Reflect the light

Exploring the climate change mitigation potential of cover crops through the albedo effect

Photo: Tine Engedal

Content

1. Introduction to cover crops and their climate change mitigation potential

Rising atmospheric concentrations of greenhouse gases are changing global climate systems, with fossil fuel use, agriculture, and land-use changes being the dominant causes in the last 250 years (IPCC, 2007). In Denmark, today, the agricultural sector accounts for an estimated 35% of total greenhouse gas emissions. In order to reduce emissions from agriculture, one of the tools currently investigated for its climate change mitigation potential is the inclusion of a cover crop in the cropping rotation.

Cover cropping involves the cultivation of a non-economic crop usually during autumn and winter between two main crops instead of leaving the soil bare. Cover cropping has historically been used for a variety of different purposes, ranging from nitrogen scavenging to avoid nitrate leaching in conventional agriculture to enhancing the N status by biological fixation of atmospheric nitrogen by legumes in organic agriculture (Doltra and Olesen, 2013; Thorup-Kristensen et al., 2003).

Cover crops can alter the net climate change mitigation potential of a cropping cycle by i) increasing field carbon inputs and consequently enhance soil organic carbon storage, ii) altering nitrogen dynamics resulting in both potential lowered fertilizer usage but also higher N_2O emissions (Basche et al., 2014). Moreover, and less investigated, cover crops can affect radiative forcing through changes in surface albedo, by reflecting a higher proportion of the solar radiation compared to bare soil (Kaye and Quemada, 2017; Pique et al., 2023).

Due to the relatively feasible applicability of cover crops over very large surface areas, the total climate mitigation potential of cover crops is considered substantial. Kaye & Quemada (2017) estimated that as much as 10 % of global greenhouse gas emissions originating from agriculture could be mitigated by adopting cover crops on 25 % on global croplands. However, while the net climate change mitigation potential of cover crops is associated with great uncertainty, the relative importance of the different factors is more established: The largest mitigation potential is typically related to soil organic carbon sequestration (Kaye and Quemada, 2017; Lugato et al., 2020), which is only 5-10% counteracted by the higher N_2O emissions of cover crops compared to bare soil (Guenet et al., 2021). Placed in-between these two agents, an estimated 13 to 19 % of the total mitigation effect of cover crops can be attributed to increased albedo (Lugato et al., 2020).

Given that around 60 % of Denmark consist of cultivated cropland areas and as the adoption of cover crops is high, the overall climate change mitigation of cover crops might be considerable.

2. The albedo effect

‘Albedo’ refers to the fraction of incoming shortwave irradiation that is reflected by a surface, and thus scales between 0 and 1. In simpler terms, the lower the albedo, the more solar radiation is absorbed, and correspondingly less solar radiation is reflected by a surface. Setting aside the complex details of the distribution in Earth’s surface energy balance (see section 6*v*), absorbed energy is primarily converted into heat, contributing to an increased temperature on Earth, or a net warming effect.

In nature, albedo commonly ranges between values of 0.04 to 0.8. Bright surfaces (e.g. snow) have a high albedo, and dark surfaces (e.g. forests or the deep sea) have a low albedo (Dickinson, 1983). Besides surface brightness, albedo is also affected by other surface characteristics determining how radiation is scattered or reflected at different angles and wavelengths. In the specific case of agriculture, albedo is thus influenced by both vegetation and surface ‘roughness’, plant development and (e.g. the yellowish) ripening, soil characteristics (including soil organic matter content), moisture content, and the presence of snow cover (Figure 1A), that varies over the day and over the year (Bright, 2015).

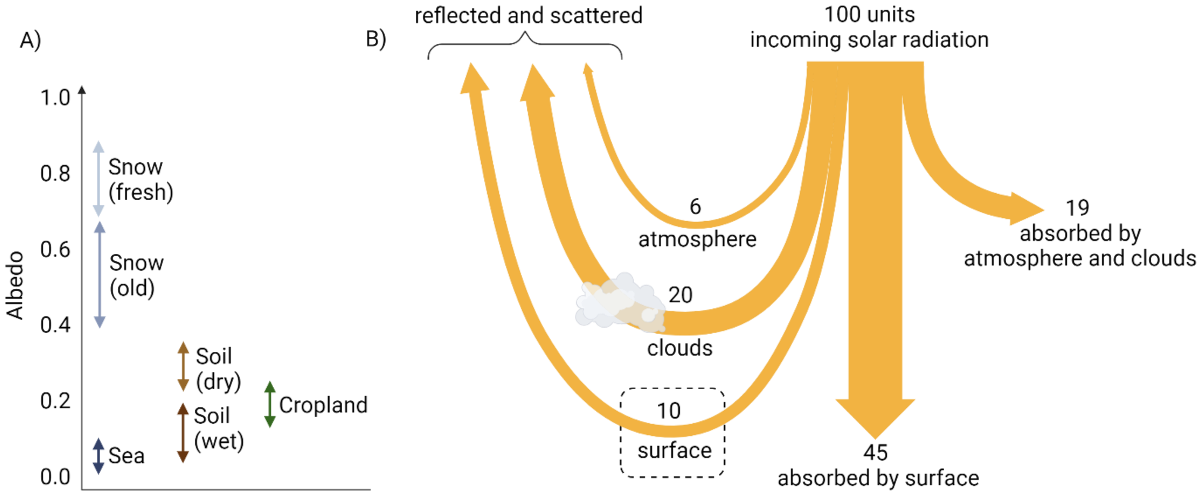

Figure 1: A) Typical albedo ranges, drawing inspiration from Sieber et al., (2020), B) Conceptual figure of the trajectory of incoming solar radiation, highlighting surface albedo, e.g. of cropland (dashed square).

Not all solar radiation reaches the surface of the Earth: Rather, a substantial part is either reflected or absorbed by the atmosphere and the clouds (Figure 1B). During winter and morning/evening hours, when the sun is at a lower zenith angle (the angle of the sun above the horizon), the radiation has to traverse a longer path through the atmosphere, resulting in more scattering and reflection and thus a lower amount of solar radiation reaching the ground (Dickinson, 1983; Yang et al., 2008). In contrast, during summer or at mid-day when the sun in overhead (higher zenith angles), surfaces receive more radiation. As the *impact* of an altered surface albedo on global warming depends on the amount of radiation reaching the ground (see section 5), it is of high importance to account for the temporary variation in solar radiation when evaluating the albedo effect of cover crops (Gueymard et al., 2019).

3. The albedo effect of cover crops

Typically, the albedo of cover crops tends to be higher than the albedo of bare soil on European cropland (Pique et al., 2023). However, due to the high variability in reflective properties of both soil and cover crops, generalizations cannot be made unconditionally (Kaye and Quemada, 2017).

Snow has one of the highest albedo in nature making its inclusion crucial when assessing the overall albedo impact of cover crops (Pique et al., 2023). While snow covers a bare soil surface more easily, the presence of a cover crop can, depending on the height of the snow, reduce snow coverage by increasing the surface area (Kaye and Quemada, 2017). Hence, cover crops might result in a lower albedo compared to bare soil and thus to a net warming effect during periods of preventing full snow cover (Kaye and Quemada, 2017; Lombardozzi et al., 2018; Lugato et al., 2020; Pique et al., 2023). Here, particular plant characteristics come into play in the interaction between cover crops and snow. Tall, leafy species, for example, penetrate through the snow, preventing complete snow coverage (Figure 2). In contrast, low-growing species are more easily covered by snow, which enhances albedo during snowy periods.

Figure 2: Snow cover of bare soil with few weeds (left) and of a winter rye cover crop (right). Photos: Tine Engedal.

However, the general notion is that, for the vast majority of cases, the albedo of cover crops is still higher when evaluated over the full period compared to bare soil (Hunter et al., 2019; Kaye and Quemada, 2017; Pique et al., 2023). This is highly due to the minor relevance of the higher albedo of snow in areas where snowfall is limited to periods with relatively low incoming radiation (Sieber et al., 2019). Only the combination of cover crops with a low albedo, soils with a high albedo (e.g. mineral-bright or dry soils) and the consideration of snow resulted in a net warming instead of a cooling effect when estimated by Kaye & Quemada (2017).

There has been several attempts to quantify the climate change mitigation effect of cover crops due to changes in albedo. Carrer et al. (2018), Kaye and Quemada (2017) and Lugato et al. (2020), which did not account for snow periods, estimated the albedo effect of cover crops to have a CO_2 equivalency of

16, 12-46, and 5.7-16.3 g CO_2e/m^2/year, respectively. Recently, Pique et al. (2023) estimated the potential to be 10.8 g CO_2e/m^2/year in the context of European cropland, accounting for snow. For Southern Sweden, Sieber et al., (2022) estimated that an undersown cover crop from August to April (including periods of snow) would mitigate 44 g CO_2e/m^2/year, potentially reflecting the importance of the length of cover crop growing window (i.e. from establishment to termination). However, these estimates cannot easily be compared as depending on the basic assumptions and objectives of the studies, differences in both the area of adoption included in the potential, the number of cropping cycles suitable for cover crops and the length of cover crop growth. Moreover, such estimates must be considered with great caution due to the great uncertainty associated with converting albedo effects into CO_2 equivalents (Bright et al., 2016). Lastly, these estimates are heavily impacted by regional climate conditions and can thus not be readily used to evaluate the potential of cover crops' albedo effect in a Danish context. While the potential for albedo change of cover crops is modelled for Denmark based on satellite data in Pique et al. (2023) and Carrer et al. (2018), there is a lack of available published data based on ground measurements.

In the specific case of Denmark, due to one third of the terrestrial land being cultivated, the albedo effect of a high adoption of cover crops could considered substantial – although the difference between bare soil and cover crop albedos is relatively small (Figure 1A). For example, in Carrer et al. (2018), the annual mean increase in surface albedo for Denmark is estimated as low as 0.00122 from introducing cover crops for three months. This rather low value (i.e. on the scale from 0 to 1) should then be seen in the context of the overall low incoming solar irradiance during the seasons where cover crops are cultivated: The vast majority of the radiation and hence the climate impact of albedo occur from April to August, see Sieber et al., 2022b, p. 9). Both of these factors limit the potential climate change mitigation of cover crops trough albedo change.

The rotation between summer and winter-sown crops means that not all cropping rotations are suitable for the integration of cover crops. In Denmark, the current adoption of cover crops is estimated at 25 percent of the total cultivated land in 2020 (Sommer and Knudsen, 2021). Taghizadeh-Toosi and Olesen (2016) operate under the assumption that, at most, one-third of rotations in Denmark are suitable for the incorporation of cover crops, indicating that the overall adoption potential may be approaching its maximum capacity and further adoption therefore is limited.

4. Quantifying changes in albedo

The quantification of changes in albedo can be carried out by combining ground-based measurements, which are subsequently interpolated using satellite data.

Ground-based measurements of albedo can be conducted using a radiometer, which assesses both incoming and out-going shortwave radiation. Subsequently, albedo can be computed by dividing the outgoing radiation by the incoming radiation. Depending on the prioritization of either high spacious or temporal resolution, the radiometer can be used as a handheld device (Figure 3) in order to compare many different surfaces as a certain point in time or installed on stationary "towers" as to continuously inspect the changes of a certain surface over longer periods (see Sieber 2020).


Photo: Tine Engedal

Figure 3: Handheld radiometer.

In the case of non-continuous measurements, interpolation or 'gap-filling' must be carried out to obtain data that corresponds to the whole period. Not only should all days of the season be taken into account, but also variation in incoming radiation during the day due to factors such as the moisture content of the soil and plants, the zenith angle of the sun and cloud cover (as affecting albedo, section 2). In simple terms, interpolation is used to estimate values that lie between known values.

Being widely available, satellite data can be used to assess the albedo effect from a range of different spectral data sources: Surface reflectance can be obtained from spectral bands in the visible and the near-infrared spectrum or indirectly by assessing the Normalized Difference Vegetation Index (NDVI) using near-infrared and red bands. Some products also offer albedo data specifically developed based on the relationship between reflectance in different bands and ground-based albedo measurements. However, such albedo products (e.g. NASA's MODIS product) could have grid cell sizes that are too large to adequately describe smaller differences in crop fields in heterogeneous agricultural landscapes. In contrast, other satellite constellations (e.g. PlanetScope's Dove satellites) provide images down to three meters per pixel resolution. The spacious and temporal resolution of data needed depend on the specific objectives.

Satellite-based albedo data should be validated with ground-based measurements (*ground truthing*), e.g by using devices as a radiometer as described above. Interpreting satellite imagery for albedo analysis requires expertise in remote sensing and access to suitable satellite data and specialized software. Additionally, and in order to evaluate the global warming effect, atmospheric corrections may be necessary to account for factors like cloud cover and atmospheric transmittance.

5. Radiative Forcing and Global Warming Potential

Radiative forcing is used to quantify the change in the Earth's energy balance caused by factors that influence climate (e.g. greenhouse gases, aerosols, solar radiance), that either trap more energy within the atmosphere (positive radiative forcing, indicating a warming effect) or allow more energy to escape into space (negative radiative forcing, indicating a cooling effect). Radiative forcing represents the change in the energy balance at the top of the atmosphere due to various factors and is expressed in watts per square meter (W/m^2). A calculated radiative forcing provides a simple means to compare the contribution of different gasses or other agents to global mean temperature change (Myhre et al., 2013).

The change in radiative forcing due to the altered albedo of cover crops can be calculated based on the measured (and typically modelled) change in albedo ($\Delta\alpha$), the shortwave incoming radiation ($R_{S\downarrow}$) and the atmospheric transmittance (τ) (see equation 6 in Sieber et al., 2019). Following this relationship, it is clear that differences in plant cover during summer, where the incoming radiation is much higher, result in higher changes in the radiative forcing compared to the autumn-winter period where cover crops are usually cultivated.

The other term, the atmospheric transmittance (τ), refers to the ability of the Earth's atmosphere to allow solar radiation to pass through it and is influenced by factors such as aerosols, gases, and cloud cover (Figure 1B). While the atmospheric transmittance on the way *down* ($\tau_\downarrow$) through the atmosphere is already accounted for as part of the incoming radiation in ground-based measurements, the $\tau_\uparrow$ must be estimated to correctly estimate the radiative forcing, which is based on the energy balance at the ‘top of atmosphere’ (TOA). τ can be estimated as the ratio between ratio between $R_{S\downarrow}$ and the incoming solar radiation at TOA based on the assumption that $\tau_\downarrow = \tau_\uparrow$ (Pique et al., 2023; Stephens et al., 2015). However, locally and seasonally difficulties in such measurements have led to the application of a fixed transmittance factor of 0.854 following Bright and Kvalevåg (Bright and Kvaleväg, 2013), which is a reasonable approximation for site-specific assessments (Bright, 2015). Note that satellite-derived albedo data might or might not already be corrected for TOA transmissivity.

Global Warming Potential (GWP) is a metric that calculates carbon dioxide equivalents based on an agent’s radiative forcing, and was designed to compare the global warming effect of gases within a time horizon of 100 years (Danny Harvey, 1993; Santero and Horvath, 2009). The GWP of cover crops compared to bare soil (or the chosen reference) can be derived from the ratio between the mean radiative forcing and the Absolute Global Warming Potential of carbon dioxide ($AGWP_{CO2}$) (See Sieber et al., 2019, equation 7). As such, the GWP allows comparing the relative importance of the different *agents* of cover crops (e.g. soil organic carbon storage, nitrous oxide emissions, albedo change) in a climate change mitigation context.

6. Challenges and critical assumptions

Estimating the albedo effects of cover crops under Danish conditions involves several challenges and assumptions, reflecting the complexity of interactions between vegetation, soil, and climatic factors. Some of the critical challenges and assumptions associated with this estimation are listed below:

i. **Selecting the correct reference/baseline**

   The change in albedo due to cover cropping is directly determined by the choice of reference or soil baseline. Soil properties (e.g. soil mineral color and moisture content), land use history (e.g. soil darkness due to content of organic matter), weed management and other management practices (e.g. tilling due to brighter residues left on the soil surface) may influence the reflective properties of soil. Also, it should be carefully considered whether a completely bare soil or a soil with volunteers (e.g. weeds) is chosen as the reference.

ii. **Cover crops species and growth characteristics**

   Different cover crop species exhibit varying growth patterns, heights, and leaf structures. These characteristics influence how they interact with both sunlight and snow cover. Also, the climate effect of a changed albedo is most crucial when solar radiation is high, e.g. in summer. Therefore, rapid cover establishment (and late termination) can become essential for effective albedo influence. Assessment of albedo is thus both species and management/timing specific. Consequently, the estimation should assume a representative mix of cover crop species, considering their growth habits, phenological stages and recognizing the significance of rapid cover in high-solar-radiation periods.

iii. **Representativeness**

   In order for the estimates to adequately reflect the actual geophysical system, models must represent both temporal and spatial variability. For example, this involves capturing variations over time, such as daily (and nightly) irradiance and weather conditions, as well as accounting for spatial differences, including field variability. Also, when calculating local transmittance or establishing a fixed transmittance factor, commonly associated with considerable uncertainty, it is imperative to ensure that the model adequately captures these nuances.

iv. **Altered surface energy balance**

   While the climate effect of a changed albedo is linked to the Earth’s energy balance at the top of the atmosphere, it is important to also consider the altered energy balance at surface-level. Changes at the surface can alter the distribution between sensible and latent heat fluxes, effectively impacting evapotranspiration (i.e. impacting surface cooling) and heat transfer to the surrounding air (Bright, 2015). Thus, altered surface properties can influence temperatures and the hydrological cycle at local to regional scale.

v. **Considering future climate change**

   Climatic changes can influence temperature, precipitation patterns, and snowfall. These changes may alter the dynamics of albedo effects. For example, if global warming reduces the snow period in Denmark, the net albedo effect of cover crops might increase over time. Predictions for future impacts of the albedo effect of cover crops should consider projections on future climate and weather conditions.

This report highlights the significant potential of cover crops in mitigating climate change through the albedo effect, alongside challenges and assumptions inherent in such estimations. Generalizing albedo effects across diverse landscapes may oversimplify local conditions, emphasizing the necessity of context-specific assessments. Data from a Danish context is crucial for quantifying albedo effects accurately, considering various scenarios and influencing factors. Such data aids in modeling the energy balance for climate models, offering valuable insights for farmers and policymakers alike.

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