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Climate cooling benefits of cellulosic bioenergy crops from elevated albedo

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Abstract

Changes in land surface albedo can alter ecosystem energy balance and potentially influence climate. We examined the albedo of six bioenergy cropping systems in southwest Michigan USA: monocultures of energy sorghum (*Sorghum bicolor*), switchgrass (*Panicum virgatum* L.), and giant miscanthus (*Miscanthus × giganteus)*, and polycultures of native grasses, early successional vegetation, and restored prairie. Direct field measurements of surface albedo (α_s) from May 2018 through December 2020 at half-hourly intervals in each system quantified the magnitudes and seasonal differences in albedo (Δ_α) and albedo-induced radiative forcing ($RF_{\Delta\alpha}$). We used a nearby forest as a historical native cover type to estimate reference albedo and $RF_{\Delta\alpha}$ change upon original land use conversion, and a continuous no-till maize (*Zea mays L.*) system as a contemporary reference to estimate change upon conversion from annual row crops. Annually, α_s differed significantly ($p<0.05$) among crops in the order: early successional (0.288±0.012SE) >> miscanthus (0.271±0.009)≈energy sorghum (0.270±0.010)≥switchgrass (0.265±0.009)≈restored prairie (0.264±0.012)> native grasses (0.259±0.010)> maize (0.247±0.010). Reference forest had the lowest annual α_s (0.134±0.003). Albedo differences among crops during the growing season were also statistically significant, with growing season α_s in perennial crops and energy sorghum on average ~20% higher (0.206±0.003) than in no-till maize (0.184±0.002). Average non-growing season (NGS) α_s (0.370±0.020) was much higher than growing season α_s (0.203±0.003) but these NGS differences were not significant. Overall, the original conversion of reference forest and maize landscapes to perennials provided a cooling effect on the local climate ($RF_{\alpha MAIZE}$: $-3.83\pm1.00\,W\,m^{-2}$; $RF_{\alpha FOREST}$: $-16.75\pm3.01\,W\,m^{-2}$). Significant differences among cropping systems suggest an additional management intervention for maximizing the positive climate benefit of bioenergy crops, with cellulosic crops on average ~9.1% more reflective than no-till maize, which itself was about twice as reflective as the reference forest.

KEYWORDS
albedo, bioenergy, climate impact, cropland, forest, land use change, radiative forcing

1 | INTRODUCTION

Land surface albedo (α_s), the ratio of outgoing shortwave radiation to the incoming shortwave radiation (Henderson-Sellers, 1980; Henderson-Sellers & Hughes, 1982; Russel, 1916), is one of the most important measures in radiation and energy budgets (Bright, 2015; Chen et al., 2021). Albedo is a vital indicator of energy partitioning because it reflects solar energy absorbed by a land surface (e.g., grasslands, forest, or urban lands) and then converted to heat, versus the amount reflected back to space with no warming impact (Ollinger et al., 2008). Theoretically, if more solar radiation is reflected back to space, the global climate is cooled—raising the potential for contributing to climate change mitigation through land surface management (Bright et al., 2012; Carrer et al., 2018, 2021; Muñoz & Kravchenko, 2011; Ouyang et al., 2022). Spatial and temporal changes in albedo have been closely explored, as albedo not only directly affects climate warming and cooling (Campbell & Norman, 2012) but also indirectly affects changes in evaporation and transpiration, and also local climate through its impact on surface energy fluxes and the hydrologic cycle (Akbari et al., 2009; Cherubini et al., 2012; Pachauri et al., 2014).

Promoting cellulosic bioenergy crops has been proposed as a way to replace fossil fuels to reduce emissions of greenhouse gases (GHG) to the atmosphere (IPCC, 2022; Robertson et al., 2017, 2022). Albedo change upon conversion of prior vegetation to cellulosic crops could either attenuate or magnify this benefit depending on its effects on radiative forcing—with the exact magnitude not yet fully resolved because of nonlinear effects, large uncertainties for multi-century processes, and assumptions about changing atmospheric conditions when converting albedo to radiative forcing (Chen et al., 2021). Critically, research on albedo in agricultural landscapes is still severely lacking (Flato et al., 2013; Henderson-Sellers & Wilson, 1983; Ouyang et al., 2022; Smith et al., 2020). The albedo of short-statured vegetation such as grasslands is likely to be more variable than forests due to differences in surface emissivity—the amount of radiant heat which has been reflected or absorbed—which can in turn affect vegetative indices of evaporation and transpiration, and plant phenology (e.g., canopy height and leaf area and duration). In annual croplands, agronomic management practices such as tillage, fertilization, and cover crops can further affect albedo (Pielke Sr et al., 2011). Thus, the impacts of large-scale cellulosic bioenergy production on land surface albedo could be significant, where perennial bioenergy grasses' replacing row crops could lead to significant changes in regional temperature.

Previous studies on albedo-induced warming effects are mostly based on satellite data (Fang et al., 2007; Sciusco et al., 2020, 2022; Zhang et al., 2010), while biophysical models (Cherubini et al., 2012; Smith et al., 2020) and ground surface measurements (Abraha et al., 2021; Miller et al., 2016) have been lacking. Within the latter studies, measurements have been restricted to the effects of albedo on only one to two bioenergy crop species, over very short periods that do not thoroughly inform longer temporal changes, through the use of remote sensing that can potentially miss entire portions of the growing season, or through modeling studies that may be oversimplified and not reflect realistic changes seen on the landscape. Very few studies have been based on ground measurements, which offer high spatial and even higher temporal resolutions. Our study offers a multi-year, highly resolved assessment of six alternative cellulosic cropping systems, including three polycultures, relative to both a contemporary annual crop that currently dominates the US Midwest and historical forest cover, in order to assess surface reflectivity on diverse types of land use management and in diverse ecosystems.

Here, we examine temporal changes in the albedo of managed bioenergy cropping systems by directly quantifying albedo-induced radiative forcing at half-hour intervals over monthly, seasonal, and annual periods for six bioenergy crops, a reference maize crop, and a reference forest in southwest Michigan USA. We hypothesize first that perennial crops will have a higher albedo compared to annual crops; second, that the surface reflectivity of crops will differ significantly by season (i.e., growing season, winter, monthly, annually); third, that the albedos of different bioenergy crops are time dependent as each species and ecosystem are affected by climate, seasonality, and agronomic practices; and finally, that there are landscape cooling differences between bioenergy cropping systems and our two reference systems of maize and forest. Our specific objectives are to: (1) estimate the magnitudes and temporal changes of albedo in different cellulosic bioenergy crops over a 3-year period, (2) compare these albedos to those of continuous maize and forest reference systems, and (3) quantify albedo-induced radiative forcing ($RF_{\Delta\alpha}$) to evaluate warming/cooling impacts on the climate.

2 | MATERIALS AND METHODS

2.1 | Study site

This study was conducted at the Biofuel Cropping Systems Experiment (BCSE, http://glbrc.org/ (See Figure S1 for description of experiment)) of the Great Lakes Bioenergy Research Center (GLBRC), located at the Kellogg Biological Station Long-term Ecological Research site in southwest Michigan, USA (Robertson and Hamilton, 2015; 42° 24' N, 85° 24' W, 288 m a.s.l.). The BCSE is located in a diverse, rural- to-semirural landscape with cropping systems typical of the upper Midwest US. The climate is humid continental temperate with a 30-year (1981–2010) average annual air temperature of 9.9°C, ranging from a monthly mean of −4°C in January to 23°C in July, and average annual precipitation of 1027 mm evenly distributed throughout the year (NCDC, 2013). Soils at the site are in the Kalamazoo and Oshtemo soil series, fine-loamy, mixed, semiactive, and Mesic Typic Hapludalfs formed under a forested landscape in loamy outwash overlaying sand and gravel (Crum & Collins, 1995; Thoen, 1990). BCSE systems were established in a randomized complete block design, replicated in five 30 meter × 40 meter plots (Gelfand et al., 2020).

A total of eight experimental units comprise this experiment. Six candidate bioenergy cropping systems include no-till energy sorghum (*Sorghum bicolor* (L.) Moench., an annual, photoperiod insensitive sorghum hybrid, TAM 17900); switchgrass (*Panicum virgatum L.*, variety Cave-in-Rock); giant miscanthus (*Miscanthus × gigantea*); native grasses (a polyculture of five grasses native to North America—Little bluestem (*Schizachyrium scoparium* [Michx.] Nash), Big bluestem (*Andropogon gerardii* Vitman), Canada wild rye (*Elymus canadensis* L.), Indiangrass (*Sorghastrum nutans* [L.] Nash), and switchgrass (variety Southlow); early successional vegetation (comprised of grasses and fobs from the pre-establishment seedbank and subsequent colonizers after land was abandoned); and restored prairie (a C3 and C4-species mix of species as described in Sanford et al. (2016) provided by a local prairie restoration contractor). Species composition of the successional and restored prairie systems are available at https://lter.kbs.msu.edu/datatables. Each bioenergy crop was planted and managed according to standard agricultural practices for the region (Table 1; Sanford et al., 2016). Additionally, two reference sites represent the historical and modern landscape: A continuous no-till maize (*Zea mays L.*) system representing a contemporary row-crop common in the US Midwest Corn Belt, and an 87-year-old managed hybrid-spruce forest located at the Kellogg Experimental Forest (KEF; 42° 21' N, 85° 21'W) depicting a 2.5-acre forest established in 1932 from abandoned agricultural land.

2.2 | Data collection and instrumentation

Continuous measurements of albedo at the BCSE and KEF were made from May 2018 to December 2020. At the BCSE site seven measurement stations were deployed at the BCSE in each of six cropping systems. Each station consisted of a tower equipped with a four-component net radiometer (SN-500, Apogee Instruments), two net radiometers (Q.7.1, REBS, USA), and one soil water content reflectometer (CS616, Campbell Scientific Inc. (CSI)). One tower was also equipped with a precipitation gauge (TE525, CSI) and temperature sensor to measure air temperature and relative humidity (HMP 60, CSI). Maize (in 2018) and restored prairie (in 2019) both included an additional four-component net radiometer. The heights of the towers in each plot were adjusted over the study period in order to maintain a field of view above the canopy layer. Sensors were

TABLE 1 Planting (P) and harvesting (H) dates (month/day) for all crops at the BCSE site

Year	Maize		Sorghum		Switchgrass		Miscanthus		Native grasses		Early succesional		Restored prairie	
	P	H	P	H	P	H	P	H	P	H	P	H	P	H
2008					6/19		5/23		6/17		5/05		6/17	
2018	5/01	10/04	6/02	11/07	—	10/24	—	11/07	—	10/24	—	10/24	—	10/24
2019	5/19	10/29	6/07	11/20	—	11/08	—	11/05	—	10/24	—	10/23	—	10/23
2020	5/13	10/29	5/27	11/17	—	11/03	—	11/14	—	11/03	—	11/03	—	11/03

placed ~30–40 cm above the canopies, consistent with other studies in agricultural landscapes (Raupach, 1994; Zeri et al., 2011). At the forested KEF site, we deployed an eddy covariance tower 34 m tall equipped with a four-component net radiometer (CNR4, Kipp & Zonen, Netherlands), precipitation gauge (TE525), and an IRGASON (CSI).

2.3 | Statistical analysis

Albedo (α_s) is the ratio of reflected ($SW_\uparrow$) to incident solar radiation ($SW_\downarrow$):

$$\alpha_s = \frac{SW_\uparrow}{SW_\downarrow}. \tag{1}$$

Our quality control protocols consisted of checking data for values within the expected range, e.g., $0 < \alpha_s < 1$; $0 < SW_\downarrow < 1500\,\mathrm{W\,m^{-2}}$. Data potentially subject to errors (i.e., instrument tilt; snow cover on an upfacing radiometer dome, temporary tower removal) were eliminated. In the case of maize and restored prairie, where two net radiometers existed simultaneously on the albedo tower, gap-filling was completed where needed. Otherwise, discarded observations were treated as gaps for both incoming and outgoing irradiance at the same interval for all sites. Larger gaps of several hours to up to 30 consecutive days occurred due to instrument failure (see Table S1 for complete tower coverage throughout the study period).

Change in albedo (Δ_α) in this study is determined as the albedo of a specific crop less the albedo of a reference (i.e., the forest or maize systems):

$$\Delta\alpha = \Delta s_{\mathrm{crop}} - \Delta s_{\mathrm{ref}}, \tag{2}$$

where Δ_α is the local change in albedo at a specific time, Δs_{crop} is the crop albedo and Δs_{ref} is the reference albedo. Here, we used both maize and forest as our reference landscapes. Maize is the dominant annual cropping system in the US Midwest, while spruce forest represents a major Michigan land cover type before European settlement (Brown et al., 2000); thus, both respectively serve as modern and historical references of representative landscape changes.

We calculated values for the growing season (GS), non-growing season (NGS), and annually. GS was defined as May through October (DOY of 121-304) following previous studies of similar bioenergy species in our region (Sciusco et al., 2020; Zeri et al., 2011), where plant emergence occurs in early May, and harvesting at the KBS BCSE is completed in November, after a killing frost. NGS includes all other days not defined as GS. The daily mean albedo for each site was computed by aggregating 5-minute data into half-hourly time steps.

Upwelling transmittance (T_a) is usually considered a constant average of 0.854 for clear sky conditions (Cherubini et al., 2012; Lenton & Vaughan, 2009). However, to reduce bias caused by day-to-day differences in cloud cover, T_a was manually calculated as the ratio of incoming solar radiation at the top of the atmosphere (SW_{TOA}) to that at the surface ($SW_\downarrow$), assuming a same value of upward and downward atmospheric transmittances (Carrer et al., 2018; Sciusco et al., 2020). $SW_\downarrow$ was obtained from each tower daily, while SW_{TOA} was calculated as:

$$Sw_{TOA} = I_{sc} \times I_\theta \times d_r, \tag{3}$$

where I_{sc} is the solar constant ($1367\,\mathrm{W\,m^{-2}}$), I_θ is the extraterrestrial irradiance intensity using the cosine of the solar zenith angle, and d_r is the average Earth-Sun distance calculated for each day of the year (see Chen et al., 2021 for a detailed model). The daily zenith angle was derived from NOAA Earth System Research Laboratories for calculating solar radiation (NOAA, 2005).

Radiative forcing provides a basis for comparing surface albedo with other climate forcing variables. Radiative forcing ($RF_{\Delta\alpha}$, $\mathrm{W\,m^{-2}}$) is calculated as

$$RF_{\Delta\alpha} = -\frac{1}{N}\sum_{N=1}^{N} SW_\downarrow \times \Delta_\alpha \times T_k, \tag{4}$$

where $RF_{\Delta\alpha}$ is the albedo-induced radiative forcing at the top-of-atmosphere, Δ_α is the mean albedo difference from a reference over a specific season, $SW_\downarrow$ is local incoming solar radiation, N is the number of days for each season (i.e., GS, NGS, annual), and T_k being the "two-way" transmittance of the atmosphere, calculated by $T_k = {T_a}^2$, where T_a is the upward atmospheric transmittance factor. Negative values of $RF_{\Delta\alpha}$ indicated a cooling effect due to increased albedo compared with the albedo of the reference site.

Differences in annual and seasonal albedo were analyzed by mixed models analysis of variance (ANOVA) using the statistical package R (R Development Team, 2013), with crop type as fixed effects and years as random effects. For all tests, the statistical significance using Tukey HSD was evaluated at $p < 0.05$. Diurnal changes in Δ_α for each site were also explored by analyzing daily averages between our reference sites of maize and forest. Finally, temporal variances in surface reflectivity affected by daily changes were modeled with a local polynomial regression (LPR). This nonparametric technique was used to determine a weighted average in order to fit a smooth curve between our variables. This allowed any daily estimates near "outlier" points from being highly biased while still ensuring a smooth fit (Cleveland et al., 1990).

3 | RESULTS

3.1 | Annual row crops

The average annual albedo of our annual row crops ranged from 0.212 ± 0.005SE in 2018, to 0.270 ± 0.010 in 2019 and 0.271 ± 0.010 in 2020 (Table 2). Energy sorghum (0.270 ± 0.010) and maize (0.247 ± 0.010) had lower albedos than most other cropping systems throughout the study period. During the growing season, maize albedo (0.184 ± 0.002) was lower than energy sorghum (0.208 ± 0.004) (Figure 1). During the non-growing season both crops had slightly higher albedos than most other cropping systems at 0.362 ± 0.018 and 0.373 ± 0.013, respectively.

3.2 | Perennial crops

Combined, perennial crops had consistently higher annual and growing season α_s compared to annual crops ($p < 0.05$) (Figure 1). Annual average α_s was highest in early successional (0.288 ± 0.010), and miscanthus (0.271 ± 0.010), intermediate in switchgrass (0.265 ± 0.01) and restored prairie (0.264 ± 0.010), and lowest in native grasses (0.254 ± 0.010). Among the perennial crop types, miscanthus had the highest mean growing season α_s in 2018 (0.251 ± 0.003) and 2019 (0.227 ± 0.002) and native grasses lowest (0.186 ± 0.002) (Figure 1a). Albedo was more variable during the non-growing season and ranged between 0.24 and 0.85. The non-growing season α_s was much higher than the growing season α_s but with statistically insignificant differences among crops.

3.3 | Comparisons across systems

Differences in the growing season α_s and annual α_s were statistically significant ($p < 0.05$) among crops and between forest and perennial crops, as well as between perennials and the maize system. The annual mean albedo for all systems ranged from 0.134 in the reference forest, 0.247 for the reference crop maize, to 0.264–0.288 for the six bioenergy crops (Table 2). Mean diurnal variation of α_s during different seasons were apparent for all sites, but varied in magnitude and by season and cropping system (Figure 2).

3.4 | Seasonality

Variations in α_s expected upon converting either maize or forest to a candidate bioenergy crop (Equation 2; Figure S2), were similar among crops across both growing season and annual time frames. Conversion of forest to bioenergy crops resulted in higher RFs than conversion of maize to bioenergy crops (Figure 3). Average cooling effects from modeling the conversion of maize to another bioenergy crop yielded $-3.83 \pm 1.00\,\mathrm{W\,m^{-2}}$ (Table 3), while modeled conversions from forest to another bioenergy crop showed a $-16.75 \pm 3.01\,\mathrm{W\,m^{-2}}$ cooling effect. Highest daily averages in mean growing season RF were observed in miscanthus (RF_{FOREST}: $-20.99 \pm 3.45\,\mathrm{W\,m^{-2}}$; RF_{MAIZE}: $-9.49 \pm 1.66\,\mathrm{W\,m^{-2}}$) and switchgrass ($RF_{FOREST}$: $-17.37 \pm 2.68\,\mathrm{W\,m^{-2}}$; RF_{MAIZE}: $-6.07 \pm 0.96\,\mathrm{W\,m^{-2}}$). There was also a clear seasonality in RF when modeling

TABLE 2 Growing season, non-growing season, and annual α_s (mean ± SE) for the six bioenergy crops, reference maize, and reference forest sites.

	Growing season			Non-growing season			Annual		
Crop	**Mean**	**SE**	**Sig.**	**Mean**	**SE**	**Sig.**	**Mean**	**SE**	**Sig.**
Maize	0.184	0.002	***	0.362	0.018	*	0.247	0.010	***
Sorghum	0.208	0.004		0.373	0.013		0.270	0.010	*
Switchgrass	0.217	0.004	*	0.373	0.014		0.265	0.009	*
Miscanthus	0.230	0.002	***	0.356	0.022	*	0.271	0.009	
Native grasses	0.186	0.002	***	0.354	0.020	**	0.259	0.010	***
Early successional	0.212	0.002	***	0.400	0.028	***	0.288	0.012	***
Restored prairie	0.187	0.005	***	0.372	0.027		0.264	0.012	**
Forest	0.123	0.002	***	0.145	0.005	***	0.134	0.003	***
Study period	0.203	0.003		0.37	0.02		0.266	0.01	

Note: Sig. represents p values showing level of significance among mean values: ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$,.: $p < 0.01$.

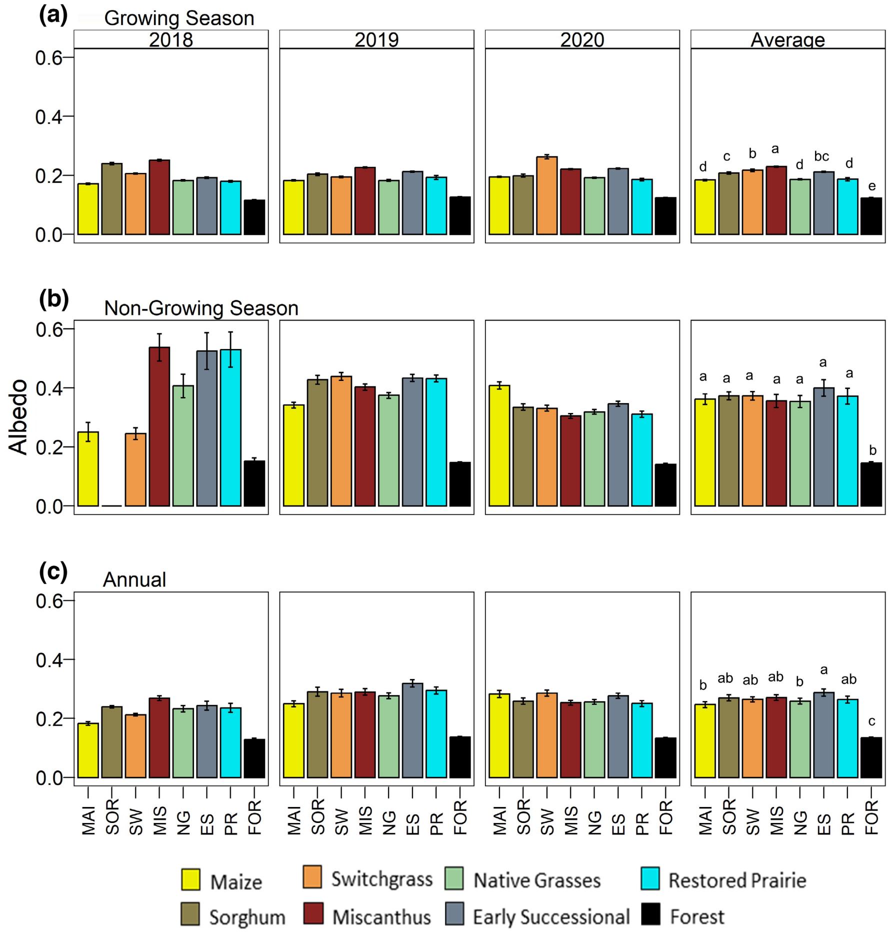

FIGURE 1 Mean albedo for (a) the growing season, (b) non-growing season, and (c) entire year for the six bioenergy cropping systems, the reference maize system, and the reference forest. Groupings of different letters indicate statistical differences ($p < 0.05$) for the three-year study period; error bars represent $\pm$1SE.

the conversion from annual row crop maize to another candidate crop. During the non-growing season, average cooling effects of maize were small, on the order of $-0.95 \pm 0.88\,\mathrm{W\,m^{-2}}$ (Table 3) for all perennials cropping systems versus a $-4.54 \pm 0.93\,\mathrm{W\,m^{-2}}$ during the growing season. Overall, early successional, miscanthus, and native grasses resulted in the greatest average annual cooling relative to the no-till maize system.

4 | DISCUSSION

We documented changes in α_s for six bioenergy cropping systems (energy sorghum, switchgrass, miscanthus, native grasses, early successional grassland, and restored prairie) in southwest Michigan USA to better understand differences in the potential contributions of albedo alterations to climate change. We also compared bioenergy cropping systems to reference systems of no-till maize and native forest. We are not aware of other studies comparing this many systems side-by-side with direct, finely resolved albedo measurements over three field seasons. Our findings generally support our hypotheses that perennial crops have a higher albedo than the annual crops, and that albedo for all systems differed significantly by season and year, and that RFs have strong seasonal variations.

4.1 | Hypothesis 1: Albedo of perennial versus annual cropping systems

For the three-year period of this study, annual mean α_s ranged from 0.134 for the reference forest to 0.247 for the reference maize and from 0.264 to 0.288 for our annual and perennial bioenergy cropping systems (Table 2; Figure 1). These values are consistent with earlier α_s comparisons of perennial grasses and annual row crops of maize and energy sorghum (Campbell & Norman, 2012; Fritschen, 1967; Krishnan et al., 2012; Miller et al., 2016).

Although our perennial crops overall (0.269 ± 0.01) had a higher α_s compared to annual crops (0.259 ± 0.01), energy sorghum (0.270 ± 0.01) was an exception in that its α_s was more similar to that of the perennial crops, likely due to a later planting date than maize. It is also worth noting that our no-till maize system was a continuous rotation rather than rotated with soybean. This provides a more conservative estimate of α_s change from conventional cropland, first because soybean has a higher surface reflectance

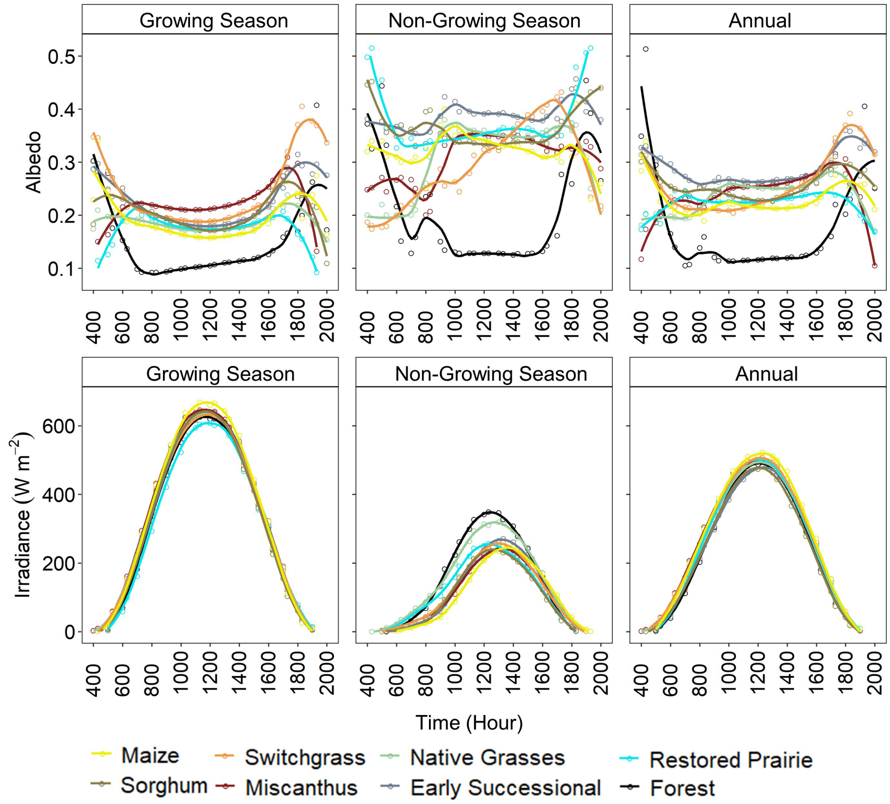

FIGURE 2 Diurnal variation in average albedo and solar irradiance for the growing season, non-growing season, and annual time scales for six bioenergy systems, a reference no-till maize system, and a reference forest. Averages represent 30-min time steps.

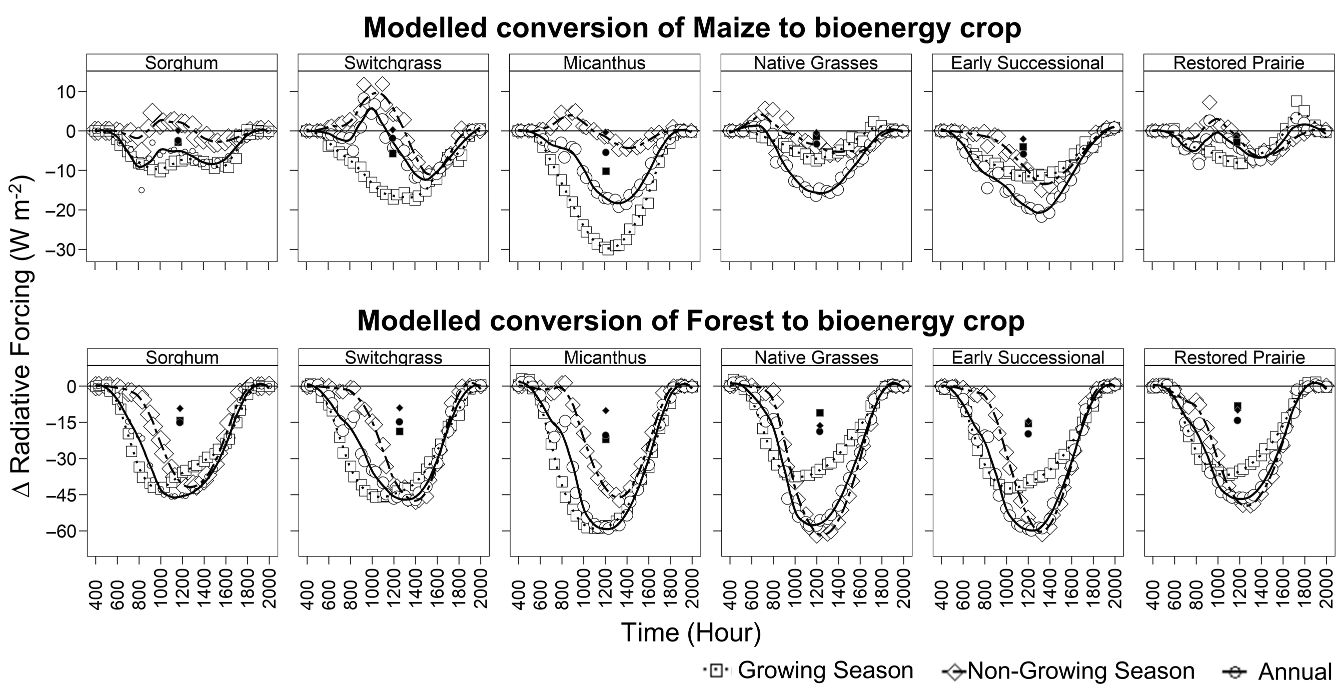

FIGURE 3 Diurnal changes in radiative forcing (RF) due to conversion of forest (top panel) and no-till maize (bottom panel) to candidate bioenergy cropping systems (early successional, native grasses, switchgrass, miscanthus, restored prairie, energy sorghum). Each point represents a 30-min mean time step; growing season averages appear as squares, non-growing season as diamonds and annual as circles. Error bars represent ± 1SE.

than maize, and secondly because no-till management (used for soil and water conservation) is more reflective than conventional tillage due to more surface residue and undisturbed soil. Energy sorghum, which is also a no-till annual crop, also displayed a higher α_s (0.270 ± 0.01) compared to maize, but was still lower than perennial crops.

TABLE 3 Average radiative forcing (RF; $W\,m^{-2}$) inferred for conversion of no-till maize (leftmost columns) and forest (rightmost columns) to different bioenergy cropping systems. SE refers to ±1 standard error.

	Conversion from maize						Conversion from forest					
	Growing season		Non-growing season		Annual		Growing season		Non-growing season		Annual	
Crop	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Energy sorghum	−3.72	0.58	−0.18	0.22	−3.08	0.49	−14.84	2.36	−10.76	2.23	−15.26	2.70
Switchgrass	−6.07	0.96	0.13	0.74	−2.13	0.71	−17.37	2.68	−11.66	2.48	−15.53	2.71
Miscanthus	−9.49	1.66	−0.22	0.28	−5.13	1.02	−20.99	3.45	−11.32	2.47	−18.48	3.36
Native grasses	−1.68	0.38	−1.03	0.37	−4.26	0.91	−12.93	2.17	−16.42	3.43	−17.15	3.27
Early successional	−4.41	0.70	−3.34	0.73	−6.77	1.16	−15.94	2.42	−15.08	3.16	−19.35	3.36
Restored prairie	−1.87	0.50	−1.06	0.40	−1.59	0.39	−12.72	2.08	−13.12	2.69	−14.76	2.63
Average	−4.54	0.93	−0.95	0.88	−3.83	1.00	−15.8	2.53	−13.06	2.74	−16.75	3.01

Energy sorghum is usually planted several weeks later than maize in our region, which appeared to be the major factor contributing to its greater α_s than maize. With the soil's being bare throughout the months of April, May and early June, planting date can affect α_s as the irradiance reaching surface soil occurs for a much longer period compared to perennials, which typically emerge in early May in our region, and thus energy sorghum can have a greater warming effect in early spring. Thus, crop-species can influence surface-induced α_s which can result in substantial climate change effects (Chen et al., 2019). In general, differences among cropping systems were greatest early in the growing season. Differences were less apparent at peak growing season when all systems had closed canopies, resulting in greater irradiance interception.

Our reference forest was a mix of both coniferous and deciduous species. Bonan (2008) showed that forests have lower surface albedo than most other cover types, which contributes to climate warming. Sciusco et al. (2020) used satellite imagery to show that α_s within forest landscapes in southwest Michigan were ~3% lower than α_s of those of bioenergy croplands. We also found consistently lower albedos in our reference forest system relative to both perennial and annual row crops (Figure 2, α_s: 0.135).

4.2 | Hypothesis 2: Seasonal differences in albedo among cropping systems

Seasonal albedo patterns were observed within our study sites. (i.e., growing season, winter, monthly, annually). Differences in α_s were most likely influenced by differences in agronomic practices including planting densities, planting times, harvest dates, and stover retention, as well as differences in plant morphology and canopy growth. In winter months (January–March), temporal variations among all bioenergy crops appeared quite high, especially when snow was present. In early spring (February–April), the perennial grass cropping systems had consistently higher albedos than no-till maize. However, during the growing season (May–October), all bioenergy crops had similar α_s values. After harvests (November–December), α_s was elevated in all bioenergy croplands. The reference forest had the lowest monthly α_s of all study sites, reflecting its conifer composition, and changed little throughout the year (Table S2). The effect of tall, complex forest canopies on α_s during winter periods can affect the amount of radiation absorbed or reflected. Similar to other studies (e.g., Betts & Ball, 1997; Robinson & Kukla, 1984), albedo in winter mixed forests are estimated to be around 0.110–0.150. Thus, changes in α_s observed during both the growing and non-growing seasons can vary during periods of high snow, winter thaws, weather, and sunlight intensity, and can have significant cooling of seasonal mean and annual temperatures.

4.3 | Hypothesis 3: Climate, agronomic practices, and plant species effect on albedo

Finally, we hypothesized that albedos of different bioenergy crops are time dependent as each species and ecosystem are affected by climate, seasonality, and agronomic practices. Modifying surface albedo through alternative avenues, such as crop residue management and landscape conversion from climate and agronomic practices, may add additional cooling benefits to the warming climate.

Zeri et al. (2011) and Miller et al. (2016) noted the differences in albedo in perennials as well as annual row crops were highly influenced by planting density, plant morphology, and canopy architecture. Maize had much lower α_s during the growing season than did the perennial systems (Figure 1). This was due to the immediate growth of perennials at the start of the last frost in March. As maize was planted at the sites around early May, the land surface was still moderately exposed due to late seeding and small seedlings during the same period. Bare earth left exposed to the atmosphere during the first few weeks of the growing season allows the maize system to absorb more solar radiation than vegetated fields until their canopies fully develop; hence overall α_s of the perennial systems remains much lower.

Similar agronomic variables such as phenology, cover crops, crop residue management, planting date, row spacing, crop variety, and canopy duration also play an integrative role in affecting albedo (Campbell & Norman, 2012; Luyssaert et al., 2014; Moore et al., 2021; Odum, 1984). Energy sorghum's growth habit is similar to that of maize, but with more side shoots, a more extensively branched root system, and it is planted in conventional 0.38 m rows rather than 0.75 m for maize, which allows for optimum use of moisture and sunlight, resulting in a higher surface reflectance more similar to the albedo of perennial crops than to that of maize. After approximately 6 weeks to fully establish a closed canopy, energy sorghum remains green until fall harvest. Consequently, its average albedo (0.270) was comparable to that of perennials.

Albedo during the non-growing periods was markedly higher when the landscape was completely or partially covered with snow. During the winter periods, stover breaks up the snowpack, leading to changes in energy reflection. Though not part of this study, previous research has shown that winter cover crops can also induce a localized cooling effect by reflecting more incoming radiation back into the atmosphere (Lugato et al., 2020). Taken together, our results suggest that large scale conversions of landscapes by expanding bioenergy cropping systems may significantly affect local climate in the Midwest U.S. due to altered albedo values (Georgescu et al., 2009, 2011; Mykleby et al., 2017).

4.4 | Radiative forcings from forest are more pronounced compared to maize

When comparing RFs for alternative representations of historical (forest) and contemporary (maize) converted land uses, RFs had strong seasonal variations. Overall, converting forest to cropland led to substantial decreases in RF, and therefore climate cooling, with the degree of cooling dependent on crop type. The peak difference in annual mean *RF* between maize and other bioenergy croplands (except forest) averaged $-3.83 \pm 0.78\,\mathrm{W\,m^{-2}}$, with early successional, miscanthus and native grasses having the highest cooling potentials at $-6.77 \pm 1.16\,\mathrm{W\,m^{-2}}$, $-5.13 \pm 1.02\,\mathrm{W\,m^{-2}}$ and $-4.26 \pm 0.91\,\mathrm{W\,m^{-2}}$, respectively.

This was similar to prior findings of Miller et al. (2016) who used highly resolved albedo measurements to compare miscanthus, switchgrass, and annual row crops of rotational maize/soybean, and found that the perennials switchgrass and miscanthus had a daily cooling potential of $-5\,\mathrm{W\,m^{-2}}$, and miscanthus of $-8\,\mathrm{W\,m^{-2}}$, compared to maize. Similarly, Sciusco et al. (2020) and Sciusco et al. (2022), who integrated spatial and temporal changes as main drivers of albedo variations, showed that cropland had higher albedo and intra-annual variabilities, with an average RF between $-5.6\,\mathrm{W\,m^{-2}}$ to $-1.2\,\mathrm{W\,m^{-2}}$ when compared to forests. Abraha et al. (2021) also assessed the biogeophysical climate impact of albedo using multiple modeled conversions from an unconverted reference CRP grassland using radiation measures from eddy covariance towers, which showed that switchgrass and restored prairie fields provided albedo-induced cooling.

Forest conversion can lead to significant albedo-induced cooling, but harvesting forest can create large initial carbon debt requiring long payback periods before net gains in albedo-induced cooling are achieved (Mykleby et al., 2017). Harvesting large forests and planting bioenergy crops can reduce or remove carbon stores within the crop and soil itself (Chen et al., 2004; Noormets, 2016), which could potentially cause higher emission of GHG, i.e., warming effects. Changing forest cover can further affect climate change through complex forest-atmosphere dynamics including plant phenology, land changes, and climate (Duveiller et al., 2021). Fu et al. (2021) observed negative *RF* due to albedo-induced GWP by deforestation, while Bastable et al. (1993) also noted that the widespread deforestation for croplands could lead to positive feedback effects' dampening the cooling effects from elevated albedo. Conversions of non-agricultural land such as forests with high initial carbon stocks to the cultivation of another bioenergy crop could also result in large carbon debt before net mitigation is achieved as much as a century later (Amiro et al., 2010; Field et al., 2020; Robertson et al., 2017). However, forests also aid in generating cloud cover, and reflect more radiation back into the atmosphere, adding to the long-term net cooling effect on landscapes. Thus, as negative RFs can contribute to climate change mitigation by increasing reflected surface radiation (Caiazzo et al., 2014), understanding how these changes can alter the Earth's surface properties are crucial for developing land-based mitigation policies.

4.5 | Assumptions and uncertainty

Change in α_s is highly correlated with land surface properties such as vegetation type and cover, snow cover, soil moisture (Ahmad & Lockwood, 1979; Weidong et al., 2002), and changes in climate such as drought or floods (Bright et al., 2012). Modifying the surface albedo of croplands through different agronomic practices such as planting date and density, crop residue management, tillage, and harvest may affect warming and cooling influences (Davin et al., 2014). The vegetative structure of crops can also affect radiation absorption and reflectance; crops with complex geometries and textures can have lower albedos than those with single stalks and leaves such as maize. Seasonal changes from bare-ground to seeding, growth, and finally senescence and harvest can also affect surface albedo through changes in crop height, crop cover, leaf texture, and leaf age (Henderson-Sellers & Wilson, 1983; Monteith, 1959).

Management effort, economic costs of inputs, and landowner preference for a specific crop will also affect crop choice, as will environmental impacts unrelated to climate mitigation (Robertson et al., 2017). Other environmental impacts include nitrogen and phosphorus pollution from excess fertilizer use, as well as potential biodiversity impacts on pollinators, insect pests and pest predators, and other taxa. Energy sorghum, for example, takes much more management effort and cost than an equivalent perennial crop, and receives more herbicides, is often fertilized more heavily and often tilled, leading to soil and nutrient loss. Likewise, miscanthus, despite its high productivity (Gelfand et al., 2020; Heaton et al., 2008), as a non-native grass supports far fewer insect and vertebrate taxa than switchgrass or other native grasses, and is also invasive (Lowry et al., 2022; Williams & Feest, 2019). Thus, environmental and economic trade-offs must be considered in addition to albedo considerations when choosing among alternate bioenergy crops.

Accurate quantification of RF from a specific land surface depends on reliable measurements of atmospheric transmission. This can be determined using the atmospheric transmittance (T_a) (Chýlek & Wong, 1998; Lenton & Vaughan, 2009) or clearness index (K_T) (Bright et al., 2012; Paulescu et al., 2021; Sciusco et al., 2022). Both measurements account for changes in solar irradiance measured on the surface and its counterpart measured at the top of the atmosphere. Muñoz and Kravchenko (2011) and Cherubini et al. (2012) assume a global constant of 0.854 for upward atmospheric transmittance from clear sky conditions. However, this is usually initiated at a 60° angle, and is not a good representation in regions of highly variable weather. Instead of using the global mean we employed a daily calculation of T_a as the ratio of $SW_{\downarrow} / SW_{TOA}$ from daily measurements of T_a obtained from our albedo towers in each cropping system. By calculating T_a for each individual day, we reduced bias during periods of highly variable weather and cloud cover, and thereby reduced error estimates in radiative forcing by up to 30% (Sciusco et al., 2020) As the differences in RF with the use of K_T and T_a were negligible, we determined the use of T_a for calculations in RF were sufficient.

Larger gaps of several hours to up to thirty consecutive days existed within our dataset due mainly to the agronomic management needs of croplands (i.e., removal of towers during seeding, herbicide spraying, fertilizer input, harvest, etc.), as well as unforeseen instrument failure. In addition, the pilot year was initiated in mid-May of 2018, such that late winter and early spring measurements for our first year were missing (Table S1). This may have caused slightly higher surface reflectivity than on average, compared to those measured at eddy covariance towers, which are usually permanent fixtures within landscapes. However, despite this drawback, the use of multiple mobile micrometeorological towers was highly effective in addressing the potential of changes in surface albedo in multiple candidate bioenergy landscapes.

Future research should examine the interactions of albedo with other biogeophysical, biogeochemical, and micrometeorological changes. Additionally, long-term observation-based, quantitative estimates of annual to decadal-scale changes of shortwave radiation may also be useful for capturing rare events that are not detected by shorter timescale methods.

5 | CONCLUSIONS

Direct measurements of albedo for 3 years in candidate bioenergy cropping systems in southwest Michigan USA showed their potential for localized cooling based on potential conversion from a historical reference forest or from a contemporary reference maize crop. Annual mean albedos for all systems ranged in the order early successional >> miscanthus ≈ energy sorghum ≥ switchgrass ≈ restored prairie > native grasses >> maize >>forest. Annual albedos closely mirrored average growing season albedos, such that differences among ecosystems mainly occurred during the growing season. Increased albedo and therefore net climate cooling was observed for all bioenergy crops relative to the reference no-till maize system, and for all systems including no-till maize relative to the reference forest system. Our results underscore the importance of including albedo change in life cycle assessments of the climate benefits of bioenergy cropping systems, based now solely on biogeochemical change.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data presented in this work are available at the Great Lakes Bioenergy Research Center Sustainability Research Data Catalog: https://data.sustainability.glbrc.org/.

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REFERENCES

Abraha, M., Chen, J., Hamilton, S. K., Sciusco, P., Lei, C., Shirkey, G., Yuan, J., & Robertson, G. P. (2021). Albedo-induced global warming impact of conservation reserve program grasslands converted to annual and perennial bioenergy crops. *Environmental Research Letters*, *16*(8), 084059. https://doi.org/10.1088/1748-9326/ac1815

Ahmad, S. B., & Lockwood, J. G. (1979). Albedo. *Progress in Physical Geography*, *3*, 510–543. https://doi.org/10.1177/030913337900300403

Akbari, H., Menon, S., & Rosenfeld, A. (2009). Global cooling: Increasing world-wide urban albedos to offset CO_2. *Climatic Change*, *94*(3), 275–286. https://doi.org/10.1007/s10584-008-9515-9

Amiro, B. D., Barr, A. G., Barr, J. G., Black, T. A., Bracho, R., Brown, M., Chen, J., Clark, K. L., Davis, K. J., Desai, A. R., Dore, S., Engel, V., Fuentes, J. D., Goldstein, A. H., Goulden, M. L., Kolb, T. E., Lavigne, M. B., Law, B. E., Margolis, H. A., … Xiao, J. (2010). Ecosystem carbon dioxide fluxes after disturbance in forests of North America. *Journal of Geophysical Research Biogeosciences*, *115*, G00K02. https://doi.org/10.1029/2010JG001390

Bastable, H. G., Shuttleworth, W. J., Dallarosa, R. L. G., Fisch, G., & Nobre, C. A. (1993). Observations of climate, albedo, and surface radiation over cleared and undisturbed Amazonian forest. *International Journal of Climatology*, *13*(7), 783–796. https://doi.org/10.1002/joc.3370130706

Betts, A. K., & Ball, J. H. (1997). Albedo over the boreal forest. *Journal of Geophysical Research: Atmospheres*, *102*(D24), 28901–28909. https://doi.org/10.1029/96JD03876

Bonan, G. B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, *320*(5882), 1444–1449. https://doi.org/10.1126/science.1155121

Bright, R. M. (2015). Metrics for biogeophysical climate forcings from land use and land cover changes and their inclusion in life cycle assessment: A critical review. *Environmental Science Technology*, *49*(6), 3191–3303. https://doi.org/10.1021/es505465t

Bright, R. M., Cherubini, F., & Strømman, A. H. (2012). Climate impacts of bioenergy: Inclusion of carbon cycle and albedo dynamics in life cycle impact assessment. *Environmental Impact Assessment Review*, *37*, 2–11. https://doi.org/10.1016/j.eiar.2012.01.002

Brown, D. G., Pijanowski, B. C., & Duh, J. D. (2000). Modeling the relationships between land use and land cover on private lands in the upper Midwest, USA. *Journal of Environmental Management*, *59*(4), 2427–2263. https://doi.org/10.1006/jema.2000.0369

Caiazzo, F., Malina, R., Staples, M. D., Wolfe, P. J., Yim, S. H. L., & Barrett, S. R. H. (2014). Quantifying the climate impacts of albedo changes due to biofuel production: A comparison with biogeochemical effects. *Environmental Research Letters*, *9*(2), 024015. https://doi.org/10.1088/1748-9326/9/2/024015

Campbell, G. S., & Norman, J. (2012). Radiation fluxes in natural environments. In *An introduction to environmental biophysics* (2nd ed., pp. 167–184). Springer-Verlag.

Carrer, D., Pinault, F., Lellouch, G., Trigo, I. F., Benhadj, I., Camacho, F., Ceamanos, X., Moparthy, S., Munoz-Sabater, J., Schuller, L., & Sánchez-Zapero, J. (2021). Surface albedo retrieval from 40-years of earth observations through the EUMETSAT/LSA SAF and EU/C3S programmes: The versatile algorithm of PYALUS. *Remote Sensing*, *13*(3), 372. https://doi.org/10.3390/rs13030372

Carrer, D., Pique, G., Ferlicoq, M., Ceamanos, X., & Ceschia, E. (2018). What is the potential of cropland albedo management in the fight against global warming? A case study based on the use of cover crops. *Environmental Research Letters*, *13*(4), 044030. https://doi.org/10.1088/1748-9326/aab650

Chen, J., Lei, C., & Sciusco, P. (2021). Biophysical models and applications in ecosystem analysis. In *Modeling ecosystem global warming potentials* (pp. 119–149). Michigan State University Press. https://muse.jhu.edu/book/82816

Chen, J., Paw, U. K. T., Ustin, S. L., Suchanek, T. H., Bond, B. J., Brosofske, K. D., & Falk, M. (2004). Net ecosystem exchanges of carbon, water, and energy in young and old-growth Douglas-fir forests. *Ecosystems*, *7*(5), 534–544. https://doi.org/10.1007/s10021-004-0143-6

Chen, J., Sciusco, P., Ouyang, Z., Zhang, R., Henebry, G. M., John, R., & Roy, D. (2019). Linear downscaling from MODIS to Landsat: Connecting landscape composition with ecosystem functions. *Landscape Ecology*, *34*(12), 2917–2934. https://doi.org/10.1007/s10980019-00928-2

Cherubini, F., Bright, R. M., & Strømman, A. H. (2012). Site-specific global warming potentials of biogenic CO_2 for bioenergy:

Contributions from carbon fluxes and albedo dynamics. *Environmental Research Letters*, *7*(4), 045902. https://doi.org/10.1088/1748-9326/7/4/045902

Chýlek, P., & Wong, J. G. D. (1998). Cloud radiative forcing ratio: An analytical model. *Tellus A*, *50*(3), 259–264.

Cleveland, R. B., Cleveland, W. S., McRae, J. E., & Terpenning, I. (1990). STL: A seasonal-trend decomposition procedure based on loess. *Journal of Official Statistics*, *6*(1), 3–73. https://www.proquest.com/scholarly-journals/stl-seasonal-trend-decomposition-procedure-based/docview/1266805989/se-2

Crum, J. R., & Collins, H. P. (1995). *KBS soils. Kellogg Biological Station Long-term Ecological Research Special Publication*. https://doi.org/10.5281/zenodo.2560750

Davin, E. L., Seneviratne, S. I., Ciais, P., Olioso, A., & Wang, T. (2014). Preferential cooling of hot extremes from cropland albedo management. *Proceedings of the National Academy of Sciences*, *111*(27), 9757–9761. https://doi.org/10.1073/pnas.1317323111

Duveiller, G., Filipponi, F., Ceglar, A., Bojanowski, J., Alkama, R., & Cescatti, A. (2021). Revealing the widespread potential of forests to increase low level cloud cover. *Nature Communications*, *12*(1), 1–15. https://doi.org/10.1038/s41467-021-24551-5

Fang, H. L., Liang, S. L., Kim, H. Y., Townshend, J. R., Schaaf, C. L., Strahler, A. H., & Dickinson, R. E. (2007). Developing a spatially continuous 1 km surface albedo data set over North America from Terra MODIS products. *Journal of Geophysical Research*, *11*, D20206. https://doi.org/10.1029/2006JD008377

Field, J. L., Richard, T. L., Smithwick, E. A., Cai, H., Laser, M. S., LeBauer, D. S., Long, S. P., Paustian, K., Qin, Z., Sheehan, J. J., Smith, P., Wang, M. Q., & Lynd, L. R. (2020). Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels. *Proceedings of the National Academy of Sciences*, *117*, 21968–21977. https://doi.org/10.1073/pnas.1920877117

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C., & Rummukainen, M. (2013). Evaluation of climate models. In *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* (pp. 741–866). Cambridge University Press.

Fritschen, L. J. (1967). Net and solar radiation relations over irrigated field crops. *Agricultural Meteorology*, *4*(1), 55–62. https://doi.org/10.1016/0002-1571(67)90042-8

Fu, B., Li, B., Gasser, T., Tao, S., Ciais, P., Piao, S., Balkansi, Y., Li, W., Yin, T., Han, L., Han, Y., & Xu, J. (2021). The contributions of individual countries and regions to the global radiative forcing. *Proceedings of the National Academy of Sciences*, *118*(15), e2018211118. https://doi.org/10.1073/pnas.2018211118

Gelfand, I., Hamilton, S. K., Kravchenko, A. N., Jackson, R. D., Thelen, K. D., & Robertson, G. P. (2020). Empirical evidence for the potential climate benefits of decarbonizing light vehicle transport in the US with bioenergy from purpose-grown biomass with and without BECCS. *Environmental Science & Technology*, *54*(5), 2961–2974. https://doi.org/10.1021/acs.est.9b07019

Georgescu, M., Lobell, D. B., & Field, C. B. (2009). Potential impact of US biofuels on regional climate. *Geophysical Research Letters*, *36*, L21806. https://doi.org/10.1029/2009GL040477

Georgescu, M., Lobell, D. B., & Field, C. B. (2011). Direct climate effects of perennial bioenergy crops in the United States. *Proceedings of the National Academy of Sciences*, *108*(11), 4307–4312. https://doi.org/10.1073/pnas.1008779108

Heaton, E. A., Dohleman, F. G., & Long, S. P. (2008). Meeting US biofuel goals with less land: The potential of miscanthus. *Global Change Biology*, *14*, 1–15. https://doi.org/10.1111/j.1365-2486.2008.01662.x

Henderson-Sellers, A. (1980). Albedo changes—Surface surveillance from satellites. *Climatic Change*, *2*(3), 275–281. https://doi.org/10.1007/BF00137991

Henderson-Sellers, A., & Hughes, N. A. (1982). Albedo and its importance in climate theory. *Progress in Physical Geography*, *6*(1), 1–44. 10.1177%2F030913338200600101

Henderson-Sellers, A., & Wilson, M. (1983). Surface albedo data for climatic modeling. *Reviews of Geophysics*, *21*(8), 1743–1778. https://doi.org/10.1029/RG021i008p01743

IPCC. (2022). Climate change 2022: Mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change. In P. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, & J. Malley (Eds.), *Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change* (pp. 3–33). Cambridge University Press. https://doi.org/10.1017/9781009325844.001

Krishnan, P., Meyers, T. P., Scott, R. L., Kennedy, L., & Heuer, M. (2012). Energy exchange and evapotranspiration over two temperate semi-arid grasslands in North America. *Agricultural and Forest Meteorology*, *153*, 31–44. https://doi.org/10.1016/j.agrformet.2011.09.017

Lenton, T. M., & Vaughan, N. E. (2009). The radiative forcing potential of different climate geoengineering options. *Atmospheric Chemistry and Physics*, *9*(15), 5539–5561. https://doi.org/10.5194/acp-9-5539-200

Lowry, C. J., Matlaga, D. P., West, N. M., Williams, M. M., & Davis, A. S. (2022). Estimating local eradication costs for invasive miscanthus populations throughout the eastern and midwestern United States. *Invasive Plant Science and Management*, *15*(3), 115–121. https://doi.org/10.1017/inp.2022.20

Lugato, E., Cescatti, A., Jones, A., Ceccherini, G., & Duveiller, G. (2020). Maximising climate mitigation potential by carbon and radiative agricultural land management with cover crops. *Environmental Research Letters*, *15*(9), 094075. https://doi.org/10.1088/1748-9326/aba137

Luyssaert, S., Jammet, M., Stoy, P. C., Estel, S., Pongratz, J., Ceschia, E., Churkina, G., Don, A., Erb, K., Ferlicoq, M., & Gielen, B. (2014). Land management and land-cover change have impacts of similar magnitude on surface temperature. *Nature Climate Change*, *4*(5), 389–393. https://doi.org/10.1038/nclimate2196

Miller, J. N., VanLoocke, A., Gomez-Casanovas, N., & Bernacchi, C. J. (2016). Candidate perennial bioenergy grasses have a higher albedo than annual row crops. *Global Change Biology: Bioenergy*, *8*(4), 818–825. https://doi.org/10.1111/gcbb.12291

Monteith, J. L. (1959). The reflection of short-wave radiation by vegetation. *Quarterly Journal of the Royal Meteorological Society*, *85*(366), 386–392. https://doi.org/10.1002/qj.49708536607

Moore, C. E., von Haden, A. C., Burnham, M. B., Kantola, I. B., Gibson, C. D., Blakely, B. J., Dracup, E. C., Masters, M. D., Yang, W. H., DeLucia, E. H., & Bernacchi, C. J. (2021). Ecosystem-scale biogeochemical fluxes from three bioenergy crop candidates: How energy sorghum compares to maize and miscanthus. *Global Change Biology: Bioenergy*, *13*(3), 445–458. https://doi.org/10.1111/gcbb.12788

Muñoz, J. D., & Kravchenko, A. (2011). Soil carbon mapping using on-the-go near infrared spectroscopy, topography, and aerial photographs. *Geoderma*, *166*(1), 102–110. https://doi.org/10.1016/j.geoderma.2011.07.017

Mykleby, P. M., Snyder, P. K., & Twine, T. E. (2017). Quantifying the trade-off between carbon sequestration and albedo in midlatitude and high-latitude North American forests. *Geophysical Research Letters*, *44*(5), 2493–2501. https://doi.org/10.1002/2016GL071459

NCDC. (2013). *Climate Data Online (CDO), National Climatic Data Center (NCDC)*. NCDC National Oceanic and Atmospheric Administration, https://www.ncdc.noaa.gov/cdo-web/search

NOAA. (2005). *ESRL global monitoring laboratory - global radiation and aerosols*. Earth System Research Laboratories Global Monitoring Laboratory. https://gml.noaa.gov/grad/solcalc/

Noormets, A. (2016). Trade-off between forest productivity and carbon sequestration in soil. In *Proceedings of the 18th biennial southern silvicultural research conference*, e-Gen. Tech. Rep. SRS-212 (Vol. *212*, pp. 351–354). US Department of Agriculture, Forest Service, Southern Research Station. https://www.fs.usda.gov/treesearch/pubs/50700

Odum, E. P. (1984). Properties of agroecosystems. In R. Lowrance, B. R. Stinner, & G. J. House (Eds.), *Agricultural ecosystems: Unifying concepts* (pp. 5–11). John Wiley.

Ollinger, S. V., Richardson, A. D., Martin, M. E., Hollinger, D. Y., Frolking, S. E., Reich, P. B., Plourde, L. C., Katul, G. G., Munger, J. W., Oren, R., & Smith, M. L. (2008). Canopy nitrogen, carbon assimilation, and albedo in temperate and boreal forests: Functional relations and potential climate feedbacks. *Proceedings of the National Academy of Sciences*, *105*(49), 19336–19341. https://doi.org/10.1073/pnas.0810021105

Ouyang, Z., Sciusco, P., Jiao, T., Feron, S., Lei, C., Li, F., John, R., Fan, P., Li, X., Williams, C. A., Chen, G., Wang, C., & Chen, J. (2022). Albedo changes caused by future urbanization contribute to global warming. *Nature Communications*, *13*(1), 3800. https://doi.org/10.1038/s41467-022-31558-z

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., Church, J. A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N. K., Edenhofer, O., Elgizouli, I., Field, C. B., Forster, P., Friedlingstein, P., Fuglestvedt, J., Gomez-Echeverri, L., Hallegatte, S., … van Ypserle, J.-P. (2014). Climate change 2014: synthesis report. In: Core Writing Team, R. K. Pachauri & L. A. Meyer (Eds.), *Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change* (p. 151). IPCC.

Paulescu, M., Paulescu, E., & Badescu, V. (2021). Nowcasting solar irradiance for effective solar power plants operation and smart grid management. In *Predictive modelling for energy management and power systems engineering* (pp. 249–270). Elsevier. https://doi.org/10.1016/B978-0-12-817772-3.00009-4

Pielke, R. A., Sr., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., Goldewijk, K. K., Nair, U., Betts, R., Fall, S., & Reichstein, M. (2011). Land use/land cover changes and climate: Modeling analysis and observational evidence. *Wiley Interdisciplinary Reviews: Climate Change*, *2*(6), 828–850. https://doi.org/10.1002/wcc.144

R Development Team. (2013). *R foundation for statistical computing* (p. 3). Austria.

Raupach, M. R. (1994). Simplified expressions for vegetation roughness length and zero-plane displacement as functions of canopy height and area index. *Boundary-Layer Meteorology*, *71*(1), 211–216. https://doi.org/10.1007/BF00709229

Robertson, G. P., Hamilton, S. K., Barham, B. L., Dale, B. E., Izaurralde, R. C., Jackson, R. D., Landis, D. A., Swinton, S. M., Thelen, K. D., & Tiedje, J. M. (2017). Cellulosic biofuel contributions to a sustainable energy future: Choices and outcomes. *Science*, *356*(6345), eeal2324. https://doi.org/10.1126/science.aal2324

Robertson, G. P., Hamilton, S. K., Paustian, K., & Smith, P. (2022). Land-based climate solutions for the United States. *Global Change Biology*, *28*(16), 4912–4919. https://doi.org/10.1111/gcb.16267

Robinson, D. A., & Kukla, G. (1984). Albedo of a dissipating snow cover. *Journal of Applied Meteorology and Climatology*, *23*(12), 1626–1634. https://doi.org/10.1175/1520-0450(1984)023<1626:AOADSC>2.0.CO;2

Russel, H. N. (1916). On the albedo of the planets and their satellites. *Proceedings of the National Academy of Sciences*, *2*(2), 74–77. https://doi.org/10.1073/pnas.2.2.7

Sanford, G. R., Oates, L. G., Jasrotia, P., Thelen, K. D., Robertson, G. P., & Jackson, R. D. (2016). Comparative productivity of alternative cellulosic bioenergy cropping systems in the North Central USA. *Agriculture, Ecosystems & Environment*, *216*, 344–355. https://doi.org/10.1016/j.agee.2015.10.018

Sciusco, P., Chen, J., Abraha, M., Lei, C., Robertson, G. P., Lafortezza, R., Shirkey, G., Ouyang, Z., Zhang, R., & John, R. (2020). Spatiotemporal variations of albedo in managed agricultural landscapes: Inferences to global warming impacts (GWI). *Landscape Ecology*, *35*(6), 1385–1402. https://doi.org/10.1007/s10980-020-01022-8

Sciusco, P., Chen, J., Giannico, V., Abraha, M., Lei, C., Shirkey, G., Yuan, J., & Robertson, G. P. (2022). Albedo-induced global warming impact at multiple temporal scales within an upper Midwest USA watershed. *Land*, *11*(2), 283. https://doi.org/10.3390/land11020283

Smith, C. J., Kramer, R. J., Myhre, G., Alterskjær, K., Collins, W., Sima, A., Boucher, O., Dufresne, J. L., Nabat, P., Michou, M., & Forster, P. M. (2020). Effective radiative forcing and adjustments in CMIP6 models. *Atmospheric Chemistry and Physics*, *20*(16), 9591–9618. https://doi.org/10.5194/acp-20-9591-2020

Thoen, G. F. (1990). *Soil survey of Barry County, Michigan*. (USDA Soil Conservation Service, Michigan Agricultural Experiment Station, and Michigan Technological University, Washington DC) (pp. 187–286). The Service, US Government Printing Office.

Weidong, L., Baret, F., Xingfa, G., Qingxi, T., Lanfen, Z., & Bing, Z. (2002). Relating soil surface moisture to reflectance. *Remote Sensing of Environment*, *81*(2–3), 238–246. https://doi.org/10.1016/S0034-4257(01)00347-9

Williams, M. A., & Feest, A. (2019). The effect of miscanthus cultivation on the biodiversity of ground beetles (coleoptera: Carabidae), spiders and harvestmen (Arachnida: Araneae and Opiliones). *Agricultural Sciences*, *10*, 903–917. https://doi.org/10.4236/as.2019.107069

Zeri, M., Anderson-Teixeira, K., Hickman, G., Masters, M., DeLucia, E., & Bernacchi, C. J. (2011). Carbon exchange by establishing biofuel crops in Central Illinois. *Agriculture, Ecosystems & Environment*, *144*(1), 319–329. https://doi.org/10.1016/j.agee.2011.09.006

Zhang, X. T., Liang, S. L., Wang, K. C., Li, L., & Gui, S. (2010). Analysis of global land surface shortwave broadband albedo from multiple data sources. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *3*(3), 296–305. https://doi.org/10.1109/jstars.2010.2049342

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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Supporting Information

Climate Cooling Benefits of Cellulosic Bioenergy Crops from Elevated Albedo

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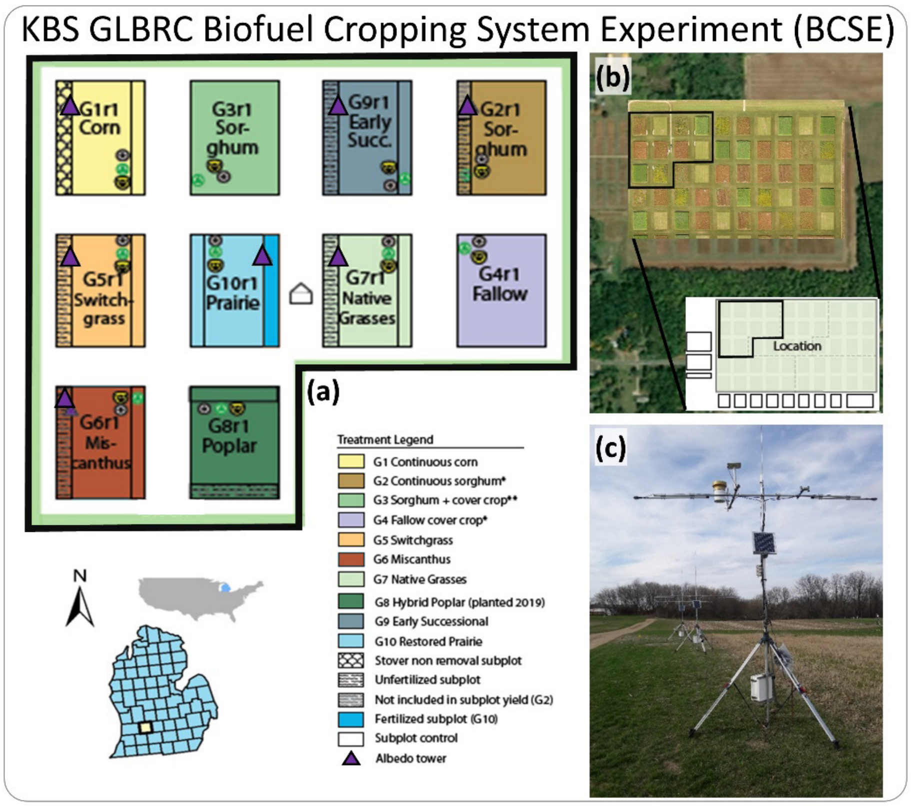
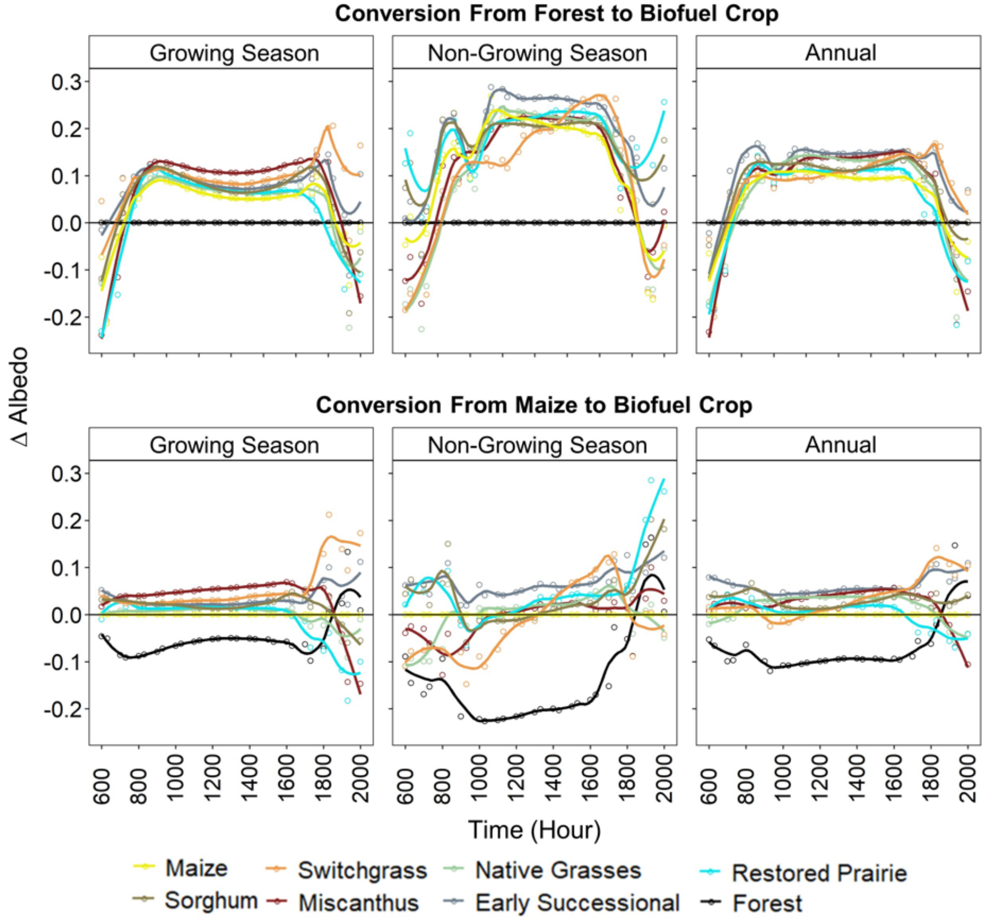
Supplementary Figure 1: Plot map (a) showing replicate block and location of the seven albedo towers (purple triangle) within selected experimental plots of the BCSE; (b) unmanned aerial vehicle mosaicked photo taken of experimental plots by KBS research technician. Drone photo is overlaid on a Landsat satellite image of the study site with replicate block outlined in black; (c) photo of representative albedo tower; and Map modified from https://lter.kbs.msu.edu/research.



Supplementary Figure 2: Change in albedo (Δα) due to conversion of forest (top row) and annual maize (bottom row) reference systems compared to six bioenergy crops over growing season, non-growing season, and annual periods.



Supplementary Table 1: Coverage of cropping system measurements over the entire study period from 2018 to 2020.

Crop	Year	Days (N)	Coverage (%)
Maize	2018	182	75%
	2019	315	86%
	2020	278	76%
Energy sorghum	2018	120	49%
	2019	220	60%
	2020	306	84%
Switchgrass	2018	194	80%
	2019	316	87%
	2020	296	81%
Miscanthus	2018	113	46%
	2019	303	83%
	2020	283	78%
Native Grasses	2018	198	81%
	2019	355	97%
	2020	330	90%
Early Successional	2018	131	54%
	2019	335	92%
	2020	292	80%
Restored Prairie	2018	131	54%
	2019	262	72%
	2020	319	87%
Average Period	**2018**		**63%**
	2019		**82%**
	2020		**82%**

Supplementary Table 2: Mean monthly albedos for the six bioenergy cropping systems, modern reference maize, and historical reference forest systems.

Month	Site: Maize		Sorghum		Switchgrass		Miscanthus		Native Grasses		Early Successional		Restored Prairie		Forest	
	α	Stdv (±)	α	Stdv (±)	α	Stdv (±)	α	Stdv (±)	α	Stdv (±)	α	Stdv (±)	α	Stdv (±)	α	Stdv (±)
Jan	0.495	0.25	0.51	0.28	0.466	0.31	0.466	0.23	0.497	0.24	0.503	0.25	0.419	0.22	0.169	0.06
Feb	0.703	0.18	0.602	0.23	0.666	0.25	0.57	0.20	0.579	0.21	0.59	0.20	0.58	0.21	0.213	0.08
Mar	0.339	0.23	0.239	0.18	0.331	0.26	0.423	0.25	0.259	0.13	0.404	0.22	0.385	0.20	0.126	0.04
Apr	0.196	0.02	0.145	0.04	0.258	0.11	0.204	0.03	0.224	0.05	0.212	0.07	0.383	0.17	0.121	0.04
May	0.180	0.04	0.157	0.06	0.215	0.03	0.197	0.03	0.207	0.02	0.201	0.02	0.255	0.07	0.138	0.03
Jun	0.200	0.04	0.164	0.06	0.219	0.02	0.218	0.03	0.217	0.01	0.225	0.02	0.236	0.06	0.147	0.02
Jul	0.190	0.03	0.188	0.05	0.228	0.02	0.242	0.02	0.202	0.01	0.208	0.02	0.225	0.04	0.128	0.01
Aug	0.188	0.02	0.225	0.03	0.258	0.09	0.241	0.02	0.183	0.01	0.212	0.03	0.174	0.02	0.117	0.01
Sep	0.169	0.02	0.23	0.03	0.183	0.06	0.231	0.02	0.155	0.02	0.205	0.03	0.146	0.02	0.112	0.02
Oct	0.159	0.03	0.222	0.03	0.16	0.03	0.228	0.03	0.143	0.02	0.216	0.04	0.13	0.03	0.109	0.02
Nov	0.294	0.20	0.145	0.08	0.244	0.09	0.18	0.05	0.308	0.22	0.324	0.21	0.306	0.24	0.133	0.07
Dec	0.257	0.18	0.22	0.18	0.282	0.16	0.287	0.18	0.303	0.18	0.292	0.16	0.275	0.20	0.129	0.04
Avg **2018-2020**	0.247	0.17	0.266	0.19	0.265	0.17	0.271	0.14	0.259	0.17	0.288	0.18	0.264	0.18	0.134	0.05