 3-2). Bare-soil cover was highest in the drought years of 2009 and 2012 in each stratum, and was very low in later years of monitoring, despite the drought in 2018 (see Figure 3-3I). Precipitation had a very small effect on canopy gaps.

3.2.2 Trends in Capitol Reef NP grasslands (2009–2018)

3.2.2.1 Vegetation trends

At the ungrazed CRS deep grasslands, most vegetation-cover indicators remained unchanged from 2009 to 2018 (Table 3-3, Figure 3-4). However, cover of warm-season grasses increased 1.7% (note that these numbers are absolute changes in percent cover and not percent increases), and shrub cover decreased by 0.8% from 2009 to 2018 (Table 3-3, Figure 3-4D, E).

In the grazed Hartnet allotment, there were decreases in all vegetation-cover indicators in both rocky and deep grasslands, except warm-season grasses, which remained unchanged (see Table 3-3, Figure 3-4D). This is striking, especially when compared to the trends in the retired CRS allotment, where shrub cover was the only decreasing vegetation-cover indicator.[1] The decreasing trends in vegetation cover were notably steeper in the rocky grasslands than in the deep grasslands for all vegetation-cover indicators except cool-season grass cover.

Shrub cover was the only vegetation indicator that showed a consistent change (decrease) among the strata. However, shrub cover decreased more from 2009 to 2018 (-3.0%) at the Hartnet rocky grasslands than at the Hartnet or CRS deep grasslands (-0.9% and -0.8%, respectively; see Table 3-3, Figure 3-4E). In the Hartnet rocky grasslands, there was a simultaneous increase in shrub density (see Table 3-3). However, no change in shrub density was detected at the CRS or Hartnet deep grasslands.

Frequency of exotic plants decreased from 2011 to 2018 in the CRS and Hartnet deep

[1]Although decreasing shrub cover could also be interpreted as a sign of range improvement, we interpreted it as a sign of declining condition in this report because (1) many of the shrub species present were ones used by wildlife and livestock, and (2) cover of shrubs declines during drought.

Table 3-3. Direction of trend, slope betas, and trend for trend models of each indicator and stratum, Capitol Reef National Park, 2009–2018.

Indicator	Stratum	Direction of trend[A]	Trend slope betas (95% CI)	Trend over all years of monitoring[B]
Total cover	Cathedral/Rock Springs deep grasslands	⬌	0.01 (-0.04 to 0.06)	+0.3%
	Hartnet deep grasslands	⬇	-0.06 (-0.12 to -0.01)	**-1.9%[C]**
	Hartnet rocky grasslands	⬇	-0.20 (-0.26 to -0.15)	**-6.9%[C]**
Perennial grass cover	Cathedral/Rock Springs deep grasslands	⬌	0.04 (-0.04 to 0.010)	+0.7%
	Hartnet deep grasslands	⬇	-0.09 (-0.17 to -0.01)	**-1.5%[C]**
	Hartnet rocky grasslands	⬇	-0.26 (-0.34 to -0.18)	**-3.9%[C]**
Cool-season perennial grass cover	Cathedral/Rock Springs deep grasslands	⬌	-0.09 (-0.19 to 0.01)	-0.9%
	Hartnet deep grasslands	⬇	-0.21 (-0.33 to -0.09)	**-1.0%[C]**
	Hartnet rocky grasslands	⬇	-0.19 (-0.30 to -0.07)	**-0.9%[C]**
Warm-season perennial grass cover	Cathedral/Rock Springs deep grasslands	⬆	0.12 (0.03 to 0.20)	**+1.7%[C]**
	Hartnet deep grasslands	⬌	-0.01 (-0.10 to 0.08)	-0.1%
	Hartnet rocky grasslands	⬇	-0.27 (-0.38 to -0.17)	**-2.7%[C]**
Shrub cover	Cathedral/Rock Springs deep grasslands	⬇	-0.08 (-0.15 to -0.01)	**-0.8%[C]**
	Hartnet deep grasslands	⬇	-0.09 (-0.17 to -0.01)	**-0.9%[C]**
	Hartnet rocky grasslands	⬇	-0.23 (-0.30 to -0.16)	**-3.0%[C]**
Shrub density	Cathedral/Rock Springs deep grasslands	⬌	0.02 (-0.05 to 0.08)	+169 shrubs/ha
	Hartnet deep grasslands	⬌	0.04 (-0.02 to 0.09)	+869 shrubs/ha
	Hartnet rocky grasslands	⬆	0.04 (0.01 to 0.08)	**+1,349 shrubs/ha[C]**
Frequency of exotic plants	Cathedral/Rock Springs deep grasslands	⬇	-0.86 (-1.29 to -0.46)	**-5.5%[C]**
	Hartnet deep grasslands	⬇	-0.72 (-1.05 to -0.40)	**-18.1%[C]**
	Hartnet rocky grasslands	⬌	0.29 (-0.15 to 0.71)	+3.3%
Biological soil crust cover	Cathedral/Rock Springs deep grasslands	⬆	0.66 (0.56 to 0.76)	**+11.0%[C]**
	Hartnet deep grasslands	⬆	0.31 (0.14 to 0.47)	**+1.3%[C]**
	Hartnet rocky grasslands	⬆	0.34 (0.21 to 0.49)	**+1.4%[C]**
Bare-soil cover	Cathedral/Rock Springs deep grasslands	⬇	-1.20 (-1.40 to -1.01)	**-6.3%[C]**
	Hartnet deep grasslands	⬇	-0.88 (-1.06 to -0.70)	**-5.9%[C]**
	Hartnet rocky grasslands	⬇	-0.81 (-1.05 to -0.60)	**-1.2%[C]**
Soil-stability rating	Cathedral/Rock Springs deep grasslands	⬆	1.36 (1.21 to 1.51)	**+2.0[C]**
	Hartnet deep grasslands	⬆	0.44 (0.29 to 0.57)	**+0.7[C]**
	Hartnet rocky grasslands	⬆	0.74 (0.60 to 0.87)	**+1.4[C]**
Canopy-gap size	Cathedral/Rock Springs deep grasslands	⬇	-0.10 (-0.15 to -0.06)	**-23 cm[C]**
	Hartnet deep grasslands	⬇	-0.15 (-0.20 to -0.10)	**-92 cm[C]**
	Hartnet rocky grasslands	⬇	-0.08 (-0.13 to -0.04)	**-27 cm[C]**

[A]⬇=decreasing trend; ⬆=increasing trend; ⬌=no trend.
[B]Trend from 2009 to 2018 for all indicators except frequency of exotic species, which is from 2011 to 2018. Trend is the long-term change in an indicator, evaluated at the mean of model covariates, such as cool-season and/or previous-year monsoon precipitation.
[C]Indicates significant increasing or decreasing trend (also in bold red text).

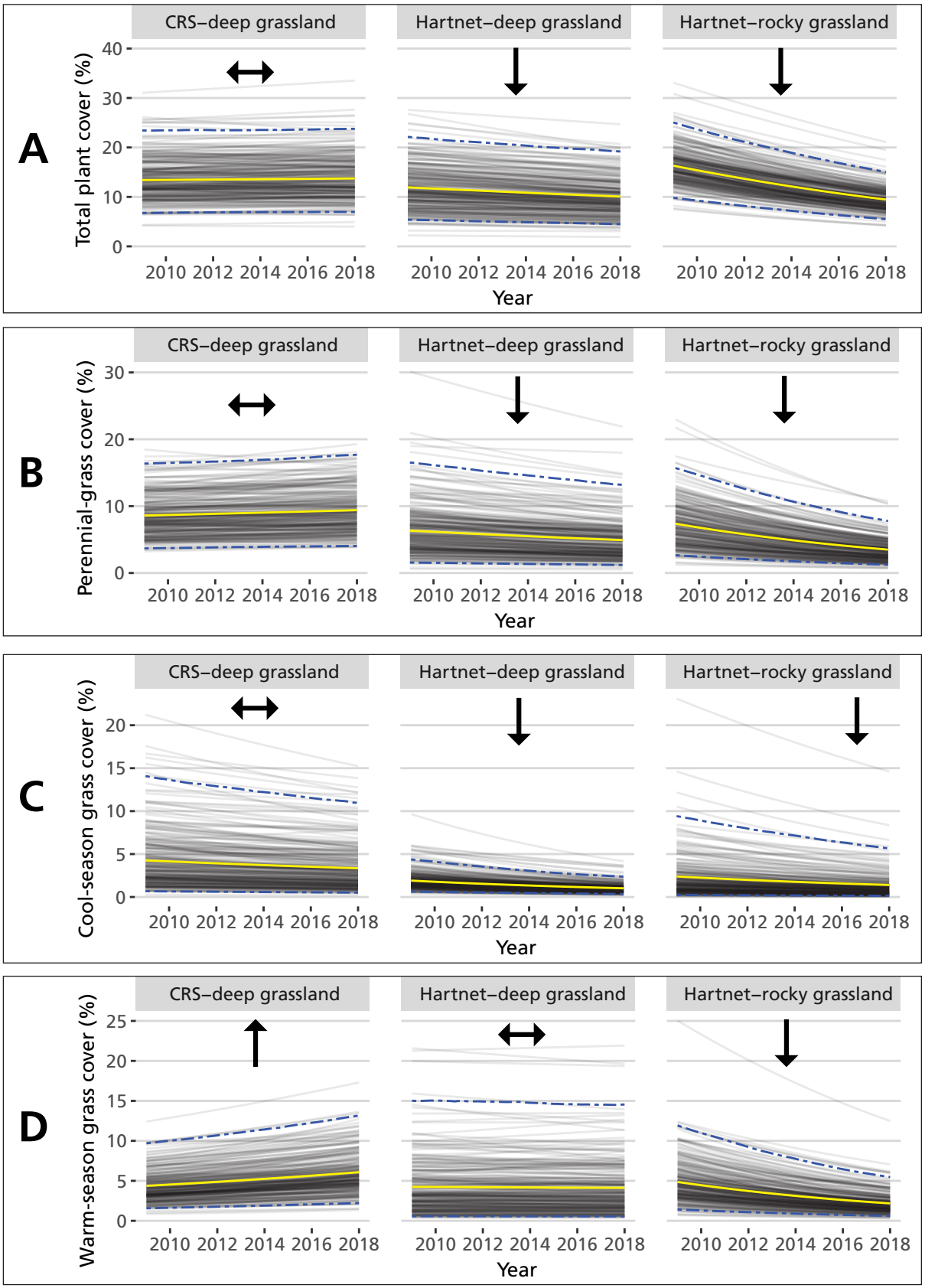


Figure 3-4A–D. Posterior predicted means (solid yellow lines) and 95% credible intervals (gray dashed lines) for trends in total plant cover, perennial-grass cover, cool-season grass cover, and warm-season grass cover in each stratum, Capitol Reef National Park, 2009–2018. Draws of means (solid gray lines) express probability of different means: the darker the area, the more certain we are that the means fall in those areas. Up and down arrows indicate the direction of significant trends. CRS = Cathedral/Rock Springs.

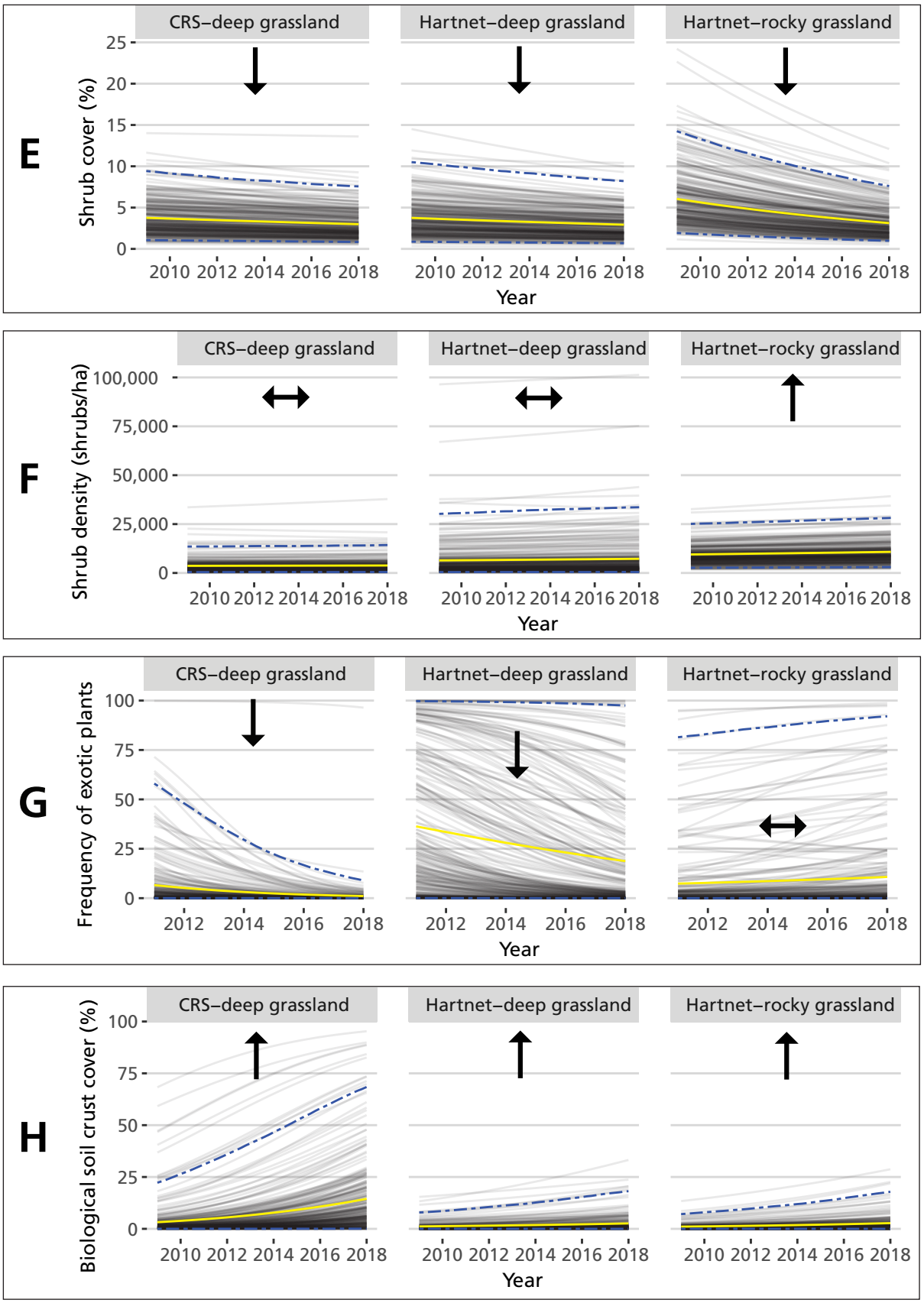


Figure 3-4E–H. Posterior predicted means (solid yellow lines) and 95% credible intervals (gray dashed lines) for trends in shrub cover, shrub density, frequency of exotic plants, and biological soil crust cover in each stratum, Capitol Reef National Park, 2009–2018. Draws of means (solid gray lines) express probability of different means: the darker the area, the more certain we are that the means fall in those areas. Up and down arrows indicate the direction of significant trends. CRS = Cathedral/Rock Springs.

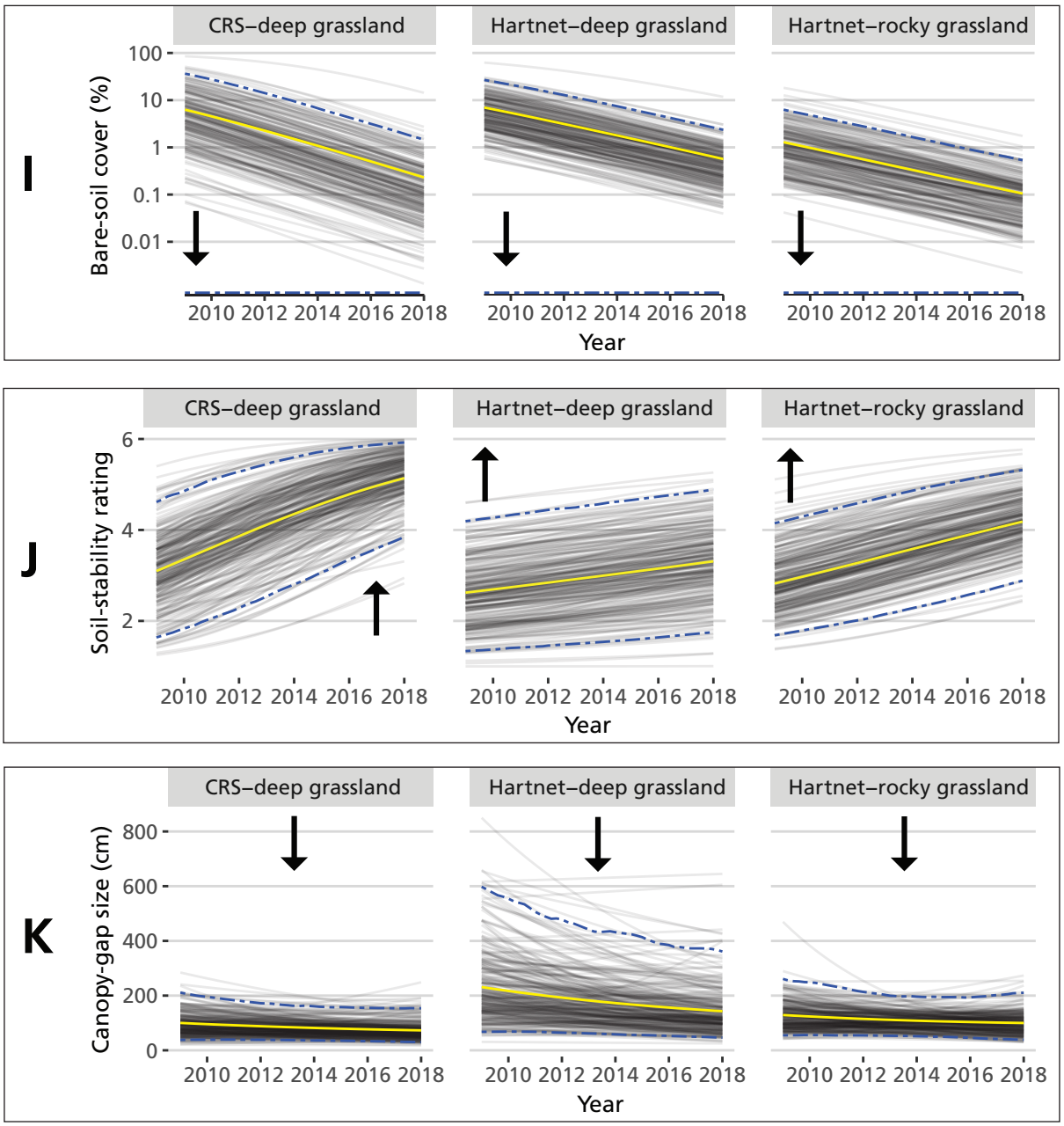


Figure 3-4I–K. Posterior predicted means (solid yellow lines) and 95% credible intervals (gray dashed lines) for trends in bare-soil cover, soil stability, and canopy-gap size in each stratum, Capitol Reef National Park, 2009–2018. Draws of means (solid gray lines) express probability of different means: the darker the area, the more certain we are that the means fall in those areas. Up and down arrows indicate the direction of significant trends. Bare-soil cover is displayed on a log scale to show more detail at low numbers. CRS = Cathedral/Rock Springs.

grasslands (-5.5% and -18.1%, respectively), but did not change in the Hartnet rocky grasslands (see Table 3-3, Figure 3-4G).

3.2.3 Soil-stability trends

Trends in soil surface cover and stability were similar among strata. Biological soil crust cover and soil stability increased, and bare-soil cover and canopy-gap size decreased across all three strata from 2009 to 2018 (see Table 3-3, Figure 3-4H–K). In the CRS deep grasslands, biological soil crust cover and soil stability increased at a faster rate (+11.0% and +2.0, respectively) than in either grassland type in the Hartnet allotment (deep grasslands: +1.3% and +0.7; rocky grasslands: +1.4% and +1.4). Canopy-gap size decreased at a faster rate in the Hartnet deep grasslands (-92 cm) than in the CRS deep grasslands (-23 cm) or Hartnet rocky grasslands (-27 cm) (see Table 3-3).

3.2.4 Comparing trends and changes in annual status from 2009 to 2018

All trends were modeled at the mean of any covariates included in the model (cumulative GDD, cool-season and/or previous-monsoon precipitation) to evaluate the unexplained change over time (i.e., underlying causes that were not included as covariates in the model). When the direction of a trend differed from the direction of change in status (Table 3-4), this was because the indicator was highly influenced by the short-term effects of the climate covariates included in the model (see Table 3-2). For example, mean perennial-grass cover in CRS deep grasslands increased from 2009 to 2018 in status but showed no trend (Table 3-4), demonstrating that increases in cover were due to higher cool-season plus previous-monsoon precipitation in later years of monitoring (see Table 3-2).

Average to above-average precipitation in water years 2013–2016 (see Figures 3-1, 3-2) appears to have had a positive influence on nearly all vegetation indicators across the three strata from 2009 to 2018 (see Table 3-4). Most negative trends in vegetation cover had a change in status that was less negative or stable (see Table 3-4). This was true for total, perennial-grass, and cool-season grass cover in the Hartnet deep and rocky grasslands. Stable trends in total and perennial-grass cover at CRS deep grasslands looked more like increases in cover in the 2009–2018 change in status (see Table 3-4). Changes in warm-season perennial grass cover at the CRS deep grasslands was one of the only indicators with similar increasing trends and change in status (see Table 3-4).

Similarly, decreasing or stable trends for frequency of exotic plants showed a more dramatic decrease in the change in status from 2009 to 2018 (see Table 3-4), and shrub density increased more in the 2009–2018 change in status than in the trend over this time.

In most cases, changes in soil metrics were similar for trends and changes in status from 2009 to 2018 (see Table 3-4).

Table 3-4. Change in status, direction of trend, and trend for each indicator and stratum, Capitol Reef National Park, 2009–2018.

Indicator	Stratum	Change in status[A]	Direction of trend[AB]	Trend[A]
Total cover	Cathedral/Rock Springs deep grasslands	+2.3%	⬅➡	+0.3%
	Hartnet deep grasslands	+0.4%	⬇	**-1.9%[C]**
	Hartnet rocky grasslands	-2.9%	⬇	**-6.9%[C]**
Perennial-grass cover	Cathedral/Rock Springs deep grasslands	+1.8%	⬅➡	+0.7%
	Hartnet deep grasslands	+0.02%	⬇	**-1.5%[C]**
	Hartnet rocky grasslands	-1.5%	⬇	**-3.9%[C]**
Cool-season perennial grass cover	Cathedral/Rock Springs deep grasslands	+0.1%	⬅➡	-0.9%
	Hartnet deep grasslands	-0.2%	⬇	**-1.0%[C]**
	Hartnet rocky grasslands	-0.2%	⬇	**-0.9%[C]**
Warm-season perennial grass cover	Cathedral/Rock Springs deep grasslands	+1.8%	⬆	**+1.7%[C]**
	Hartnet deep grasslands	+0.5%	⬅➡	-0.1%
	Hartnet rocky grasslands	-1.0%	⬇	**-2.7%[C]**
Shrub cover	Cathedral/Rock Springs deep grasslands	-0.4%	⬇	**-0.8%[C]**
	Hartnet deep grasslands	-0.5%	⬇	**-0.9%[C]**
	Hartnet rocky grasslands	-2.2%	⬇	**-3.0%[C]**
Shrub density	Cathedral/Rock Springs deep grasslands	+464.6 shrubs/ha	⬅➡	+169 shrubs/ha
	Hartnet deep grasslands	+1,169.8 shrubs/ha	⬅➡	+869 shrubs/ha
	Hartnet rocky grasslands	+1,870.3 shrubs/ha	⬆	**+1,349 shrubs/ha[C]**
Frequency of exotic plants	Cathedral/Rock Springs deep grasslands	-23.7%	⬇	**-5.5%[C]**
	Hartnet deep grasslands	-41.5%	⬇	**-18.1%[C]**
	Hartnet rocky grasslands	-10.3%	⬅➡	+3.3%
Biological soil crust cover	Cathedral/Rock Springs deep grasslands	+9.7%	⬆	**+11.0%[C]**
	Hartnet deep grasslands	+0.8%	⬆	**+1.3%[C]**
	Hartnet rocky grasslands	+1.2%	⬆	**+1.4%[C]**
Bare-soil cover	Cathedral/Rock Springs deep grasslands	-5.4%	⬇	**-6.3%[C]**
	Hartnet deep grasslands	-7.9%	⬇	**-5.9%[C]**
	Hartnet rocky grasslands	-1.4%	⬇	**-1.2%[C]**
Soil-stability rating	Cathedral/Rock Springs deep grasslands	+2.1	⬆	**+2.0[C]**
	Hartnet deep grasslands	+0.7	⬆	**+0.7[C]**
	Hartnet rocky grasslands	+1.4	⬆	**+1.4[C]**
Canopy-gap size	Cathedral/Rock Springs deep grasslands	-37 cm	⬇	**-23 cm[C]**
	Hartnet deep grasslands	-106 cm	⬇	**-92 cm[C]**
	Hartnet rocky grasslands	-41 cm	⬇	**-27 cm[C]**

[A]Change in status/direction of trend/trend from 2009 to 2018 for all indicators except frequency of exotic species, which is from 2011 to 2018. Change in status is the change in an indicator from the first to last year of monitoring, driven in part by variations in cool-season and/or monsoon precipitation during the years monitored (i.e., change in status reflects actual changes in an indicator on the ground). Trend is the long-term change in an indicator, evaluated at the mean of model covariates, such as cool-season and/or previous-year monsoon precipitation. "Change in Status" is from a version of the model that used the actual values of the covariates each year. "Trend" is from a version of the model that includes the covariates at their means. When condition/trend differed from change in status, this indicates that cool-season and/or previous-monsoon precipitation were important in driving short-term changes in the indicator. When condition/trend differed little from change in status, this suggests that an underlying cause of the trend was not included in the model.

[B]⬇=decreasing trend; ⬆=increasing trend; ⬅➡=no trend.

[C]Indicates significant increasing or decreasing trend (also in bold red text).

4 Discussion

4.1 Summary of conditions

Overall, vegetation and soils in the Cathedral/Rock Springs allotments are in relatively good condition, and trends are stable or improving (Table 4-1). Vegetation in the CRS deep grasslands was generally stable, with increases in warm-season grass cover. The allotments had low invasion by exotic annual plant species and good recovery from past grazing based on limited historical data.

In Hartnet deep grasslands, cool-season grass cover was very low, which may be due to both livestock-grazing pressure and warming conditions that did not favor cool-season grasses. Frequency of exotics was somewhat high, which has been shown to be related to livestock disturbance. Hartnet rocky grasslands had fairly low invasion by exotic-plant species, but grass and shrub cover were decreasing and particularly susceptible to declines during drought in this soil type.

Soils in the CRS deep grasslands were in moderately good condition and continued to improve (see Table 4-1), but recovery from trampling disturbances is a slow process. Many areas of the Hartnet deep grasslands had soils trampled by livestock

Table 4-1. Summary of conditions for grasslands in Capitol Reef National Park with different grazing histories and grassland types.

		Condition/Trend[A]		
Vital sign	Indicator	Cathedral/Rock Springs deep grasslands (retired)	Hartnet deep grasslands (grazed)	Hartnet rocky grasslands (grazed)
Upland plant communities	Total cover	⇔	⇩	⇩
	Perennial-grass cover	⇔	⇩	⇩
	Cool-season grass cover	⇔	⇩	⇩
	Warm-season grass cover	⇧	⇔	⇩
	Shrub cover	⇩	⇩	⇩
	Shrub density	⇔	⇔	⇧
	Frequency of exotic species	⇧	⇧	⇔
Soil stability	Biological soil crust cover	⇧	⇧	⇧
	Bare-soil cover	⇧	⇧	⇧
	Soil-stability rating	⇧	⇧	⇧
	Canopy-gap size	⇧	⇧	⇧

[A]Green ● indicates the indicator was in good condition. Yellow ● indicates condition that warrants moderate concern. Red ● indicates condition that warrants significant concern. An upward arrow means the condition is improving. A sideways arrow means the condition is unchanging. A downward arrow means the condition is deteriorating. Note that decreasing frequency of exotic species, bare-soil cover, and canopy-gap sizes are considered improving trends. A dashed line means confidence is low. A solid line means confidence is medium. No conditions were reported with high confidence due to the relatively short dataset (≤10 years), wide credible intervals, and limited historical data. There are few reference conditions available in the arid west due to widespread historical livestock grazing. Condition colors will become more informed with additional years of monitoring data and may change as more information is gathered. Because the purpose of this report was to inform management, condition colors were included based on the literature and the author's professional judgment.

and in relatively poor condition, but wetter-than-average years likely contributed to some improvement in soil conditions. Soils in rocky grasslands had somewhat lower stability and BSC cover, but the surface was well protected by high cover of rocks that limited bare soil, prevented erosion, and limited the surface area where BSCs could form.

4.2 Grassland recovery in retired allotments

4.2.1 Vegetation

By comparing the available historical data to NCPN long-term monitoring data and looking at changes over the past 10 years, we can provide some evidence that grasslands retired from grazing in the northern part of Capitol Reef NP park have recovered over the past 10–30 years. The actual amount of recovery is difficult to quantify due to a lack of data from before the Cathedral and Rock Springs allotments were retired. Historical records are incomplete and spatially limited, but they provide reference points for comparing the condition of the Cathedral allotment over time. (No historical information on vegetation condition or rangeland health was available for the Rock Springs allotment.) The NCPN did not collect monitoring data before 2007, when its pilot grassland monitoring began. The park's historical records include grazing intensity (AUMs) within the park (see Section 1.2), and a few grazing-management reports for allotments. The Bureau of Land Management (BLM) managed livestock grazing allotments within the park until recently.

Table 4-2. Percent live cover of vegetation in Bureau of Land Management long-term monitoring transects in the Cathedral allotment within Capitol Reef National Park, 1979–1998.[A]

	Live vegetation cover (%)		Frequency of Indian ricegrass	
Year	T-3	T-4	T-3	T-4
1979	2.6	2.6	0	2
1989	5.0	ND	0	ND
1993	1.8	9.1	6	18
1996	15.0	2.0	46	29

[A]Data from McEwen (1999). All but two of these values are lower than live cover in 2018 (mean 10.6% live cover, 95% credible interval 5.2–18.0%). ND=no data; transect was not monitored that year.

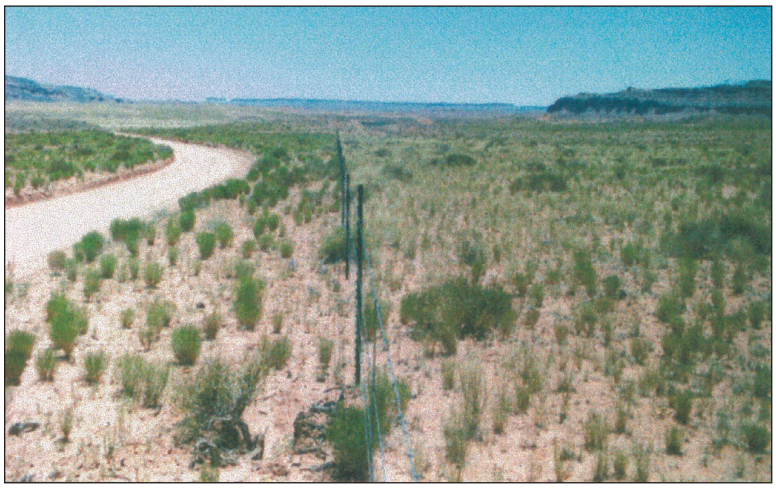


Figure 4-1. Historical photo of the Cathedral allotment near the Temple of the Sun and Moon section of Capitol Reef NP (circa 1998). On the north side of the fence (left) is Bureau of Land Management land grazed by cattle. On the south side of the fence (right), where there is much higher density of *Stipa hymenoides* (Indian ricegrass), is an area of Capitol Reef NP that had not been grazed for approximately eight years.

One BLM report evaluated the condition of the Cathedral allotment 10 years after most of the AUMs were retired within the park (McEwen 1999). The data were limited spatially to two transects maintained by the BLM in the Cathedral Valley inside the park, one on the eastern side (T-3) and one on the western side (T-4). Both were monitored in 1979, 1993, and 1996. T-3 was also monitored in 1989. The minimal livestock grazing in the Cathedral allotment from 1989 to 1999, after ~80% of AUMs were retired, appears to have allowed Indian ricegrass to begin recovering during this period. Although numbers of mature grass species, including Indian ricegrass, galleta, *Sporobolus cryptandrus* (sand dropseed), blue grama, and *Sporobolus airoides* (alkali sacaton), fluctuated from year to year during monitoring (McEwen 1999), there was a clear pattern of increasing frequency of Indian ricegrass after 1989, with 0–2 individuals counted in each transect in 1979–1989 and 29–46 individuals counted in each transect by 1996 (Table 4-2). This was also documented in photos (McEwen 1999) that show clear increases in Indian ricegrass in a part of the Cathedral allotment within the park after eight years without livestock grazing (Figure 4-1).

In the historical data, total live cover varied by transect and year, ranging from 1.8% to

15.0% (see Table 4-2). Low values of total cover in the historical data (1.8–2.6%) were well below the lowest values of total cover in NCPN monitoring (8.3% and 4.1–14.3% mean and 95% CI in 2009; see Figure 3-3A), providing evidence that total cover in the Cathedral allotment was lower in some years while it was actively grazed by livestock. Higher values of total cover in the historical data (5.0–15.0%; see Table 4-2) were within the range of NCPN total-cover data from 2009 to 2018 (see Figure 3-3A). Historical data were not available for plant functional groups or species. No historical data were available for the Rock Springs allotment, but NCPN monitoring data show that cover there tended to be similar to or higher than cover in the Cathedral allotment, suggesting it is currently in good condition.

Analysis of NCPN monitoring data provides some evidence of continued recovery of vegetation in the CRS allotments from 2009 to 2018, and additional evidence that soils are recovering. Although trends in most vegetation indicators were stable from 2009 to 2018, warm-season grass cover increased for both trend and change in status (see Table 3-4). We also expected to see increases in cool-season grass cover—a sign of recovery from past livestock grazing—but conditions appeared to be unchanged over our 10 years of monitoring (see Table 3-4). Historical data and photos suggest much recovery may have occurred before NCPN monitoring began (McEwen 1999).

In addition, cool-season grasses are generally predicted to fare less well than warm-season grasses in hotter, drier future conditions of the Southwest US (Munson et al. 2011; Gremer et al. 2015; Hoover et al. 2015; Hoover et al. 2019). As such, increasing temperatures and related decreases in soil moisture may have offset any potential increases in cool-season grass cover due to grazing recovery.

4.2.2 Soils

Historical data do not contain comparable records on the condition of soils in the Cathedral or Rock Springs deep grasslands. However, we know trampling damages biological soils crusts (BSCs) and decreases soil stability, and these changes can persist for more than 40 years after removal of livestock grazing (Duniway et al. 2018). Looking at the condition of soils in the Hartnet deep grasslands, where there is much overlap in soil types with the CRS deep grasslands (NRCS and NPS 2014), gives us an idea of what soil conditions may have been like before livestock grazing was retired. Soil stability and BSC cover were higher and increasing at a faster rate in deep grasslands in the retired CRS allotments than in the grazed Hartnet allotment (see Figures 3-3J, H and 3-4J, H), providing some evidence that soils were actively recovering in the retired grazing allotments. A soil-stability rating increase of 2.1 in the CRS allotments from 2009 to 2018 (see Table 3-1) was an impressive rate of recovery. Soil stability is positively correlated with BSC cover, among other things (Herrick et al. 2001), and our repeat photos show substantial crust development over the 10 years of monitoring (Figure 4-2).



Figure 4-2. Repeat photos of the soil surface at a monitoring plot (#22) in the Cathedral allotment in 2009 (left) and 2018 (right). Pinnacling of biological soils crust increased substantially by 2018.

Bare-soil cover was relatively high in the CRS deep grasslands in 2009; we are not sure why. Trespass cattle have been noted in these allotments. Elk also use the area in higher snow years, and increased trampling and damage to BSCs is more likely in these years.

4.3 Effects of livestock grazing on Hartnet grasslands

To evaluate the effects of livestock grazing on grasslands in the northern part of Capitol Reef NP, we compared conditions and trends in deep grasslands actively grazed by cattle in the Hartnet allotment with those retired from grazing for 10–30 years in the CRS allotments. The condition of deep grasslands in the CRS allotments is not the perfect reference for desired conditions of deep grasslands in the Hartnet allotment. The Hartnet allotment contains some deep grasslands at lower elevations, and a wider range of soil types than the other two allotments (NRCS and NPS 2014). However, the similar locations, elevations, soil types, and ecological sites overall make this comparison relevant and important to understanding potential grazing impacts in the Hartnet allotment. In making this comparison, we assume there has been substantial recovery of vegetation and soils in the CRS allotments since grazing was retired (see previous section). There is much overlap in soils and ecological sites between the CRS and Hartnet deep grasslands (NRCS and NPS 2014), and this analysis provides the most thorough evaluation of ecological condition to date for this part of the park.

Historical data for the Hartnet allotment are sparse. One BLM report contained a map of range condition in the Hartnet allotment and stated that "the majority of the allotment was still in a poor condition in 1961" (Hansen 1966), not long after the BLM began formally managing livestock grazing there. The report also stated that "no change in condition occurred from 1958 to 1961" (Hansen 1966). This appears to be the extent that vegetation condition and rangeland health were assessed (or at least documented) prior to 2015, when a formal rangeland-health assessment documented poor conditions in much of the Hartnet allotment (Fisk and Borthwick 2016). Similarly, our recent evaluation found that conditions of most vegetation and soil indicators in the Hartnet deep grasslands warranted moderate to significant concern (see Table 4-1), compared to the good condition of most of these indicators in the CRS allotments.

We do know that a maximum of 1,141 AUMs were permitted in the Hartnet allotment each year. This use occurred mainly on the valley bottoms in the South Desert and along the Hartnet Road (Fisk and Borthwick 2016), which aligns reasonably well with the area of NCPN's Hartnet deep-grassland stratum.

4.3.1 Vegetation

The low amount of cool-season grass cover in the Hartnet deep grasslands was particularly notable (see Figure 3-3C). It is well-documented that cool-season grass cover and biomass decrease as livestock grazing intensity increases in semiarid grasslands with a mix of cool- and warm-season grasses (Irisarri et al. 2016; Hart et al. 1993; Manley et al. 1997). Cool-season grasses tend to be preferred sources of forage for cattle due to higher palatability of many species (Mayne 2004). Thus, they are often preferentially grazed before many warm-season grass species. The timing of regional livestock grazing and grass growth further exarcerbates this phenomenon. Cattle grazing in the Hartnet allotment occurred from October to May each year, which overlapped with many months of the growing season for cool-season grasses (i.e., approximately March–June and sometimes September–October when moisture was available; Comstock and Ehleringer 1992). Warm-season grasses, on the other hand, grow primarily in warmer months (i.e., approximately May–September; Comstock and Ehleringer 1992). No livestock grazing occurred in the Hartnet allotment during most of these months.

Indeed, warm-season grasses in the Hartnet deep grasslands appeared to be faring better than cool-season grasses. Wetter-than-average monsoons in 2014–2017 helped keep the cover of warm-season grasses somewhat

higher in most later years of monitoring (see Figure 3-3D), and the trend was at least stable under mean cool-season and monsoon precipitation conditions (see Figure 3-4D).

Overall, our analysis indicated declining trends (i.e., declining condition of resources) for four of the seven vegetation indicators in the grazed Hartnet deep grasslands, compared to only one declining trend in the retired CRS deep grasslands (see Table 4-1). Average to above-average precipitation in later years of monitoring (2013–2016; see Figures 3-1, 3-2) kept changes in grass cover from 2009 to 2018 less negative than would have been predicted under mean precipitation conditions (see Table 3-4), but these trends are still concerning. In addition to pressure from livestock grazing, which ceased after the monitoring period, declining trends in vegetation in the Hartnet deep grasslands may also be related to increasing aridity as the Southwest continues to warm (Garfin et al. 2014)—something we did not include as a covariate in our trend models. Care should be taken when interpreting our data because differences are small and credible intervals in our models are relatively wide. However, the direction and consistency of these trends across several indicators are clear.

4.3.2 Soils

Our analysis suggests soil conditions are improving in all of the monitored grasslands, but improvement is happening much more slowly in the grazed (Hartnet) deep grasslands than the ungrazed (CRS) deep grasslands. For example, from 2009 to 2018, BSC cover was +0.8–1.2% in grazed vs. +9.7% in ungrazed allotments, and soil-stability rating was +0.7–1.4 vs. +2.1, respectively (see Table 3-1; Figure 3-3H, J). Cover of biological soil crust is still low in the Hartnet deep grasslands (1.5% in 2018; see Table 3-1). Improvements in soil stability, BSC cover, and bare-soil cover may be more related to wetter conditions in the later years of monitoring (i.e., average to above-average water years in 2013–2016; see Figures 3-1, 3-2), which can help repair trampling damage from livestock and wildlife, than to livestock grazing management. It is unclear why bare-soil cover remained so low in 2017 and 2018 in the Hartnet deep grasslands (see Figure 3-3I), considering the drought conditions.

Larger canopy-gap sizes are related to increased susceptibility of soils to wind erosion (Herrick et al. 2005). We found weak evidence that gaps between plant canopies were larger in the grazed Hartnet deep grasslands than in the ungrazed CRS deep grasslands. However, the improving trend (i.e., decreasing size) in canopy gaps occurred at a faster rate in the Hartnet deep grasslands than in the CRS deep grasslands. Favorable climate conditions during the later monitoring years may have helped to decrease canopy-gap sizes in the Hartnet deep grasslands. This provides hope that additional improvement will occur during favorable climate conditions now that livestock grazing is retired. For now, though, the condition of these indicators suggests there is still a moderate-to-high potential for wind and water erosion.

4.4 Climate drivers and drought effects on grasslands

In our analysis, cool-season and monsoon precipitation were both important drivers of vegetation and soil condition in Capitol Reef NP grasslands (see Table 3-2). Cool-season precipitation recharges soil water important for spring growth of native perennial cool-season grasses in this region (Comstock and Ehleringer 1992)—as well as the success of exotic annual grasses, such as cheatgrass (Bradford and Lauenroth 2006; Munson et al. 2011; Prevey and Seastedt 2015). Monsoon precipitation favors warm-season grasses on the the Colorado Plateau because they thrive in hotter conditions when moisture is available (Sage et al. 1999).

Our analysis indicated the effect of the previous year's monsoon precipitation was twice as strong as that of cool-season precipitation on all grass-cover metrics and total vegetation in Capitol Reef NP grasslands (see Table 3-2). Climate legacies of a year or more can affect growth in these grasslands (Thoma et al. 2016) because previous-year precipitation increases tiller density in desert grasslands (Reichmann et al. 2013),

providing a structural foundation for grasses to take better advantage of water and nutrients the following spring. There were some exceptionally wet monsoon years during our monitoring (i.e., 2013 and 2014; see Figure 3-2C), and it is possible that soil moisture from these events could have persisted into the cool season.

The high number of exotics detected in 2011 (Figure 3-3G), the first year exotic frequency was sampled, was driven by the large amount of cool-season precipitation received earlier that water year (Figure 3-2B). Cool-season precipitation was included in the model (see Table 3-2). However, decreasing trends in exotic frequency in the deep grasslands (see Table 3-3) should be interpreted with caution. This model has two years' less data than the other models presented in this report, and the trend likely represents a short-term decrease from the high number of exotic annuals detected in 2011.

The importance of seasonal precipitation to biological soil crusts (Darrouzet-Nardi et al. 2015) and soil stability in non-agricultural soils (Dimoyiannis 2009) has not been well-studied, but NCPN models provided evidence that cool-season precipitation increased biological soil crust cover (minimal relationship), decreased bare-soil cover, and that both cool-season and monsoon precipitation increased soil stability (see Table 3-2). The influence of cool-season and monsoon precipitation on soil stability was similar, suggesting that moisture in both seasons was important to soil stability.

In the Hartnet rocky grasslands, vegetation cover declined from 2009 to 2018 for all indicators analyzed (see Table 3-4, Figure 3-4), and was lower during the drought conditions of 2018 than in any of the other years monitored (see Figure 3-3). Considering that livestock grazing tends to be lighter in these areas (Fisk and Borthwick 2016; McEwen 1999), plant responses appeared to be driven more by ecological site (i.e., soil and site conditions) than by livestock-grazing pressure. Because they can't store as much water as non-rocky soils, rocky soils can exacerbate the impact of drought conditions on plants (Munson et al. 2015). This appears to have happened in the Hartnet rocky grasslands during the exceptional drought of 2017–2018, and was also noted for the drought conditions of 2012, in an earlier analysis of Capitol Reef NP grassland data (Witwicki et al. 2016). The 2018 water-year conditions were even drier (see Figures 3-1, 3-2). In spring 2019, cover of grasses and shrubs in the rocky grasslands appeared to recovering (author observation). It will be interesting to analyze these data in the future to better understand recovery in these areas.

There is still much uncertainty about how seasonal precipitation may or may not change in the future (Garfin et al. 2014). We know this is especially important to cool- and warm-season grasses. Changes in seasonality of precipitation could be some of the most important drivers of change in mixed cool- and warm-season semiarid grasslands, such as those in Capitol Reef NP. In addition, NCPN's long-term monitoring data are collected in late spring each year. We would expect patterns in our monitoring data to reflect the overall condition of grasses, but our monitoring is not designed to detect changes during other times of year that may be important. In fact, recent work to develop relationships between upland monitoring and landscape-scale data have proven to be particularly challenging.

4.5 Additional questions

There was a consistent decreasing trend in shrub cover in all strata. The decreases in shrub cover were relatively small, especially in deep grasslands, and do not seem to be specific to any particular species. Shrub density did not change in CRS or Hartnet deep grasslands—and actually increased in the Hartnet rocky grasslands—due to increases in seedlings (>10 cm tall; data not shown). In the CRS deep grasslands, declining shrub cover, along with increasing perennial grass cover, could be viewed as another sign of recovery from past grazing. However, this is something we should continue to watch until we better understand what is driving the trend.

Although we evaluated mean canopy-gap size in the trend models presented here, we did not have a model developed to evaluate

basal-gap size at time of writing. Because areas with small canopy gaps (≤50 cm) are less susceptible to wind erosion, Herrick and colleagues (2005) recommend using the proportion of transects covered by large gaps between plant canopies (>50 cm) as an indicator of susceptibility to wind erosion and/or exotic-plant invasion. Similarly, the proportion of transects covered by large gaps between plant bases reflects increased susceptibility to water erosion and runoff, because plant bases slow water movement down slopes (Herrick et al. 2005). We are currently working to evaluate trends in the proportion of >50-centimeter gaps for both canopy and basal gaps. Models using this metric will be more relevant to management than the one used in this report.

Another question that could use additional investigation is why bare-soil cover decreased, and biological soil crust cover and soil stability increased, in a grazed allotment. We suspect this is related to climate conditions during the years of monitoring, but additional research is needed to improve our understanding of these results.

Livestock grazing in the Hartnet allotment was retired on May 1, 2018. In May 2019, NCPN monitoring crews began documenting any changes in vegetation or soils associated with this change in management. None of these data are included in this report. However, the crews noted some early signs of recovery in spring 2019: many tiny bunches of Indian ricegrass in the Hartnet deep grasslands that appeared to be thriving after the wet winter of 2018–2019. It is unclear whether any of these grass seedlings survived the dry conditions later that summer, but events like this provide hope that cool-season grass cover in the Hartnet deep grasslands will increase after conditions are favorable for establishment, similar to the increases in Indian-ricegrass frequency seen in the Cathedral allotment during the 1990s (McEwen 1999).

5 Conclusions

Long-term monitoring data were useful for tracking grassland recovery in two retired grazing allotments and for documenting the impacts of livestock on grasslands in an actively grazed allotment in Capitol Reef NP. Although our dataset spanned only 10 years (2009–2018), comparisons with historical data provided insight on how much these grasslands have recovered since they were last fully utilized in 1989.

Vegetation and soils in the retired Cathedral and Rock Springs allotments are in relatively good condition, and trends are stable or improving. Similar to earlier assessments, we found that conditions of cool-season grasses and soils in actively grazed areas of the Hartnet allotment were in relatively poor condition. Livestock grazing in the Hartnet allotment was retired on May 1, 2018. Moving forward, NCPN monitoring will shift its focus to document any changes in vegetation or soils associated with this change in management.

Climate is one of the most important drivers of grass cover in semiarid grasslands. Our work highlights the importance of both cool- and warm-season precipitation in stimulating plant growth and repairing trampled soils, and documents the effects of drought on these grasslands. In addition, the different grassland types we monitor highlight how certain soil and site conditions can exacerbate the effects of drought on plants. As our long-term monitoring dataset grows, it will become increasingly useful in understanding how these grasslands will change in a warmer, drier future, and how managers might best target actions to address these changes.

Appendix A. Additional Information on Bayesian Trend Models

This appendix presents a brief overview of Bayesian data analysis. However, a thorough understanding of Bayesian data analysis is not needed to understand the results presented in this report.

A.1 Overview of Bayesian data analysis

According to Kruschke (2015), Bayesian data analysis involves the following steps:

1. *Define a descriptive model for the relevant data.* In our case, this is understanding the changes in indicators of upland vegetation and soil condition over time, and understanding the relationships between indicators of upland vegetation and soil condition and the climate conditions that are driving changes. Linear models with slopes and intercepts were developed, like those used in frequentist statistics. However, there is often more random variation built into Bayesian models than into their frequentist counterparts. Bayesian models also contain a *likelihood*, which decribes the distribution of the response data (e.g., normal, lognormal, binomial, Poisson, negative binomial). The *deterministic model* that describes the data is related to the distribution of the likelihood.
2. *Specify a prior distribution on the parameters. The prior must pass muster with skeptical scientists evaluating the analysis.* In some cases, previous analyses help to inform the values of priors. In the data analyzed in this report, vague priors were used that allow for equal credibility across a wide range of possible values for each parameter, meaning there will be effectively no biasing of the resulting posterior distribution.
3. *Use Bayesian inference to re-allocate credibility across parameter values. Assuming that the model is a reasonable description of the data, interpret the posterior distribution with respect to the relevant issue.* The posterior distribution describes values of the slope, intercept, and other parameters that are credible, given the data. This range of values can be described through a 95% credible interval, which can be interpreted as a 95% confidence that the true value of the mean of the indicator falls within the lower and upper values for the interval.
4. *Check that the posterior predictions mimic the data with reasonable accuracy by conducting a posterior predictive check. If not, consider a different descriptive model.* To assess model fit, we compared the field data with data simulated from the Bayesian model and used test statistics to determine if they were sufficiently similar.

A.2 Bayesian trend modeling

Bayesian modeling provides an eloquent way to model status and trends of data with complex sampling design features that are challenging with traditional frequentist statistical approaches (Hobbs et al. *in prep*). For example, hierarchical Bayesian models can easily accept data from the NCPN's five-year repeating sampling schedule (Witwicki et al. 2017, appendices A and B) and non-normally distributed data from categories, counts, proportions, and binomial distributions. In addition, Bayesian models provide a cohesive approach for determining status at a given point in time and trend over time using the same model, unlike frequentist methods. This approach also allowed us to examine the influence of important covariates at any hierarchical level in the model (plot, strata, park) that influence vegetation and soils, such as climate (Hobbs et al. *in prep*).

These models are hierarchical because they allow parameters (slopes and intercepts) to vary at multiple levels—in this case, at the plot and stratum levels. We made inference at the stra-

tum scale based on the statistical distribution of slopes and intercepts at the plot scale. These models take into account that there can be wide variation in an indicator among sites. We incorporate these differences to inform stratum-level trends, rather than averaging over them.

Because these models are Bayesian, they predict the plot response for all years—even years when data were not collected. This means plots are modeled during years when they are not visited, thereby preventing the possibility that inference on trends could be influenced by annual variation in the set of plots observed in a particular year. Additionally, plots observed more frequently have greater weight in inference than plots observed infrequently, a straightforward method to account for the difference in visitation frequency among plots due to the repeating five-year sampling schedule.

A.3 Equations

The general formula for Bayesian models is

$$[\textit{Model parameters} \mid \textit{data}] \; \alpha \; [\textit{data} \mid \textit{likelihood model}] \; [\textit{priors}]$$

where " | " is "as conditional on" and α is "is proportional to".

For a simple model where intercepts are allowed to vary among sites within a single stratum and slopes are the same for all sites with no other covariates, the model can be written as

$$[\beta_0, \beta_1, \sigma^2_{\beta_0}, \mu_{\beta_0} \mid y] \; \alpha \; [y_i \mid \beta_{0+} \beta_1 x_i, \sigma^2] \; [\beta_0 \mid \mu_{\beta_0}, \sigma^2_{\beta_0}] \; [\beta_1] \; [\mu_{\beta_0}] \; [\sigma^2_{\beta_0}]$$

where β_0 is the intercept, β_1 is the common slope, $\sigma^2_{\beta_0}$ is the variance of the intercept, and μ_{β_0} is the mean of the intercepts. The expression $[y_i \mid \beta_0 + \beta_1 x_i, \sigma^2]$ reads the probability of the observation conditional on the model parameters and error variance. As such, it represents a general expression for the likelihood. Specific distributions (e.g., binomial, beta, Poisson) are chosen depending on the values of the observations, (i.e., their "support").

The likelihood model varies based on the distribution of the indicator. In the case of the shrub-density model, the simplified likelihood can be written as:

$$y \sim \textit{Negative binomial}(e^{\beta_0 + \beta_1 x + \beta_2 x_2}), \backslash kappa$$

where β_2 is the row vector of covariates in a covariance matrix, x_2 is the corresponding column vector of coefficients, and \kappa is a dispersion parameter.

A.4 Variance structures

We built hierarchical models with different variance structures to determine which best fit our data. The following three types of variance structures were examined:

- **Hierarchical site:** The variance of observations at a given site is drawn from a hyperdistribution of variances shared by all of the sites in the sample. In other words, there's an underlying distribution of the variances of observations within sites that gives rise to the variance of observations at a specific site.
- **Fixed site:** As above, variances vary by site, but the variance of observations at each site is estimated completely independently of one another. There's not a shared hyperdistribution of variances.
- **Fixed stratum:** Variance is forced to be the same for all sites within a stratum.

A.5 Model checking and selection

All models were checked for convergence using the Gelman-Rubin diagnostic (Gelman and

Rubin 1992). A properly converged model will not meaningfully change the posterior distribution with more iterations in the Markov Chain Monte Carlo (MCMC) process, which ensures the model output provides reliable inference (Hooten and Hobbs 2015). In many cases, models would only only converge under the most appropriate variance structure for the data (see Table A1).

To assess model fit, we compared the field data with data simulated from the Bayesian model to compute the probability that test statistics summarizing the real and simulated data were sufficiently similar. The Bayesian p value (P_B) tests whether the distribution of the data that would arise from our model is more extreme than the distribution of the observed data. Ideal values should be close to 0.5, with extremes of >0.9 or <0.1 indicating a poor fit (Hooten and Hobbs 2015).

We did did not find evidence of any spatial or temporal autocorrelation in the residuals, perhaps because of the addition of climate covariates in the models.

To choose the "best" model among those with either varying intercepts (β_0), or varying slopes and intercepts (β_0 β_1), and with different combinations of covariates, we minimized posterior predictive loss. Posterior predictive loss (Gelfand and Ghosh 1998) contains a goodness-of-fit term and a penalty term based on the number of model parameters. Its goal is to minimize loss by comparing replicate data created at each iteration of the MCMC chain with observed data. Generally, we found that models with random intercepts only (β_0) converged more often than models with random slopes and random intercepts (β_0 β_1), so we focused on these types of models for most of our trend analyses.

A.6 Details of Bayesian trend models in this report

Table A1 provides an overview of the eleven Bayesian models we constructed to predict the status and trend of our indicators. Final models were an excellent fit to the data, as shown by Bayesian p values (P_B). Response data were centered for all models. Standardized adaptive priors (McElreath 2015) were used in the exotic-frequency model in order for it to converge. The canopy-gap model accounted for truncation (because gaps <20 cm were not recorded) and censoring (because the full length of gaps at the ends of the transects were not recorded) in the data.

Table A1. Details of Bayesian trend models used in this report, including the indicator, model type, likelihood, deterministic model, variance structure, climate covariates, burn-in and iterations of the Markov Chain Monte Carlo sampler, and Bayesian p value (P_B) of the mean and variance.

Indicator	Model type	Likelihood	Deterministic model	Variance structure	Climate covariates[A]	Burn-in and iterations of MCMC sampler[B]	P_B of the mean and variance[C]
Total cover	β_0	Beta binomial	Inverse logit	Fixed stratum	Cool-season P, Monsoon P, Cumulative GDD	305000, 30000	0.51, 0.58
Perennial-grass cover	β_0	Beta binomial	Inverse logit	Fixed stratum	Cool-season P, Monsoon P, Cumulative GDD	305000, 30000	0.50, 0.66
Cool-season perennial-grass cover	β_0	Beta binomial	Inverse logit	Fixed stratum	Cool-season P, Monsoon P, Cumulative GDD	305000, 30000	0.54, 0.72
Warm-season perennial-grass cover	β_0	Beta binomial	Inverse logit	Fixed stratum	Cool-season P, Monsoon P, Cumulative GDD	305000, 30000	0.52, 0.68
Shrub cover	β_0	Beta binomial	Inverse logit	Fixed stratum	Cool-season P, Monsoon P, Cumulative GDD	305000, 30000	0.52, 0.59
Shrub density	β_0	Negative binomial	Exponential	Fixed stratum	Monsoon P	305000, 30000	0.50, 0.73
Frequency of exotic plants	β_0	Beta binomial	Inverse logit	Fixed stratum	Cool-season P	455000, 30000	0.57, 0.43
Biological soil crust cover	β_0	Zero inflated beta binomial	Inverse logit	Fixed stratum	Cool-season P	305000, 30000	0.52, 0.67
Bare-soil cover	β_0	Zero inflated beta binomial	Inverse logit	Fixed stratum	Cool-season P	305000, 30000	0.54, 0.55
Soil-stability rating	β_0	Ordinal latent normal	Linear	Hierarchical site	Cool-season P, Monsoon P	15000, 10000	0.44, 0.43
Canopy gap size	$\beta_0 \beta_1$	Lognormal	Log linear	Fixed stratum	Cool-season P, Monsoon P	305000, 30000	0.62, 0.56

[A]P=precipitation; GDD=growing-degree days
[B]MCMC= Markov Chain Monte Carlo
[C]P_B=Bayesian p value

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Natural Resource Stewardship and Science
1201 Oak Ridge Drive, Suite 150
Fort Collins, Colorado 80525

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