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To cite this article: Ke Yu *et al* 2024 *Environ. Res. Lett.* **19** 074042

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ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
16 December 2023

REVISED
2 June 2024

ACCEPTED FOR PUBLICATION
14 June 2024

PUBLISHED
25 June 2024

LETTER

Quantifying albedo impact and radiative forcing of management practices in European wheat cropping systems

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Keywords: surface albedo, management practices, temporal evolution, radiative forcing

Supplementary material for this article is available online

Abstract

Management practices that increase the surface albedo of cultivated land could mitigate climate change, with similar effectiveness to practices that reduce greenhouse gas emissions or favor natural CO_2 sequestration. Yet, the efficiency of such practices is barely quantified. In this study, we quantified the impacts of seven different management practices on the surface albedo of winter wheat fields (nitrogen fertilizer, herbicide, fungicide, sowing, harvest, tillage, and crop residues) by analyzing observed daily albedo dynamics from eight European flux-tower sites with interpretable machine learning. We found that management practices have significant influences on surface albedo dynamics compared with climate and soil conditions. The nitrogen fertilizer application has the largest effect among the seven practices as it increases surface albedo by 0.015 ± 0.004 during the first two months after application, corresponding to a radiative forcing of -4.39 ± 1.22 W m^{-2}. Herbicide induces a modest albedo decrease of 0.005 ± 0.002 over 150 d after application by killing weeds in the fallow period only, resulting in a magnitude of radiative forcing of 1.33 ± 1.06 W m^{-2} which is higher than radiative forcing of other practices in the same period. The substantial temporal evolution of the albedo impacts of management practices increases uncertainties in the estimated albedo-mediated climate impacts of management practices. Although these albedo effects are smaller than published estimates of the greenhouse gas-mediated biogeochemical practices, they are nevertheless significant and should thus be accounted for in climate impact assessments.

1. Introduction

The biophysical effect of land management practices on albedo (the fraction of light reflected by the land surface) may cause local climate warming of the same order of magnitude as greenhouse gas (GHG) emissions on agricultural lands (Lobell *et al* 2006, Devaraju *et al* 2015, Lugato *et al* 2020, Liu *et al* 2022). However, it has not been included in countries' climate change mitigation commitments and received little attention for improving the climate resilience of agriculture due to uncertainties of albedo-mediated mitigation potential, missing representation of albedo in farm models, difficulties in reporting and verification, and dependence on the climate effects on models and assumptions (Davin and de Noblet-ducoudré 2010, Thomas *et al* 2016, Seneviratne *et al* 2018, Chen 2021).

Changes in surface albedo induced by management practices impact regional (global) climate either by directly affecting the radiative forcing at the top atmosphere, or the atmosphere hydrothermal dynamics influenced by the albedo-mediated surface energy partitioning (Bright 2015, Huang *et al* 2020, Li *et al* 2023). The variation of air temperature by the two processes mitigates or intensifies the regional (global) warming induced by GHG emissions. Managing surface albedo is therefore an option to reduce the impact of agriculture on climate and may help to deal with other issues like erosion, low water infiltration, and highly degraded soils. This can be achieved by covering the surface in fallow periods with crop residues or cover crops which reflect more radiation than dark topsoil, or by reducing tillage which decreases the surface roughness of fields, thereby increasing the albedo during the fallow period (Davin *et al* 2014, Seneviratne *et al* 2018, Sieber *et al* 2022). As an example, a widespread introduction of cover crops in fallow periods could increase surface albedo in Europe by about 4%, corresponding to a mitigation potential of 159.00 kg CO_2e ha^{-1} yr^{-1} (Carrer *et al* 2018). Other land management practices, such as biochar application, may affect albedo more indirectly and in a non-intended way (Genesio *et al* 2012). Fertilizers enhance crop growth and herbicides suppress weeds, thereby affecting surface albedo by influencing the fraction of radiation absorbed by leaves. But the climate mitigation potential of such practices for albedo management remains uncertain (Hirsch *et al* 2018).

In this study, we used the random forest model and visualization techniques based on partial dependence plots to address two research questions:

(1) To what extent (and how) do management practices influence the temporal albedo dynamics in winter wheat crops and their subsequent fallow periods in Europe?

(2) How do albedo-mediated biophysical impacts compare with estimates resulting from GHG budgets?

We addressed these two questions using machine learning and daily surface albedo dynamics derived from incoming and outgoing shortwave radiation measurements at eight European cropland sites with information on management practices.

2. Methodology

2.1. Datasets

2.1.1. Flux tower data

We obtained ecosystem-scale carbon, water, and energy fluxes, as well as meteorological data from flux sites under cropland use through the Integrated Carbon Observation System (ICOS) Data Portal (Bernhofer *et al* 2023, Brümmer *et al* 2023, Brut *et al* 2023, Buysse *et al* 2023, Dumont *et al* 2023, Schmidt *et al* 2023, Tallec *et al* 2023), and European Fluxes Database Cluster (EFDC, www.europe-fluxdata.eu/). We only considered periods during which winter wheat was cultivated as the main crop, i.e. crop growth periods from sowing to harvest and the subsequent fallow periods until the next main crop period other than winter wheat. Out of the 32 European fluxnet sites in the data, only eight sites (BE-Lon, FR-Gri, FR-Lam, FR-Aur, DE-RuS, DE-Geb, DE-Kli, CZ-KrP) had sufficient information available (supplementary figure 1). The data spans the period 2000–2020 with a total of 126 site years. The data includes measurements of incoming and outgoing shortwave radiation (SW_IN, SW_OUT), incoming shortwave radiation at the top of the atmosphere (SW_IN_POT), air temperature, soil temperature, vapor pressure deficit, wind speed, precipitation, air pressure, superficial soil water content, sensible heat flux, and latent heat flux. Except for SW_IN and SW_OUT, all fluxes were provided as daily values. Data were quality-controlled and gap-filled using uniform methods (Pastorello *et al* 2020). Two climatic variables that potentially affect surface albedo dynamics were further derived, i.e. the ratio between diffuse and total solar radiation (Kd), which reflects atmosphere conditions such as cloud cover (Boland *et al* 2008), and the Bowen ratio which shows the surface hydrothermal transport (supplementary text 1.1). We applied a coarse-resolution cloud cover filtering based on daily moderate-resolution imaging spectroradiometer (MODIS) MO(Y)D04_L2 product (https://ladsweb.modaps.eosdis.nasa.gov/) to exclude days with very low incoming shortwave radiation at the surface which prevents us from estimating albedo adequately.

The daily shortwave mid-day albedo α was averaged from SW_IN and SW_OUT from 11:00 to 13:00

Central European Summer Time at each site (Lin *et al* 2022):

$$\alpha = \frac{SW\_OUT}{SW\_IN}. \quad (1)$$

2.1.2. Crop management data
We assessed the impact of management practices on albedo dynamics using a crop management database provided by site managers (supplementary table 1). The legacy effect of selected management practices on albedo dynamics is represented as the number of days since the implementation of given practices with an upper bound after which the practices were assumed to have no effect anymore (see below). The practices include physical management and input-related ones. The former encompasses tillage, sowing and harvest events of winter wheat, the presence of crop residues on the soil surface (including stalks left standing) (coincides with harvest date), and type of cover crops. The latter involves the applications of mineral fertilizer, manure, fungicide, herbicide, insecticide, growth regulator, and stalk stabilizer (table 1). In cases where multiple events occurred for given practices, timers were reset to one at each event. For cases where the time since the last event of a practice is unavailable (i.e. the first occurrence of a practice in the management records) we set the timer to the duration of the assumed maximum legacy effect of management practices (supplementary figure 2). We further categorized mineral fertilizer by calcium, nitrogen, sulfur, and magnesium, and we accounted for the depth of tillage and the type of cover crop.

2.2. Statistical analysis

2.2.1. Isolation of the management practice impacts on surface albedo dynamics
We trained random forest models to disentangle the effects of management practices on daily surface albedo dynamics from other influences (see below) (figure 1). The random forest model effectively handles nonlinear relationships and can be used to disentangle the effects of different predictors on the target variables (surface albedo) (Friedman 2001, Svetnik *et al* 2003). We selected 28 potential features for which site information is available (table 1), including climatic and ecological features ($n = 9$), soil properties ($n = 3$), site identity ($n = 1$), days since management practices ($n = 13$, i.e. one for each management practice considered), types of cover crops ($n = 1$) and depths of tillage ($n = 1$). The selected features do not include crop growth or phenology which drive albedo dynamics during the cropping period, but instead included the climatic and edaphic drivers of crop growth. The nine daily climatic and ecological features were derived from the flux tower dataset (see section 2.1.1). The three time-invariant soil properties were obtained from the Harmonized World Soil Database (HWSD) based on the site locations (Wieder *et al* 2014). They were employed to characterize soil properties across all data points for each site. Site identity reflects site heterogeneity due to factors not accounted for. Each of the eight sites is identified by a categorical label ranging from one to eight. All features are continuous except for site identity, tillage depth, and cover crop type. At first, all features were included in the random forest models and recursive feature elimination was then implemented to select relevant features for a given period (supplementary text 1.2).

Two random forest models were trained using the combined data from all eight sites, respectively: (1) for both growing and fallow periods spanning winter wheat sowing to the next main crop sowing (2645 data points); (2) for fallow periods after winter wheat harvest to the next main crop sowing (798 data points). The latter was done to identify factors influencing the albedo during the fallow period specifically (3–7 months). Harvest events always coincide with the occurrence of crop residues, and it is impossible to distinguish their effects (not shown). Thus, for interpretation of results we refer to the albedo dynamics on the days after harvesting events as the impact of harvest for growing and fallow periods and as the impact of crop residues for fallow periods (figures 3(a) and (c)).

The dataset was split randomly into 80% for training and tuning and 20% for testing. We applied 10-fold cross-validation to the training dataset for hyperparameters tuning (i.e. number of decision trees (ntrees) from 300 to 1000, number of variables sampled (mtry) from 2 to 7 at each split). The model with the optimal set of parameters was selected, trained on the whole training dataset, and evaluated using the testing dataset. We used the coefficient of determination (R^2) and root mean square error (RMSE) as quality indicators during tuning, training, and testing (supplementary table 6). Recursive feature elimination was used during the training step to reduce the number of predictors (Guyon *et al* 2002). We tested for overfitting by comparing the final R^2 and the R^2 during the cross-validation process. For more information see supplementary text 1.2 and supplementary figure 2. The duration of the legacy effects of management practices on daily surface albedo differs among practices. This analysis focuses on the short-term impacts of management practices, as the observation period is too short to disentangle effects which operate on a time scale of years and longer. Therefore, we artificially limited the maximum duration before the random forest training to 210 d for growing and fallow periods, and 150 d for fallow periods. These two durations were selected by testing a range of 30–300 d when the improvements of R^2 and RMSE with increasing duration in random forest models were levelling off (supplementary figure 4). A risk of confused feature contribution might occur if the duration is not limited, especially in fallow periods (not shown).

Table 1. Features used in the analysis, including climatic and ecological features, soil properties, site identity, and features related to management practices. Features of management practices contain timing and characteristics.

Features	Labels	Explanations
Air temperature (°C), vapor pressure deficit (hPa), wind speed (m s^{-1}), precipitation (mm), Ratio between diffuse and total solar radiation (−), air pressure (kPa)	$Temp_a$, VPD, ws, Pre, Kd, PA	Climatic features
Soil temperature (°C), soil water content (%), Bowen ratio (−)	$Temp_s$, SWC, β	Ecological features
Clay content (%), sand content (%), silt content (%)	$Clay_c$, $sand_c$, $silt_c$	Soil properties
Site identity (−)	SiteIden	—
Ca fertilization (days) N fertilization (days) S fertilization (days) Mg fertilization (days)	D_{Ca} D_N D_S D_{Mg}	Days since the fertilizer supply
Fungicide application (days) Herbicide application (days) Insecticide application (days)	D_{Fug} D_{Her} D_{Ins}	Days since pesticide application
Growth regulator (days) Stalk stabilizer (days)	D_{gr} D_{ss}	Days since growth regulator and stalk stabilizer application
Tillage (days, cm)	D_{Til}, $Depth_{Til}$	Days since tillage, and depths of tillage. The depths include 5, 7.5, 10, 12, 15, 25, 30 and 40 cm. The depth of 7.5 cm for tillage is the average from records of the range of '5–10 cm'. 20 d after each tillage practice were marked by their corresponding depth records, while others as 0 cm.
Sowing	D_{sow}	Days since sowing
Crop residues/harvest (days)	D_{res}, D_{Har}	Days since the occurrence of crop residues/harvest
Cover crop	$Type_{cc}$	The label of cover crop types (mustard, fababean, oil radish, oil radish and mustard, soft wheat)

Ca, N, S, Mg are calcium, nitrogen, sulfur, and magnesium.

Partial dependence plots were utilized to quantify changes in daily albedo since the application of each management practice (Friedman 2001). For each practice i, albedo change is defined as the difference between albedo estimated at a given day d (noted $\alpha_{pdp,m}$) and the baseline albedo ($\alpha_{av,m}$) for the wheat growing and fallow periods together ($m = w$) and fallow period alone ($m = f$), respectively:

$$\Delta\alpha_m(d,i) = \alpha_{pdp,m}(d,i) - \alpha_{av,m}(i). \quad (2)$$

Baseline albedo is estimated from the averaged albedo for time points after the maximum duration of a management effect till the same event occurs again (supplementary table 2). This estimate was used as a proxy for bare soil albedo, as no bare soil control was available at the sites included in this analysis. Partial dependence plots are not suitable to quantify interactions among features here, because of the small sample sizes available for each pair of features.

2.2.2. Climate impact resulting from management practices on surface albedo

The radiative forcing (W m^{-2}) caused by surface albedo variation is defined as the change in energy flux at the top of the atmosphere (Jones *et al* 2015, Bright and Lund 2021). To quantify the impact of management practices on the climate via the induced changes in surface albedo, the radiative forcing was derived as follows (Carrer *et al* 2018):

$$\mathrm{RF}_{\Delta\alpha(d,i)} = -\frac{1}{N_{\mathrm{days}}}\sum_{1}^{N_{\mathrm{days}}}\mathrm{SW\_IN}(d)\times T_{\mathrm{au}}(d) \times \Delta\alpha_m(d,i) \quad (3)$$

where $\mathrm{RF}_{\Delta\alpha(d,i)}$ is the average of radiative forcing of albedo change in N_{days} caused by implementing management practices; $T_{au}(d)$ represents upward atmospheric transmittance (Unitless), which can be retrieved from SW_IN/SW_IN_POT. $\Delta\alpha(d, i)$ has

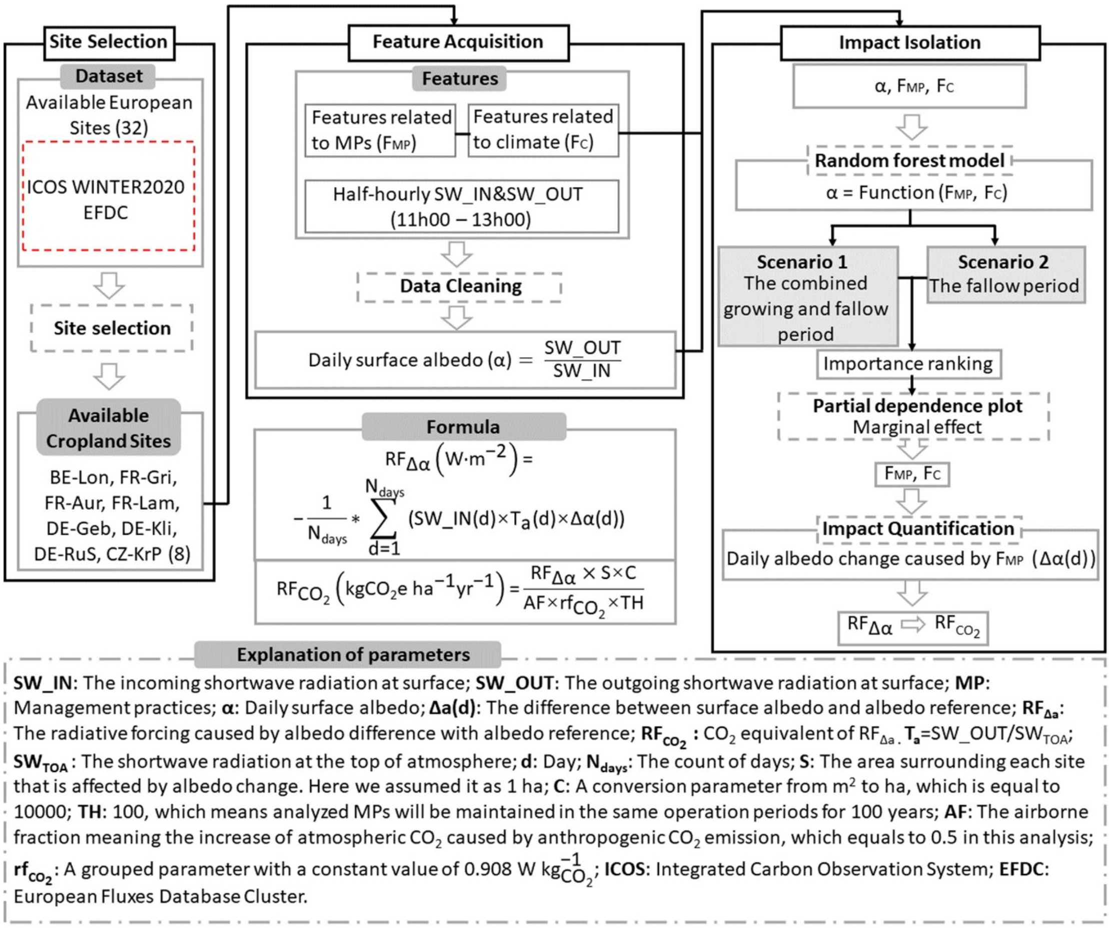

Figure 1. The flow chart of the data processing procedure.

the same meaning as in equation (2). We computed the radiative forcing for (1) $N_{days} = 210$ for the combined growing and fallow periods and (2) $N_{days} = 150$ for fallow periods.

We further converted $RF_{\Delta\alpha(d,i)}$ to equivalent CO_2 emission or removal using global warming potential (GWP) to compare with estimates from the literature of albedo (GHG)-induced radiative forcing (supplementary table 3). The calculation of GWP can be seen in supplementary text 1.3.

3. Results

3.1. Comparison of the importance of features for daily albedo predictions

The trained random forest model, with optimized hyperparameters (ntrees = 600 and mtry = 3), showed a good performance in predicting the daily albedo over both the growing and fallow period with R^2 and RMSE of 0.64 and 0.02, respectively. When considering fallow periods only, the R^2 and RMSE were 0.58 and 0.02, respectively (figures 2(a) and (c)). The small difference between the R^2 derived from the test dataset and the R^2 obtained during the cross-validation process (4%) revealed very low overfitting.

The ten most important features selected to predict the daily albedo depended on the periods of simulation. For growing and fallow periods, the most influential features were related to management practices as well as climatic and ecological features (in descending order of importance): D_N, Kd, soil temperature, soil water content, D_{Fug}, D_{Har}, D_{Her}, air pressure, D_{sow}, and D_{Til}. For fallow periods, climatic and environmental characteristics were more influential than management-related features: Kd, soil temperature, soil water content, wind speed, D_{res}, sand and clay contents, D_N, D_{Til}, and D_{Her} (figures 2(b) and (d)).

Nitrogen fertilizer Herbicide, tillage, and harvest (crop residues) were identified as important drivers for both periods, while only fungicides and sowing were selected for growing and fallow periods as they were applied during the growing period of winter wheat only. With respect to climatic and ecological features, Kd affects surface albedo most significantly, followed by soil temperature and soil water content in both periods. Tests of feature importance in different durations of maximum legacy effects additionally support the dominant effect of nitrogen fertilizer and Kd on surface albedo dynamics (supplementary figure 5).

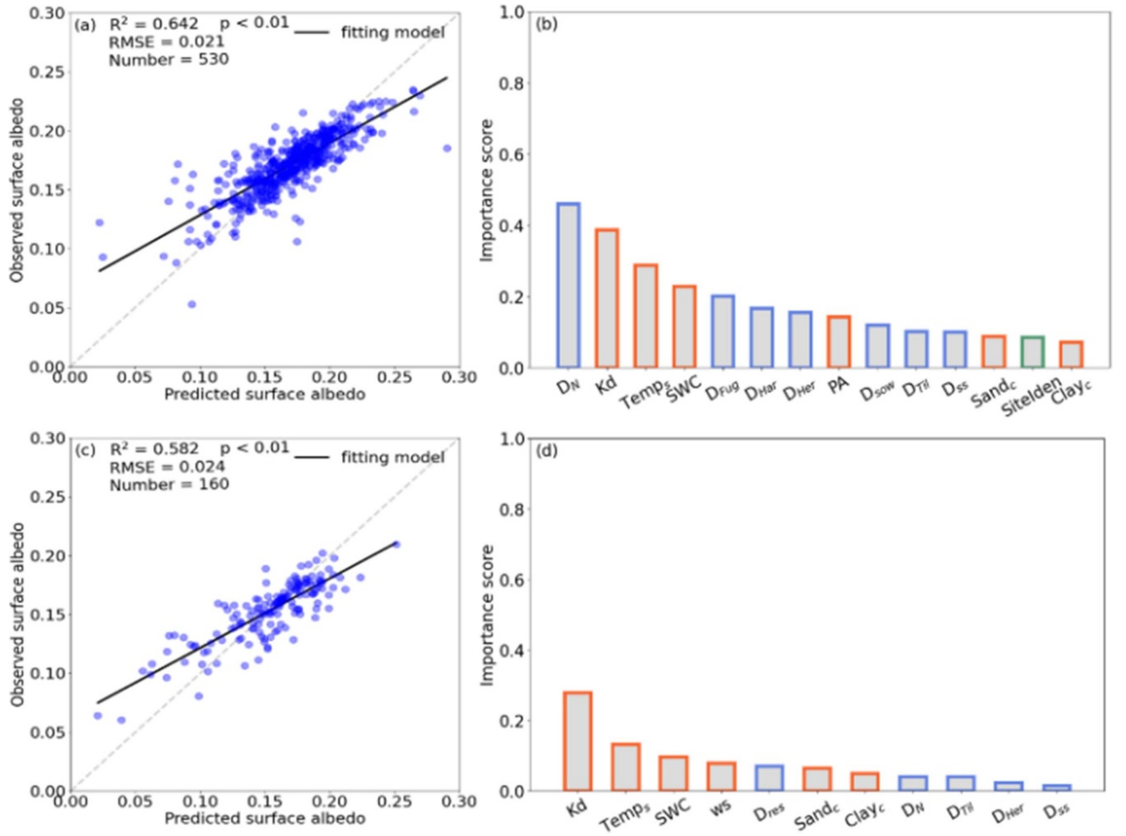

Figure 2. The performance of the random forest model for predicting daily surface albedo for (a) and (b) growing and fallow periods, and (c) and (d) fallow periods. (a)–(c) are the scattering plots between the predicted surface albedo from the random forest model and the observed surface albedo for the test dataset. (b)–(d) show the importance ranking of selected features using the Gini index. Kd, Temp_s, SWC, ws, PA, SiteIden, D_{N}, D_{Fug}, D_{Har}, D_{Her}, D_{sow}, D_{ss}, D_{Til}, and D_{res} represent the ratio of diffuse solar radiance, soil temperature, soil water content, wind speed, air pressure, site identity, days after nitrogen fertilizer, fungicide, harvest, herbicide, winter wheat sowing, stalk stabilizer, tillage, and crop residues. Orange, blue and green boxes are features related to climatic and ecological features, days since the applications of management practices and site identity, respectively.

3.2. Time-variant impact of management practices on surface albedo

The top 10 ranked management practices lead to albedo changes ranging from -0.006 ± 0.001 (harvest) to 0.004 ± 0.007 (nitrogen fertilizer) (mean $\pm$ standard deviation) when averaged over 210 d during growing and fallow periods, and from -0.005 ± 0.002 (herbicide) to 0.003 ± 0.001 (crop residues) when averaged over 150 d during fallow periods (table 2). The largest change in albedo during growing and fallow periods was due to nitrogen fertilizer application, while during fallow periods, herbicides had the largest influence (figures 3(a) and (c)).

The albedo impact of the majority of practices varies strongly within the periods considered (figure 3). In growing and fallow periods, nitrogen fertilizer, fungicide, and herbicide increase surface albedo within the first 30–60 d after applications, followed by neutral or negative impacts (figure 3(a)). The impact of fungicide diminishes more rapidly over time compared with nitrogen fertilizer. Different from the input-related practices, the physical management practices show fewer variations in their influence on surface albedo over 210 d (figure 3(c)). Only the impact of sowing changes from negative (-0.005 ± 0.003) to positive (0.002 ± 0.001) after 120 d, attributed to the growing crop with increased albedo covering the soil surface that was destroyed during seedbed preparation. In fallow periods, the negative contribution of herbicide to the albedo change within 150 d of application is most significant, while the effect of tillage remains minor, especially after 20 d since application (figure 3(c)).

3.3. Climate impacts resulting from the effects of management practices on surface albedo

The transient albedo-mediated radiative forcing induced by management practices is small and ranges from -1.25 ± 2.15 W m^{-2} (nitrogen fertilizer) to 1.21 ± 0.93 W m^{-2} (tillage) in average over 210 d after application during growing and fallow periods. During fallow periods the range is from -0.66 ± 0.53 W m^{-2} (nitrogen fertilizer) to 1.33 ± 1.06 W m^{-2} (herbicide) in average over 150 d (table 2). Climatic and ecological features have comparable magnitudes of radiative forcing between -0.27 ± 0.62 and -1.31 ± 2.27 W m^{-2} averaged in the same two periods, respectively (supplementary table 4). Note that large temporal variations in all cases weaken their overall climate impacts.

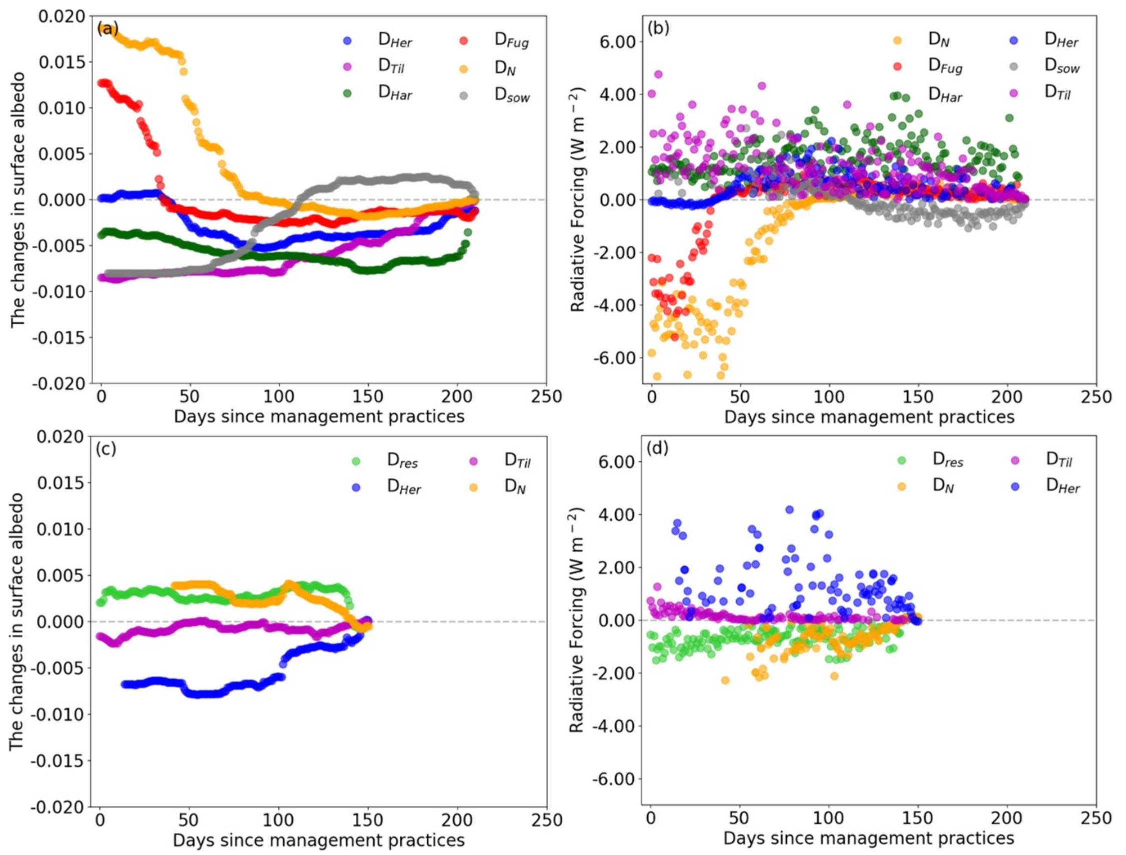

Figure 3. Changes in surface albedo and corresponding albedo-mediated radiative forcing due to the application of management practices as a function of time since onset of practice. Shown are daily albedo differences averaged over eight sites estimated from partial dependence and baseline albedo (see equation 2). (a) and (b) results for growing and fallow periods (c) and (d) for fallow periods. D_{N}, D_{Fug}, D_{Har}, D_{Her}, D_{sow}, D_{Til}, and D_{res} represent days since the applications of nitrogen fertilizer, fungicide, harvest, herbicide, winter wheat sowing, tillage and crop residues, which are in the top 10 ranked important features selected by the random forest model.

In growing and fallow periods, the nitrogen fertilizer and fungicide applications result in negative albedo-mediated radiative forcing within the first 60 and 30 d, with average values of -4.39 ± 1.22 and -1.47 ± 1.80 W m^{-2}, respectively. Subsequently, their radiative forcing becomes positive with average values of 0.03 ± 0.45 and 0.42 ± 0.24 W m^{-2} (figure 3(b)). A positive albedo-mediated radiative forcing of herbicide occurs after 30 d, with an average value of 0.92 ± 0.55 W m^{-2}. The tillage and harvest exhibit averaged positive albedo-mediated radiative forcing in 210 d, while the sowing has a minor negative albedo impact on climate (table 2).

In fallow periods, nitrogen fertilizer and crop residues lead to negative albedo-mediated radiative forcing, while herbicide and tillage induce negative albedo effects due to the decreased surface albedo with exposed soil (table 2).

4. Discussion

4.1. Management practices and climate influence the seasonal albedo dynamics

Management practices and climate jointly modulate surface albedo dynamics during growing and fallow periods, while the climate effect dominates during fallow periods (figure 2). We discuss the correlation between the surface albedo and the top five features in these two periods. D_{N}, D_{Fug}, and D_{res} relate to management practices, while Kd, soil temperature, soil water content, and wind speed refer to the climate in the following text.

Nitrogen fertilizers, fungicides, herbicides and other chemical applications impact surface albedo through sustained chemical effects on plant growth and short-lived physical alteration of the soil surface during application. The chemical effects of fertilizers and fungicides lead to an increase in albedo during the cropping period (figure 3(a)) which is in line with theory. Changes in leaf traits (e.g. pigmentation, cell structure), canopy structure, and changed soil exposure as leaf area index varies, can lead to a positive relationship between albedo and nitrogen and fungicides which declines over time. Canopy nitrogen, which increases after fertilizer addition, was shown to be positively correlated with albedo in a wide range of ecosystems, including croplands (Tranavičienė et al 2007, Hollinger et al 2010). Fungicides can increase surface albedo as infected leaves are less pigmented (e.g. for tan spot or septoria leaf blotch infection

Table 2. The averaged changes in surface albedo and the corresponding albedo-mediated radiative forcing due to the selected management practices. The albedo change is the difference between the albedo on the first day since application and the baseline albedo over growing and fallow periods (fallow periods). Shown includes the comparison of radiative forcing of different management practices (kg CO_2e ha^{-1} yr^{-1}) related to their induced albedo changes and previous estimates on the albedo-mediated biophysical impacts and the greenhouse gas (GHG)-mediated biogeochemical impacts (kg CO_2e ha^{-1} yr^{-1}). All radiative forcing in previous research were converted to the unit of kg CO_2e ha^{-1} yr^{-1} for comparison. Details of previous estimates of radiative forcing can be found in supplementary table 3.

Management practices	Albedo changes (mean ± standard deviation)	Albedo-mediated radiative forcing (mean ± standard deviation)		Periods of management practices	Previous estimates	References
		(W m^{-2})	(kg CO_2e ha^{-1} yr^{-1})			
Nitrogen fertilizer	0.004 ± 0.007 (0.002 ± 0.001)	−1.25 ± 2.15 (−0.66 ± 0.53)	−263.64 ± 455.32 (−139.62 ± 112.88)	Growing and fallow periods (fallow periods)	798.35–929.34, −29.17 (biogeochemical impact)	Ceschia *et al* (2010), Quemada *et al* (2020)
Fungicide	0.000 ± 0.004	−0.14 ± 1.32	−30.26 ± 279.13	Growing and fallow periods	30.07 (biogeochemical impact)	Ceschia *et al* (2010)
Herbicide	−0.003 ± 0.002 (−0.005 ± 0.002)	0.76 ± 0.65 (1.33 ± 1.06)	161.71 ± 137.51 (281.49 ± 224.03)	Growing and fallow periods (fallow periods)	30.07 (biogeochemical impact)	Ceschia *et al* (2010)
Winter wheat sowing	−0.002 ± 0.004	−0.05 ± 0.66	−9.83 ± 139.37	Growing and fallow periods	−227.87 (biogeochemical impact)	Ceschia *et al* (2010)
Harvest	−0.006 ± 0.001	1.14 ± 0.57	240.96 ± 119.96	Growing and fallow periods	6545 (biogeochemical impact)	Ceschia *et al* (2010)
Tillage	−0.006 ± 0.003 (−0.001 ± 0.001)	1.21 ± 0.93 (0.16 ± 0.19)	255.55 ± 197.21 (34.37 ±40.10)	Growing and fallow periods (fallow periods)	234.00, 288.00, 333.15 (albedo-mediated biophysical impact)	Sieber *et al* (2022), Liu *et al* (2022)
					312.00 (biogeochemical impact)	Liu *et al* (2022)
Crop residues	0.003 ± 0.001	−0.65 ± 0.36	−137.42 ± 76.75	Fallow periods	−79.30 (albedo-mediated biophysical impact)	Sieber *et al* (2022)
					108.95 (biogeochemical impact)	Ceschia *et al* (2010)

(Gaile *et al* 2023)) than healthy leaves, which can be reversed when treated. Both types of treatment stimulate crop growth. The phytotoxicity of fungicides might lead temporarily to leaf burn, discoloration, and stunted growth, as well as less radiation absorbed at the leaf surface (Petit *et al* 2012, Baibakova *et al* 2019), therefore even higher initial albedo change. The strength of the effects of nitrogen fertilizers and fungicides on surface albedo depends on the type and amount of applied chemicals, foliar characteristics, crop growth stages, and environmental conditions. Fertilizers such as calcium, sulfur, and magnesium were not kept in the final random forest which is consistent with nitrogen being commonly the most limiting nutrient in Europe (Ahrends *et al* 2021, Sun *et al* 2017, Houshmandfar *et al* 2018).

During the application of chemicals, the surface is altered depending on the machinery used (e.g. type of sprayer) and the conditions during the time of application. Solid fertilizer in the form of white or light-colored granules which make up 70% of fertilizers might have a direct effect on surface albedo till they completely dissolve (Ni and Pacholski 2022). This could explain the initial increase in albedo during the first 5 d after application (figure 3(a)). Spraying of liquids leaves reflective water droplets on leaf surfaces which can stay up to a few days (Rasool *et al* 2022, Vázquez *et al* 2022) which could also explain the initial increase in surface albedo within a few days of fertilizer and fungicide application (figure 3(a)). In addition, the vehicles used for application leave tire tracks which might decrease surface albedo because the vehicle tracks can exhibit wetter soil for a couple of hours. Less area is affected for a shorter time by physical effects than by the chemical ones the effects should be smaller. This can explain why the importance of fertilizer and herbicide application was low during fallow periods where chemical effects are marginal due to the absence of crops (figure 2(d)).

Covering crop residues on the soil surface tends to increase albedo due to light color (figure 3(c)) (Sieber *et al* 2022). This effect varies with factors such as orientation (standing or on the ground), surface coverage, decomposition stage, and water content (dry or wet) of residues, as well as tillage practices (Daughtry *et al* 2010). Crop residues can also reduce soil albedo by influencing the surface energy balance (Horton *et al* 1996, Du *et al* 2022) and soil properties over the course of years (Jin *et al* 2020). Both were not investigated in this study.

Distinguishing the effect of crop residues from harvesting is challenging as they often co-occur at the same time (supplementary table 5). The opposite albedo changes in growing and fallow, and fallow periods are mainly caused by different baseline albedo (see below). Overlapping between management practices also occurs for tillage and sowing (54%), and nitrogen fertilizer, fungicide and herbicide (30%), thus, the independent impacts of these practices on albedo dynamics are inevitably influenced by their concurrent implementation.

Unlike management practices, climatic factors are equally important for the cropping and fallow period. Kd modulates surface albedo by affecting the quality and quantity of the surface solar radiance reaching the surface. During the cropping period it also affects the fraction intercepted by crop canopy which affects photosynthesis and subsequent crop growth, canopy structure and leaf traits (Pinty *et al* 2005, Yang *et al* 2019, Liu *et al* 2022).

Surface albedo, soil temperature, and soil water content are tightly interconnected via surface energy balance (e.g. latent and sensible heat fluxes) which is illustrated by the high importance of soil temperature and soil water content for both periods (figures 2(b) and (d)). In addition, soil water content negatively modulates surface albedo by controlling soil color: the higher the soil water content (darker soil), the lower the surface albedo (supplementary figures 6 and 7) (Ni *et al* 2019, Yang *et al* 2020). Soil water content and temperature are interconnected and are influenced by management practices which were not assessed in this study. The variation in wind speed can modulate indirectly surface albedo during fallow periods by influencing the soil evaporation rates and thereby the soil water content (soil color) (Luu *et al* 2023). It is also considered as a feedback mechanism in albedo-induced land-atmosphere interaction (hydrothermal transport) related to the surface roughness (e.g. near-surface turbulence intensity) (Bhimireddy *et al* 2022). The indirect impact of wind speed on surface albedo explains the lower importance ranking of wind speed, compared with Kd, soil temperature, and soil water content which are directly related to the surface energy balance (figure 2(d)).

Management practice-induced changes in surface albedo could affect the two-way albedo-climate interaction by relating to variations of Kd, soil temperature, soil water content, and wind speed. This includes the radiative process (e.g. solar radiance reflectance) and non-radiative process (e.g. the land-atmosphere hydrothermal transport) (Chen *et al* 2020). The former drives the albedo-mediated radiative forcing at the top of the atmosphere (figures 3(b) and (d)), while the latter modulates the surface and atmosphere dynamics (supplementary figures 6 and 7). For example, the modified surface albedo by practices changes Kd by affecting the regional cloud and aerosol concentration via a non-radiative process, depending on aerodynamic conductance and temperature-humidity gradients (Zeng *et al* 2017, Chen *et al* 2020).

Management practices have varied legacy effects (supplementary figures 6 and 7). The nitrogen fertilizer and fungicide have cooling potential lasting 150 and 90 d after application and herbicide impacts after 60 d in growing and fallow periods (supplementary figure 8). While influences of all management practices remain relatively stable within 150 d during fallow periods (supplementary figure 9). The climate impact of management practices also depends on the incoming solar radiance and atmospheric transmittance (Hansen *et al* 1997), but this is not accounted for in our analysis. For example, applications of crop residues and cover crops usually occur in summer and fall, respectively. The seasonal variations of surface solar radiance and atmospheric transmittance that encompass the cloud cover effect and the effect of aerosols in the atmosphere might drive different albedo-mediated radiative forcing induced by these two practices even though they have similar albedo changes.

The albedo-induced climate impact of management practices depends on the considered periods and the baseline albedo which is used to derive the climate impact from partial dependence plots (see equation (2)). For example, herbicide application during the growing season improves the growth of the main crop and increases surface albedo, but its application during fallow periods exposes bare soil and decreases surface albedo (supplementary figures 8(d) and 9(d)). Differences in the baseline albedo between the two periods, explain the difference in the albedo-mediated radiative forcing for tillage between periods (table 2). The higher baseline albedo for growing and fallow periods which includes periods of high crop coverage, unlike during fallow periods, explains the higher albedo impact of tillage which exposes the bare soil. Hence, assessing and comparing the climate impacts of management practices require harmonization of baseline albedo and periods under consideration.

Our approach has shortcomings. The amount of fertilizer is omitted due to insufficient data, but instead, we assumed an optimal amount was applied at each site which might not always had been the case. Cover crops and biochar are also not evaluated here but were shown to have been addressed as having significant impacts on surface albedo through alterations in crop structure and leaf traits, and soil pigmentation, respectively (Genesio *et al* 2012, Lugato *et al* 2020). In our few sites, there was no biochar application, and only 106 data of cover crops (13% of total 798 data in fallow periods) with 11 types. Therefore, cover crop types were not retained after recursive feature elimination.

4.2. Albedo-mediated biophysical impacts can cancel or amplify the impacts of GHG emissions

The albedo-mediated impact of a management practice can be in the same direction or opposite to the biogeochemical-mediated one (table 2). In the following, GHG-mediated impacts include CO_2 and N_2O emissions unless other specified uncertainty ranges are given if available. The albedo-mediated biophysical impact of nitrogen fertilizer is much smaller than the 270 day GHG emission-based biogeochemical impacts (798.35–929.34 kg CO_2e ha^{-1} yr^{-1}) estimated for seven European winter wheat sites (Ceschia *et al* 2010). Because of the two opposite impacts, the overall climate impact of nitrogen fertilization is likely slightly smaller than previously estimated from biogeochemical impacts only. We found albedo-mediated radiative forcing of herbicide and fungicide which are in the same order of magnitude or larger than the ones from GHG emission of pesticide (30.07 ± 20.17 kg CO_2e ha^{-1} yr^{-1}) (Ceschia *et al* 2010). However, as the signs of biophysical impacts differ among the types of pesticides and the dependence of results on the period under consideration (section 4.1), a comparison is not straightforward.

The biophysical radiative forcing from sowing has the same sign but is much smaller than the impact related to the carbon contained in seeds of −227.87 kg CO_2e ha^{-1} yr^{-1} in Ceschia *et al* (2010). The positive albedo-mediated impact of harvest estimated in our analysis impacts climate negatively but is smaller than the carbon removal of 6545 kg CO_2e ha^{-1} yr^{-1} from harvesting winter wheat biomass (Ceschia *et al* 2010). Note that the harvested organic matter, if used in buildings, could lead to small sinks but not accounted for here (Ahmadi *et al* 2020). Crop residues that remain on the surface after harvest can lead to N_2O emissions equivalent to 108.95 kg CO_2e ha^{-1} yr^{-1} which is comparable in magnitude to the albedo-mediated biophysical ones either in this analysis or −79.30 kg CO_2e ha^{-1} yr^{-1} in previous research (Sieber *et al* 2022). The interaction of the biophysical and biogeochemical impacts of residues depends on the area covered and the lifetime of residues (Flower *et al* 2022). Previous analysis has shown the biogeochemical impact of 312 kg CO_2e ha^{-1} yr^{-1} from tillage via decreased soil carbon storage (Liu *et al* 2022). A decreased N_2O emission due to tillage was not found for winter wheat but for other crop types (Niu *et al* 2019). The positive albedo-mediated biophysical impacts from tillage were 34.37–255.55 kg CO_2e ha^{-1} yr^{-1} in this analysis, and 288.00–234.00 kg CO_2e ha^{-1} yr^{-1} in 52 d for 15 plots in Sweden (Sieber *et al* 2022). Both the biogeochemical and albedo-mediated biophysical impacts indicate an overall favorable impact of reduced use of tillage.

5. Conclusion

Comparing the albedo dynamics and related climate impacts by seven management practices, this analysis shows that albedo impacts are usually small but of similar levels as biogeochemical effects. It can provide valuable information for dedicated field trials and monitoring systems able to consider the substantial temporal variation we found here. Moreover, our study is the first to reveal an effect of nitrogen fertilizer on albedo, which suggests that changes in leaf color should be further investigated. Our findings also highlight that the effects of practices during growing and fallow periods such as nitrogen fertilizer and fungicides are stronger than the effects of practices during the fallow periods, like crop residues and tillage. This indicates that the crop period is more suited for climate mitigation than the fallow period. Uncertainties in our results are primarily due to limited data availability, such as few data assessing the effect of cover crops and difficulties in establishing the baseline albedo. Accurate bare soil albedo estimates from earth observation, albedo monitoring of fields, and dedicated field experiments are needed. The inclusion of other biophysical climate impacts (e.g. evapotranspiration) is needed to identify climate solutions by accounting for the interactions between agriculture and climate change. The feasibility of management practices should also consider the socio-technical-economic constraints, the interests of farmers, and the need for climate resilience.

Data availability statement

The ecosystem fluxes were downloaded from ICOS Data Portal and EFDC, and the related management information was derived from ICOS WINTER2020 collection. All data sources and codes of the random forest modelling process used in this analysis can be publicly obtained from figshare (https://doi.org/10.6084/m9.figshare.24845049.v1) (Yu *et al* 2024).

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

We acknowledge support from the ClieNFarms project (Grant Agreement ID: 101036822). CZ-Kresin was supported by the Ministry of Education, Youth, and Sports of CR within the CzeCOS program, Grant Number LM2023048. We thank Eric Ceschia, Tiphaine Tallec, Aurore Brut, Bernard Heinesch, Christian Brümmer, Frederik Schrader, Marius Schmidt, Manuel Acosta, Pauline Buysse, and Thomas Gruenwald of ICOS and EFDC stations for their additional information and thoughtful comments on the paper.

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References

Acosta M European Fluxes Database (available at: http://gaia.agraria.unitus.it/) (Accessed on 24 March 2015)

Ahmadi R, Souri B and Ebrahimi M 2020 Evaluation of wheat straw to insulate fired clay hollow bricks as a construction material *J. Clean Prod.* **254** 120043

Ahrends H E, Siebert S, Rezaei E E, Seidel S J, Hüging H, Ewert F, Döring T, Rueda-Ayala V, Eugster W and Gaiser T 2021 Nutrient supply affects the yield stability of major European crops—a 50 year study *Environ. Res. Lett.* **16** 014003

Baibakova E V, Nefedjeva E E, Suska-Malawska M, Wilk M, Sevriukova G A and Zheltobriukhov V F 2019 Modern fungicides: mechanisms of action, fungal resistance and phytotoxic effects *Annu. Res. Rev. Biol.* **32** 1–16

Bernhofer C, Eichelmann U, Grünwald T, Hehn M, Mauder M, Moderow U and Prasse H 2023 ETC L2 ARCHIVE, Klingenberg, 2017–12-31–2022-12-31, ICOS RI (available at: https://hdl.handle.net/11676/G3z0eVc7TzZilyHYhW1l4syv)

Bhimireddy S R, Wang J, Hiscox A L and Kristovich D A R 2022 Influence of stability and surface roughness on turbulence during the stable atmospheric variability and transport (SAVANT) field campaign *J. Appl. Math. Comput.* **61** 1273–89

Boland J, Ridley B and Brown B 2008 Models of diffuse solar radiation *Renew. Energy* **33** 575–84

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 *Environ. Sci. Technol.* **49** 3291–303

Bright R M and Lund M T 2021 CO_2-equivalence metrics for surface albedo change based on the radiative forcing concept: a critical review *Atmos. Chem. Phys.* **21** 9887–907

Brümmer C, Delorme J and Schrader F 2023 ETC L2 ARCHIVE, Gebesee, 2019–12-31–2022-12-31, ICOS RI (available at: https://hdl.handle.net/11676/4214v5CpbnldEJTcT_3emXV8)

Brut A, Tallec T, Granouillac F, Zawilski B and Ceschia E 2023 ETC L2 ARCHIVE, Lamasquere, 2022–12-31–2023-09-30, ICOS RI (available at: https://hdl.handle.net/11676/5msrX-9-wdL5g31PzT0af3nO)

Buysse P, Depuydt J and Loubet B 2023 ETC L2 ARCHIVE, Grignon, 2022–12-31–2023-09-30, ICOS RI (available at: https://hdl.handle.net/11676/jU9ftXkRFqo-dc91cDfOYuA8) (https://doi.org/10.1016/j.scitotenv.2022.159370)

Carrer D, Pique G, Ferlicoq M, Ceamanos X and 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 *Environ. Res. Lett.* **13** 044030

Ceschia E *et al* 2010 Management effects on net ecosystem carbon and GHG budgets at European crop sites *Agric. Ecosyst. Environ.* **139** 363–83

Chen C, Li D, Li Y, Piao S, Wang X, Huang M, Gentine P, Nemani R R and Myneni R B 2020 Biophysical impacts of Earth greening largely controlled by aerodynamic resistance *Sci. Adv.* **6** eabb1981

Chen J M 2021 Carbon neutrality: toward a sustainable future *Innovation* **2** 100127

Daughtry C S T, Serbin G, Iii J B R, Doraiswamy P C and Jr E R H 2010 Spectral reflectance of wheat residue during decomposition and remotely sensed estimates of residue cover *Remote Sens.* **2** 416–31

Davin E L, Seneviratne S I, Ciais P, Olioso A and Wang T 2014 Preferential cooling of hot extremes from cropland albedo management *Proc. Natl Acad. Sci. USA* **111** 9757–61

Davin E and de Noblet-ducoudré N 2010 Climatic impact of global-scale deforestation: radiative versus nonradiative processes *J. Clim.* **23** 97–112

Devaraju N, Bala G and Modak A 2015 Effects of large-scale deforestation on precipitation in the monsoon regions: remote versus local effects *Proc. Natl Acad. Sci. USA* **112** 3257–62

Du C L, Li L L and Effah Z 2022 Effects of straw mulching and reduced tillage on crop production and environment: a review *Water* **14** 2471–86

Dumont B, Bogaerts G, Chopin H, De Ligne A, Demoulin L, Faurès A, Heinesch B, Longdoz B, Manise T and Orgun A 2023 ETC L2 ARCHIVE, Lonzee, 2022–12-31–2023-09-30, ICOS RI (available at: https://hdl.handle.net/11676/JmEjmkD1hSr4YIuo5Uu-L69a)

Flower K C, Ward P R, Passaris N and Cordingley N 2022 Uneven crop residue distribution influences soil chemical composition and crop yield under long-term no-tillage *Soil Till Res.* **223** 105498

Friedman J H 2001 Greedy function approximation: a gradient boosting machine *Ann. Stat.* **29** 1189–232

Gaile Z, Biruta B, Ieva P, Linda S, Gunita B, Agrita S, Janis K, Irina A and Aigars S 2023 Performance of winter wheat (Triticum aestivum) depending on fungicide application and nitrogen top-dressing rate *Agronomy* **13** 318–36

Genesio L, Miglietta F, Lugato E, Baronti S, Pieri M and Vaccari F P 2012 Surface albedo following biochar application in durum wheat *Environ. Res. Lett.* **7** 014025

Guyon I, Weston J, Barnhill S and Vapnik V 2002 Gene selection for cancer classification using support vector machines *Mach. Learn.* **46** 389–422

Hansen J, Sato M and Ruedy R 1997 Radiative forcing and climate response *J. Geophys. Res.* **102** 6831–64

Hirsch A L, Prestele R, Davin E L, Seneviratne S I, Thiery W and Verburg P H 2018 Modeled biophysical impacts of conservation agriculture on local climates *Glob. Change Biol.* **24** 4758–74

Hollinger D Y *et al* 2010 Albedo estimates for land surface models and support for a new paradigm based on foliage nitrogen concentration *Glob. Change Biol.* **16** 696–710

Horton R, Bristow K L, Kluitenberg G J and Sauer T J 1996 Crop residue effects on surface radiation and energy balance—review *Theor. Appl. Climatol.* **54** 27–37

Houshmandfar A, Fitzgerald G J, O'Leary G, Tausz-Posch S, Fletcher A and Tausz M 2018 The relationship between transpiration and nutrient uptake in wheat changes under elevated atmospheric CO2 *Physiol. Plant* **163** 516–29

Huang B, Hu X, Fuglstad G A, Zhou X, Zhao W W and Cherubini F 2020 Predominant regional biophysical cooling from recent land cover changes in Europe *Nat. Commun.* **11** 1066

IPCC Climate Change 2022 Agriculture, forestry, and other land uses ed P R Shukla, et al (Cambridge Univ. Press, 2022) available at: www.ipcc.ch/report/ar6/wg3/

Jin Z Q, Shah T, Zhang L, Liu H, Peng S and Nie L 2020 Effect of straw returning on soil organic carbon in rice–wheat rotation system: a review *Food Energy Secur.* **9** e200

Jones A D, Calvin K V, Collins W D and Edmonds E 2015 Accounting for radiative forcing from albedo change in future global land-use scenarios *Clim. Change* **131** 691–703

Li Y *et al* 2023 Biophysical impacts of earth greening can substantially mitigate regional land surface temperature warming *Nat. Commun.* **14** 121

Lin X *et al* 2022 Estimating 10-m land surface albedo from Sentinel-2 satellite observations using a direct estimation approach with Google Earth Engine *ISPRS J. Photogramm. Remote Sens.* **194** 0924–2716

Liu J, Desjardins R L, Wang S, Worth D E, Qian B and Shang J 2022 Climate impact from agricultural management practices in the canadian prairies: carbon equivalence due to albedo change *J. Environ. Manage.* **302** 113938

Lobell D B, Bala G and Duffy P B 2006 Biogeophysical impacts of cropland management changes on climate *Geophys. Res. Lett.* **33** L06708

Lugato E, Cescatti A, Jones A, Ceccherini G and Duveiller G 2020 Maximising climate mitigation potential by carbon and radiative agricultural land management with cover crops *Environ. Res. Lett.* **15** 094075

Luu L N, van Meijgaard E, Philip S Y, Kew S F, de Baar J H S and Stepek A 2023 Impact of surface roughness changes on surface wind speed over western Europe: a study with the regional climate model RACMO *Geophys. Res. Atmos.* **128** e2022JD038426

Ni J J, Cheng Y F, Wang Q H, Ng C W W and Garg A 2019 Effects of vegetation on soil temperature and water content: field monitoring and numerical modelling *J. Hydrol.* **571** 494–502

Ni K and Pacholski A S 2022 Soil moisture and temperature effects on granule dissolution and urease activity of urea with and without inhibitors—an incubation study *Agriculture* **12** 2037

Niu Y H, Cai Y, Chen Z, Luo J, Di H J, Yu H, Zhu A and Ding W 2019 No-tillage did not increase organic carbon storage but stimulated N2O emissions in an intensively cultivated sandy loam soil: a negative climate effect *Soil Tillage Res.* **195** 0167–1987

Pastorello G *et al* 2020 The FLUXNET2015 dataset and the ONEFlux processing pipeline for eddy covariance data *Sci. Data* **7** 7 225

Petit A N, Fontaine F, Vatsa P, Clément C and Vaillant-Gaveau N 2012 Fungicide impacts on photosynthesis in crop plants *Photosynth. Res.* **111** 315–26

Pinty B, Lattanzio A, Martonchik J V, Verstraete M M, Gobron N, Taberner M, Widlowski J, Dickinson R E and Govaerts Y 2005 Coupling diffuse sky radiation and surface albedo *J. Atmos. Sci.* **62** 2580–91

Quemada M, Lassaletta L, Leip A, Jones A and Lugato E 2020 Integrated management for sustainable cropping systems: looking beyond the greenhouse balance at the field scale *Glob. Change Biol.* **26** 2584–98

Rasool S, Rasool T and Gani K M 2022 A review of interactions of pesticides within various interfaces of intrinsic and organic residue amended soil environment *Chem. Eng. J. Adv.* **11** 100301

Schmidt M, Becker N, Becker N, Dolfus D, Esser O, Graf A, Kettler M and Kummer S 2023 ETC L2 ARCHIVE, selhausen juelich, 2022–12-31–2023-09-30, ICOS RI (available at: https://hdl.handle.net/11676/xpWUVHGaByDhVAM-dlOlBO2o)

Seneviratne S I, Phipps S J, Pitman A J, Hirsch A L, Davin E L, Donat M G, Hirschi M, Lenton A, Wilhelm M and Kravitz B 2018 Land radiative management as contributor to regional-scale climate adaptation and mitigation *Nat. Geosci.* **11** 88–96

Sieber P, Böhme S, Ericsson N and Hansson P A 2022 Albedo on cropland: field-scale effects of current agricultural practices in Northern Europe *Agric. For. Meteorol.* **321** 108978

Sun L, Yang J, Fang H, Xu C, Peng C, Huang H, Lu L, Duan D, Zhang X and Shi J 2017 Mechanism study of sulfur fertilization mediating copper translocation and biotransformation in rice (Oryza sativa L.) *Plants. Environ. Pollut.* **226** 426–34

Svetnik V, Liaw A, Tong C, Culberson J C, Sheridan R P and Feuston B P 2003 Random forest: a classification and regression tool for compound classification and QSAR modelling *J. Chem. Inf. Comput. Sci.* **43** 1947–58

Tallec T, Ceschia E, Granouillac F, Claverie N, Zawilski B, Brut A, Lemaire B and Gibrin H 2023 ETC L2 ARCHIVE, Aurade, 2018–12-31–2022-12-31, ICOS RI (available at: https://hdl.handle.net/11676/HTw1RNlVsnlRmfW07QHieuLj)

Thomas R, Graven H, Hoskins B and Prentice I C 2016 What is meant by 'balancing sources and sinks of greenhouse gases' to limit global temperature rise *Briefing Note* **3** 1–5

Tranavičienė T, Šikšnianienė J B, Urbonavičiūtė A, Vagusevičienė I, Samuolienė G, Duchovskis P and Sliesaravičius A 2007 Effects of nitrogen fertilizers on wheat photosynthetic pigment and carbohydrate contents *Plant. Physiol.* **53** 80–84

United Nations Framework Convention on Climate Change 2015 Paris Agreement (available at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement)

Vázquez A E G, Hockemeyer K R, McConville M, Remucal C K and Koch P L 2022 Assessment of temperature and time following application as predictors of propiconazole translocation in agrostis stolonifera ACS *Agric. Sci. Technol.* **2** 592–602

Wieder W R, Boehnert J, Bonan G B and Langseth M 2014 *Regridded Harmonized World Soil Database V1.2. Data Set* (Oak Ridge National Laboratory Distributed Active Archive Center)

Yang J X, Li Z C, Zhai P M, Zhao Y Y and Gao X Q 2020 The influence of soil moisture and solar altitude on surface spectral albedo in arid area *Environ. Res. Lett.* **15** 035010

Yang X, Li J, Yu Q, Ma Y, Tong X, Feng Y and Tong Y 2019 Impacts of diffuse radiation fraction on light use efficiency and gross primary production of winter wheat in the North China Plain *Agric. For. Meteorol.* **275** 233–42

Yu K 2024 Management_climate&ecological_data_croplandsites.csv. figshare *Dataset* (https://doi.org/10.6084/m9.figshare.24845049.v1)

Zeng Z *et al* 2017 Climate mitigation from vegetation biophysical feedbacks during the past three decades *Nat. Clim. Change* **7** 432–6