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# Cover Crops May Cause Winter Warming in Snow-Covered Regions

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## Comments

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# Cover crops may cause winter warming in snow-covered regions

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## Key Points:

- Cover crops can increase cash crop yields and soil carbon storage, and can also induce regional biogeophysical climate impacts
- Where cover crops extend above winter snowpack, they decrease albedo and warm wintertime temperatures
- Winter warming can be minimized by planting less leafy cover crops or varieties that will be completely buried under the snowpack

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## Abstract

Cover crops, grown between cash crops when soil is fallow, are a management strategy that may help mitigate climate change. The biogeochemical effects of cover crops are well documented, as they provide numerous localized benefits to farmers. We test potential biogeophysical climate impacts of idealized cover crop scenarios by assuming cover crops are planted offseason in all crop regions throughout North America. Our results suggest that planting cover crops increases wintertime temperature up to 3$^{o}$C in central North America by decreasing albedo in regions with variable snowpack. Cover crops with higher leaf area indices increase temperature more by decreasing broadband albedo, while decreasing cover crop height helped to mitigate the temperature increase as the shorter height was more frequently buried by snow. Thus, climate mitigation potential must consider the biogeophysical impacts of planting cover crops, and varietal selection can minimize winter warming.

## Plain Language Summary

Planting cover crops is an agricultural management technique in which crops are grown in between cash crop seasons when the soil would otherwise be fallow. Cover crops provide many local benefits to farmers and can increase carbon storage in soils. In this study, we test how planting cover crops in all agricultural regions in North America can change wintertime temperatures. Model simulations suggest that cover crops can warm winter temperatures up to 3$^{o}$ C in regions with variable winter snowpack, such as central North America. Planting cover crop varieties that are less leafy or get buried under the variable snowpack can help to minimize winter warming. Our study suggests that the climate mitigation potential of cover crops may be offset in these regions if cover crop varieties are not carefully selected.

## 1 Introduction

Land management practices are widely employed throughout much of the world to maintain or increase ecosystem and agricultural productivity. While management decisions are typically motivated by site-specific efforts to optimize productivity, they also have the potential to alter the biogeophysical and biogeochemical properties of the land surface, which can modify local and regional climate (Lobell *et al* 2006). For example, tillage provides local benefits to farmers by destroying weeds, aerating soils, and temporarily increasing nutrient availability, but over longer timescales the practice also contributes to climate change by potentially reducing soil carbon storage (Grandy and Robertson 2007; Parton *et al* 2015) and enhancing short-term nitrous oxide ($N_2O$) emissions (Six et al. 2002, Grandy et al. 2006). However, some management strategies can be employed that can maintain or even improve cash crop yields while acting to mitigate climate change (Tonitto et al. 2006, SARE 2015). Planting cover crops, a management strategy in which plants are grown in agricultural fields during fallow seasons when cash crops are typically not grown, has the potential to mitigate climate change by increasing soil carbon storage and potentially reducing greenhouse gas emissions (Tiemann *et al* 2015, McDaniel *et al* 2016, Kaye and Quemada 2017). While there is mounting evidence that cover crops increase soil carbon globally and can remove soil nitrate that would otherwise be vulnerable to leaching or denitrification, the biogeophysical effects of planting cover crops on longer-term climate dynamics are not well studied.

Reasons for planting cover crops are myriad and along with potential C sequestration include suppression of weed growth and reduction in the need for herbicides (Lemessa and Wakjira 2015); enhancement of aboveground diversity and wildlife habitat; and disruption of disease and insect pest cycles. Additionally, cover crops can reduce soil erosion, improve soil quality, and increase microbial biomass and growth efficiency (Kallenbach et al. 2015, McDaniel *et al* 2014, Tiemann *et al* 2015, Blanco-Canqui *et al* 2015, Zhu et al. 1989, Krutz et al. 2009). Cover crops may capture excess fertilizer, reducing nitrogen leaching and potentially decreasing the amount of fertilizer required to grow cash crops (Tonitto et al. 2006). The changes in soil quality, such as increased soil aggregation, can also increase porosity and water infiltration, leading to a higher water holding capacity (Keisling et al. 1994, Blanco-Canqui *et al* 2015) that can benefit the productivity of the cash crop during summer droughts (Fyre et al. 1988, Letter et al. 2003). However, in dry regions cover crops may use water needed by the cash crop. While the magnitude of localized benefits is dependent on a number of factors, including soil and plant type, climate, and any associated management practices (Unger and Vigil, 1998; Kasper and Singer, 2011; Sainju et al. 2003; Meisinger et al. 1991; Tonitto et al. 2006), the local benefits that cover crops provide is a primary reason why farmers adopt this practice.

In addition to the many local benefits, cover cropping can change biogeochemical processes that are important at regional- and global-scales and may act to mitigate climate warming. Arguably the most beneficial biogeochemical effect of cover cropping is the increase in soil carbon sequestration, with estimates suggesting that the increase in soil carbon compensates for approximately 8% of direct agricultural greenhouse gas emissions (Poeplau and Don 2015). The biogeochemical benefits may also extend to aquatic ecosystems. For example, reduced erosion and nitrate leaching associated with cover cropping may reduce the negative impacts of agriculture by reducing sediment and nutrient loads to aquatic ecosystems (Kladivko et al. 2014; Durand 2004; Bosch et al. 2013). The extent to which cover crops mitigate or contribute to climate change through direct greenhouse gas emissions, namely $N_2O$ and methane ($CH_4$), remains uncertain and likely depends on plant type and management techniques used (Basche *et al* 2014, Tang *et al* 2014, Kaye and Quemada 2017). Despite these uncertainties, the biogeochemical benefits of cover crops are relatively well established, whereas their influence on biogeophysical fluxes of water and energy with the atmosphere are less well studied.

Agricultural systems dramatically change biogeophysical properties of the land surface by altering latent heat flux and albedo that potentially impact climate. For example, irrigating crops can lead to local cooling by increasing latent heat flux (Lobell *et al* 2006), whereas tillage can lead to warming due to reduced soil albedo (Lobell *et al* 2006, Bagley *et al* 2015, Davin *et al*

2014). Similar studies investigating the effects of planting cover crops on the biogeophysical properties of the land surface are less common. Cover crops could increase latent heat flux through increased transpiration, especially if irrigated. Cover crops also change albedo, with estimates suggesting an increase in albedo compared to bare, snow-free ground (Kaye and Quemada 2017). Despite potential changes in surface energy balance, the direct effect of planting cover crops on surface temperature has not yet been examined.

Here, we assess the effect of cover crops on surface air temperatures in North America due to biogeophysical climate feedbacks using an idealized modeling experiment. In particular, we examine the sensitivity of land-atmosphere response when cover crops are included for all cropping regions in North America using the Community Earth System Model (CESM) version 1.2. We anticipate that cover crops will directly change land surface albedo and latent heat fluxes and that these changes can combine to affect surface air temperatures. This work contributes to a broader understanding of how cover crops change biogeophysical processes at large spatial scales and is the first time, to our knowledge, that the change in surface air temperature in response to cover crops has been documented.

## 2 Materials and Methods

Model simulations were run using the land and atmosphere components of the Community Earth System Model (version 1.2). The Community Land Model (CLM, version 4.5; Oleson *et al* 2013) is used in its ‘satellite phenology’ (CLM-SP) configuration, in which leaf area indices are prescribed using MODIS leaf area index. Biogeochemical cycles and active crop management are not available options in this configuration of CLM. Instead, we utilized the satellite phenology scheme to isolate the potential biogeophysical effects of cover crops by changing the prescribed leaf area index (LAI) and stem height on agricultural land units. The CLM4.5-SP was run coupled to the Community Atmosphere Model (CAM version 5; Neale *et al* 2012) for 32 years using historical forcings and climatological sea surface temperatures, averaged from 1995 through 2005. The use of climatological SSTs reduces the interannual variability and allows the terrestrial signal to emerge more readily. Results here focus on the coupled CLM-CAM simulations, but to isolate land-only effects of cover crops we also conducted stand-alone CLM4.5-SP simulations, using observationally-based climate forcing data from Climate Research Unit - National Centers for Environmental Prediction (CRU-NCEP) from 1991-2010. All simulations were run at 2° spatial resolution.

The representation of crops during the growing season was unchanged in all CLM4.5 simulations used here. To test different idealized cover crop scenarios, we modified the CLM4.5 land surface data set over North America (Southwest bound: 30$^{o}$N, 130$^{o}$W; Northeast bound: 60$^{o}$N, 65$^{o}$W) before the cash crop growing season begins and after it ends by changing the default leaf area indices (LAI) and crop height for the crop plant functional type. Leaf reflectance was unchanged from the default value, and spatially and temporally varying leaf and soil albedo are calculated within the model based on soil color, soil wetness, stem and leaf area indices, solar zenith angle, and leaf orientation. Snow burial was updated from the default configuration, where crops and grasses were assumed to be fully buried at a snow depth of 20 cm, to being dependent on the crop or grass height (see detailed description in supplemental text). Specific changes to simulate cover crops include changing LAI to either 0 (no cover crops), 1 (sparse) or 4 (leafy) and changing crop height from the default crop and grass height of 50 cm (tall) to 0 (no cover crops) or 10 cm (short) during the fallow season (Fig. 1). These changes simulate a low and high potential range of cover crop LAI and height to show a range of climate impacts that may occur due to cover cropping if all cropland in North America was to adopt cover cropping practices, but are not intended to be a fully realistic representation of cover crops.

Our analysis focused on changes in water and energy fluxes between no cover crop and cover crop simulations during boreal winter (December-January-February) when the change in vegetation is greatest, and statistical significance was determined using a student's t-test. We additionally investigated whether planting cover crops has indirect effects that change growing season productivity and water availability using the tall, leafy cover crop configuration (LAI = 4, height = 50 cm). To disentangle the land-only versus land-atmosphere effects we also compare parallel coupled (land-atmosphere) with uncoupled (land-only) simulations.

## 3 Results

Simulating planted cover crops increased boreal winter (December-January-February) surface air temperature up to 3$^{o}$C in the central parts of Northern United States and Southern Canada (Fig. 2a-c). Temperature increases were largest in the simulations where the cover crops were tall and leafy (height = 50 cm, LAI = 4; Fig. 2b). The location of winter temperature increase was similar in the sparse (LAI = 1; Fig. 2a) and short (height = 10 cm; Fig. 2c) cover crop simulations, though the magnitude of change was smaller. Adding cover crops significantly decreased boreal winter albedo in all simulations (Fig. 2d-f). As with temperature, the decrease in albedo was largest in the simulations with tall and leafy cover crops (Fig. 2e) due to taller plants with higher leaf area shading the reflective snow, though the spatial pattern was similar across all simulations.

Differences in surface albedo relate to snow depth and the amount of leaf area that protrudes above the snow (see supplemental text for a description of snow parameterizations used in CLM4.5). In all simulations mean winter snow depth was less than 2.5 cm throughout much of the Southern United States and was greater than 30 cm in most of Canada and the Northern Rocky Mountain region (Fig. 3). The transition between the shallow and deep snow pack in the central part of North America varied slightly among the simulations, with shallower snow depths further north in the sparse and short cover crop simulations compared to the tall and leafy cover crop simulation, likely due to temperature and precipitation feedbacks.

Latent and sensible heat fluxes both increased up to 3 W $m^{-2}$ in the central part of Northern U.S. and Southern Canada in all simulations with cover crops (Fig. 4). The increases in sensible heat flux were typically more widespread than the increases in latent heat flux. Taller cover crops increased latent heat fluxes during winter more than short cover crops in Central North America, though changes in sensible heat fluxes were similar in magnitude in the sparse and short cover crop simulations.

Given changes in wintertime surface temperatures and energy balance from the coupled model, we also investigated the direct effects of cover crops compared to the indirect climate feedbacks on growing season (June-July-August) soil moisture and plant productivity. In uncoupled (CLM-only) simulations, cover crops caused wintertime albedo to decrease, similar in magnitude and spatial extent to the coupled model results, and increased wintertime latent heat fluxes (data not shown). By design, the uncoupled simulations do not represent potential land-atmosphere climate impacts. Thus, with cover crops increasing wintertime evapotranspiration in the land-only simulations, soils were drier during the growing season by >2500 g $H_2O$ $m^{-2}$ in much of Central North America and summertime plant productivity was slightly reduced in the Midwest (Fig. 5a, b). However, the parallel coupled land-atmosphere simulation suggests an important indirect impact on climate. While summertime soil moisture decreased throughout Central North America, it increased in the Southwest. The changes in summertime soil moisture were due to spatially similar but non-significant changes annual average precipitation (data not shown), including Central United States, resulting in net decreases in summertime productivity (Fig. 5c, d) up to -150 g C $m^{-2}$ $yr^{-1}$.

## 4 Discussion and Conclusions

These idealized scenarios simulate a range of possible cover crop traits and their potential biogeophysical climate feedbacks if all cropland in North America was to adopt cover cropping practices. In the scenarios tested here, planting cover crops in North America increased boreal winter (December-January-February) LAI across the study domain (Fig. 1), with increases in wintertime temperature (up to $3^{o}$C) isolated to the northern half of the study region (Fig. 2a-c). Our findings suggest that temperature and albedo changes were largely driven by interactions of the cover crops with wintertime snow cover. Even short cover crops (10 cm height) were taller than the average winter snow depth across parts of the Midwest (Fig. 3). With darker cover crops extending above the snowpack, our results showed decreased wintertime albedo (Fig. 2d-f) and concomitantly increased sensible heat flux (Fig. 4), likely due to increased net surface energy (see SI Fig 1). Similarly, using empirical albedo calculations, Kaye and Quemada (2017) found that when cover crops were only partially buried by snow, they decreased albedo and led to local winter warming, regardless of the plant albedo. Thus, higher leaf reflectance for cover crops compared with cash crops, such in Kaye and Quemada (2017) but not in this study, may not have a large impact on winter albedo. Another climate-smart agricultural practice, replacing annual crops with perennial crops, also decreased winter albedo by ~0.11 when snow was present; but during most of the year when snow was absent, annual and perennial crop fields had similar albedos (Bagley *et al* 2015). These findings align with our results in regions with little or no average winter snow like the Southern United States (Fig 2) and during other seasons (data not shown), in which including idealized cover crops did not significantly change albedo or 2-meter air temperature in any of the scenarios. The biogeophysical effects of cover cropping under no-snow conditions may also increase albedo (Kaye and Quemada 2017), but the no-snow cover crop albedo impacts are dependent on local cover crop traits and bare soil albedo (neither of which were varied in the present study).

Albedo in crop ecosystems is known to have important biogeophysical climate feedbacks. Other management practices, like residue management and irrigation, are also known to change albedo (e.g., Lobell *et al* 2006, Davin *et al* 2014, Bagley *et al* 2015), though these practices tend to change albedo in the spring, summer, and fall more than during winter. The strong effect of cover crops on winter albedo, with potential changes up to 0.2 causing up to 3°C warming during the winter (Fig. 2), highlights the importance of considering both cover crop and soil albedo in selecting the type and variety of cover crop to be planted to minimize any warming impact. Cover crops can mitigate climate warming if their albedo is equal to or greater than the underlying soil albedo when there is little or no snow (Kaye and Quemada 2017), but they will exacerbate local winter warming regardless of the cover crop albedo if the cover crops are not fully buried by snow (e.g., Fig. 2d-f), even when cover crop albedo is very high (Kaye and Quemada 2017).

Of the scenarios tested here, the cover crops with low LAI had a smaller impact on winter temperatures than leafier cover crops of the same height (Fig. 2a-b) suggesting that less leafy cover crops have a smaller impact on winter surface temperature. Increases in LAI are typically thought to decrease albedo, such as the 6% decrease in albedo that is attributed to increasing global LAI over the past three decades (Zeng *et al* 2017). Often, the decrease in albedo due to LAI is associated with summertime growth and the potential warming related to this albedo decrease is offset by a concomitant increase in latent heat flux that can lead to a net temperature decrease (Zeng *et al* 2017). Since cover crops are usually not photosynthetically active during the winter months, the latent heat flux change due to the presence of cover crops in the winter is too small to offset the albedo change (Fig. 4). Contrary to these results, Lobell et al. (2006) found that doubling modeled cover crop LAI slightly increased albedo, though this may be due to a low modeled soil albedo relative to crop albedo.

Since cover crops had a large effect on albedo in snow-covered regions, it was expected that shorter crop heights, even when leafy, would reduce the warming effect of cover crops since snow burial is important. Indeed, shorter cover crops reduced winter warming relative to taller cover crops (Fig. 2b vs 2c). However, the 10cm height of the short cover crops simulated here was still higher than the average winter snow depth in parts of central North America (Fig.

3) and therefore led to warmer, though not significant, winter air temperatures. Shorter and sparser cover crops, perhaps achieved through grazing, may allow for complete burial by snow and reduce the winter warming effect of cover crops (Kaye and Quemada 2017) but this scenario was not tested. Even some of the shortest cover crops, like white clover, easily reach heights of 7.5 cm and may not be buried in low snowpack regions if they do not readily lodge (i.e. fall over).

While our study did not examine the biogeochemical feedbacks caused by cover crops, it is important to note that cover crops can change many biogeochemical processes that impact climate, most of which are anticipated to mitigate climate change over longer time and larger spatial scales. The most prominent climate feedback is an increase in soil carbon, with estimates suggesting that cover crops can sequester soil carbon at a global rate of 0.12 Pg C $yr^{-1}$ (Poeplau and Don 2015), potentially reducing warming. Changes in soil trace greenhouse gas emissions, particularly $N_2O$ and $CH_4$, are also important potential climate feedbacks, but studies are much less conclusive, with the magnitude and direction of change being dependent on the cover crop type and other associated management techniques (Kim *et al*. 2012, Sanz-Cobena *et al*. 2014, Tang *et al* 2014, Guardia *et al* 2016). However, some studies suggest that cover crops do not have a large net impact on annual emissions (Basche *et al* 2014, Kaye and Quemada 2017).

Climate responses were important in driving the trends in temperature and energy flux changes. For example, planting cover crops did not significantly change growing season productivity when climate responses were not included (i.e., the land-only simulations; Fig. 5b). However, when CLM was coupled to CAM, cover crops decreased growing season productivity in Central North America (Fig. 5d) due to decreased soil water content during the growing season (Fig. 5c), resulting from changes in precipitation and evapotranspiration. Cover crops also directly decreased available soil water during the cash crop season in land-only simulations (Fig. 5a). Empirical evidence suggests that cover crops can increase soil water holding capacity due to changes in soil structure (Keisling *et al*. 1994, Blanco-Canqui *et al* 2015), a mechanism that is not fully represented in our CLM simulations.

While our results only examine idealized cover crop scenarios, several important conclusions emerge. It is particularly notable that cover crops can cause wintertime warming in regions where average winter snowpack is low and crops protrude above the snowpack. While cover crops provide numerous ecological benefits and may even mitigate climate change through increasing soil carbon sequestration, the mitigation potential may be offset unless varietals are selected to minimize potential winter warming, particularly in regions where there is snow cover during part or all of the winter. Particular attention should be paid to the albedo of the crops relative to the soil. Our results suggest that planting less leafy cover crops can help to mitigate the positive winter temperature response in snowy regions. Additionally, planting short crops that lodge easily or are grazed or mowed before snowfall may further minimize winter warming. Though we cannot determine the full mitigation potential of cover crops here, we highlight the importance of considering both the biogeochemical and biogeophysical consequences of planting cover crops on regional and global scales.

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## Figure Legends

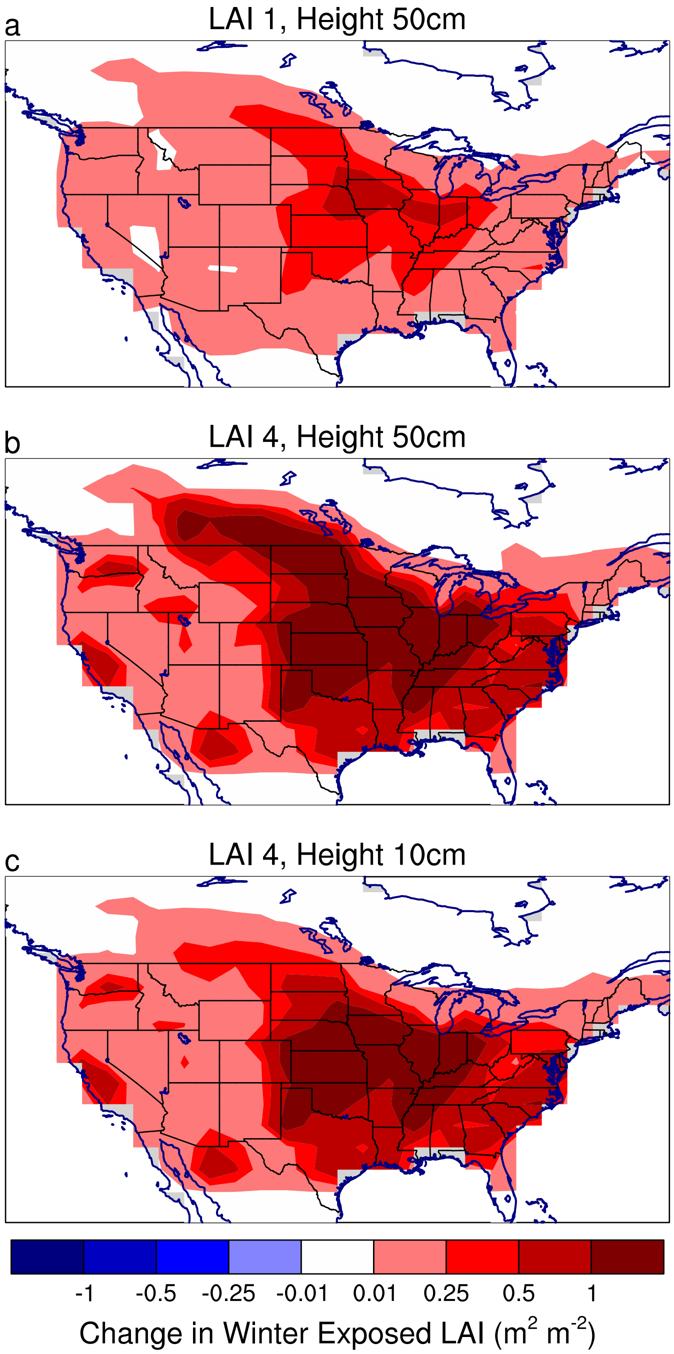
**Figure 1.** The change in grid-cell average exposed leaf area index (LAI) during the boreal winter used to simulate cover crops compared to the simulation without cover crops. Note that the changes shown here are averaged over the total land area, including both crops and natural vegetation. Modifications increase leaf area index from zero to one (sparse; a) or four (leafy; b, c) for all crops.

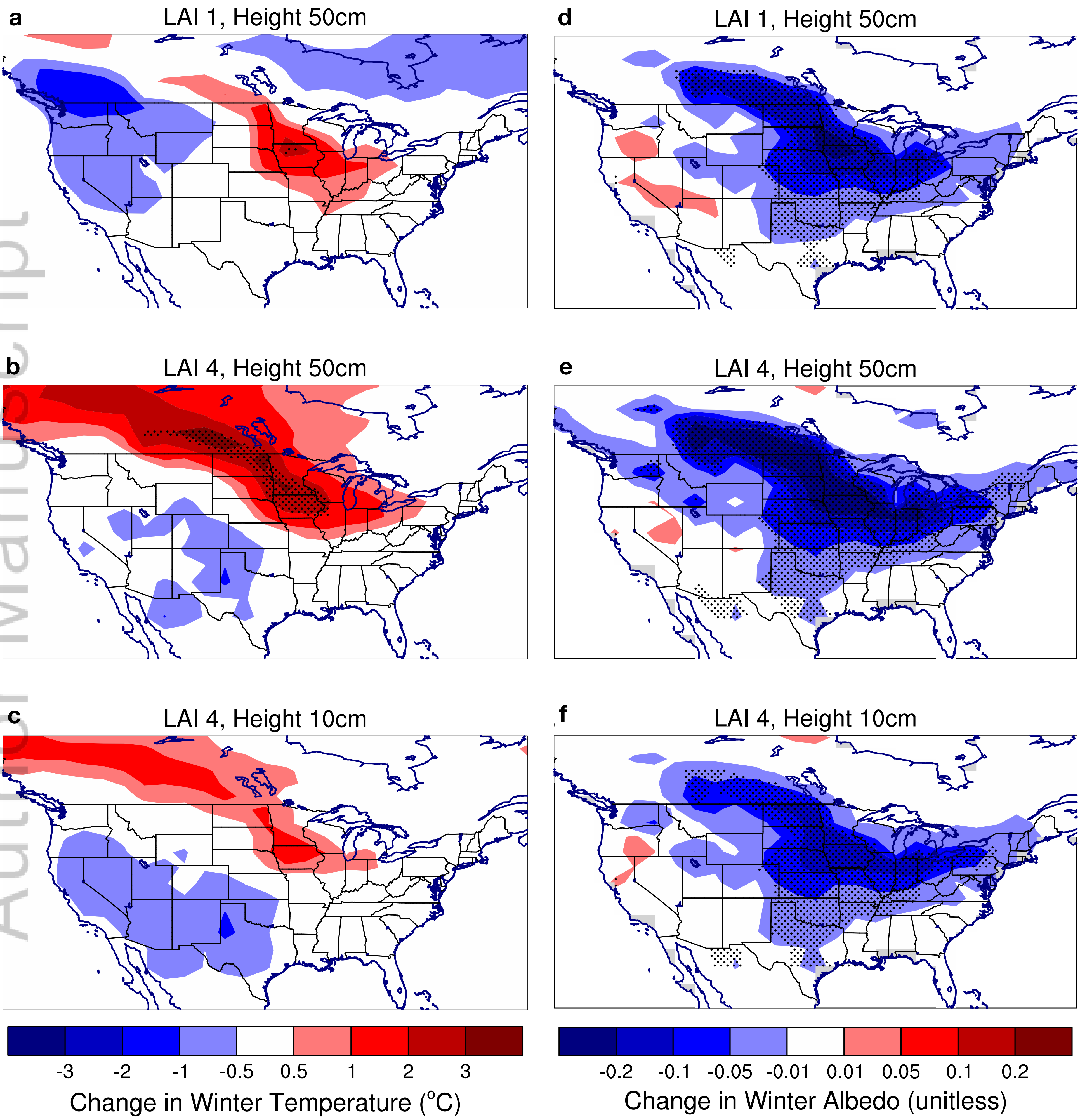
**Figure 2.** The change in 2-meter air temperature (a-c) and broadband albedo (d-f) during boreal winter (December-January-February) caused by planting cover crops relative to not planting cover crops. Simulations vary leaf area index of cover crops from one (sparse; a, d) to four (leafy; b, c, e, f) and crop height from 50 cm (tall; a, b, d, e) to 10 cm (short; c, f). Stippling indicates changes that are significant at $p<0.05$.

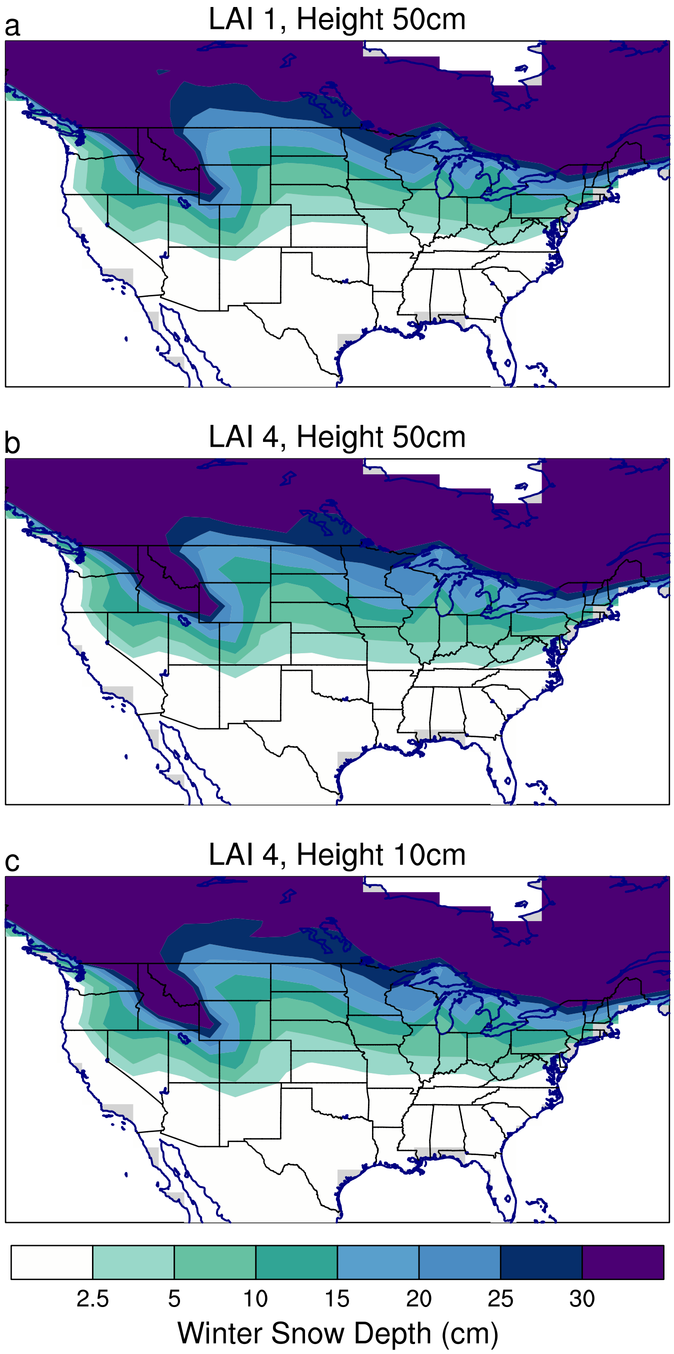
**Figure 3.** Average snow depth during boreal winter (December-January-February) in simulations where cover crops are planted with a leaf area index of one (sparse; a) or four (leafy; b, c) and grow to 50 cm (tall; a, b) or 10 cm (short; c).

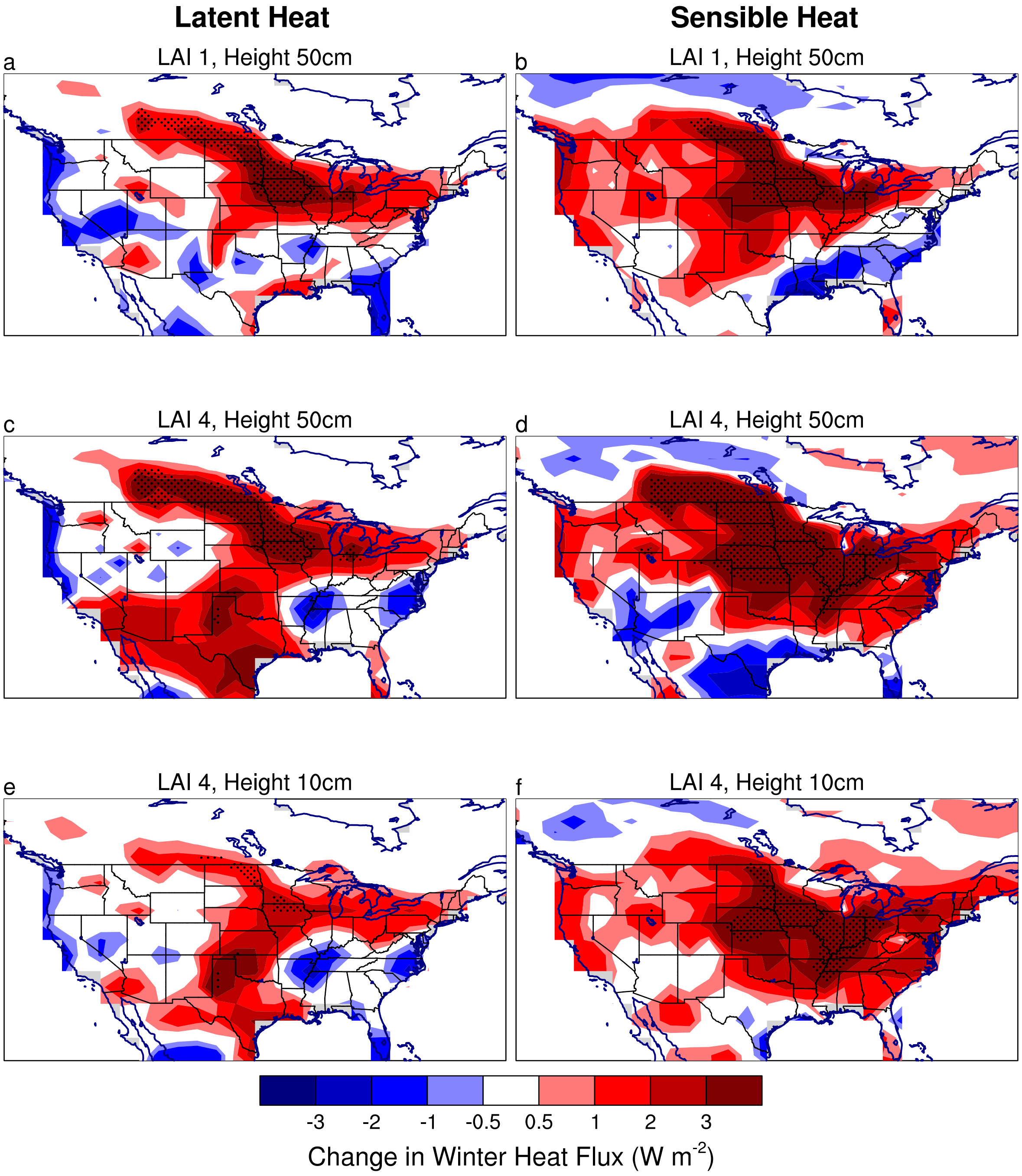
**Figure 4.** The change in latent heat flux (a, c, e) and sensible heat flux (b, d, f) during boreal winter (December-January-February) caused by planting cover crops relative to not planting cover crops. Simulations vary leaf area index of cover crops from one (sparse; a, b) to four (leafy; c, d, e, f) and crop height from 50 cm (tall; a, b, c, d) to 10 cm (short; e, f). Stippling indicates changes that are significant at $p<0.05$.

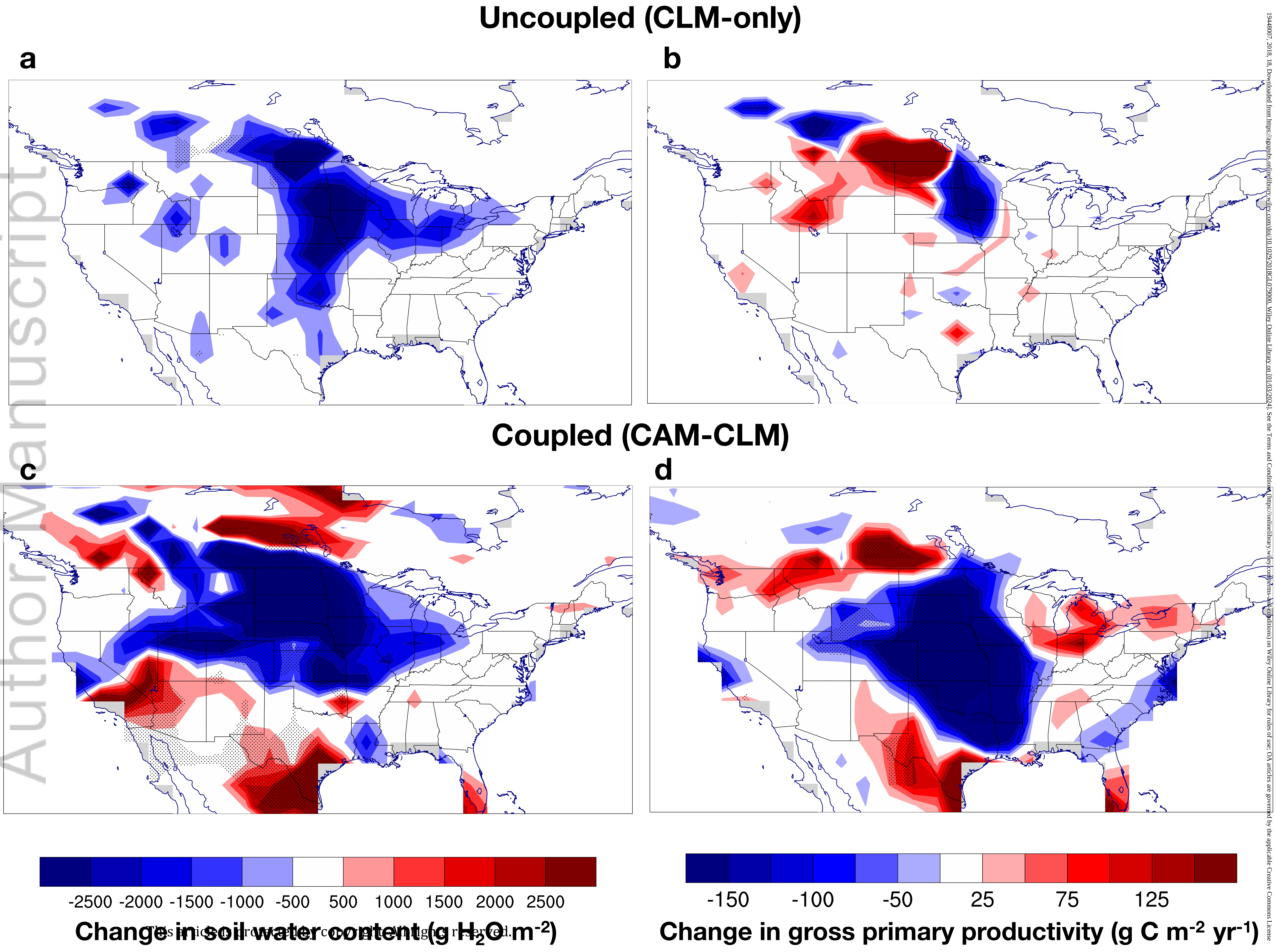
**Figure 5.** The change in soil water content (a, c) and gross primary productivity (b, d) during boreal summer (June-July-August) caused by planting cover crops with a LAI of 4 and a height of 50 cm relative to not planting cover crops. Simulations were run using either uncoupled (e.g, CLM-only; a, b) or coupled (e.g., CAM-CLM; c, d) configurations of CESM.


a
LAI 1, Height 50cm
b
LAI 4, Height 50cm
c
LAI 4, Height 10cm
-1
-0.5
-0.25
-0.01
0.01
0.25
0.5
1
Change in Winter Exposed LAI ($m^2$ $m^{-2}$)


a
LAI 1, Height 50cm
b
LAI 4, Height 50cm
c
LAI 4, Height 10cm
d
LAI 1, Height 50cm
e
LAI 4, Height 50cm
f
LAI 4, Height 10cm
-3
-2
-1
-0.5
0.5
1
2
3
Change in Winter Temperature (°C)
-0.2
-0.1
-0.05
-0.01
0.01
0.05
0.1
0.2
Change in Winter Albedo (unitless)


a
LAI 1, Height 50cm
b
LAI 4, Height 50cm
c
LAI 4, Height 10cm
2.5
5
10
15
20
25
30
Winter Snow Depth (cm)


Latent Heat
Sensible Heat
a
LAI 1, Height 50cm
b
LAI 1, Height 50cm
c
LAI 4, Height 50cm
d
LAI 4, Height 50cm
e
LAI 4, Height 10cm
f
LAI 4, Height 10cm
-3
-2
-1
-0.5
0.5
1
2
3
Change in Winter Heat Flux (W m-2)


Uncoupled (CLM-only)
a
b
Coupled (CAM-CLM)
c
d
-2500 -2000 -1500 -1000 -500 500 1000 1500 2000 2500
Change in soil water content (g $H_2O$ m$^{-2}$)
-150 -100 -50 25 75 125
Change in gross primary productivity (g C m$^{-2}$ yr$^{-1}$)