The potential for albedo-induced climate mitigation using no-till management in midwestern U.S. croplands

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No-till management is often recognized for its environmental and economic benefits, but its potential to reduce climate warming is still uncertain. Beyond ongoing debate over its effects on soil carbon storage, no-till also leaves plant residue on the surface, which can reflect more sunlight. This increase in surface reflectivity, called albedo, may help mitigate climate change by reducing the energy absorbed by the land. Here, we assessed this climate benefit of no-till across the U.S. Corn Belt using conservation survey records, county-level tillage data, and satellite observations. We found that no-till increased land surface brightness during the dormant season, reducing absorbed solar energy by an estimated 50 grams of CO_2 equivalent per square meter per year. Regionally, this could add up to 24 teragrams of CO_2 equivalent per year in potential climate benefits. Areas with low adoption, especially those with dark, carbon-rich soils, offer the greatest opportunity for further mitigation.

Nature-based Climate Solutions (NbCS) offer a broad portfolio of climate mitigation pathways, providing well-known environmental co-benefits[1] and potential economic benefits for a wide range of land managers. NbCS are designed to slow the pace of climate change through three mechanisms: (a) increasing vegetative CO_2 sequestration and storage, (b) reducing emissions of CO_2 and other greenhouse gases like CH_4 and N_2O from plants and soils, and (c) increasing the reflectivity (or albedo) of the land surface to reflect more radiation back into space[2]. Despite general agreement that NbCS can produce tangible climate benefits[3,4], their implementation is accelerating without a clear consensus on when and where specific NbCS strategies will succeed as climate mitigation tools[5–8]. Addressing this knowledge gap is a critical and timely research priority.

While conventional tillage leaves little crops residues on the soil surface during the dormant season, no-till management retains all crop residues, such as stover and other plant material, in place. Conservation tillage is intermediate between the two, leaving some (but not all) residues atop the soil. It is well-established that no-till management provides a range of environmental benefits, including improved soil health, reduced soil erosion, enhanced water quality through decreased nitrogen leaching, and more stable soil temperatures that support crop germination[9–12]. Additionally, no-till management reduces labor and equipment costs, thereby lowering overall operational expenditures[9,10,12]. However, no-till practices may increase weed pressure, thus requiring more herbicide use. They may also result in issues such as poor soil drainage, delayed planting, and

potentially reduced crop yields[11,13]. Despite these trade-offs, no-till remains one of the most widely adopted conservation practices in the Midwestern U.S., although it is still implemented on 30–40% or less of farms (Fig. 1).

Although numerous studies have examined the potential of no-till management to enhance carbon sequestration and reduce greenhouse gas emissions, there is still no clear consensus on its effectiveness in reliably increasing CO_2 storage and lowering greenhouse gas levels[14](Table 1). The debate surrounding no-till as an NbCS primarily focuses on how much atmospheric CO_2 can be sequestered and stored in the soil. While some studies have reported that no-till management significantly increases carbon storage in the top 20–30 cm of soil[15,16], others have noted a decrease in soil carbon at greater depths[17,18]. Moreover, some research suggests that the carbon storage benefits of no-till management may be temporary, disappearing after 10–20 years[16,19,20].

Because crop residues are more reflective than bare soil, no-till can provide an albedo-driven climate mitigation benefit that is independent of any greenhouse gas impacts. The literature on the albedo-driven mitigation potential of no-till is relatively scant, and much of what is known comes from modeling studies rather than observational work. Existing evidence suggests that the change in surface albedo ($\Delta\alpha$) associated with no-till management can range from 0.026 to 0.20, during the dormant season, though these impacts are variable in space due to differences in crop types, pedo-climatic drivers, and land management practices[21–26]. At least one study focused on the Canadian Prairie suggests

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Fig. 1 | The adoption of no-till management in the Midwest. The data in (**a**) is from USDA NASS and shows the percentage of fields adopting no-till management in 2017. The image (**b**) illustrates the difference in albedo (i.e., reflectivity) between no-till and conventional till fields in autumn. Photo Credit X. Wang.
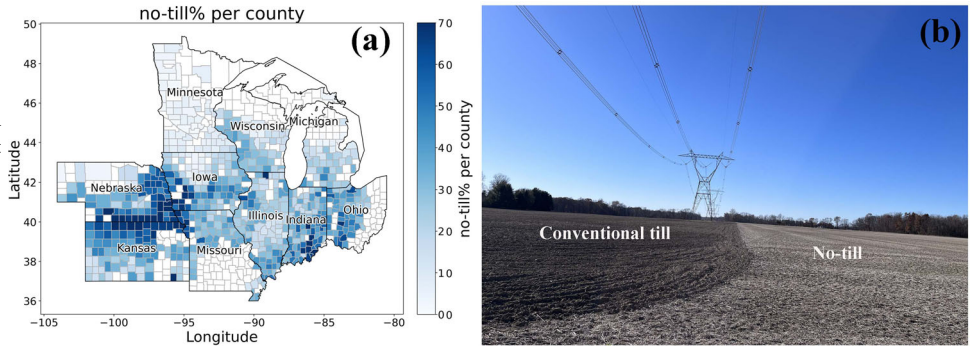

Table 1 | The climate mitigation benefits, expressed as mitigation potential in units of g CO_2-eq m^{-2}year^{-1} under different tillage practices

Management	Types	Mitigation potential	Crop types	Method	References
No-till	Albedo	11.6–17.3	Canadian Prairies	GWP100	26
Delayed tillage	Albedo	29–99	Multiple crops	GWP100	25
No-till	SOC	0.7–0.4 (<0.3 m)	Multiple crops	field-collected	58
No-till	SOC	55	Grain sorghum	modeled 100-year SOC stock	59
No-till	SOC	210 ± 51 (65 out of 67 studies <0.3 m)	Multiple crops	field-collected	16
No-till	SOC	268 (<0.1 m)	Malt barley-pea	field-collected	37
Reduced Till	SOC	340 (<0.1 m)	Corn-sugar beet	field-collected	60
No-till	SOC	0–183 (0–0.6 m)	Multiple crops	field-collected	19
No-till	SOC	110–700 (<0.3 m), will be lower <1 m	Brazil Cerrado region	field-collected	61
No-till	SOC	128 (<0.2 m)	Multiple crops	field-collected	62
No-till	SOC	202 (<0.3 m)	Cereal-legume; wheat-vetch-barley	field-collected	63
No-till	N_2O	0–125	Multiple crops	GWP100	58,64,65
No-till	CH_4	0	Multiple crops	GWP100	38,58,65–67
No-till	SOC + N_2O	0	Vineyard	GWP100	68
No-till	N_2O + CH_4	0.07	Paddy fields	GWP100	69
No-till	N_2O + CH_4	0.7	Cereal-legume; wheat-vetch-barley	GWP100	63
No-till	N_2O + CH_4 + CO_2	66	Wheat fields	GWP100	70
No-till	N_2O + CH_4 + CO_2	9.2	Wheat-maize	GWP100	66
No-till	N_2O + CH_4 + CO_2	19	Malt barley-pea fields	GWP100	37
No-till	SOC + N_2O + CH_4	13	Malt barley-pea fields	GWP100	37
No-till	SOC + N_2O + CH_4	55 (<0.3 m)	Rice fields	GWP100	71
No-till	SOC + N_2O + CH_4 + Fuel	0.3 (<0.3 m)	Corn fields	GWP100	72
No-till	GHG fluxes + different management	238 ± 88	Multiple crops	GWP100	73

To ensure comparability across studies, we recalculated Global Warming Potential (GWP) value reported in Liu et al.[26] from a 50-year to a 100-year time horizon (GWP100) using the methodology described in Myhre et al.[52].

that the albedo-driven mitigation potential of no-till, assessed using a 50-year Global Warming Potential (GWP) time horizon, is equivalent to 1.0–1.5 kg CO_2-eq/m^2[26]. Importantly, while the potential of no-till management to sequester soil carbon potentially diminishes over time, its ability to increase surface albedo remains more stable from year to year. However, we lack systematic assessments of the magnitude and spatial variability of albedo changes due to no-till across many of the world's important agricultural regions, and due in part to a scarcity of validated, ground-based data on no-till adoption.

Our study is the first to leverage extensive, validated ground-based survey data to evaluate the albedo-induced climate benefits of no-till across the U.S. Corn Belt. We used complementary but independent analyses of $\Delta\alpha$ attributable to the implementation of no-till management at the scale of individual fields in Indiana and entire counties across the Midwest. First, we explored the spatiotemporal variability in $\Delta\alpha$ as it relates to crop types and pedo-climatic drivers, specifically, soil organic content, snow cover and soil moisture. We hypothesized that higher soil moisture and greater soil organic carbon would darken the land surface, thereby increasing the magnitude of

$\Delta\alpha$. Conversely, snow cover was expected to reduce the magnitude of $\Delta\alpha$ by brightening the surface. We then transformed the estimates of albedo change into radiative forcing and, eventually, climate mitigation potential (expressed in units of CO_2 equivalents). As a final step, we generated opportunity maps describing where additional resources should be deployed to optimize the albedo-driven climate mitigation benefits of no-till across the region.

Results

No-till management significantly increases albedo compared to conventional till

During snow-free periods of the dormant season (Nov to Mar) from 2014 to 2022, the albedo of no-till fields is higher than that of conventional till fields. Specifically, for the state of Indiana, high-resolution (30 m) albedo estimates from Landsat were precisely matched to field-scale observations of tillage practices from a conservation transect survey (n = 5000–6000 fields monitored each year). While snow-free albedo distributions among different tillage classes overlapped, the highest albedos were in no-tilled fields, and the distribution is negatively skewed, whereas the lowest albedos were in conventional till fields and their distribution was positively skewed (Fig. 2a). Snow-free albedos of fields managed with conservation tillage were intermediate between no-till and conventional till fields. Albedo follows a similar distribution pattern as a function of increasing residue cover (Fig. 2b), suggesting that residue cover is likely the primary factor driving changes in albedo for different tillage practices. Using a statistical approach that relied on randomly drawing paired samples from these two distributions (see methods), we estimate that $\Delta\alpha$ between no-till and conventional till fields in Indiana had a median value of 0.028 and ranged from −0.021 to 0.077 (Fig. 2c). These same data further suggest that during the cash crop growing season (Apr. to Oct.), no-till management can potentially continue to increase albedo, though the effect is small (Supplementary Fig. 1). Thus, the rest of our results focus solely on the $\Delta\alpha$ associated with no-till implementation during the dormant season to avoid overstating its overall impact on albedo.

Next, to extend our analysis to the entire study region, we explored the relation between county-scale albedo and the fractions of farmland under no-till management in each county using the 2017 Census of Agriculture data provided by the USDA. While the county-scale albedo at any given rate of no-till adoption is highly variable in space, we find that the mean albedo in counties with very little adoption of no-till management (e.g., <5%) is ~0.130. In contrast, the mean albedo in counties that have high rates of no-till adoption (e.g., >75%) is ~0.176 (Fig. 3a) – a difference of 0.046. In an

idealized scenario, representing a shift from 0% to 100% adoption of no-till management (using the empirical model represented by the solid line in Fig. 3a), we estimate the potential $\Delta\alpha$ as 0.053. A complimentary analysis based on the adoption rate of conventional tillage (as opposed to no-till adoption) reveals that, in an idealized scenario, representing a shift from 0% to 100% adoption of conventional management (using the model represented by the solid line in Fig. 3b), the resulting change in albedo is −0.084.

Spatial factors that determine the impacts of no-till management on albedo

Higher soil organic carbon content (SOC) lowers the albedo of both conventional till and no-till fields but has a smaller effect on the albedo of no-tilled fields, thus amplifying the $\Delta\alpha$ (Fig. 4a–c). Specifically, when averaged to the county scale, the field-level transect data from Indiana clearly show that albedo decreases with increasing SOC among conventional till fields but to a lesser degree for no-till fields (Fig. 4a, b). As a result, $\Delta\alpha$ increases with increasing SOC (Fig. 4c). Similarly, at the county scale across the entire study region, a larger difference in albedo between counties with very high and very low rates of no-till adoption was detected when only counties with high SOC (≥7.5%) were considered (Fig. 3a). SOC significantly and positively influences $\Delta\alpha$, as also demonstrated by both multiple linear regression models developed using Indiana survey data to capture long-term spatial and short-term temporal variability (Supplementary Tables S1 and S2). Incident shortwave radiation flux density and soil moisture are likely important drivers of short-term temporal variability in $\Delta\alpha$ (Supplementary Table S2). These findings partially support our initial hypothesis that higher SOC levels darken bare soil, leading to an increased magnitude of $\Delta\alpha$ over the long term. Our results also refine the hypothesis by suggesting that increased shortwave radiation and reduced soil moisture likely dry surface residues more rapidly, thereby decreasing the magnitude of $\Delta\alpha$ in the short term. However, we acknowledge that the soil moisture used here have a coarse resolution, and a scarcity of clear Landsat scenes during the dormant season may prevent a robust analysis of temporal variations in soil moisture and albedo within individual fields. This is an important area for future research, particularly in identifying both short-term and long-term drivers of $\Delta\alpha$.

Crop species also matters. At the field-scale, corn fields are associated with a greater increase in $\Delta\alpha$ (Supplementary Fig. 2). However, because crop composition is relatively stable across Indiana counties—corn at 45% ±12% and soybean at 55% ±12%—its impact on county-level models is not significant. Finally, we did not detect a significant difference in albedo between conventional till and no-till fields at either the field or county scale when
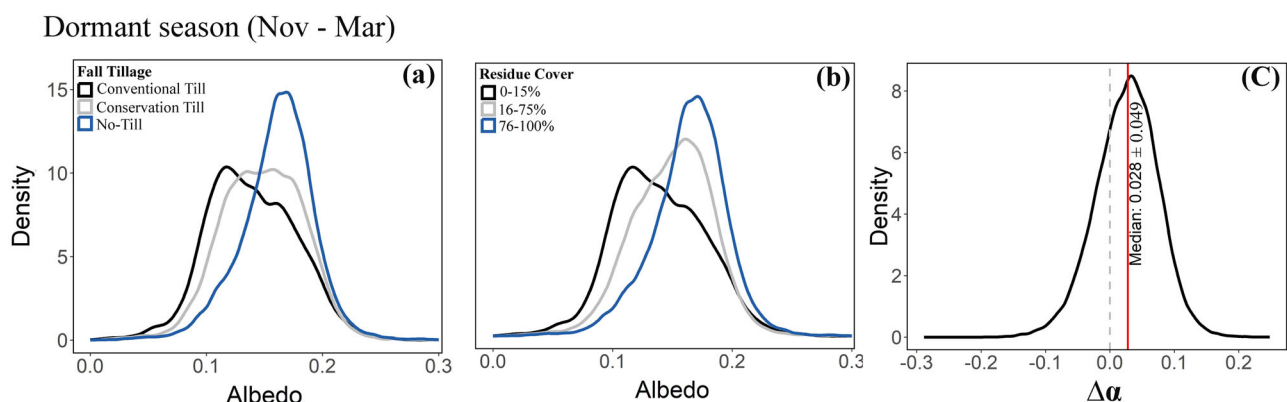

Fig. 2 | Distribution of Albedo/$\Delta\alpha$ in the fields on snow-free days during the dormant season (Nov. to Mar.) in Indiana from 2014 to 2022. The distribution is grouped by fall tillage practices (**a**), including conventional till, conservation till, and no-till, and by different residue cover percentages (**b**), including 0–15%, 15–75%, and 75–100%. Each smooth curve represents the spread of albedo or 'reflectivity' for one category, for example, in (**a**), black for no-till management, grey for conventional tillage, and blue for conservation tillage. In both (**a**) and (**b**), the distributions differ significantly, as confirmed by the Dunn test, which was chosen because it does not assume normality. In (**c**), delta albedo ($\Delta\alpha$) refers to the albedo of no-till minus the albedo of conventional till from a large ensemble of many random draws from each of their independent distributions. The red vertical solid line is the median albedo, and 0.049 is the standard deviation. The distributions include 40,000–50,000 samples from 2014 to 2022.

Fig. 3 | Relationship between county-level albedo and no-till or conventional tillage coverage in the Midwest. Data represent snow-free days during the dormant season of 2017 (Nov. to Mar.). The data points are colored blue and black to indicate the counties with low and high soil organic carbon content (SOC), respectively. For all counties, and then again for the counties with high SOC (black points), we evaluated the relation between albedo and the % of no-till or conventional till fields in each county (after first applying a binned averaging filter, see methods). We selected a square root function of the relation with no-till% (**a**) and the one with conventional till % (**b**). The functions were used later to calculate the potential $\Delta\alpha$ in the idealized scenario when shifting 0% no-till/conventional tillage management to 100% at the county scale. The shaded area is 95% confidence interval of the fitted model.
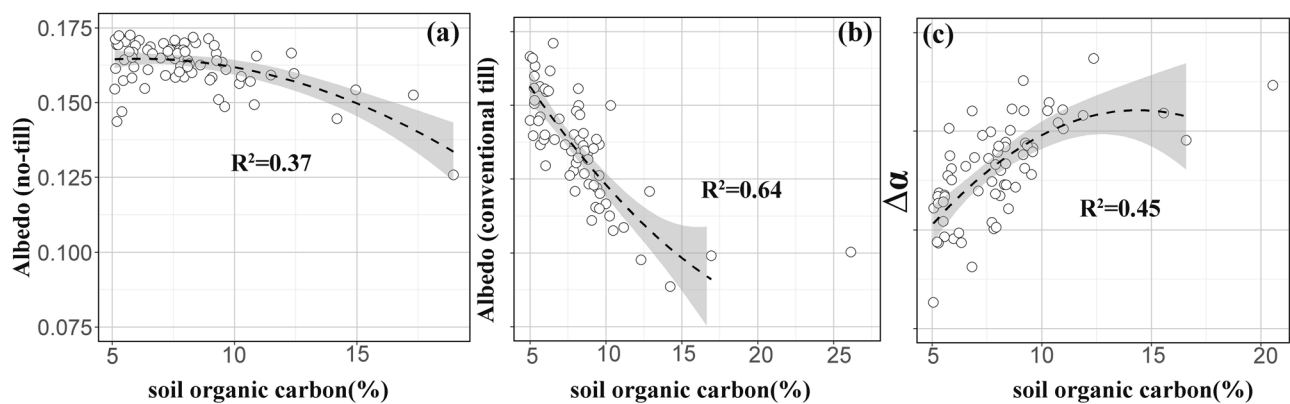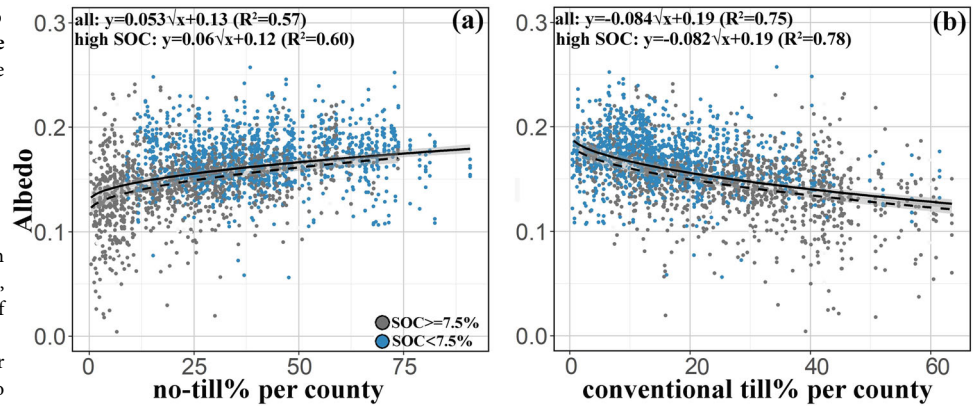

Fig. 4 | Relationships between albedo/$\Delta\alpha$ and soil organic carbon on snow-free days during the dormant season (Nov. to Mar.) in Indiana. a–c Compare soil organic carbon to the albedo of no-till fields, the albedo of conventional till fields, and the albedo differences between them ($\Delta\alpha$). These county-scale estimates are aggregated from transect field-level data. The shaded area is 95% Confidence Interval of the fitted model. We did not extend the model beyond 20% SOC due to poor data representation in this range.
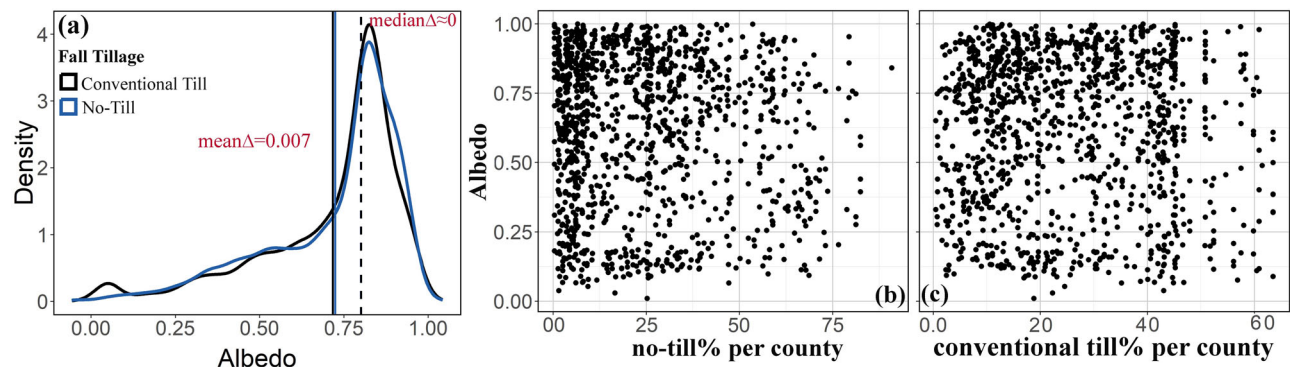

Fig. 5 | Relationships between albedo and tillage practices on snow-covered days during the dormant season (Nov. to Mar.). a Shows the density distribution of albedo on no-till and conventional till fields in Indiana on snow-covered days. **b, c** Show the relation between county-scale albedo and the rate of no-till and conventional till adoption (expressed as a percent of fields managed with each practice) on snow covered days and revealing no relationship.

snow cover was present, suggesting that snow masked any potential albedo contrast between tillage practices (Fig. 5a–c). This finding does not support our initial hypothesis regarding the effect of snow cover on $\Delta\alpha$.

Implications for radiative forcing and climate mitigation

Using established approaches (see methods), we estimated the change in radiative forcing associated with a shift from conventional tillage to no-till management. This analysis was conducted across the entire study region at the county scale in two idealized scenarios based on the functions between county-scale albedo and the fractions of farmland under no-till and conventional till management for the year 2017 (e.g. the solid lines in Fig. 3). In the first idealized scenario, representing a shift from 0% to 100% adoption of no-till management, we estimate that the resulting $\Delta\alpha$ (0.053) changes top-of-the-atmosphere (TOA) radiative forcing averaged across all farmlands in
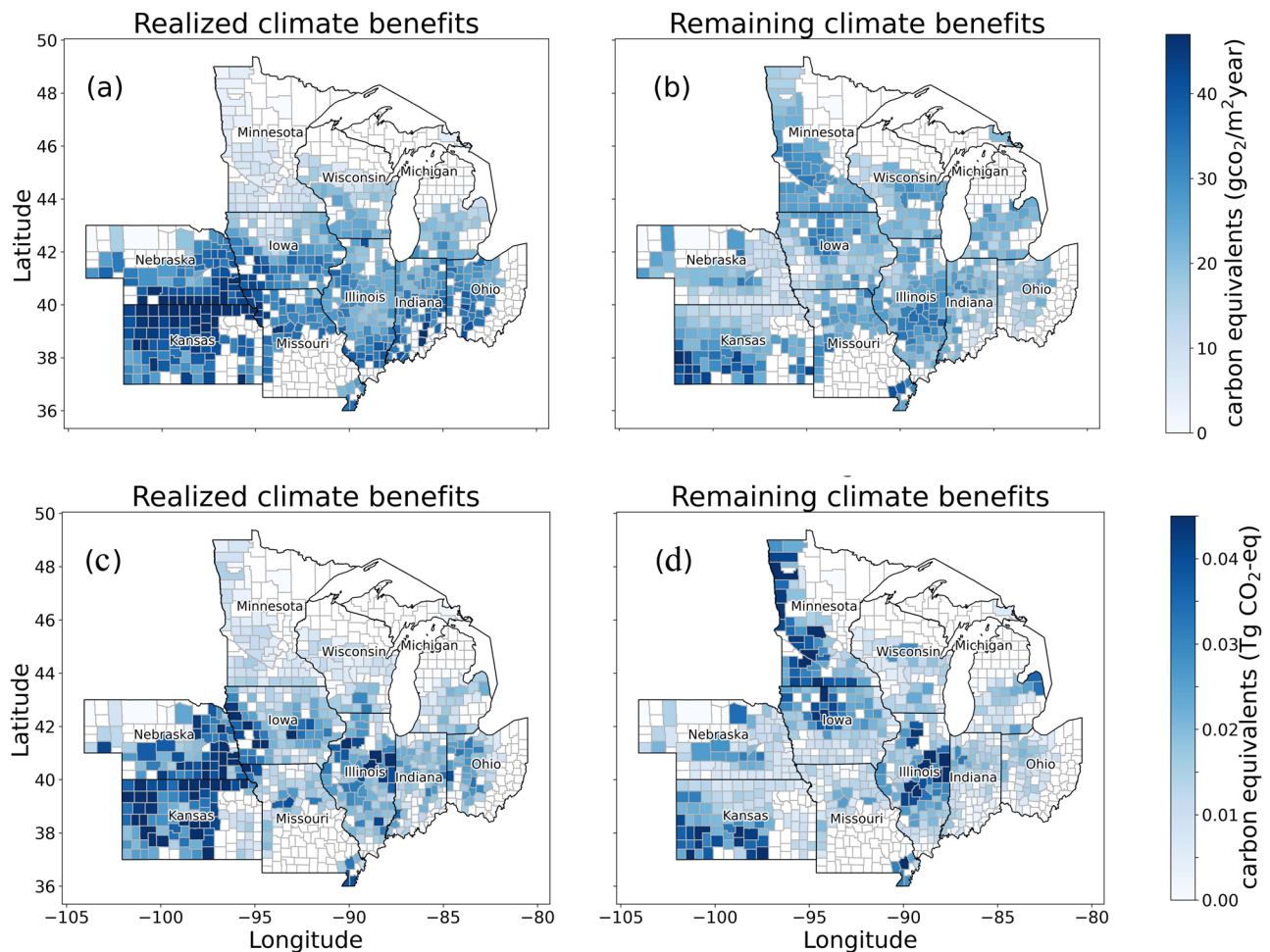
Fig. 6 | Climate mitigation and opportunity maps for no-till management in the Midwest. The (**a**) and (**b**) are climate mitigation for the Midwest's existing and remaining no-till% fields per county in gram CO_2 equivalent per meter^2 per year, g CO_2 / m^2 year^{-1} for 100 years. The (**c**) and (**d**) are climate mitigation for the Midwest's existing and remaining no-till% fields per county in Teragram of CO_2 equivalents, Tg CO_2-eq year^{-1} for 100 years. The data used in this figure comes from USDA NASS.

the study region by -2.34 ± 0.45 W/m^2. Consequently, on average across the study region, -1.31 ± 0.54 W/m^2 of this change in radiative forcing (about 56%) is already realized. The remaining changes in radiative forcing that could be achieved by additional conversion to no-till management is -1.03 ± 0.35 to -0.68 ± 0.22 W/m^2 on average (Supplementary Fig. 3a, b). Here, the higher end of the range is calculated by omitting fields managed with conservation tillage from the calculations. The lower end is estimated by assuming that the benefits of switching from conservation tillage to no-till is similar to the benefits of switching from conventional tillage to no-till– an assumption that has some empirical support at the county scale (Supplementary Fig. 4). In the second idealized scenario that assumes a shift from 0 to 100% adoption of conventional tillage, we found that the associated increase in radiative forcing was 3.76 ± 0.73 W/m^2 (Supplementary Fig. 3c, d). The spatial variability in the realized and remaining shifts in radiative forcing is high and primarily reflects the current adoption rates of tillage practices (Fig. 1). Thus, the greatest potential for reducing radiative forcing by adopting no-till management lies in counties where this practice is not widely used. Similarly, the best opportunity to prevent increases in radiative forcing by switching from no-till to conventional tillage is in counties where conventional tillage is already prevalent (Supplementary Fig. 3c, d).

As a final step, we converted these shifts in radiative forcing to units of carbon equivalents. We found that the idealized conversion from 0% to 100% no-till management across the study region would result in an area-normalized climate mitigation benefit of 50 ± 10 g CO_2-eq m^{-2}year^{-1}. Multiplying this area-normalized mitigation potential by the fraction of

total cropland in the region produces a total climate mitigation benefit of 24 ± 5 Tg CO_2-eq year^{-1} across the study region. Of this hypothetical total, we estimate that 14 ± 6 Tg CO_2-eq year^{-1} is already realized by the current rate of no-till adoption and that another 7 ± 2 to 11 ± 4 Tg CO_2-eq (Fig. 6) could be realized by converting the rest of the croppable acres in the study region to no-till management. In the idealized conversion from 0% to 100% conventional tillage, the associated increase in radiative forcing – climate trade-off as opposed to a climate benefit - amounts to 39 ± 8 Tg CO_2-eq year^{-1}, of which 17 ± 6 Tg CO_2-eq year^{-1} was met by the existing distribution of conventional till fields, and another 15 ± 7 to 22 ± 8 Tg CO_2-eq year^{-1} (Supplementary Fig. 5) would be expected if the rest of the no-till acreage in the Midwest was converted to conventional tillage. Spatial variability in the realized and remaining climate benefits and trade-offs for each scenario are high (Fig. 6, Supplementary Fig. S5), with the remaining potential concentrated in counties where tillage practice adoption rates are currently low (Fig. 1).

Discussion

Albedo changes are generally understudied in the context of NbCS[2,5,27]. Using two independent analyses at the scale of individual fields in Indiana and entire counties across the Midwest, we determined that no-till increases albedo by ~0.053 (on average) across the Corn Belt (Figs. 2 and 3). This amounts to a potential climate mitigation benefit of 24 ± 5 Tg CO_2 year^{-1} if no-till were applied to all 48 Mha of cropland in our study region (Fig. 6). When expressed on a per-area basis, the potential albedo-driven climate

benefit of no-till is ~50 ± 10 g CO_2-eq m^{-2}year^{-1}. This climate benefit is larger than many reported values for the carbon sequestration potential of no-till management but smaller than others (Table 1). Although this benefit is lower than the greenhouse gas reductions of cover crops (88–150 g CO_2-eq m^{-2}year^{-1})[28,29], it surpasses the albedo-related benefits provided by cover crops (11–48 g CO_2-eq m^{-2}year^{-1})[29]. However, no-till management may nonetheless offer greater near-term mitigation potential due to its feasibility and widespread adoption. Unlike cover crops—which require additional inputs, labor, and management—no-till is more accessible because of lower costs and simpler implementation[30,31]. Looking forward, the greatest remaining potential for no-till albedo climate benefits is concentrated in counties with low no-till adoption (Figs. 1 and 6b, d). Implementing no-till in areas with higher SOC could further enhance local climate benefits (Figs. 3 and 4). Overall, our findings suggest a substantial climate mitigation potential of no-till management in the Midwest through changes in albedo alone.

$\Delta\alpha$ of tillage management and its drivers

A key advantage of our study is the use of multiple independent datasets (e.g. the Indiana transect-level data and the county-scale USDA data) to estimate the potential change in albedo associated with implementation of no-till management. The fact that our results converge within a narrower range (0.028–0.053) increases confidence in $\Delta\alpha$ estimates for the U.S. Corn Belt, compared to broader global research, where reported values range from 0.026 to 0.2[21–24,26]. Moreover, the rich information contained in the Indiana conservation survey data permits a direct matching of field-scale management practice with field-scale remote sensing data. In this way, we avoid the need to rely on models to map the distribution of management practices across the landscape, which carries additional uncertainties.

Using Indiana transect survey data, we estimated $\Delta\alpha$ with two approaches: (1) field-level estimates based on randomly sampled field pairs, and (2) county-level estimates based on median values. Field level $\Delta\alpha$ ranged from 0.021 to 0.077, (mean = 0.028; (Fig. 2), and county level, $\Delta\alpha$ ranged from −0.012 to 0.062, (median = 0.029; Fig. 4C). These comparable values suggest that both methods yield consistent results. At the county scale across the Corn Belt, the potential $\Delta\alpha$ associated with a transition from 0% to 100% adoption of no-till management (Fig. 3a) is higher – specifically, 0.053. When the county scale data are analyzed to find the complimentary decrease in albedo associated with a transition from 0% to 100% adoption of conventional till management (Fig. 3b), the magnitude of the change is even higher (e.g. 0.084). Because SOC has a strong impact on the albedo benefits of no-till, the interaction between the current rate of no-till adoption and the distribution of SOC across the landscape helps to explain these differences. For example, the average SOC in Indiana is relatively low when compared to the rest of the region (Supplementary Fig. 6), which helps to explain why the $\Delta\alpha$ estimated from field-scale data in Indiana is lower than the $\Delta\alpha$ estimated for the entire region. Moreover, the fact that conventional till tends to be more commonly implemented in places that have higher SOC (Supplementary Fig. 7) could explain why a greater shift in albedo is estimated when converting these higher SOC fields to no-till versus implementing no-till on lower SOC fields that are conventionally managed. Overall, the rate of no-till adoption is likely the primary factor when considering climate benefits due to albedo-driven no-till management on a large scale (Figs. 1 and 6). However, SOC remains an important factor on more local scales (Figs. 3 and 4).

Understanding whether snow cover, with its high albedo, affects $\Delta\alpha$ is essential for assessing the impact of tillage practices on radiative forcing and their potential for climate mitigation. One possibility is that crop residues in no-till fields could lead to less snow cover extent than conventional tillage, for example, by breaking up the snowpack[32]. This would result in negative $\Delta\alpha$ on days with snow cover, where conventional tillage fields would have higher albedo than no-till fields. Conversely, if residues lead to more persistent snow cover extent, for example, by trapping more snow[33,34], we would expect higher positive $\Delta\alpha$ on snow-covered days. However, our results did not support either explanation, suggesting instead that tillage practices have

little impact on albedo on snow-covered days at both the field and county scale (Fig. 5), and the presence of snow masks the effects of different tillage practices on albedo. In addition to snow physically masking surface differences, satellite-based albedo retrievals are often less reliable under snow-covered conditions due to factors such as cloud cover, low solar angles, and mixed-pixel effects[35]. Timing mismatches between satellite overpasses and snow events, as well as complex interactions among snow, soil moisture, and surface residue, may further obscure no-till signals[36]. These challenges collectively hinder the detection of no-till's influence on albedo during snow-covered periods and highlight the need for further research.

Looking forward – strategies for implementation and future research

The albedo-driven climate benefits of no-till should be considered more prominently when assessing the Midwest cropland climate mitigation. In regions where no-till is already widely adopted, policies that enable farmers to maintain the practice are crucial to preventing a significant increase in radiative forcing from reverting to conventional management. To incentivize additional adoption, our opportunity maps suggest focusing resources on counties or states with low existing no-till%, dark soil, and big cropland areas. While reductions in radiative forcing from increased surface albedo represent a global mitigation benefit, other impacts of no-till are scale-dependent and often more relevant to climate adaptation than mitigation.

At local scale, no-till generally improves soil health, reduces erosion, and enhances water retention, which increases farm resilience to extreme weather[9–12]. However, in the Midwest, further research is needed to determine how combining no-till with cover cropping, irrigation, and tile drainage affects mitigation outcomes, as these interactions can enhance, diminish, or even counteract climate benefits. For example, cover crops could be optimally implemented in regions with lighter-colored soil and warmer springs and autumns. In these areas, the change in albedo from implementing no-till is smaller, and warmer shoulder seasons could sustain productive cover crop growth. Thus, carbon sequestration by cover crops is likely to offset its lower albedo benefits compared to no-till practices (Table 1). Additionally, drainage systems should be evaluated across no-till management, as water can be trapped under crop residues, increasing N_2O emissions[37,38]. The effects of no-till and its combined management practices on yield in the Midwest are also unclear. Studies provide contradictory results; for example, combining cover crops with no-till could lead to a 9.5% yield decrease[39], while long-term adoption of conservation tillage increased rainfed maize yields by an average of 9.9% in the Midwest[40]. Thus, conservation tillage—especially when shifting operations from fall to spring—may offer a more balanced approach, enhancing surface reflectivity while minimizing potential yield penalties. Most farmers do not implement a single practice in isolation, so understanding these interactive effects is essential.

In addition to its impacts on albedo, no-till management also changes surface roughness, evapotranspiration, and other biophysical feedback that determine regional surface energy budgets[22]. These changes could be beneficial; for example, no-till may mitigate hot temperature extremes in mid-latitude regions when the local cooling from soil moisture retention and associated enhanced transpiration is sufficient to offset the warming from reduced soil evaporation[22,41]. However, during the dormant season, these changes may also contribute to localized warming, helping offset cooler soil temperatures that hinder crop germination. At the same time, crop residues help retain soil moisture by reducing evaporation[42]. Future research should focus on comprehensively exploring the energy and hydrologic cycle feedback associated with no-till management.

While large-scale adoption may influence climate through changes in albedo, greenhouse gas fluxes, and energy balance, no-till adoption can interact with mitigation potential in the energy-sector, particularly by reducing the availability of crop residues. For instance, removing crop residues for high-value applications—such as cellulosic ethanol production or co-fired bioenergy—may reduce the albedo-enhancing effect of residue cover[43]. Therefore, the net climate impact of no-till depends on the balance

between albedo change, residue utilization pathways, regional energy dynamics, and practice decisions at the farm level, highlighting the importance of integrated land management strategies.

Importantly, the fact that radiative forcing impacts from albedo changes can be expressed in units of CO_2-equivalents provides an opportunity to incorporate these biophysical effects into existing carbon accounting frameworks. For example, the opportunity maps we present here could function as a tool to estimate an appropriate fractional increase (or, in some cases, reduction) of credit values. However, a robust integration of albedo impacts should also consider their durability, accounting for both environmental and socio-economic factors that influence the performance and permanence of a practice like no-till—especially given that albedo effects can persist indefinitely, unlike greenhouse gas mitigation, which may saturate over time. Here, more research is likely necessary.

Conclusions

Our study leverages the best available science to transform our understanding of the climate mitigation potential of no-till agriculture—an especially feasible NbCS applicable across most of the U.S. Corn Belt. Attention has focused on how no-till management can mitigate climate change by increasing soil carbon sequestration over the past 10–20 years, but there is still no consensus on its effectiveness. We contend that a key opportunity for climate mitigation with no-till management is through its influence on surface albedo, which has been underappreciated and understudied as a climate mitigation mechanism. In this study, we combined independent data streams and analyses at field, county, and regional scales to quantify the impact of no-till management on albedo relative to conventional tillage. We found the mitigation potential of no-till across the Midwest is $-24 \pm 5 \, \mathrm{Tg} \, CO_2$-eq year^{-1}. Finally, we identified specific regions where the climate mitigation potential of no-till is high and the adoption of this management is limited, providing actionable insights for targeted interventions in the Midwest.

Methods

We employed complementary but independent analyses that integrate high-resolution remote sensing data with extensive survey datasets, including transect-level surveys in Indiana (14,000 fields annually from 2014 to 2022) and county-scale USDA records across the Midwest (2017). Specifically, we conducted median difference analyses using field-level data and non-linear regression analyses at the county scale to calculate $\Delta\alpha$ between no-till and conventionally tilled fields. We then transformed the estimates of $\Delta\alpha$ into top-of-the-atmosphere radiative forcing and, eventually, climate mitigation potential (expressed in units of CO_2 equivalents). We finally explored how crop types and pedo-climatic drivers impact $\Delta\alpha$ and thus generated opportunity maps describing where additional resources should be deployed to optimize the albedo-driven climate mitigation benefits of no-till across the Midwest.

Ground survey data

The Indiana Transect Survey was conducted in the late winter to early spring from 2014 to 2022 by members of the Indiana Conservation Partnership. Data were shared by personal communication with the Indiana State Department of Agriculture and United States Department of Agriculture Natural Resources Conservation Service. This survey involved the collection of around 16,000–18,000 GPS points on major roads across Indiana each year. For each GPS Point, at least two surveyors recorded the information in the left and right fields of each GPS point. The information collected from the fields includes latitude, longitude, previous crop types, fall tillage practices, and residue density. In this study, we only focused on the fields larger than 500×500 m (around 5000–6000 samples yearly) to reduce signals from adjacent fields when using remotely sensed data. We further separated fall tillage practices into no-till, conservation, and conventional tillage.

Across the Midwest US, the USDA NASS provided each county's 2017 Census of Agriculture data. This data included the area in acres of harvested cropland and three different tillage practices used in this cropland, including

no-till, conventional tillage, and conservation tillage, excluding no-till (conservation tillage for simplicity). We calculated no-till%, conservation till %, and conventional till% per county by the area of harvested cropland divided by the cropland areas implemented with three tillage practices, respectively. It is important to note that the Indiana Transect data were collected during the winter and early spring, whereas the NASS data were gathered at the time of planting. For the Transect data, visible surface residue in fall or early spring does not necessarily indicate continuous no-till management, as fall or spring tillage could have occurred prior to planting. For the NASS data, farmers may report 'no-till' based on the use of no-till planters (corn) or drills (soybean), even if some tillage was performed earlier in the season. In both cases, fields labeled as 'no-till' may include management histories that reduce the expected albedo signal. The Midwest US includes Iowa (IA), Missouri (MO), Illinois (IL), Wisconsin (WI), Indiana (IN), Ohio (OH), Nebraska (NE), Kansas (KS), Minnesota (MN), and Michigan (MI). The 2017 USDA NASS Cropland Data layer (USDA NASS, 2017) was used to mask the non-cropland area.

Remotely sensed albedo

At the field level in Indiana and county level in the Midwest US, the broadband shortwave albedo was estimated from the narrowband surface reflectance layers (SRs) of the Landsat8 Collection 2, which are provided by the United States Geological Survey (USGS) and are fully available and ready to use in Google Earth Engine (GEE). We retrieved Landsat albedo data from 2014 to 2022. For each field, if no-till practices were surveyed in the fall of a given year (e.g., 2014), we extracted albedo data from the subsequent dormant season (i.e., November 2014 to March 2015). Conversely, if no-till was surveyed in the spring (e.g., 2022), we used albedo data from the preceding dormant season (i.e., November 2021 to March 2022). This approach was applied consistently to ensure that albedo measurements reflected the period immediately following the adoption of no-till practices. Surface reflectance data was atmospherically corrected using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS), which generates surface reflectance estimates from a radiative transfer model with inputs of TOA reflectance, TOA brightness temperature, and auxiliary data such as water vapor, ozone, geopotential height, aerosol optical depth, and digital elevation[44]. Snow and cloud coverage information, including cloud shadowing, can be retrieved from the quality assessment band and were made available by the USGS through the GEE. We removed data affected by clouds and cloud shadows. Then, we included and excluded the snow-affected data for the analysis on snow-free and snow-covered days, respectively (see the details in the section Possible drivers of $\Delta\alpha$). Albedo was estimated using the narrowband-to-broadband shortwave albedo algorithm developed for the OLI instrument[36]. This method has been validated and applied in multiple studies[26,45–47].

$$\begin{aligned} \text{Albedo} = {} & 0.356 \times \alpha2 + 0.130 \times \alpha4 + 0.373 \times \alpha5 \\ & + 0.085 \times \alpha6 + 0.072 \times \alpha7 - 0.0018 \end{aligned} \tag{1}$$

where $\alpha2$, $\alpha4$, $\alpha5$, $\alpha6$, and $\alpha7$ represent narrowband band albedo of Landsat 8 OLI band 2, 4, 5, 6, and 7, respectively. This empirical model was developed using extensive radiative transfer simulations under various surface and atmospheric conditions and snow[45,48]. For the county scale analyses, Landsat albedo values from fields that were larger than 500×500 m were averaged to the county scale. Our analysis analyzed snow-free conditions only because we found that on snow-covered days, albedo showed little difference across tillage practices (Fig. 5).

Delta albedo($\Delta\alpha$) calculations

For Indiana transect survey data on snow-free days, we used the density function in R studio to plot the albedo grouped by the three tillage practices/ density of crop residues in the dormant season (Nov. to Mar.). For the no-till and conventional till density plots, we randomly selected 40,000 sample pairs by drawing one sample from each tillage group per iteration. We then calculated the $\Delta\alpha$ for each pair and plotted the resulting density distribution

of $\Delta\alpha$. Some of our analyses rely on estimates of county-scale $\Delta\alpha$ aggregated from the Indiana transect data. To do this, first, we stratified the sample population by county; then, we calculated the median albedo for no-till and conventional till fields within each county; finally, we determined the difference between them as $\overline{\Delta\alpha_i}$. We retained only the counties with more than 10 no-till fields and 10 conventional till fields to more accurately represent county-level albedo changes resulting from no-till and conventional tillage practices.

For the Midwest on snow-free days during the dormant season, we quantified the change in albedo attributable to no-till using the relation between monthly county-mean albedo and the fraction of fields in each county managed with no-till (e.g., Fig. 3). The monthly county-mean albedo represents the average albedo value across all crop fields within each country for each month. To reduce the influence of spatial variability, we first apply a binned averaging filter to compute the mean albedo within each percentage bin. The resulting values are then used to fit a function that quantifies the relationship between albedo and no-till% per county: $y = 0.053\sqrt{x} + 0.13$. For county i, we calculate the potential $\Delta\alpha_i$ due to an idealized transition from 0 to 100% no-till adoption using this function. We then calculated the realized $\Delta\alpha_i$ using the same equation, but with the value of x_i represented by the county-specific no-till adoption rate from the 2017 NASS data. Finally, we calculated the remaining $\Delta\alpha_i$ as the difference between the potential and realized $\Delta\alpha_i$. Next, we further focused on the counties with high soil organic content (SOC > 7.5%); the resulting function is $y = 0.06\sqrt{x} + 0.12$. Finally, we repeated all these calculations for idealized scenario of conversion from 0% to 100% conventional till management. The resulting functions were $y = -0.084\sqrt{x} + 0.19$ for all counties, and $y = -0.082\sqrt{x} + 0.19$ for the counties with higher SOC. We used a square-root function to model the relationship between no-till percentage and albedo, as no-till is more common in low-SOC regions (Fig. 3a), where bare soil albedo—approximated by conventionally tilled fields—declines non-linearly with increasing SOC (Fig. 4b). Thus, the albedo shift with no-till partly reflects SOC patterns, contributing to non-linear dynamics in the data. The same reasoning applies to the relationship between conventional till% and albedo.

Radiative forcing calculations

In the Midwest on snow-free days, we used the empirical method (Equation 17)[49] to translate the three albedo changes (potential/realized/remaining $\Delta\alpha_i$) at the county level to top of the atmosphere radiative forcing averaged across all farmlands in the study region in W/m². The three $\Delta\alpha_i$ estimates were calculated based on the functions combining all data from the dormant season for each county (see details in the section Delta albedo ($\Delta\alpha$) calculations), as we found that $\Delta\alpha$ appeared relatively stable across different months (Supplementary Fig. 8). Thus, we used the dormant-season average values of different inputs to calculate the monthly mean radiative forcing across the dormant season as:

$$RF_{\Delta\alpha,i,monthly} = \overline{SW_{i,m}^{SFC}} \times \overline{\sqrt{T_{i,m}}} \times (1 - \overline{f_{i,m}})\Delta\alpha_i \quad (2)$$

$RF_{\Delta\alpha,\,i,monthly}$ is the mean radiative forcing in the county i from 2017 November to 2018 March. $\overline{SW_{i,m}^{SFC}}$ is the mean downwelling solar flux at the surface in the county i from 2017 November to 2018 March $\overline{\sqrt{T_{i,m}}}$ is the mean clearness index in the county i from 2017 November to 2018 March. The clearness index is calculated from the ratio between the downwelling solar flux at the surface and the downwelling solar flux at the top of the atmosphere. These data were downloaded from Earth's Radiant Energy System Energy Balance and Filled products. $\overline{f_{i,m}}$ is the mean fraction for snow-covered days in the county i.

The global and annual RF due to albedo changes was then calculated as:

$$RF_{\Delta\alpha,\,i,annual,global} = RF_{\Delta\alpha,\,i,monthly} \times \frac{Area(i)}{A_{Earth}} \times \frac{5}{12} \quad (3)$$

In the Midwest, i is the county i; Area(i) is the cropland area in the county i. A_{Earth} is the global surface area (5.1×10^8 km²); Five is the number of dormant season months, and twelve is the total number of months within a year. We again note that this approach assumes that tillage management only affects albedo during the dormant season (e.g. 2017 Nov–2018 Mar), despite some evidence that impacts may linger into the growing season (see Supplementary Fig. 1).

Transforming results into units of CO₂ equivalent

Next, we converted the results into units of CO_2 equivalents using an approach for determining GWP that explicitly accounts for the lifetime and dynamic behavior of CO_2 to convert RF to CO_2 equivalent[50,51].

$$GWP_i\left[kg\ of\ CO_2 - eq\right] = \frac{\int_{t=0}^{TH} RF_{\Delta\alpha,\,i,annual,global}(t)}{k_{co_2}\int_{t=0}^{TH} y_{co_2}(t)} \quad (4)$$

where i is the county i; k_{co_2} is the radiative efficiency of CO_2 in the atmosphere (W/m²/kg) at a constant background concentration of 391 ppmv, which is taken as 1.75×10^{-15} W/m²/kg[52], and $RF_{\Delta\alpha,i,annual,global}$ is the global RF caused by albedo changes (W/m²). y_{co_2} is the impulse-response function (IRF) for CO_2 that ranges from 1 at the time of the emission pulse ($t = 0$) to 0.41 after 100 years, and here it is set to a mean value of 0.52 over 100 years[53]. The time horizon (TH) of our GWP calculations was fixed at 100 years following IPCC standards and previous studies[29,54–56]. We sum up the GWP from each county to get the total GWP across the Midwest. We annualize our calculations by assuming the conversion was spread evenly over 100 years, following a previously established approach[29], which permits a more direct comparison with results from other studies investigating the climate impacts of various conservation agriculture practices. Finally, we expressed GWP estimates in absolute terms and categorized them as a 'climate mitigation benefit' when associated with an increase in albedo and negative radiative forcing, and as a 'climate trade-off' when associated with a decrease in albedo and positive radiative forcing.

Possible drivers of $\Delta\alpha$

Snow cover can strongly change the albedo of land regardless of tillage practices (Fig. 5). The snow-free and snow-covered conditions were derived from level 3 MODIS/Terra Snow Cover (MOD10CM.006), and the data quality was controlled by removing all pixels not classified either as best (QA = 0) or good (QA = 1).

The pedo-climatic drivers and crop types could also impact $\Delta\alpha$. At both the field and county levels, we obtained surface SOC data from OpenLandMap[57]. We also collected co-located climatic variables during the dormant season following the implementation of tillage practices. These variables included soil moisture from the NASA-USDA Enhanced SMAP Global Soil Moisture dataset; precipitation and incident shortwave radiation flux density from the DAYMET dataset; and temperature and vapor pressure deficit (VPD) from the TerraClimate dataset. Additionally, at the county level, we included the corn ratio, defined as the proportion of fields where corn was the previous crop, divided by the total number of fields in the county.

Analyses

In this study, we calculate albedo separately for snow-free and snow-covered conditions. For snow-covered conditions, we include snow-affected albedo data, plot the density plots of this albedo for no-till and conventional till fields, and compare county-level albedo and the no-till% or conventional till% per county to understand if snow changes the effects of different tillage practices on albedo.

For snow-free conditions, we remove snow-affected data and calculate the albedo, $\Delta\alpha$, radiative forcing, and CO_2 equivalents. To understand the major drivers of county-level $\Delta\alpha$, we compared SOC to the county-level albedo of no-till and conventional till fields and the difference in albedo between them ($\Delta\alpha$). We also employed multiple linear regression models to

identify key drivers of county-level Δα, including SOC, incident shortwave radiation flux density, soil moisture, temperature, precipitation, VPD, as well as county-level corn ratio. Firstly, we used multi-year dormant season averages (2014–2022) for both Δα and crop type and pedo-climatic variables, to capture long-term spatial variability; and another using annual dormant season averages to incorporate temporal variability. These explanatory variables were calculated as dormant-season means of no-till and conventional till fields within each county over the same period, and their influence was assessed using model coefficients and *p*-values. Please refer section Possible drivers of Δα for the data source. Note that we focus on understanding the drivers of county-level Δα rather than field-level variations because pedo-climatic variables are coarse at the field scale. Additionally, identifying the drivers at the county level is more relevant for informing and implementing agricultural and conservation policies, which are often designed and applied at broader administrative scales rather than at individual fields.

Data availability

Landsat data used here are available via https://www.usgs.gov/landsat-missions/landsat-collection-2-level-2-science-products; MODIS snow cover data used here are available via https://nsidc.org/data/mod10a1/versions/61; SOC from OpenLandMap (https://opengeohub.org/about-openlandmap/); DAYMET: https://developers.google.com/earth-engine/datasets/catalog/NASA_ORNL_DAYMET_V4; PRISM: https://www.prism.oregonstate.edu/; TerraClimate: https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE; NASA-USDA Enhanced SMAP Global Soil Moisture Data: https://nsidc.org/data/spl4smgp/versions/7; The data for calculating Radiative Forcing from Earth's Radiant Energy System Energy Balance: https://ceres.larc.nasa.gov/data/#energy-balanced-and-filled-ebaf. The data used to reproduce the figures in this paper can be accessed through: https://zenodo.org/records/15715633. Due to privacy concerns, the latitude and longitude for each sample point from Indiana Transect Survey Data have been removed.

Code availability

The code can be assessed through: https://zenodo.org/records/15715633.

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Author contributions

X.W., K.N., and M.B. designed the study and conducted most of the data analysis. L.Y. facilitated access to the Indiana transect data and contributed to improving the manuscript's clarity. C.W. provided expertise in albedo and global warming potential and contributed to enhancing the manuscript. J.T. assisted in interpreting the Indiana transect data and supported manuscript development. T.R. contributed to the interpretation of albedo driver analysis and helped refine the manuscript. S.S. provided insights on the economic value of no-till residuals and contributed to the manuscript's improvement.

Competing interests

The authors declare no competing interests.

Additional information

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