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RESEARCH ARTICLE

Experimental manipulation of soil-surface albedo alters phenology and growth of *Bromus tectorum* (cheatgrass)

Toby M. Maxwell · Matthew J. Germino · Seth Romero · Lauren M. Porensky · Dana M. Blumenthal · Cynthia S. Brown · Peter B. Adler

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Abstract
Purpose The sensitivity of wildland plants to temperature can be directly measured using experimental manipulations of temperature in situ. We show that soil surface temperature and plant density (per square meter) have a significant impact on the germination, growth, and phenology of *Bromus tectorum* L., cheatgrass, a short-statured invasive winter-annual grass, and assess a new experimental temperature manipulation method: the application of black and white gravel to warm and cool the soil surface.

Methods We monitored height, seed production, and phenological responses of cheatgrass, seeded into colored gravel at low and high densities at two sites in the western USA: Boise, ID and Cheyenne, WY. Soil surface temperature and volumetric water content were measured to assess treatment effects on soil surface microclimate.

Results Black gravel increased mean temperatures of the surface soil by 1.6 and 2.6 °C compared to white gravel in Cheyenne and Boise, respectively, causing 21–24 more days with soil temperatures > 0 °C, earlier cheatgrass germination, and up to 2.8-fold increases in cheatgrass height. Higher seeding density of cheatgrass led to 1.4-fold taller plants on black gravel plots at both sites, but not white gravel at the Boise site, indicating a possible thermal benefit or reduction of water demand due to plant clustering in warmer treatments.

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T. M. Maxwell (✉)
Department of Biological Sciences, Boise State University, Boise, ID, USA
e-mail: tobymaxwell@boisestate.edu

M. J. Germino
U.S. Geological Survey, Forest and Rangeland Ecosystem Science Center, Boise, ID, USA

S. Romero · L. M. Porensky · D. M. Blumenthal
U.S. Department of Agriculture, Agricultural Research Service, Fort Collins, CO, USA

C. S. Brown
Department of Agricultural Biology, Colorado State University, Fort Collins, CO, USA

P. B. Adler
Department of Wildland Resources and the Ecology Center, Utah State University, Logan, UT, USA

Conclusions Manipulating soil-surface albedo altered the soil microclimate and thus growth and phenology of cheatgrass, whose life history and growth form confer a strong dependency on soil-surface conditions.

Keywords Climate change · Albedo · Cheatgrass (*Bromus tectorum*) · Experimental warming · Phenology · Plant density

Introduction

Vegetation responses to warming are a major aspect of global change (IPCC 2018), and effective climate-adaptation of land management requires an understanding of plant sensitivity to temperature variation. Plant and soil responses to experimental manipulation of warming can provide a strong basis for inference (Korell et al. 2020; Maxwell et al. 2021) compared to observational studies or model simulations of plant response to historic or spatial climate variation (Elmendorf et al. 2015), because experiments can limit confounding effects such as those arising from unquantified differences between sites. Warming is of particular interest because air and soil temperature affect plant phenology, which can drive population and ecosystem scale dynamics, e.g., interspecific competition and carbon storage (Cleland et al. 2007). Altered plant phenology due to warming can also exacerbate plant invasions, particularly when invaders have a different life history strategy than native plants (Sherry et al. 2007; Blumenthal et al. 2016).

Bromus tectorum (Cheatgrass) is a widespread exotic annual that has capitalized on an open phenological niche in the historically perennial sagebrush steppe and is now largely responsible for the annual degradation of > 1 million acres of native plant communities (Doherty et al. 2022). Both experiments and models suggest that warming will exacerbate cheatgrass invasion in some parts of its range (Bradley 2009, Zelikova et al. 2013; Compagnoni and Adler 2014; Blumenthal et al. 2016). Enhancing ecosystem resistance to cheatgrass invasion is often only possible through the application of herbicides that suppress its germination and kill seedlings, although targeted grazing also shows some promise (e.g., Bailey et al. 2019; Porensky et al. 2021). Successful application of both tools relies on accurate understanding of cheatgrass phenology and how it will shift with changes in climate and weather (Young and Clements 2000; Donaldson and Germino 2022). Cheatgrass has a high degree of phenological plasticity, and thus more research is needed to enable land managers to predict cheatgrass growth patterns and combat its spread (Zelikova et al. 2013).

The main avenues for manipulating soil or plant surface temperatures in field settings are through altering sensible heat exchange (convection or conduction) or radiation (longwave or shortwave). Manipulations of air temperature or latent heat exchange may also alter soil temperatures, but are less common and feasible, and manipulations of latent heat exchange are highly undesirable because they alter water balance and corresponding physiological functioning (Aronson and McNulty 2009). Heat exchange for plants and soils have commonly been altered with 1) “open-top” (OTC) or other clear chambers that reduce convective cooling of leaves warmed in sunlight, 2) infrared lamps or overhead roofs that increase downwelling longwave radiation to surfaces, or 3) using electric resistance cables to heat soils or specific plant tissues via conduction (Romero-Olivares et al. 2017). OTCs have been used most extensively among the many field-based warming experiments (7230 published studies with the phrase “open top chamber” reported in Google Scholar, March 2022), but are known to disturb the spatial patterns of precipitation around subject plants and soils, and further, their effect on soil temperatures is diurnally asymmetric (i.e., warming only occurs during the daytime, which does not match observed patterns of climate change; IPCC 2018; Marion et al. 1997; Snyder et al. 2019). Such differences between real (i.e., climate-change induced) and experimental alterations of energy balance, precipitation and soil moisture are particularly problematic in semiarid settings where small differences in soil water availability can influence plants and soil fauna (Norton et al. 2008; Porazinska et al. 2022).

In semiarid landscapes with low-statured species, the microclimate near the soil surface is an important factor for plant demography and growth (Geiger 1957), particularly for short-lived species whose population growth rates are relatively sensitive during seed and seedling stages (e.g., annuals). Altering solar radiation balance by increasing or decreasing surface albedo is a compelling way to manipulate soil-surface microclimate in semiarid and arid regions with little cloud cover and overhead foliar canopy—factors which otherwise intercept solar radiation and shade soil surfaces. Albedo manipulations are applied in crop and horticultural sciences, where colored plastic mulches have been used to increase temperature and water retention in soils (Amare and Desta 2021; Franquera and Mabesa 2016). Many semiarid landscapes have soils that are relatively light or muted in color (variations of tan, grey, or red), and blackening soils can increase daytime temperatures (Boyd et al. 2017). Conversely, in the semiarid regions that have dark soils, cooling may be achieved by adding white or light-colored surfaces. Use of albedo and OTC treatments to alter solar heat exchange induces temporal asymmetry in temperature treatments, but thermal conductance from soil surfaces to deeper depths during daytime may store the heat into nocturnal periods and partially reduce the asymmetry (Campbell and Norman 1998).

Any method for experimental climate manipulation will cause some unwanted changes of plant and soil environments alongside the intended alterations. Color of soil surfaces can only be changed experimentally by adding materials, e.g., pigments, paints, or colored particles. Selection of materials that minimize unwanted interference of the flow of water, air, seeds, and other mass is necessary to avoid introducing confounding factors into experimental designs. Direct painting or pigmentation of soils may cause undesirable chemical interactions and aeolian deposition may reduce the target color. Adding particles coated with inert paints is an attractive alternative that should minimize interference with infiltration, but may result in a mulching effect, i.e., insulation that decreases evaporation and latent heat loss. However, the drier conditions and scarce rainfall that define semiarid regions generally result in less evaporation and, thus, fewer complications from mulching. On the other hand, convective (wind-driven) cooling or warming of insolated blackened or whitened surfaces, respectively, is another counteracting factor that should be more prevalent in semiarid landscapes owing to relatively sparse and short statured vegetation and, thus, greater exposure of soil surfaces to wind (Campbell and Norman 1998). The textural properties of particles added to alter albedo are an important factor, considering that finer textured particles such as sand can incorporate more readily with soil and then disrupt water-retention characteristics, i.e., matric potential. Moreover, finer textured particles added to the soil surface are relatively more prone to alluvial or aeolian removal from plots to burial by deposition of particulate matter from external sources, both of which would diminish albedo treatment effects (Boyd et al. 2017; and C.S. Boyd, pers. comm.). A relatively thin layer of gravel, on the other hand, is less prone to these issues and may provide a tolerable balance of target warming and non-target environmental effects.

Structural and life-history traits of plant species should strongly affect their biological responses to soil-surface warming. For example, perennials that are deeper rooted, longer-lived, and have population growth rates less sensitive to germination and seedling emergence should be less sensitive to soil-surface temperature alteration than smaller plants with shallower roots (Stuble et al. 2021). Shallow rooted annuals are often responsive to changes in microclimate which leads to flexible traits such as the possibility but not dependence on fall germination which yields a competitive advantage over slower growing species (Roundy et al. 2007). Many semiarid ecosystems formerly dominated by perennials are being invaded by exotic-annual grasses, such as the notorious cheatgrass (*Bromus tectorum* L.) invasion of western North America. Cheatgrass increases wildfire occurrence by initiating the ‘annual grass fire cycle’ and thus the prevalence of bare soil is greater in invaded areas (D’Antonio and Vitousek 1992). In turn, there is likely stronger and more widespread coupling of vegetation to soil-surface conditions, increasing the relevance of bare soil-surface microclimate to plant community and ecosystem functioning (Germino et al. 2016a, b). Plant density should also strongly affect convective heat exchange and latent heat fluxes at the soil surface, which is particularly relevant to cheatgrass because it can occur in very high densities, causing variation in soil surface radiation balance and evapotranspiration (Goldberg et al. 2001).

Our goal was to test new methods to manipulate and study plant-soil-climate interactions. We pursued two objectives. First, we evaluated the effects of altered soil albedo and seeding density on soil microclimate and second, we quantified the impact of any differences in microclimate on cheatgrass growth and key aspects of plant fitness. The results of this study will enhance our understanding of the effects of weather on phenology and growth of cheatgrass and how those effects could exacerbate the cheatgrass-fire cycle.

Methods

Experimental plots and treatments were deployed in a completely randomized, full-factorial design on flat terrain in two natural grasslands, one in a relatively summer-dry climate in Boise, Idaho, and the second in a relatively summer-wet climate in Cheyenne, Wyoming (Prism Climate group 2014). The ecological site description for the Boise site was Snake River Plain with an overstory of sagebrush and an understory of perennial grasses and for the Cheyenne site was northern central high plains with mixed rhizomatous and bunchgrass perennial grasses (United States Department of Agriculture, Natural Resources Conservation Service, 2006). Although methods were not identical, examination of whether relative biological responses to treatments were consistent between sites can provide evidence for the repeatability of the treatment effects and their applicability across widely varying environmental and ecological conditions.

The Boise site was located around 43.506867 N, -116.140375 E, on loam soils where 30-year mean annual precipitation is 330 mm and mean annual temperature is 10.8 °C and during the experiment (October 2020-June 2021) average precipitation and temperature were 245 mm and 5.5 °C (Fig. S2). The site was dominated by cheatgrass, crested wheatgrass (*Agropyron cristatum* L), a non-native, perennial cool-season grass, and storksbill (*Erodium cicutarium*), a non-native, annual forb. The Cheyenne site was located near 41.177586 N, -104.899255 E on loam soil where 30-year mean precipitation is 381 mm and annual temperature is 7.3 °C (Fig. S2) and during the experiment (October 2020-July 2021) the average precipitation and temperature were 320 mm and 5.1 °C. Vegetation at this site was also dominated by crested wheatgrass.

At each site, twelve plots total, either 1 × 1 m for high-density seedings, or 1.5 × 1.5 m for low-density seedings, were established by removing 2.5 cm of topsoil, vegetation, and any rocks, and then lightly raking the plots to level the disturbed soils. Plots were separated by approximately 1 m of undisturbed area and the entire project site was 12 × 4 m. Six plots were randomly assigned to each plot size/density treatment. Two plots of each size were then randomly assigned to one of three treatments: black, white, or an untreated control (four plots total for each). At the center of each plot, a 5 × 5 grid of 25 seeds were sown at either 1-cm (for high density plots) or 10-cm (for low density plots) seed spacing. After inserting microclimate sensors and cheatgrass seeds (described below), four of the plots were covered to ~ 1 cm depth or 6.8 kg m^{-2} with gravel that was coated with unreactive black or white enamel (Estes Co product #40,706, black or #40,707, white; estesco.com). We chose 3.2–6.4-mm diameter gravel over finer or coarser options because a pilot experiment conducted prior to this study showed minimal risk of burial by soil redistribution or transport by wind, and reduced impacts to soil water content. Each planted area had a 50-cm buffer of weeded, graveled soil on all sides to minimize edge effects.

Seed sowing

Local cheatgrass seeds were collected in summer 2019 at the Boise site and in summer 2020 at the Cheyenne site. The seeds were cleaned, screened for disease (i.e., smut fungus, *Ustilago bullata*.) and glued to the shaft of marked toothpicks (12 cm length), using a small amount of inert, water soluble glue (Elmer's brand, all-purpose glue). The toothpicks and seeds were then inserted into soils such that the seed tip was just below 2.5 cm depth from the soil surface. The toothpicks enabled us to identify seeded plants separately from seedlings that emerged from background seed banks. Seeds were placed on toothpicks such that awns were facing upwards (away from tip) and palea facing away from the toothpick with glue on the lemma to prevent interference with germination. Seeding occurred on the 30th of September and 1st of October 2020, at the Boise and Cheyenne sites, respectively, by using a narrow-gauge nail pressed into soil to create a pilot hole in the soil for each toothpick.

Soil Sensors

At the Boise site, a type-T, copper-constantan thermocouple with a 1-cm sensing length embedded with epoxy into a narrow plastic pipette tip was inserted into the soil at the center of each plot's planted area to measure temperatures at 0–1 cm depth in the actual soil (i.e., 1–2 cm depth below the top of the gravel layer). Measurements were recorded using a CR1000 datalogger (Campbell Scientific Inc, Logan UT). At the Cheyenne site, combined volumetric water content and temperature probes (model 5TE, 5 cm, Decagon, Pullman, WA) were placed vertically at the center of each planted area and interfaced to Decagon EM50 dataloggers. The sensor prongs and housing were fully inserted into the soil such that temperature was measured across approximately 0–5 cm soil depth.

Sensors were read by the dataloggers at one-minute intervals and mean values were recorded hourly, and daily temperatures were then calculated as the mean of the maximum and minimum hourly temperatures for each day. Data from some sensors were excluded from the analysis due to repeated disturbance (i.e., chewing cords, moving of gravel) of the soil surface by animals and frost heave. Standard errors of the temperature measurements were calculated as the seasonal means of daily means of hourly standard errors between the two sensors for each treatment. At both sites, volumetric water content (VWC) data were collected, but results were unreliable due to equipment malfunction and freezing temperatures that led to frost heave and sensor displacement. Thus, a follow up experiment was done in spring 2022 where plots with black and white gravel were established and planted in the same manner at two sites: one hot and dry (mean annual temperature 10.9 C, mean annual precipitation 257 mm) and another cool and wet (mean annual temperature 8.4 C, mean annual precipitation 431 mm), both in southwest Idaho. In this follow-up experiment, instantaneous VWC measurements from 10 plots per treatment were obtained with probes connected to a hand-held reader temporarily inserted from 0–5 cm depth at two different phenological periods – early spring melt, and at seed ripening (model EC5, Decagon, Pullman WA, i.e., sensor not continuously recorded). These spatially robust snapshot measurements of VWC were made halfway between the edge of each plot and the planted area.

Monitoring and harvest

Beginning in March 2021, height and phenological stage were monitored every 2–3 weeks. During the first visit, the first five germinants encountered in the grid were marked for repeat sampling. Plant height, specifically the vegetative height up to the tip of the longest leaf, was measured to 0.1 mm, by gently stretching the tallest leaf for each plant along a ruler and measuring the length to the base of the plant. Phenological stage was monitored according to a protocol adapted from Moore et al. 1991 where "V0" indicated plants with an emerged but not fully developed leaf, or "V1", "V2", or "V3" indicated plants having 1, 2, and 3 fully grown leaves, respectively, or "$>$ V3" indicated plants with more leaves that had not reached the "boot" stage in which seed heads swell inside flag leaf sheaths. After seeds began developing, flowering stages were recorded according to seed colors where early seed development was 'green' and as plants began to senesce seeds turned 'purple', and finally, when plants and seeds began to brown, plants were classified as 'ripening'.

Plants were harvested individually once they reached the 'ripening' stage by clipping at the soil surface, dried at 60 °C and weighed for biomass. Seeds were separated from the plants after drying and 50 seeds were weighed to generate a per-seed weight. All seeds from each plant were then weighed and the per-seed weight used to calculate seed production i.e., fecundity.

Site and long-term soil climate

Site-level 30 year climate normals were extracted from the 4-km resolution gridded PRISM dataset (Prism Climate Group 2014). PRISM data were downloaded and processed using the *prism* (Hart and Bell 2015), *raster* (Hijmans 2022), *rgdal* (Bivand et al. 2022), *sp* (Pebesma and Bivand 2005), and *rgeos* (Bivand and Rundel 2021) packages in R (R Core Team 2020). Daily local weather data were aggregated from the Boise Idaho Airport weather station 5.7 miles from the Boise field site (National Centers for Environmental Information: Climate Data Online), and the High Plains Grasslands Research Station Weather Station near Cheyenne, Wyoming, each of which provided archived hourly precipitation, temperature, wind speed, barometric pressure, dewpoint, snow depth, and relative humidity. Cloud cover data were obtained from the United States National Center for Environmental Prediction Atmospheric Model Intercomparison Project using Google Earth

Table 1 Treatment effects on biophysical variables and plant demographics. Mean soil temperature and days above 0 °C from planting to harvest are shown for the colored gravel and density treatments. Germination counts at first census (Boise: October 30th, 2020; Cheyenne: March 5th, 2021) are shown as an average percentage of planted seeds by treatment (25 seeds total). Plant heights are shown at the time of harvest (Boise: June 8th; Cheyenne: July 22nd). Where present, letters indicate significant differences ($P < 0.05$) for groups within each site and survey date according to the Least Significant Difference means comparison test

Site	Treatment	Planting Density	Mean Soil Temperature (Annual, SE)	Days > 0 °C	Germination	Plant height (SE)	Biomass (SE)	Biomass (SE)	Fecundity (SE)
Boise			°C	Days	% of seeds	mm	g/plot	g/plant	seeds/plant
	Black-gravel	High	10.9 (1.2)a	204a	70 a	191.0 (45.1) a	3.8 (0.7) bc	0.22 (0.035) a	40 (8) a
		Low	11.2 (0.50)a		84 a	133.9 (26.5) b	1.0 (0.2) c	0.31 (0.27) a	44 (37) a
	White-gravel	High	8.4 (0.31)b	180b	58 ab	57.5 (10.3) c	4.1 (1.6) bc	0.29 (0.19) a	68 (46.6) a
		Low	8.5 (0.19)b		68 a	111.0 (34.4) b	10.5 (7.5) bc	0.98 (0.82) a	175 (137) a
	Ambient	High	8.2 (0.57)b	193ab	8 bc	122.5 (52.8) b	7.4 (6.2) bc	0.38 (0.30) a	76(60) a
		Low	9.9 (0.49)ab		28 c	101.3 (31.1) bc	3.0 (2.6) bc	0.26 (0.027) a	48(6) a
Cheyenne	Black-gravel	High	8.2 (0.39)a	227a	34 a	307.0 (24.1) a	42.9 (35.7) abc	4.47 (2.1) a	1195 (647) a
		Low	8.2 (0.20)a		34 a	287.4 (23.5) ab	50.2 (2.2) ab	6.78 (2.0) a	1625 (473) a
	White-gravel	High	6.9 (0.17)ab	206b	4 b	311.6 (21.8) a	42.0 (17.7) abc	4.45 (0.98) a	1354 (360) a
		Low	6.5 (0.39)b		0 b	303.1 (21.9) ab	90.3 (0.4) a	6.61 (1.6) a	1637 (333) a
	Ambient	High	7.7 (0.26)ab	224a	30 a	237.4 (26.8) ab	34.8 (26.1) bc	2.21 (1.6) a	619 (419) a
		Low	7.8 (0.16)ab		10 b	236.9 (28.7) b	51.4 (40) ab	5.10 (3.2) a	1182 (957) a

Table 2 Significant effects of treatments on soil temperature and significant drivers of differences between gravel treatments are shown according to F values of repeated measures ANOVA and significance, where '.' $P<0.10$ *$p<0.05$, ** $p<0.01$, ***$P<0.001$, N.S. indicates no significance. Hourly temperature measurements were analyzed in the soil temperature model where sensor ID was used to control for error associated with repeated measures while there was no random effect in the temperature difference model

		Boise				Cheyenne			
Response variable	Predictor variable	d.f	Coefficient (SE)	F	Significance	d.f	Coefficient (SE)	F	Significance
Soil temperature	Gravel color	2	0.33	12.4	*	2	0.673	44	**
	Seeding density	1	0.00028	0.014		1	0.006	0.26	N.S
	Date/Time (hourly)	5121	0.99	286	***	2015	0.994	1206	***
	Gravel color: seeding density	2	0.016	0.40	N.S	2	0.046	1.0	N.S
	Gravel color:Time	10,242	0.41	1.1	***	4030	0.393	2.3	***
	Seeding density:Time	5121	0.41	2.2	***	2015	0.110	0.86	N.S
	Gravel color: seeding density:Time	10,242	0.27	0.61	N.S	4030	0.178	0.75	N.S

Engine (Kanamitsu et al. 2002; Gorelick et al. 2017). Weather stations were located at approximately the same elevation and aspect as each site (flat ground) but were not co-located with the experiments. Days above 0 °C were calculated as the number of days that mean soil surface temperature was greater than 0 °C in each temperature treatment only for days where 24 h of data were available for at least one sensor per treatment combination (218 and 289 days for Boise and Cheyenne, respectively; Ball et al. 2004).

Statistics

We analyzed data from the Boise and Cheyenne sites separately due to differences in soil temperature depths. To assess gravel color and planting density effects on both mean soil temperature and the number of days where the soil was > 0 °C, two factor General Linear Models with Least Significant Difference tests were used (Table 1). The effect of the gravel treatments on hourly soil temperatures within each treatment was analyzed by repeated measures ANOVA with individual sensors as the experimental units (Table 2). Hourly timepoints were only included if all sensors reported data for all 24 h of a particular day.

We also tested for the effect of gravel color, planting density, and their interaction on plant height over the entire experiment using a Generalized Linear Model with sampling date and individual plant ID as random variables (Table 3). To distinguish treatment effects on cheatgrass height, seed production and biomass at our final monitoring date (harvest), a two factor General Linear Model with Least Significant Difference tests was used to assess differences in plant height, plant biomass, and seed production according to gravel and planting density treatments (Table 1).

A General Linear Model was constructed to evaluate the difference in temperature between black and white gravel treatments as a response to daily averages of cloud cover, barometric pressure, wind speed, relative humidity, dew point, snow depth, precipitation, and temperature (Table 3). We selected covariates by first testing for multi-collinearity which revealed correlation between several variables associated with wind speed, the strongest co-variate with our response variable was kept. Where variables were not normally distributed, they were log transformed. To fit the model, we generated a model including all covariates, then removed the least significant variable one at a time until the model with lowest AIC was found (Aho et al. 2014). All final models were evaluated for accuracy by plotting model predicted vs model residual values,

Table 3 Significant effects of treatments on plant height according to Student's T values, where '.' P < 0.10 *p < 0.05, ** p < 0.01, ***P < 0.001, N.S. indicates no significance. Plant ID and date are controlled as random effects. Intercept values are the "base" for which all other level are compared to. Conditional R^2 was 0.74 and 0.78 for the log(plant height) models of Boise and Cheyenne, respectively. Adjusted R^2 was 0.51 and 0.53 for the ΔTemperature models of Boise and Cheyenne, respectively

		Boise				Cheyenne			
Response variable	Predictor variable	d.f	Coefficient (SE)	t	Significance	d.f	Coefficient (SE)	t	Significance
log(Plant height)	Intercept (high density/ ambient)		4.23 (0.26)	16.0	***		3.92 (0.45)	8.7	***
	Low Density	268.9	-0.42 (0.10)	-4.4	***	368.9	-0.28 (0.13)	-2.2	*
	White Gravel	268.5	-0.66 (0.087)	-7.6	***	369.0	-0.12 (0.12)	-0.93	N.S
	Black Gravel	268.2	0.40 (0.086)	4.7	***	371.9	0.21 (0.13)	1.7	
	Low Density: white	269.0	0.60 (0.13)	4.6	***	368.4	0.03 (0.17)	0.15	N.S
	Low Density: black	268.8	-0.01 (0.13)	-0.090	N.S	370.4	0.08 (0.18)	0.43	N.S
Temperature difference (Black-white gravel)	Intercept		3.69 (0.79)	4.67	***		2.54 (0.20)	12.8	***
	Air temperature	200	0.032 (0.0092)	3.49	***	283	0.049 (0.005)	10.6	***
	Daily precipitation	200	-2.053 (0.86)	-2.39	*	–	–	–	–
	Daily average wind speed	200	-0.096 (0.022)	-4.31	***	283	-0.079 (0.017)	-4.5	***
	Cloud Cover	200	-0.0074 (0.0031)	-2.37	*	283	0.0008 (0.0018)	0.42	N.S
	Daily average relative humidity	200	-0.025 (0.0072)	-3.48	***	283	-0.012 (0.0025)	-4.8	***

which were never correlated. All mixed effects models were run using the package *lme4* in R (Bates et al. 2015; R Core Team 2020).

Results

Site and soil climate

Daily mean soil-surface temperatures in black-gravel plots were 2.6 °C and 1.6 °C warmer than white-gravel plots and 2.1 °C and 0.6 °C warmer than untreated plots, at the Boise (0–1 cm sensor depth) and Cheyenne (0–5 cm depth) sites on average, respectively (Table 1, Fig. 1). Black-gravel plots were warmer than white-gravel plots on 99% and 95% of days at Boise and Cheyenne, respectively (Fig. 1). Repeated measures ANVOA models of soil temperature showed significant effects of gravel color at both sites, and of planting density at the Boise site (Table 2). A General Linear Model described 51% and 53% of the variability in the difference in temperature between colored gravel treatments at Boise and Cheyenne, respectively, with highly significant positive effects of daily air temperature (positive coefficient) and negative effects of relative humidity and wind speed that counteracted the effect of gravel on soil temperature (Table 2). The effect of cloud cover negatively impacted treatment effects at the Boise site but was not significant in Cheyenne (Table 2).

There were diurnal fluctuations in the temperature effects of the gravel treatments with the greatest difference between treatments apparent in the afternoon and evening (> 5°C) and little difference by midnight (Fig. 2). Temperature differences were maintained when cloud cover was absent, and to a lesser extent on cloudy days, but not while the plots were covered in snow (Fig. 2, Table 2). However, temperature differences between treatments were evident within two days of snowmelt (Fig. 2). Treatment effects on

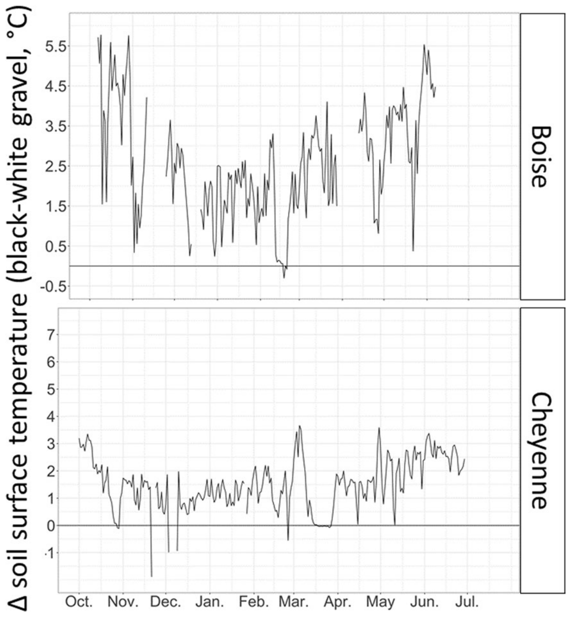

Fig. 1 Differences between daily average soil surface temperatures for black compared to white gravel for Boise (Top) and Cheyenne (Bottom) sites

temperatures were most evident in spring and fall (Fig. 1, S2). Black-gravel plots were also warmer than white-gravel plots overnight, with a more pronounced effect at the Cheyenne site (Fig. S3). The net effect of temperature differences was apparent in the number of days above 0 °C. Relative to ambient, i.e., no gravel, plots, days above 0 °C increased by 3–11 days in black-gravel plots and decreased by 13–18 days in white-gravel plots depending on site and planting density (Table 1).

In the follow up study at two different sites in southwest Idaho in spring 2022 we found that VWC was significantly greater under white compared to black-gravel plots, both early and late in the cheatgrass growing season, and across both the relatively warm/dry and cool/wet sites. Differences between gravel colors were more pronounced later in the growing season as well as in the hot and dry site compared to the cool and wet site (Fig. S4).

Demography

At both the Boise and Cheyenne sites, plant height at harvest varied as a function of both planting density and gravel treatment (Fig. 3; Table 1, 2). The main effects of low-density planting or white-gravel were shorter plants while high-density planting or black-gravel yielded taller plants (Table 1, Fig. 3). At the Boise site, an interaction between planting density and gravel treatment also occurred: plant heights were greater in white-gravel low-density plots than in white-gravel high-density plots (Fig. 3; Table 1). For ambient and black-gravel plots, high-density planting led to greater plant heights. No significant differences were identified in per plant biomass or seed production at harvest between treatments, however, a non-significant trend towards higher mean biomass and seed production in low density and in white-gravel plots suggests that soil climate had an effect that might be detected with additional replicates (Table 1). Plot scale biomass was highest in low density white-gravel plots at both sites, but differences were not statistically significant.

Phenology

Across both sites, phenology was accelerated on black-gravel plots compared to white-gravel plots. In the Boise site, at the first census in mid-March, 73% of plants in black-gravel plots were in the V3 or later stage (i.e., had greater than 3 fully developed leaves), compared to only 20% of plants in white-gravel plots (Fig. 4). In the Cheyenne site, most plants in the black-gravel plots had reached the V1 growth stage (i.e., one fully developed leaf) by early April, while most plants in the white-gravel plots did not reach this stage until early May (Fig. 4). Across sites, plants were similarly developed across black- and white-gravel treatments at harvest time despite growth differences in the early season. Differences in phenology between planting densities were less apparent, although results from the Cheyenne experiment suggest accelerated ripening of seeds in the high-density treatment (Fig. S5).

Discussion

Gravel treatment effects on soil climate

Addition of colored gravel to soil surfaces significantly changed soil-surface temperatures and VWC, and impacted cheatgrass growth and phenology across two

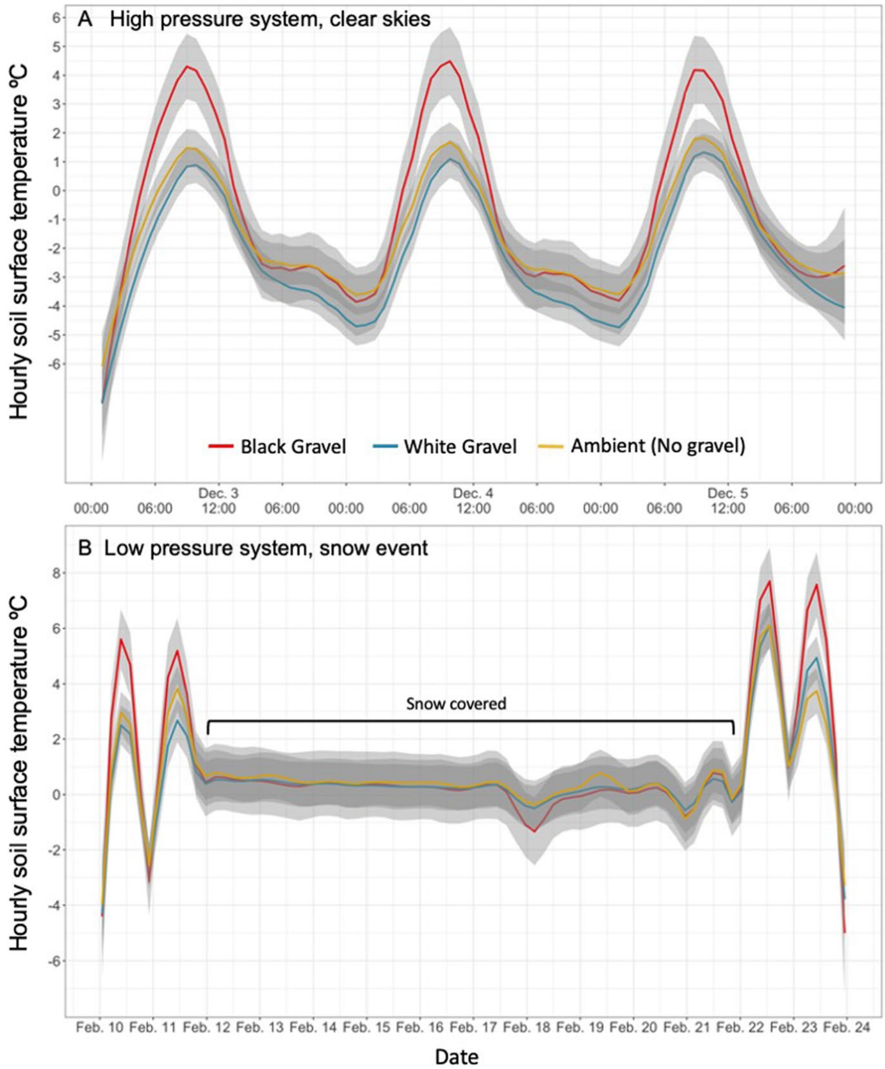

Fig. 2 Diurnal cycles of soil temperature during a period with no cloud cover in Boise (A) and hourly data showing diurnal cycles of soil temperature before, during, and after a snow event at the Boise site (B) where 23 cm of snow fell between February 12th and 14th and remained through February 21st. Treatments are indicated by color where ambient is yellow, white-gravel is blue, and black-gravel is red, with 95% confidence intervals in grey shading. Strong treatment effects were observed on February 10th (clear skies) in addition to February 11th (cloudy skies), and treatment effects resumed by February 23rd following snowmelt

semiarid sites with different climate patterns, native plant communities, and cheatgrass phenology. These patterns fit with previous studies that showed increased temperature and decreased water content under black compared to white sand (Boyd et al. 2017). Gravel effects on soil temperature were counteracted by latent heat loss, cloud cover, and convective cooling, as indicated by negative coefficients in a linear model (Table 2). Substantial differences in soil temperature between black-gravel and white-gravel plots led to approximately 3-week differences in growing season length at both sites, where the difference mostly occurred as an extension of the fall growing season at the Boise site, and was evenly distributed between fall and spring at the Cheyenne site (Fig. 4). Observed diurnal differences between treatments were sustained across a wide range of snow-free weather conditions, and the daily mean treatment effects were still strong > 9 months after application, indicating at least one growing season of robust treatment effects from our gravel application. The difference in the effective growing season length was the result of mean 1.6–2.6 °C warming by black gravel compared to white gravel, which is similar to increases projected for the twenty-first century (IPCC 2018) (Fig. 2). Our experimental treatment created diurnal asymmetry of warming where the greatest differences in treatment effects (up to 14 °C) occurred daily between 12:00 noon and 18:00. However, nighttime differences between black-gravel and white-gravel treatments were still generally positive (ranging from ~ 0–2 °C), depending on the weather (Fig. S3), indicating that

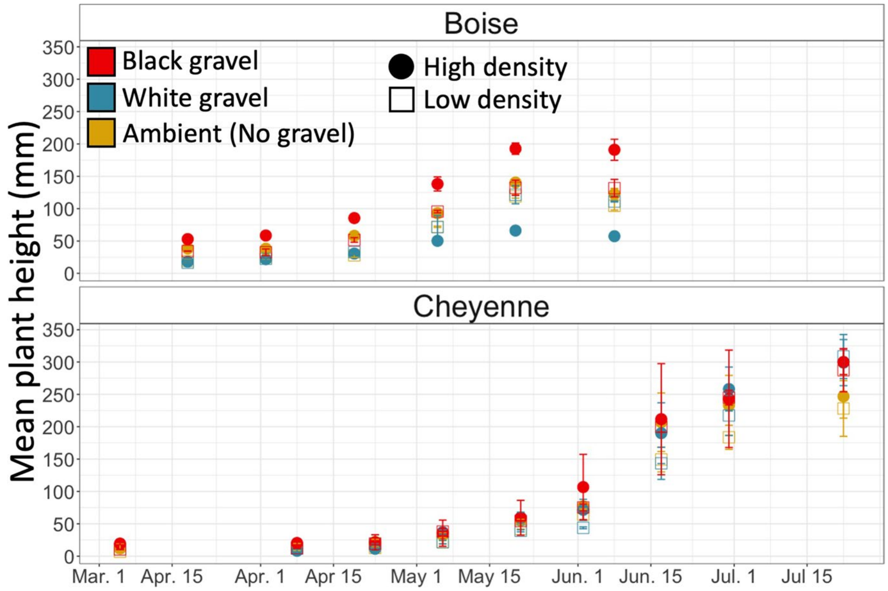

Fig. 3 Mean plant length (height) ± standard error of each treatment combination over the course of the spring growing season. Ambient plots are in yellow, white-gravel in blue, and black-gravel in red, with high density plantings represented by filled circles, and low-density planting represented by open squares. Harvest occurred on the final sampling date which was June 8th at the Boise, and July 22nd at the Cheyenne site

the effect of the treatments penetrated deep enough into the soil to buffer the lack of treatment forcing in absence of solar radiation, overnight. This pattern of temporal asymmetry is only partially consistent with greenhouse-gas induced warming that increases downwelling long-wave radiation and mainly increases nighttime minimum temperatures indicating that this method is appropriate for simulating seasonal but not diurnal shifts in temperature that are expected with climate change (Vose et al. 2005). In the follow up study, black-gravel treatments always had lower VWC than white-gravel, suggesting that differences in soil temperature between treatments were large enough to override the mulching effect of gravel coverings on soil water content (Fig. S4).

The colored-gravel treatment effects on soil temperature at the Cheyenne site were generally similar to those observed at the Boise site, with some small differences. Differences in effect sizes could reflect differences in either site conditions or sensor depths. We cannot separate the effects of site identity and sensor depth and type on the treatment effects, but it is nonetheless noteworthy that the colored gravel significantly impacted the soil across the deeper, 5-cm soil measurement zone at the Cheyenne site. The colored gravel treatments significantly impacted soil temperature in the germination zone (as indicated by treatment effects on soil surface temperature, days above 0 °C and germination rates, Tables 1, 2). The similarities in colored-gravel treatment effects on cheatgrass across the two sites suggest a degree of generalizability.

Treatment effects on phenology and growth of cheatgrass

Warmer soils in black gravel treatments led to advanced phenology and greater plant height. The mechanism is likely associated with the strong treatment effects that increased growing season length by up to three weeks in black-gravel plots, with most of the additional days above 0 °C occurring in the fall and winter. Similarly, experimental warming with infrared heaters or open top chambers has been found to hasten cheatgrass phenology and increased biomass production in previous studies, including one at the Cheyenne site studied here (Blumenthal et al. 2016; Howell et al. 2020). In the Western US, cheatgrass often germinates in the fall, and when successful, this early germination can confer an advantage to those individuals that are already established by the time the soil melts in spring (Mack and Pyke 1983). Our results show that warming of > 1.6 °C can modify soil conditions to favor early germination, produce taller plants, and accelerate phenology.

Higher density cheatgrass plantings led to warmer temperatures and taller plants at the Boise site in black-, but not white-gravel plots, suggesting that temperature was a stronger driver than competition for light in determining plant height in high density plots. Despite this interaction at the Boise site, plants were generally taller in high density compared to low density plots (Tables 1

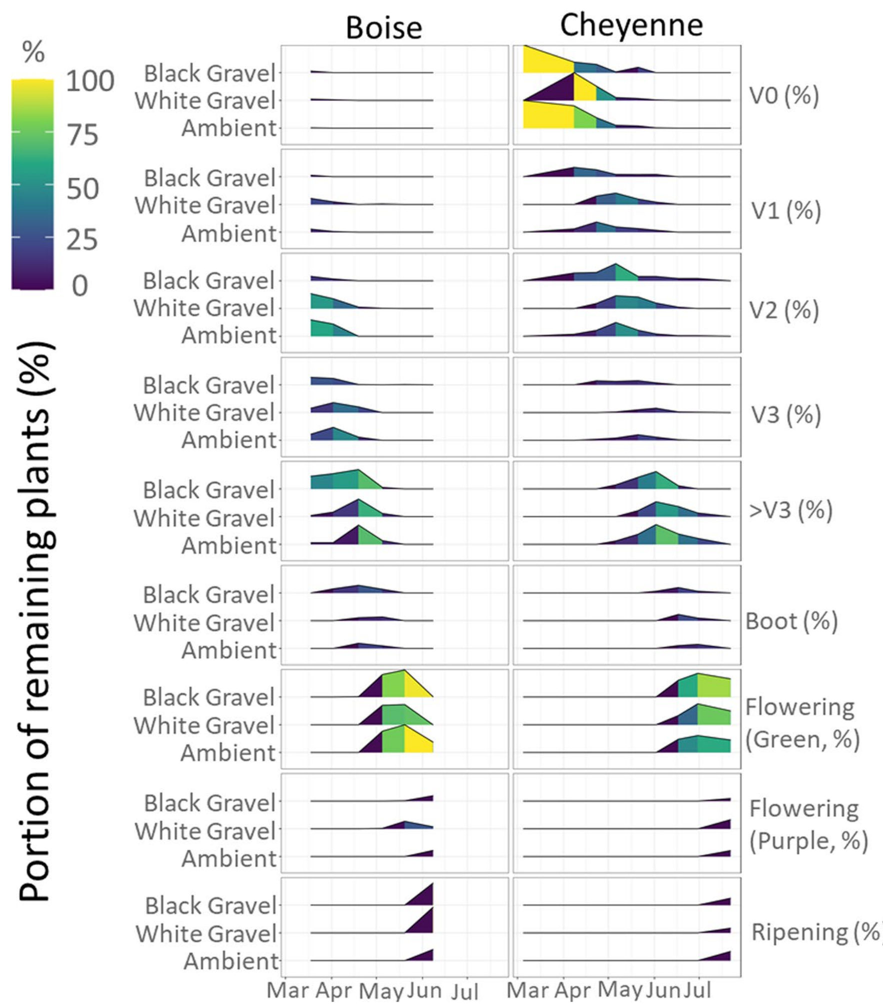

Fig. 4 Phenological response to gravel-color treatments. Panels show the percent of alive ("remaining") plants exhibiting the respective phenological status (scale of each Y-axis) is 0–100% between light grey gridlines and is also represented by the purple to yellow color gradient where the color represents the survival percentage at the beginning of a particular time period. V0: Emerged leaf not fully developed; V1: 1 fully emerged leaf; V2: 2 fully emerged leaves; V3: 3 fully emerged leaves; > V3: More than 3 fully emerged leaves; Boot – Seeds swelling in flag leaf; Flowering 1: Green seeds emerged; Flowering 2: Purple seeds emerged; Ripening: seeds browning

and 2) which suggests that high density cheatgrass growth is at least partially limited by access to light, but that cheatgrass responds to this limitation by etiolating. Two potential mechanisms may explain increased plant height in our high-density black-, but not white-gravel plots. First, the greater density, i.e., clustering, of cheatgrass plants may have imposed greater aerodynamic resistance, i.e., lower windspeeds in plots, in turn reducing the convective cooling that counteracted the added radiative heating that occurred in black gravel plots. In this scenario, the cooling effect would not be a primary driver of differences in growth between high and low density white-gravel plots because they were overall cooler (Goldberg et al. 2001). A second potential mechanism is that greater VWC in white gravel plots led to the well documented effect of decreasing root growth (but increasing aboveground growth), but only in lower density white gravel plots where competition for resources was presumably relatively less (Casper and Jackson 1997).

Method evaluation and applicability beyond this study

Altering soil climate via colored gravel is suited to ecosystems where canopy cover is sparse and, thus, exposure of the soil surface to solar radiation is relatively high. The magnitude of the gravel color effect on temperature depended on air temperature, average wind speeds, cloud cover and relative humidity (Table 2). Nonetheless, significant differences in temperature between the gravel color treatments were maintained over the course of the winter at both sites, where air and soil temperatures were often below 0 °C. Other factors that could have diminished the albedo effect of the gravel include 1) deposition of dust or degradation of pigment color intensity (e.g., by UV) and thus shortwave energy absorbance of the gravel, 2) high winds causing convective heat exchange that counteracted the altered solar radiation balance, or 3) snow or foliar canopy cover that shaded the gravel. The treatments maintained significant temperature effects over the course of this experiment even though each of these conditions was at least briefly met.

The colored gravel method relies on manipulating albedo to alter the radiant energy balance at the soil surface and thus does not interfere with gas exchange or altered precipitation inputs. Other methods of manipulation such as OTCs may simulate unlikely climate conditions, for example, 1) warming in conjunction with decreases in vapor pressure deficit, 2) extreme surface temperature increases of up to 20 °C or 3) altered diurnal temperature patterns, especially when the soil is wet due because OTCs limit convective heat transfer (Aronson and McNulty 2009). Our gravel treatments avoid most these unwanted experimental artifacts. One limitation of both OTCs and colored gravel is the lack of temperature control where different site conditions (or vegetation communities within a site) may alter the magnitude of the effect of the manipulation. Additionally, differences in soil moisture in either method may impact soil nutrient availability and growing season length. Neither approach mimics the diurnal patterns of heat flux that have resulted from rising atmospheric CO_2 concentrations, however the gravel method does maintain higher temperatures in black-gravel plots compared to white gravel plots throughout the night (Fig. 2A). Nonetheless, we found that our treatments performed across a range of weather conditions expected in rangelands of the sagebrush steppe and mixed-grass prairie, suggesting that the use of colored gravel to manipulate surface albedo is an effective treatment for climate manipulation studies of germinating plants in these regions.

Implications

Black gravel (i.e., soil surface warming) led to accelerated phenology, especially in the early growth stages for cheatgrass, but did not have a clear effect on late season growth, seed ripening, or fecundity in our study. Our results suggest that cheatgrass could flower earlier under warming or dry conditions, but more research is needed because other studies have shown that responses to spring weather conditions may be driven more by local (genotypic) adaptation rather than by weather (Rice et al. 1992). More generally, given sufficient fall and spring moisture, cheatgrass is likely to have an increasing competitive advantage in warmer conditions due to its ability to germinate and grow earlier than other species (Roundy et al. 2007; Zelikova et al. 2013).

Spraying pre- and post-emergent herbicides is a common and effective tool that can limit early germination, but the application must occur in specific phenological windows (i.e., just prior to germination) to maximize efficacy (Young and Clements 2000; Donaldson and Germino 2022). Similarly, control of cheatgrass using targeted grazing (e.g., Bailey et al. 2019; Porensky et al. 2021) relies on the accurate identification of specific plant phenological windows during which the plant is palatable and preferred over native species. Land managers must consider soil surface conditions (e.g., albedo) in addition to local weather to anticipate germination timing and plan management activities. Our results also suggest that other factors contributing to the success of annual grasses more generally – e.g., dense thatch layers that tend to form in annual grass dominated plant communities (Jones et al. 2015) – may operate via alterations to the soil surface, creating a warmer and wetter microclimate. Thatch thickness, and accordingly its effect on microclimate, will vary by annual grass species and invasion severity, impacting phenology and the ideal timing for management interventions (e.g., herbicides, Germino et al. 2016b). Our research found that climate, plant community and disturbance effects on soil surface conditions must be considered to accurately predict cheatgrass growth patterns and to successfully manage its spread.

Conclusions

Climate change impacts are a concern for managing rangelands (Polley et al. 2013), and experimental manipulations allow us to measure plant sensitivity to directional temperature variation. We tested a new experimental method by using black and white gravel to alter soil albedo and found that it effectively changed soil surface temperatures. Using this method, we found that 1) altered soil albedo impacted soil microclimate which 2) affected cheatgrass growth and phenology. We note that interpretation and implementation of our method should consider temporal and spatial asymmetry in thermal effects and how they relate to expected temperature variation under future climate scenarios across the many climate zones that occur in Western US rangelands.

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Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Toby Maxwell and Seth Romero. The first draft of the manuscript was written by Toby Maxwell and Matt Germino and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests Cynthia S. Brown is partially supported by the Colorado Agricultural Experiment Station**.** Toby M. Maxwell, Matthew J. Germino, Seth Romero, Lauren M. Porensky, Dana M. Blumenthal and Peter Adler have no relevant financial or non-financial interests to disclose.

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