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REVIEW ARTICLE

Using cover crops to mitigate and adapt to climate change. A review

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Abstract Cover crops have long been touted for their ability to reduce erosion, fix atmospheric nitrogen, reduce nitrogen leaching, and improve soil health. In recent decades, there has been resurgence in cover crop adoption that is synchronous with a heightened awareness of climate change. Climate change mitigation and adaptation may be additional, important ecosystem services provided by cover crops, but they lie outside of the traditional list of cover cropping benefits. Here, we review the potential for cover crops to mitigate climate change by tallying all of the positive and negative impacts of cover crops on the net global warming potential of agricultural fields. Then, we use lessons learned from two contrasting regions to evaluate how cover crops affect adaptive management for precipitation and temperature change. Three key outcomes from this synthesis are (1) Cover crop effects on greenhouse gas fluxes typically mitigate warming by ~100 to 150 g CO_2 e/m^2/year, which is higher than mitigation from transitioning to no-till. The most important terms in the budget are soil carbon sequestration and reduced fertilizer use after legume cover crops. (2) The surface albedo change due to cover cropping, calculated for the first time here using case study sites in central Spain and Pennsylvania, USA, may mitigate 12 to 46 g CO_2 e/m^2/year over a 100-year time horizon. And (3) Cover crop management can also enable climate change adaptation at these case study sites, especially through reduced vulnerability to erosion from extreme rain events, increased soil water management options during droughts or periods of soil saturation, and retention of nitrogen mineralized due to warming. Overall, we found very few tradeoffs between cover cropping and climate change mitigation and adaptation, suggesting that ecosystem services that are traditionally expected from cover cropping can be promoted synergistically with services related to climate change.

Keywords Adaptive management · Agriculture · Albedo · Cover crops · Climate change · Global warming · Greenhouse gases · Mitigation · Review

Contents

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1 Introduction

Cover cropping is an old practice and there is a long history of research documenting benefits for farms and the environment. This research legacy has been canonized in numerous review papers that synthesize the state of knowledge regarding benefits for soil erosion, nitrogen (N) fixation, and N leaching (Blanco-Canqui et al. 2015; Dabney et al. 2001; Thorup-Kristensen et al. 2003; Tonitto et al. 2006; Unger and Vigil 1998). However, none of these reviews analyze cover crops in relation to anthropogenic climate change. With the concurrent increases in both cover crop adoption and climate change awareness over the past several decades, there is a growing need to understand their interactions. The response to this need by the scientific community is evidenced by a flurry of analyses assessing how cover crops affect carbon (C) sequestration and greenhouse gas emissions from soil (Basche et al. 2014; Poeplau and Don 2015). Yet, while research linking cover crops and climate change is expanding, the studies are still piecemeal. That is, most papers, even review papers, treat only one aspect (e.g., just soil C) of the cover crop-climate change interaction. The goals of this paper are to synthesize existing research to develop the first comprehensive review of cover crop impacts on climate change mitigation, and to use lessons learned from two contrasting regions to analyze additional benefits of cover crops for climate change adaptation.

Climate change mitigation refers to strategies that reduce anthropogenic forcing of the climate system (IPCC 2007). For agricultural systems, typical biogeochemical mitigation strategies include reducing N fertilizer production and associate greenhouse gas emissions, reducing direct emissions of greenhouse gases from soils to the atmosphere, or increasing sinks for greenhouse gases in the soil (Camargo et al. 2013). Agricultural practices may also affect biophysical radiative forcing by changing albedo, which changes the amount of incoming shortwave radiation that is reflected back to the atmosphere or absorbed by the biosphere (Bright et al. 2015). Calculating the mitigation potential for a practice requires summing the positive and negative effects of the practice on greenhouse gases and albedo using common units. While some components of mitigation have been synthesized for country-based technical reports (Eagle et al. 2012; Justes et al. 2012), these reports only considered a subset of mitigation factors, without contrasting key choices (e.g., planting legumes vs non-legumes) affecting cover crop mitigation. A critical gap, noted by Poeplau and Don (2015), is the lack of any prior calculation of albedo impacts of cover cropping.

Even with a concerted global effort, mitigation is not likely to eliminate anthropogenic forcing of the climate system. In this case, the impacts of climate change may still be moderated through adaptation. In agricultural systems, adaptation can be realized by implementing practices that make existing systems more resilient to climate change or by redesigning the system to take advantage of the new climate (IPCC 2007). Increasing resilience means increasing the capacity (sometimes called adaptive capacity) of the system to absorb disturbance without qualitatively changing the fundamental interactions that characterize the system (Brand and Jax 2007). For example, an agricultural system that has a high resilience, or adaptive capacity, might continue to maintain adequate yields and low nutrient losses in the face of anomalous droughts or extreme rain events. In this paper, we will explore the potential for cover crops to increase or decrease the adaptive capacity of agricultural systems to climate change.

For both mitigation and adaptation, there are likely to be region- or even site-specific relationships between cover crops and climate change. Mitigation and adaptation strategies may be more successful when they are tailored to regional and local conditions (Rosenzweig and Tubiello 2007; Smith et al. 2007), for example by integrating climate change predictions with specific agricultural practices within a given region. To illustrate this tight coupling, portions of our analysis draw on two contrasting systems where substantial research has been conducted on cover crops in the context of climate variability. The first is an irrigated maize grain system that is prevalent throughout southern Europe (Fig. 1, Box 1). The second is a rainfed grain rotation prevalent for producing animal feed throughout the Mid-Atlantic of the USA, which is also relevant for the eastern "Corn Belt" and most of the northeastern USA (Fig. 2, Box 2). Both cases focus on winter cover crops with all biomass returned to the soil. While these systems do not account for all of the ways cover crops can be used, by contrasting long and short cover crop windows in humid and semi-arid ecosystems, they illustrate a wide range of interactions between cover crops and climate change. Furthermore, because of the rich history of research at these sites, we are able to examine tradeoffs between climate change mitigation or adaptation services and more traditional ecosystem services sought from cover crops.

2 Mitigation

2.1 Mitigation methods

To determine whether cover crops can help mitigate climate change, we tallied all of the sources and sinks of greenhouse gases in common units of grams of CO_2 equivalents per square meter per year (g CO_2 e/m^2/year; Table 1). We also included, for the first time, an estimate of the climate change mitigation that may arise from cover crop-induced changes in surface albedo. Calculating mitigation potential requires setting some boundaries for the analysis. We set the boundary as mitigation that can be attributed to a farm field. We also restrict our analysis to N fertilizer, as the energy involved in its synthesis and the gases emitted in the N cycle are crucial in

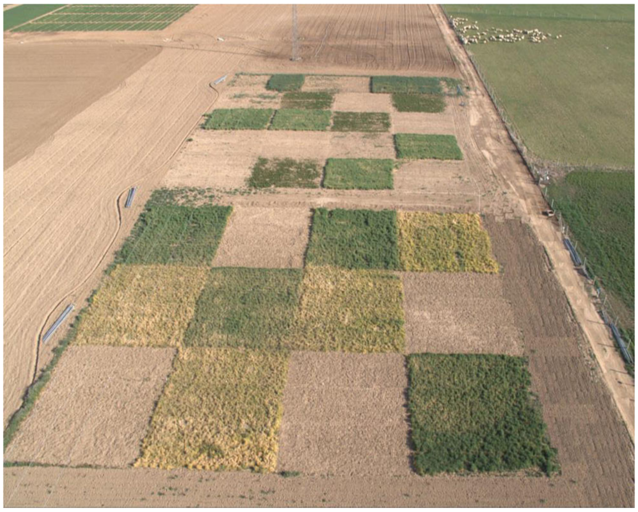

Fig. 1 Two cover cropping experiments in Aranjuez, Spain, in spring. All cover crops were planted after harvesting irrigated maize for grain. The experiment in the foreground compares killing dates of barley-vetch mixtures. *Yellow plots* have been sprayed with herbicide to terminate the cover crop, *green plots* are living cover crops, and *brown plots* are bare soil controls. The experiment in the background is a long-term (10 year) comparison of monocultures and mixtures of barley and vetch

climate change mitigation (Camargo et al. 2013). Though cover crops can affect P and K fertilizer use, we assumed the specific effect of cover crops would be small. We restrict the analysis to primary and secondary energy sources (sensu Camargo et al. 2013), which accounts for direct fuel use and production of inputs. Given these boundaries, we identified nine processes that we expect to be the most important in determining the climate mitigation potential of cover cropping on a particular farm field (Table 1). For each of these processes, we contrasted legume and non-legume cover crops to evaluate how farmer selection of these plant functional groups may impact mitigation potential.

Our overall approach for synthesizing information on mitigation was to use a broad literature review to calculate both typical values and the likely range of potential values across a wide variety of sites, and then to use knowledge from our well-studied cases (Boxes 1 and 2) to illustrate specific management and climatic factors that affect mitigation. To determine the typical values and the range of potential values for mitigation, our first choice was to use existing comprehensive meta-analyses that synthesized key literature values for mitigation resulting from cover cropping. For both soil C sequestration and N_2O fluxes very recent meta-analyses were available (Basche et al. 2014; Poeplau and Don 2015). When no meta-analysis was available for a process, our second choice was to use meta-analyses of key components of the process to calculate mitigation potential. This approach was used in five cases: (1) downstream N_2O fluxes were calculated from meta-analyses of NO_3 leaching (Tonitto et al. 2006; Quemada et al. 2013), (2) emissions from farm fuel use were calculated from a meta-analysis of farm operation greenhouse gas emissions (Camargo et al. 2013), (3) the mitigation potential from reduced fertilizer use was calculated from an existing literature review of energy costs to produce fertilizer (Camargo et al. 2013), and (4) the fertilizer credit for non-legume cover cropping was based on meta-analyses of soil C accumulation (Poeplau and Don 2015), and the fertilizer credit for legume cover crops was supported by a review of fertilizer replacement values for vetch and clover (Ketterings et al. 2015). For methane, no reviews were available or possible (because the literature was too sparse on the subject), so we relied on data from our intensively studied Spanish site (Box 1).

For albedo, none of these approaches were appropriate because there were no existing calculations of the effect of cover crops on albedo and no existing albedo measurements from our sites. In this case, our approach was to link literature values for soil and plant albedo with local plant cover and radiation data from our intensively studied sites to calculate the effect of cover crops on albedo. Shifting land area to surfaces with a higher albedo increases the amount of shortwave radiation that is reflected away from Earth's surface and eventually out of the atmosphere. This decrease in net radiation to the land and atmosphere has a cooling effect on global climate. Conversely, shifting to surfaces with lower albedo can increase net radiation and contribute to warming. Thus, if cover crops and bare soil have different albedos, cover cropping will impact climate change mitigation by altering net radiation. We explored the albedo effect of cover cropping using realistic combinations of high- and low-albedo plants

Box 1 Description of an irrigated maize system in central Spain

This system is a maize-sunflower crop rotation from semi-arid climates where annual precipitation is less than 400 mm. To specify the climate regime and draw on our own research, we focus on applying this rotation in central Spain (near Aranjuez), where mean annual precipitation is 350 mm. Precipitation is lower during summer (17 mm from July to August) and higher during autumn (131 mm from September to November). Mean monthly temperature in August is 24.2 °C, and in January is 6 °C. Maize is typically planted in April and harvested for silage in September or grain in October. After maize is harvested, many farmers do not plant cover crops but there are still growing degree days left in the autumn to enable growth of many species. Early autumn precipitation or a small irrigation (≈20 mm) is enough to ensure cover crop establishment. Sunflower (or other summer crops as onions, tomatoes, melons, etc.) are harvested in September–October. Mild autumn temperatures allow grasses (i.e., small grain cereals), legumes (i.e., vetch), or a mix of both to be grown as cover crops. In spring, cover crops are terminated with herbicides or combination of mowing, rolling, or tillage. Leaving the cover crop residue mulch on the soil surface is a good strategy to prevent water evaporation and ensure soil moisture at the time of planting the cash crop. Then, cash crops are no-till planted through the residues. Irrigation is applied by a sprinkle irrigation systems according to the crop evapotranspiration requirements (maize ~660 mm, sunflower ~300 mm) corrected by rainfall. In this region, synthetic fertilizers are used to supplement the N supplied by cover crops or organic amendments. With proper water and nitrogen management, the typical yield of grain corn in our experiment is 14 Mg/ha at 14 % moisture

Fig. 2 A cover cropping experiment in Pennsylvania, USA, within a maize-soybean-wheat rotation in late summer. In the *center* is a maize crop where rainout shelters are used to study drought. To the *left* are cover crops planted in mid-August after wheat was harvested. *Different colored plots* reflect different species of cover crops. Photo credit: Lou Saporito

with high- and low-albedo soils (Table 2) at contrasting locations where we have monitored plant and soil cover over winter (Boxes 1 and 2).

Surface albedo of cover-cropped fields was calculated from the albedo of plants and soils weighted by monthly fractional plant cover. The albedo end members for this surface cover mixing model, that is the albedo of bare soil and the albedo of a surface of complete plant cover, were based on literature values. The albedo of dark or wet soil is typically between 0.10 and 0.15, while lighter or drier agricultural soils typically have albedos of 0.2, and dry soils that are sandy or have low C concentrations (e.g., <1 % organic C) may have albedos >0.25 (Campbell and Norman 1998; Iqbal 1983; Matthias et al. 2000; Post et al. 2000). We used the strong relationship ($r^2 = 0.93$) between albedo and Munsell color chart value for a wide range of wet and dry soils (Post et al. 2000) to predict soil albedo for our scenarios. Both of our case study sites have Munsell Values between 3 and 5, which, according to the correlations in Post et al. (2000), correspond to an albedo range of 0.10 to 0.24. We used this range to represent potential variation in soil albedos, while we used an albedo of 0.17 (predicted from a Munsell value of 4) as our typical soil albedo.

Many published data for the albedo of crops are from fields with incomplete plant cover, so the measurements actually integrate the albedos of both plant and soil surfaces. We searched for data that indicate the albedo of plants alone (i.e., with no soil influence) by focusing on measurements of dense plant canopies (e.g., reported high leaf area index values). Monteith (1959) hypothesized that most crop plants had albedos of ~0.26 and his data on wheat, alfalfa, and sugar beets conformed to this hypothesis. Later, studies on wheat (Song 1999), soybean (Blad and Baker 1972), and cowpea (Oguntunde and van de Giesen 2004) also support the idea that C3 plant canopies of high leaf area index have an average albedo near 0.26, so we used this as the typical plant albedo in our scenarios. However, sun angle (which varies with time of day, latitude, and season) has a larger effect on plant than soil albedo, and studies that account for this variation find that the albedo of crop canopies can range from 0.21 to 0.30 across solar zenith angles typical of the cover cropping season (Song 1999, Blad and Baker 1972, Oguntunde and van de Giesen 2004, Monteith and Szeicz 1961). Thus, to bracket the range of possible plant albedos, we used 0.21 and 0.30 in our scenarios. At the USA experimental site, cover crops are terminated with mowing and tillage, so the cover crop albedo influence effectively ends at cover crop termination. However, at the Spanish experimental site, the soil surface is completely covered with residues after the cover crops are killed with herbicide (Alonso-Ayuso et al.

Box 2 Description of a rainfed grain rotation in the Mid-Atlantic region of the USA

This system is a maize-cover crop-soybean-winter wheat-cover crop rotation from temperate climates where annual precipitation is greater than 800 mm. To specify the climate regime and draw on our own research, we focus on applying this rotation in central Pennsylvania, USA, where mean annual precipitation is 975 mm, average July temperature is 22 °C, and average January temperature is 3 °C. Maize is typically planted in late May and harvested for silage in late September or grain in November. After maize grain is harvested, many farmers do not plant cover crops because there are so few growing degree days left in autumn that establishment and growth of even the most cold-tolerant plants is limited. After the earlier maize silage harvest, many farmers will plant cover crops, but even at this earlier date, cold autumn temperatures are a limitation, and the only cover crops that will establish and produce significant biomass are small grains (mainly cereal rye) and vetch. In spring, cover crops sown after maize are terminated with herbicides or some combination of mowing, rolling, or tillage. Soybeans are planted (often no-till) by early June and harvested in October, followed as quickly as possible by autumn planting of wheat or another winter small grain. Wheat is harvested by late July, after which cover crops are planted in early August for a long growth period until the next maize crop. Cover crops sown prior to maize often include legumes (crimson clover, Austrian winter pea, or vetch) to provide N to the maize, but may also include grasses (triticale, oats, or rye) and brassicas (especially forage radish). In this region, manure is often used in lieu of synthetic fertilizer. Typical yields at our experimental sites are 45 Mg/ha for corn silage at 65 % moisture, for wheat 3.5 Mg/ha of grain at 13.5 % moisture, and 3.2 Mg/ha at 13 % for soybean grain

Table 1 Processes affecting climate change mitigation by legume or non-legume cover crops and estimated typical values (and range in parentheses) for radiative forcing in units of CO_2 equivalents (CO_2e)

Process	CO_2 e (g/m^2/year)		Source of variation
	Non-legume	Legume	
Soil C sequestration	117 (78, 156)	117 (78, 156)	Site to site variation, time cover cropping
Soil N_2O efflux	−4 (1, −9)	−2 (3, −6)	Fertilizer N rate, incorporation
Reduced downstream N_2O flux	3 (0, 22)	0 (0, 13)	Cover crop effect on N leaching
Reduced N fertilizer use			
Green manure credit	0	20 (8, 59)	Cover crop N fixation
Organic matter credit	4 (0, 20)	4 (0, 20)	Same as soil C sequestration
Soil CH_4 flux	0	0	Too few studies for variation
Farm operations fuel use	−4 (−1, −10)	−4 (−1, −10)	Planting and termination choices
Total biogeochemical	116	135	
Albedo change	25 (−39, 111)	25 (−39, 111)	Soil and plant albedos, snow, see Table 2
Grand total	141	160	

Positive values represent net mitigation of radiative forcing, while negative values represent sources of radiative forcing. All values were rounded to the nearest whole number

2014) and the albedo effect of these residues is prevalent for approximately 1 month until a maize canopy develops. We calculated residue albedo values from the spectral reflectance data in Quemada and Daughtry (2016) and found that albedos for residue of a grass (wheat: dry = 0.3, moist = 0.2) and a legume (soybean: dry = 0.19, wet = 0.28) were similar to values we had identified for live plant canopies. Thus, at the Spanish site, we extended the cover crop effect on albedo for 1 month past the termination date by assuming that the residues had the same albedo range as live plant canopies.

For each month, the albedo of a cover-cropped field was calculated from a linear mixing model using the plant and soil albedo end members (Table 2) and field measurements of soil cover from our research sites (Boxes 1 and 2). The change in net shortwave radiation at the top of the atmosphere (ΔRn for a given month) was calculated as the product of local mean monthly downwelling shortwave radiation (W/m^2), the change in albedo from cover cropping (albedo of cover-cropped field minus bare soil albedo), and a constant (0.85) representing the transmissivity of shortwave radiation from the Earth's surface to the top of the atmosphere (Bright et al. 2015). Monthly values for scenarios in Table 2 are shown in Figs. 3 and 4. The average of these monthly values was corrected for the fraction of time that fields are cover cropped (cover cropped months/12) to calculate the ΔRn for each square meter of cover cropped area (W/m^2). The albedo effect ranged from −4 to 10 W/m^2, which is comparable to other land use transitions in the temperate zone (Anderson-Teixeira et al. 2012; Zhao and Jackson 2014).

To convert ΔRn (in W/m^2) to CO_2 equivalents, we used the equation g CO_2 e/m^2 = 1166 × ΔRn, where the constant 1166 accounts for the fraction of global land area that we were analyzing (1 m^2 out of 5.1×10^{14} m^2), the climate sensitivity to albedo change relative to CO_2 change (the ratio 0.52:1), the

Table 2 Changes in climate mitigation in units of CO_2 equivalents (CO_2 e) that result from the albedo change when shifting from bare soils to winter cover cropping

Scenario name		Scenario parameters		Change in g CO_2 e/m^2/year with cover crops			
				Pennsylvania, USA			Aranjuez, Spain
Plant albedo	Soil albedo	Plant albedo	Soil albedo	No snow	Full snow	Partial snow	No snow
Typical	Typical	0.26	0.17	45	25	12	46
High	Low	0.30	0.10	111	87	67	101
High	High	0.30	0.24	33	26	6	30
Low	Low	0.21	0.10	61	48	22	56
Low	High	0.21	0.24	−17	−13	−39	−15

Positive values reflect increased albedo, which mitigates warming. The full snow scenario buried all cover crops with snow (albedo = 0.65) from mid-December to mid-March. The partial snow scenario buried all of the soil but only half of the cover crop canopy for the same time period

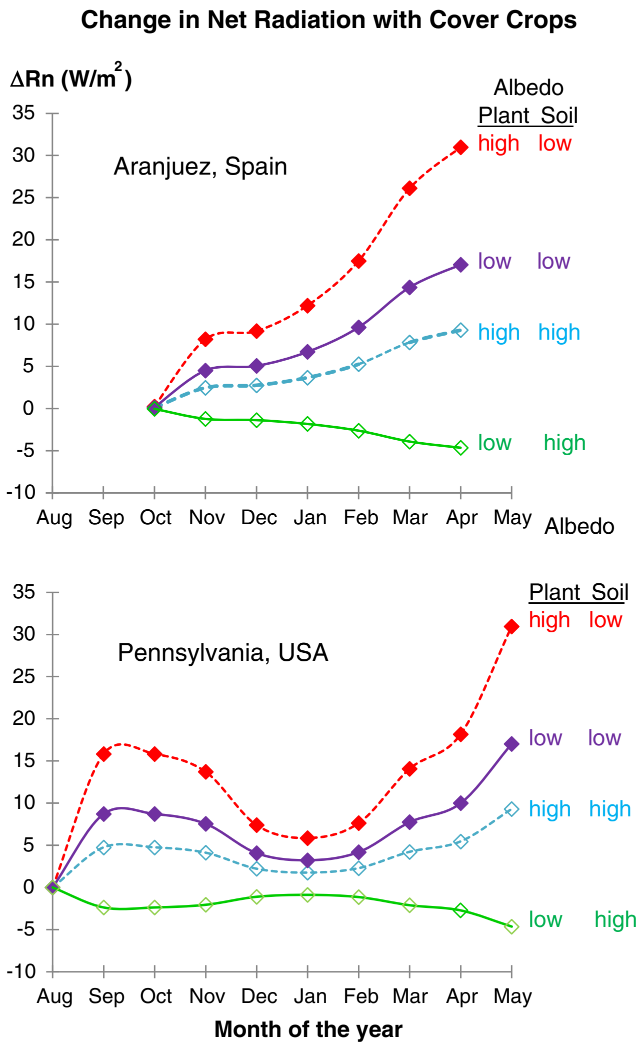

Fig. 3 *Top panel* The change in net radiation (ΔRn) due to albedo shifts when bare soil is replaced by winter cover cropping for each month of the cover cropping season in Aranjuez, Spain, with no snow cover. *Bottom panel* The same data for Pennsylvania, USA. *Different colored lines* contrast combinations of high and low plant and soil albedo (Table 2). *Solid symbols* low soil albedo; *unfilled symbols* high soil albedo; *solid lines* low plant albedo; *dashed lines* high plant albedo

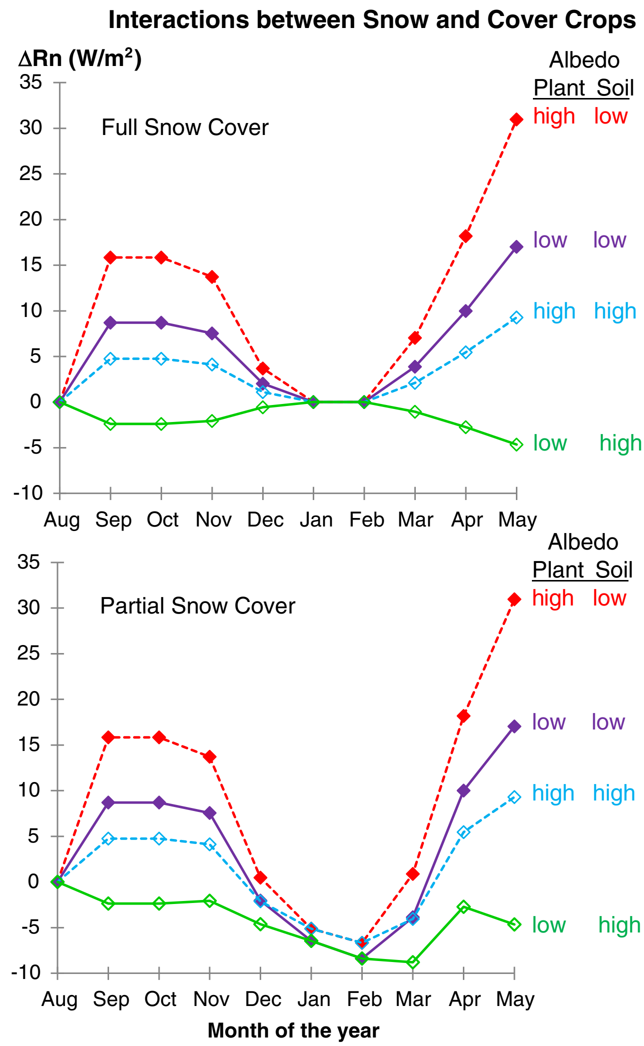

Fig. 4 *Top panel* The change in net radiation (ΔRn) due to albedo shifts when bare soil is replaced by winter cover cropping for each month of the cover cropping season in Pennsylvania, USA, with snow completely burying both soil and cover crops over winter (mid-December to mid-March). *Bottom panel* The same as top panel, but with snow completely burying soil and only partially burying cover crops in winter. *Different colored lines* contrast combinations of high and low plant and soil albedo (Table 2). *Solid symbols* low soil albedo; *unfilled symbols* high soil albedo; *solid lines* low plant albedo; *dashed lines* high plant albedo

radiative forcing that arises from a change in atmospheric CO_2 concentration (from a base concentration of 391 ppmv), the fraction of emitted CO_2 that remains in the atmosphere, the molecular mass of C in CO_2, and unit conversions, as described in detail in Zhao and Jackson (2014). This product represents the mass of atmospheric CO_2 needed to cause a change in radiative forcing equal to the albedo-caused change in net radiation. One challenge in linking this mass of CO_2 with other data in Table 1 is that we need to assign an analysis time over which we distribute this new hypothetical pulse of atmospheric CO_2. Anderson-Teixeira et al. (2012) treat this problem explicitly and suggest that the analysis time could be any duration up to 100 years, and should be comparable to the time frame of ecosystem biogeochemical change following land conversion. In our case, the best indicator of the time frame of ecosystem change is the time it takes soil C to reach steady state after cover cropping begins, which lies somewhere between 50 and 150 years (see Section 2.1.1). Based on Anderson-Teixeira et al.'s (2012) recommendations, the time horizon of our global warming potential calculations (100-year horizon for converting N_2O and CH_4 to CO_2 e), and our review of the time horizon of soil C change from cover cropping (50 to 150 year horizon to reach steady state), we assumed the pulse of CO_2 that was simulating albedo change could be distributed over 100 years. That is, the per-year CO_2 e from albedo change is 1/100th of the total CO_2 e due to albedo change. As Anderson-Teixeira et al. (2012) note, short analysis times overemphasize the albedo effect, while long analysis times deemphasize this effect. It would be best if there were a more concrete approach to determining analysis time, but this is currently an active area of research in environmental biophysics (Bright et al. 2015) and no superior methods exist. Fortunately, the sign of the albedo effect, which indicates whether albedo changes lead to warming or cooling, is not dependent on the analysis time.

2.2 Mitigation results

2.2.1 Soil carbon

There is substantial evidence that cover cropping increases soil C sequestration. Both models (Schipanski et al. 2014) and meta-analyses of field studies (McDaniel et al. 2014) reveal these increases. However, there is significant variability among sites, and the effect of cover cropping on soil C appears to increase with reduced tillage, complex crop rotations, and high N inputs (Lal 2015). In our experimental sites in Spain, the rate of C sequestration calculated by combining the DSSAT-CENTURY model (Gijsman et al. 2002) and experimental data was 24 g/m^2/year larger for the cover crops than for the control treatment (Soldevilla et al. 2014). Low C sequestration is typical under the hyperthermic conditions of the Mediterranean basin due to rapid mineralization rates (Gervois et al. 2008). In the Pennsylvania, USA, site, we used the Cycles model to simulate a low input rotation, like that described in Box 2 but with the only N supplied to maize being the clover cover crop. Under these conditions, the rye cover crop that followed maize was very N-limited and accumulated much lower biomass than we observed in field experiments (<0.1 Mg/ha dry biomass in simulations compared to 2–8 in field experiments), yet soil C in simulations that included cover crops still grew by ~15 g/m^2/year relative to simulations without cover crops (Schipanski et al. 2014). Our case study sites show that cover crops promote C sequestration even under challenging conditions, but they also point to a need for understanding factors that control variation in soil C sequestration from this practice.

For our estimate of mitigation through soil C sequestration, we used results from the meta-analysis of Poeplau and Don (2015). Using data from 37 sites where cover crop treatments were compared to controls, they plotted time since cover cropping began versus soil C and calculated the rate of soil C sequestration as 32 ± 8 g/m^2/year. There was no statistical difference between legume and non-legume cover crops (Poeplau and Don 2015). Mean soil depth of the samples used in this analysis was 22 cm, so it likely provides a conservative estimate of soil C sequestration. The meta-analytical estimate from Poeplau and Don (2015) is comparable to values tabulated by Justes et al. (2012), Eagle et al. (2012), and Lal (2015) from many of the same studies. Because each gram of C sequestered in soil equates to 3.66 fewer grams of CO_2 in the atmosphere, the soil C sequestration rate from Poeplau and Don (2015) is equal to a mitigation rate of 117 ± 29 g CO_2 e/m^2/year (Table 1). It is important to note that the mitigation potential of soil C sequestration has a finite lifespan because eventually this pool reaches a steady state. Models and empirical measurements suggest the duration of this C sink is at least 50 years, and may last as long as 150 years (Poeplau and Don 2015; Schipanski et al. 2014).

Cover crops may also affect soil C sequestration by decreasing erosion rates. The effect of erosion on C sequestration depends on the balance between enhanced decomposition during transport, slower decomposition of buried sediment, and changes in rates of new C addition and stabilization at the point of erosion (Berhe et al. 2007). One keystone decadal scale analysis of several agricultural sites in Europe and the USA found that these processes approximately balance, such that erosion is neither a source nor sink for CO_2 (Van Oost et al. 2007). Based on this careful study, we chose not to calculate the C mitigation potential of reduced erosion from cover cropping. However, this is an active area of research, and as a consensus emerges it may be appropriate to include erosion in cover crop mitigation analyses.

2.2.2 Soil to atmosphere N_2O fluxes

Agricultural soils are an important source of N_2O to the atmosphere. Because N_2O is a potent greenhouse gas with a long lifespan in the atmosphere, the 100-year warming potential of a gram of N_2O is 298 times greater than a gram of CO_2 when carbon-climate feedbacks are accounted for (CO_2 e from N_2O emissions = 298 × N_2O emission rate; IPCC 2013). Nitrous oxide fluxes from agricultural soils largely result from denitrification of nitrate, which occurs at higher rates in saturated soils. Cover crops often reduce both soil water and nitrate concentrations (Justes et al. 2012; Tribouillois et al. 2015); so, there is reason to expect that they may reduce the flux of N_2O from soils to the atmosphere. On the other hand, high C inputs from cover crops may stimulate denitrification since the process is driven by heterotrophic respiration (Mitchell et al. 2013). Likewise, high N inputs immediately following legume cover crop termination may lead to high nitrification and subsequent denitrification rates that could elevate N_2O losses. Basche et al. (2014) conducted a meta-analysis of 26 field studies to synthesize disparate reports of cover crop effects on N_2O. Their key finding was that when N_2O fluxes were measured over an entire growing season, there was no detectable difference between cover crop plots and no-cover crop controls. Within specific time periods legume cover crops may have higher emissions than non-legumes (especially when fertilizer N inputs are low), and incorporated cover crops may have higher emissions than cover crops left on the surface. Field studies at our Spanish case study site illustrate these points nicely. We found that legume cover crops had higher N_2O emissions than non-legumes when the cover crops were growing. In contrast, after the cover crops were killed and maize had been planted, plots with a non-legume cover crop history tended to have higher N_2O emissions than plots with a legume cover crop history (Guardia et al. 2016), especially when the cover crops were incorporated into the soil (Sanz-Cobena et al. 2014). Summing the cover crop and maize periods, relative to a fallow control, vetch cover crops increased N_2O fluxes by 0.01 g N/m^2/year (though not statistically significant) regardless of incorporation, while barley had very small effects on N_2O fluxes (relative to fallow control) when it was not incorporated and increased N_2O fluxes by 0.01 g N/m^2 when it was incorporated into soil (Sanz-Cobena et al. 2014; Guardia et al. 2016). These results are consistent with Mitchell et al. (2013) in suggesting that high C inputs from non-legume cover crops can stimulate N_2O production.

While there is substantial variation in N_2O emissions depending on cover crop type (legume vs non-legume) and management (incorporation and supplemental N rate), the meta-analysis by Basche et al. (2014) suggests that on average cover crops will not alter N_2O emissions relative to a fallow system. When cover crops do alter N_2O emissions, the effect may be an increase or decrease of about 0.01 g N/m^2/year (Basche et al. 2014; Mitchell et al. 2013; Sanz-Cobena et al. 2014; Guardia et al. 2016) relative to fallow. A 0.01 g N/m^2/year change in N_2O emissions is 0.016 g N_2O/m^2/year or roughly 4.7 g CO_2 e/m^2/year (Table 1). Additionally, some N_2O is emitted from soils where cover crop seeds are being produced, and this amounts to 1.6 (legume) to 4 (non-legume) g CO_2 e/m^2/year (Camargo et al. 2013) after accounting for typical seeding rates.

2.2.3 Downstream N_2O fluxes

Another source of N_2O from agriculture occurs when nitrate leaches from farm fields and is later denitrified. When cover crops decrease nitrate leaching, they should diminish this "downstream" N_2O flux. There have been several meta-analyses that provide estimates of the expected reduction in nitrate leaching from cover crops. Tonitto et al. (2006) found that N leaching was 70 % lower in non-legume cover-cropped systems than fallow systems and 40 % lower in legume cover crop systems than fallow. Quemada et al. (2013) found that for irrigated systems leaching is 50 % lower when non-legumes are planted, and that legume cover crops did not change N leaching relative to fallow controls. With optimal N management, these irrigated systems leach about 2.5 g N/m^2/year without cover crops or with legume cover crops, and non-legume cover crops reduce leaching by 1.25 g N/m^2/year (Gabriel et al. 2013; Quemada et al. 2013). While this provides a reasonable benchmark, or "typical" value, leaching in both irrigated and non-irrigated systems is highly variable, ranging from 0 to 15 g N/m^2/year (Di and Cameron 2002; Constantin et al. 2010; Quemada et al. 2013); so reductions in leaching from cover cropping could range from 0 to 10 g N/m^2/year for non-legumes and 0 to 6 g N/m^2/year for legumes. Syakila and Kroeze (2011) provide a rough estimate of how much leached N may be converted to N_2O after transport to groundwater, rivers, and estuaries. Their approximation is that N_2O produced on this flowpath is 0.0075 g N_2O/g N leached. Thus, we calculate that a typical value for mitigation by non-legume cover crops = 1.25 g N leached/m^2 × 0.0075 g N_2O/g N leached = 0.009 g N_2O/m^2/year = 2.8 g CO_2 e/m^2/year (Table 1). Since we cannot calculate variability in N_2O production rates downstream from the fields, we used variation in leaching reduction rates to calculate the range in mitigation potential from this flux.

2.2.4 Reduced N fertilizer use

The final N cycle component to mitigation is the reduction in N fertilizer associated with cover crop use. The production of N fertilizer is the single largest source of energy use in agricultural production (Camargo et al. 2013). Most crop production guides recommend that farmers reduce synthetic fertilizer inputs to cash crops that follow legume cover crops (Clark 2007). In both of our case study regions, autumn-sown legume cover crops can accumulate 5 to 30 g N/m^2 before termination prior to maize crops in spring (Alonso-Ayuso et al. 2014; Finney et al. 2016a, b; Gabriel et al. 2013; Poffenbarger et al. 2015). The amount of cover crop N that is mineralized to supply N for the cash crop is variable, but one recommendation (Clark 2007) for farmers in the region of our Pennsylvania research site is to divide aboveground legume cover crop N by 2 when cover crops are incorporated into soil and reduce supplemental fertilizer by this amount. White et al. (2016) combined an ecologically based N cycle model with ~200 observations of corn yield following cover crops at our Pennsylvania research sites and found that lag times between cover crop death (e.g., winter-kill species) and maize uptake can increase the fraction of cover crop N (e.g., increasing from 27 to 41 %) that becomes available to the maize crop. Our research in Spain suggests that available N might be one third of cover crop N when the cover crops are not incorporated (Gabriel et al. 2013). Thus, maize following legumes in temperate regions would require 2 to 15 g/m^2 less fertilizer than maize without the legume cover crop. A typical scenario at our research sites is that vetch, pea, or clover cover crop biomass is ~10 g N/m^2 providing a fertilizer credit of 5 g N/m^2. This estimate corresponds well to a literature review of "fertilizer replacement" values for these cover crops in dairy grain rotations in the northeastern USA (Ketterings et al. 2015). Camargo et al. (2013) found that a mean value of the global warming potential of N fertilizer synthesis was 3.9 g CO_2 e/g N fertilizer, so a reduction of 5 g N/m^2 corresponds to ~20 g CO_2 e/m^2/year lower radiative forcing when legume N is used to replace fertilizer N.

Typical recommendations for non-legume cover crops are to maintain the same fertilization levels as with no-cover crop fallows, so there is no direct mitigation credit for reduced fertilizer use when these covers are used. However, soil organic matter content is a variable in some N fertilizer recommendation calculators (Shapiro et al. 2008), and to the extent that cover crops increase soil organic matter both legume and non-legume cover crops would eventually (on decade time scales) result in lower fertilizer recommendation rates. Evidence for the coupled C and N sequestration and the benefits for N availability to cash crops have been reported for both legumes at our Spanish case study site (Gabriel and Quemada 2011) and non-legume cover crops (Constantin et al. 2010). Using the C accumulation rates of Poeplau and Don (2015), along with the fertilizer calculator developed in Nebraska, USA, for maize (Shapiro et al. 2008), suggests that every 10 years of cover cropping increases the soil organic matter concentration by about 0.3 %, and mineralization of N from this new organic matter reduces fertilizer requirements by 1 g N/m^2/year. After 50 years of cover cropping this credit might be 5 g N/m^2/year, but it would likely not increase beyond that level as soils would reach a steady state C and N storage. Thus, the N fertilizer credit for the increasing soil organic matter pool from a farm with a history of cover cropping might reasonably be 1 g N/m^2/year, with a range from 0 to 5 g N/m^2/year depending on the total duration of cover cropping. Converting these values to mitigation potential (as above using 3.9 g CO_2 e/g N fertilizer) yields 3.9 g CO_2 e/m^2 for a farm with a decade of cover cropping. We applied this value, and a range of 0 to 20 g CO_2 e/m^2 (0 for fields with short cover cropping history; 20 for fields with very long cover crop history) to both legume and non-legume cover crops because both accumulate soil C at the same rate (Poeplau and Don 2015).

2.2.5 Soil CH_4 fluxes

Estimates of changes in soil-atmosphere CH_4 fluxes are rare, in part because early research suggested that agronomic practices had little effect on this gas (Robertson et al. 2000). Indeed, we know of only two studies (Sanz-Cobena et al. 2014, Guardia et al. 2016) associated with our Spanish case study that directly compare CH_4 fluxes between cover crops and fallow. Sanz-Cobena et al. (2014) found no statistical differences between four cover crop treatments and bare fallow in a maize-cover crop-maize system; all treatments were small net sinks for atmospheric CH_4. Given that so little research has been conducted in this area, it is worth noting that, while not significantly different from other treatments, one legume cover crop treatment had a smaller soil sink (and in one season was even a source) for CH_4 than other cover crop treatments (Sanz-Cobena et al. 2014). Guardia et al. (2016) compared barley and vetch cover crops and the subsequent maize crop managed with integrated soil fertility management (e.g., decreased synthetic fertilizer applications accounting for cover crop N supply) and also found that all treatments were statistically similar and a small sink for atmospheric CH_4. Based on the systems level work of Robertson et al. (2000) and the specific contrasts of Sanz-Cobena et al. (2014) and Guardia et al. (2016), we assumed that cover crops have no effect on CH_4 fluxes from soils.

2.2.6 Farm operations fuel use

Cover crops increase the number of field passes that farmers must make, but the amount depends on methods of planting and killing. Based on our experience in the mid-Atlantic of the USA and central Spain (Boxes 1 and 2), cover cropping typically requires one extra field pass to plant the cover crop and one extra pass to kill the cover crop with a herbicide. Additional passes, such as weed management, may occur during the cover crop phase, but they would also occur in fallow areas, so they are not considered “extra” passes. To no-till drill cover crops requires about 7 L/ha of diesel fuel, which amounts to 2.3 g CO_2 e/m^2, while a herbicide application requires about 0.5 g CO_2 e/m^2 (Camargo et al. 2013), for a total of 2.8 g CO_2 e/m^2/year (Table 1). We used this as a typical value and then used a range of possible planting and killing approaches to generate the expected variation in CO_2 e from farm operations fuel. The low estimate was from planting a winter-killed cover crop by broadcasting seed and incorporating with a simple harrow (Camargo et al. 2013). The high estimate is from a cover crop planted into a seedbed prepared with a chisel plow and cultipacker and then killed by mowing.

2.2.7 Albedo change

We first considered albedo effects of only soil and plants without any snow cover, which would be typical for the Spanish case, but not necessarily for the USA case. With no snow, we found that under most scenarios, and with the most likely combinations of soil and plant albedo, cover cropping mitigated warming (i.e., lead to cooling) by increasing reflected radiation (Table 2). The plant and soil albedo combination that we expect to be typical for no-snow conditions mitigated warming at a rate of 46 or 45 g CO_2 e/m^2/year (in Spain and the USA, respectively). Other scenarios that mitigated warming were low-albedo soils coupled with either low- or high-albedo crops, and high-albedo soils coupled with high-albedo crops. The only combination that exacerbated warming was high-albedo soils coupled with a low-albedo crop.

The similar values in these no-snow scenarios at typical albedos mask some important differences in factors governing the albedo effect of cover crops at the two sites. Monthly downwelling radiation was similar between these sites, so the main differences arose from cover crop planting and killing dates, residue management, and the development of cover crop ground cover over time. In the USA case, cover crops were planted in August after a small grain and reached peak cover (80 %) in the late autumn. After the winter, plant cover was ~50 % until April when regrowth brought cover back to 80 % prior to termination, which included incorporation into the soil that effectively ended the cover crop impacts on albedo. These plant growth and residue management patterns produce large effects on albedo in the fall and late spring (Fig. 3). In the Spain case, cover crops were planted in October after maize harvested for grain and they achieved high cover rapidly and maintained >90 % cover until termination at the end of March (in this case by herbicide with residue left on the surface), after which cover crop residue continued to impact albedo for 1 month (Fig. 3). Thus, in Spain, the fall cover crop window following maize grain does not overlap with months that have high radiation inputs, but persistent winter and spring cover (including residue cover) lead to large albedo effects in these seasons. The opposing impacts of seasonality and residue management approximately balance so that so that the overall effect of cover crops on albedo is similar between the sites, at least for no-snow scenarios with typical plant and soil albedos.

Snow has a large impact on winter albedo because of the albedo of snowpack (~0.65; Campbell and Norman 1998; Iqbal 1983) is much higher than plant or soil albedos. Furthermore, the presence or absence of plants emerging from snowpack is one of the most important biophysical feedbacks to climate change in northern latitudes (Bright et al. 2015; Zhao and Jackson 2014). We examined snow cover crop albedo interactions in our Pennsylvania, USA, case (Box 2) by simulating snow that buried soil and cover crops completely for three winter months (one half of December and March, all of January and February), and then simulating snow that completely buried soil, but buried only one half of cover crop surface area for 3 winter months. The latter scenario simulates a cover crop canopy that persists above snowpack and lowers the overall field albedo. All of the scenarios that included full snow cover of both plants and soil moderated the cover crop impact on albedo (Table 2), as expected, because when both plants and soils are buried by snow, the change in albedo due to cover cropping is zero (Fig. 4). Partial snow burial of cover crops further reduced the mitigation potential from cover crops. High-albedo plants (though still with an albedo much lower than snow) emerging over winter snowpack, still had a mitigating effect (relative to no-cover crop) because the warming effect of cover crops in winter was more than balanced by the cooling effect in spring (Fig. 4). This was also the case for low-albedo plants coupled with low-albedo soils. However, when high-albedo soils were planted with low-albedo cover crops that emerged over snowpack, the large difference between the snow and cover crop albedo exacerbated (relative to the full or no snow cases) the warming effect of cover crops both for winter (Fig. 4) and over a year (Table 2).

One additional management factor that may lead to differences among sites in albedo is cash crop residue cover. Spectral reflectance data suggest that the albedo of crop residues is similar to soils when the residues are moist and increase as the residues dry. In the medium moisture range, residues of maize, wheat, and soybean have albedos of 0.25, 0.20, and 0.19, respectively (Quemada and Daughtry 2016). Thus, in no-till or reduced tillage systems, where relatively high-albedo plant residues cover lower albedo soils, the effect of cover crops on albedo could decrease as a function of cash crop residue cover. For example, using the typical cover crop and soil albedos for the Spain case, the albedo effect of cover cropping would diminish from our calculated value of 46 g CO_2 e/m^2/year (Table 2) to 36, 25, or 15 g CO_2 e/m^2/year as the soil cover of moist maize residue (albedo = 0.25) increased from 25 to 50 to 75 %.

Overall, our analysis revealed that under most combinations of realistic plant and soil albedos, cover cropping will result in mitigation of warming via albedo change. Nevertheless, it is clear that some combinations of high-albedo soils (e.g., sandy or high in gypsum or carbonates) combined with low-albedo cover crops can contribute to warming, especially when cover crops overtop snowpack or when high-albedo cash crop residues have significant soil cover. Based on the scenarios for Table 2, we speculate that typical values lie between 12 and 46 g CO_2 e/m^2/year, and we tentatively used 25 g CO_2 e/m^2/year for comparison with other mitigation factors in Table 1. However, without more data on the range of variability in plant and soil albedos, the fraction of the cover crop canopy that is buried by snow, and the fraction of the soil that is covered with cash crop residues, it is difficult for us to refine our analysis further. Finally, we focused our analysis on albedo effects on global radiative forcing because we were interested in mitigating global climate change. However, albedo and other aspects of the local energy balance related to cover cropping (e.g., changing heat fluxes) can also affect local climate. Some of these local changes, including local warming and local evaporation effects on regional precipitation could be just as important as global climate change. These are active areas of research in environmental biophysics, but the science is not yet sufficient to support a review.

2.2.8 Mitigation summary

If we sum what we consider typical values from Table 1, legume and non-legume cover crops mitigate climate warming through changes in both biogeochemical processes and albedo. Estimated total mitigation from altered greenhouse gas fluxes was 116 and 135 g CO_2 e/m^2/year for non-legumes and legumes, respectively. If we add in albedo effects, typical mitigation due to cover cropping could total ~150 g CO_2 e/m^2/year (based on 141 for non-legume and 160 for legume cover crops; Table 1). While summing these typical values is informative, we are unable to simply sum the maximum and minimum values from Table 1 to estimate total variation because some of these fluxes are related. As a clear example, it is unlikely that maximum values for infield N_2O flux would coincide with maximum values for downstream N_2O flux attributed to the same field. A high value for infield N_2O flux implies high N retention in the cover crop and field soils, which belies the high N leaching rates that would generate high downstream N_2O fluxes. Nevertheless, it is worth noting that even if we sum all of the "worst case scenarios" from Table 1, cover cropping still results in net climate change mitigation.

To calculate radiative forcing impact globally, we would need to know the total area that could become cover-cropped in the future. This value is currently not known, but following Poeplau and Don (2015) a rough estimate can be calculated by assuming that 25 % of the global cropland areas (16 million km^2; Siebert et al. 2010) or 4 million km^2 could potentially be cover cropped. This value is based on data showing that half of agricultural land already being planted in winter cereals (thus not available for cover cropping) and the assumption that another quarter may not be cover cropped do to other constraints (e.g., cold temperatures, low water availability, rotations). If this level of adoption were realized, cover cropping could mitigate ~150 g CO_2 e/m^2/year × (4 × 10^{12} m^2) = 0.6 Pg CO_2 e/year. This amounts to about 10 % of the 5 to 6 Pg CO_2 e/year that the IPCC estimates to originate from agriculture (Smith et al. 2007).

Improved projections of cover crop impacts on climate change mitigation will require both improved estimates of potentially cover-cropped land area, and reduced uncertainty for some of the processes in Table 1. One important outcome of our review is that it highlights which processes are large enough to warrant further research and which have the largest potential range of mitigation. The uncertainty in the rate of soil C sequestration is as large as most other terms in Table 1. Further research is required to understand how factors such as species choices, termination strategies, and tillage interact with soils and climate to affect C sequestration. Likewise, the green manure N fertilizer credit is one of the largest and most uncertain terms in Table 1. A major current research gap is the lack of models and decision support tools that enable predictions of N supply from green manures (White et al. 2016). Additional research in this area could have a multi-fold impact by reducing uncertainty in the climate change mitigation and increasing the efficiency of synthetic fertilizer use. Finally, our calculations represent the first estimates of cover crop albedo effects, and they point to a substantial role for this process in determining cover crop effects on mitigation. The variance in our estimates is extremely large because we cannot yet fully simulate albedo interactions among snow, soil, cash crop residues, living cover crops, and cover crop residues. Thus, our synthesis highlights soil carbon, green manure credits, and albedo as critical areas for refining mitigation estimates. While other terms in Table 1 have high uncertainty, the magnitude of the impact on CO_2 e is small enough that additional research is unlikely to change our overall interpretation of the cover crop effects on climate mitigation.

Our estimates of climate change mitigation from altered greenhouse gas fluxes (116 and 135 g CO_2 e/m^2/year for non-legumes and legumes) are larger than those arising when farmers shift from conventional to no-till cultivation for 20 years in humid and dry regions (94 and 48 g CO_2 e/m^2/year, respectively; Six et al. 2004, van Kessel et al. 2013). The soil C accumulation rate from cover cropping (78 to 156 g CO_2 e/m^2/year; Table 1) is comparable to rates for the first 20 years after conversion to no-till (81 or 36 g CO_2 e/m^2/year for humid or dry regions, respectively; Six et al. 2004). One key difference is that legume cover cropping reduces fertilizer inputs while shifting to no-till does not. Indeed, transitioning to no-till can initially reduce yields (van Kessel et al. 2013), which may increase fertilizer use and associated greenhouse gas fluxes. A major area of uncertainty in comparing no-till and cover cropping is the greenhouse gas impact of N_2O fluxes. While Six et al. (2004) estimated that transitioning to no-till increased N_2O fluxes in the first 10 years and then decreased fluxes more than 10 years after the transition, a more recent meta-analysis (which we used for the above estimate of CO_2e from no-till) by van Kessel et al. (2013) found that no-till and conventional tillage had similar N_2O fluxes on average, and that no-till may decrease N_2O fluxes long after adoption (>10 years), especially in dry systems. The range of estimates for the impact of no-till conversion on N_2O mitigation (roughly −100 to 100 CO_2 e/m^2/year; Six et al. 2004) appears to be much wider than the range for cover crop adoption (Table 1). Despite these uncertainties, our analysis reveals that climate change mitigation from cover cropping is comparable to transitioning to no-till.

Thus far, our analysis has not taken into account yield differences between crops that follow cover crops versus crops that follow bare fallow. In a wide range of disparate systems legume cover crops consistently increase yields by

5 to 30 % (Finney et al. 2016b; Gabriel et al. 2013; Miguez and Bollero 2005; Quemada et al. 2013). Yields of cash crops following non-legume cover crops are generally similar to or slightly (e.g., <10 %) greater than those following bare fallow as long as the C/N ratio and biomass are managed to limit microbial N immobilization during cover crop residue decomposition (Finney et al. 2016b). Thus, for non-legume cover crops, the climate mitigation benefits of cover cropping come with no trade-off in yields, while for legume cover crops our data point to a "win-win" scenario in which yields and climate mitigation are both improved by cover cropping. There are also economic considerations to take into account, for example, in determining whether the net income from higher yields and lower fertilizer costs associated offset cover crop seed costs. These factors are important, but they depend heavily on commodity price fluctuations, seed costs (which may go down with greater demand), and government incentives or subsidies.

3 Adaptation

Even under the best-case scenarios for global mitigation, anthropogenic climate change will likely continue (IPCC 2013). Furthermore, spatially robust predictions of climate change remain elusive, especially for precipitation. Thus, it makes sense to consider how cover crops might help agricultural systems become more resilient to climate change, and whether they increase or decrease the adaptive capacity of agroecosystems. We organize our discussion around three aspects of climate change: (1) extreme rain events, (2) drought, and (3) incremental directional warming. For each of these climate change types, we analyze potential tradeoffs between adaptation and traditional benefits expected from cover crops for yield, erosion, and soil water and N management. In terms of resilience, we examined how adaptive management of cover crops might help maintain yields and lower environmental impacts (e.g., low erosion and N losses) of agriculture as the climate changes. More so than mitigation, successful adaptation depends on nuanced relationships between climate change and cropping systems dynamics, so we draw extensively on the two contrasting systems where these relationships are well-described (Figs. 1 and 2, Boxes 1 and 2).

3.1 Extreme rain events

In the coming decades, it is very likely that the intensity of precipitation events will increase in mid-latitude agricultural areas (IPCC 2013, Trenberth 2011). One of the biggest threats of higher rainfall intensity is increased erosion, and given the well-documented reduction in erosion by cover crops (Dabney et al. 2001), they can undoubtedly be used to adapt to this type of climate change in some cases. The benefit of cover cropping will depend on the seasonality of rainfall. For example, in the Mid-Atlantic, USA, region, recent records show that rainfall intensity is increasing in conjunction with the hurricane season in October (Spierre and Wake 2010; Lu et al. 2015), while some models forecast drier autumns and wetter winters (Shortle et al. 2015). In either case, cover crops with significant biomass by October (e.g., cover crops planted after wheat or interseeded into maize) would substantially reduce erosion. Cover crops would also reduce impacts of extreme rain events on leaching losses of autumn-applied manures and fertilizers, which are common in this region.

In central Spain, prediction of total rainfall in future scenarios is uncertain but all the models agree on an increase of extreme events, particularly in autumn and spring (Olesen et al. 2007). Field research has shown that the majority of leaching from irrigated maize in this region occurs during the autumn-winter period (≈77 %) or early spring (≈15 %) and is associated with heavy rain events (Gabriel et al. 2012). The effect of cover crops on reducing leaching is more notable during these periods; compared to a fallow field, grass cover crops reduced leaching by 2.5-fold and legume cover crops reduced leaching by 25 %. If the increased C from cover cropping also increases soil aggregate stability, then the benefits of cover crops for erosion may extend to extreme rain events that fall outside the period when cover crops are actually growing. After 7 years of cover cropping, both grass and legume cover crops enhanced water stable aggregates in Aranjuez, Spain, though the effect from grass cover crops was greater because it added more C as biomass (García-González et al. 2016). The improvements in soil structure and the soil coverage by the cover crop, either the living crop or the residue mulch, also protect the soil from soil crusting, a common phenomenon in Mediterranean areas, which multiplies the deleterious effect of extreme rain events (Ries and Hirt 2008).

In contrast, cover crops could reduce resilience of cash crop yield to extreme rain events if increased precipitation intensity is synchronous with the timing of key field operations. For example, if higher rainfall intensity overlaps with the transition from cover crops to cash crops, farmers may not have time for the extra field operations required for cover cropping. Specifically, a difficult transition between killing the cover crop and planting cash crops can lead to delayed cash crop planting or poor seedbed preparation that limits cash crop establishment. This risk is lower with no-till cash crop planting, and may diminish further if "planting green" (i.e., no-till planting cash crops into a living cover crop that is subsequently killed) becomes a widespread practice.

3.2 Drought

Along with more precipitation falling in extreme events, climate change is also expected to bring longer periods with no rainfall to some regions. This will result in more drought, even when annual precipitation inputs do not change (Trenberth 2011). In some dry regions, cover crops may reduce resilience to drought when transpiration reduces water availability to cash crops (Unger and Vigil 1998). However, research suggests that in our semi-arid and humid case study regions, there is potential for cover crops to increase adaptive capacity to maintain yields and low N losses under increased drought.

In semi-arid Spain, the increase in rainfall distribution variability is expected to enhance the risk of drought (Minguez et al. 2007). A significant increase in drought resilience arises from adaptive management of cover crop termination (kill date) in the spring (Alonso-Ayuso et al. 2014). In late winter and spring, cover crop growth is usually vigorous and in 3–4 weeks can deplete soil water storage in the upper layers. Reduction in spring soil water content by cover crops was up to 60 mm in Spain and to 80 mm in California (McGuire et al. 1998; Mitchell et al. 1999). In typical or wet years, cover crops can be left alive until transpiration dries the soil to levels optimal for cash crop establishment. In drought years, cover crops can be killed early, which not only reduces transpiration, but produces mulch that can increase soil water storage by harvesting rain and reducing evaporation (Alonso-Ayuso et al. 2014). In this 2-year experiment in Central Spain (Fig. 1), soil in the fallow plots contained 35 to 55 mm more water than a barley-vetch cover crop mixture when the cover crop was terminated, but a month later at the time of cash crop planting, no differences were observed. Later, during the maize growing season, previously cover-cropped plots contained more water than previously fallow plots due to increased infiltration and decreased evapotranspiration from the mulching effect of cover crop residues. The result of the combined effects on water availability by cover crop transpiration and residue mulch preservation will become more uncertain with increasing variability of rainfall distribution. Under these circumstances, advanced soil moisture sensors could help farmers use kill date as an adaptive management tool for drought.

In the Mid-Atlantic, USA, region, it is predicted that drought during the cash crop growing season (typically July), will become worse with climate change (Hayhoe et al. 2007; Walthall et al. 2012). One adaptive management tactic for this type of drought is to use brassica (e.g., radish and rapeseed) cover crop species with deep taproots that break through compacted soil. After radish or rapeseed cover crops have diminished compaction, maize crops have higher yields due to greater access to deep water (Chen and Weil 2011), increasing resilience to drought. We are currently testing the idea that resilience to summer drought in Pennsylvania, USA is related to cover crop N management. One challenge to resilience is that wide C/N cover crops, particularly grasses that are incorporated into soil can immobilize enough N to reduce early season maize growth, which could reduce season-long resource capture (radiation, nutrients, and water) and increase susceptibility to summer drought (M. Hunter, pers. comm.). In this case, integrated soil fertility management (Guardia et al. 2016) may provide more adaptive capacity for yield resilience than cover cropping alone. Given the uncertainty in precipitation change, we are testing cover crop mixtures that include forage radish, legumes, and grasses. These mixes could provide multifunctional adaptation to both extreme rain events and drought as grasses are best for decreasing erosion (Ramírez-García et al. 2015b), legumes reduce the risk of N limitation to cash crop growth, and brassicas enable deep root exploration by the cash crop. In cases when droughts do reduce cash crop production and N uptake, cover crop mixtures with a rapid fall growing species may be most effective at reducing N losses. Thus, the seeding rate of different species in mixtures could be a lever for adaptive management by increasing the abundance of the species that provides the most needed function.

3.3 Warming

One of the key impacts of warming is intensified drought due to increased evaporative demand (Lobell et al. 2013), and the drought adaptations discussed above may reduce these effects. Here, we focus on interactions between cover cropping and other aspects of directional increases in air and soil temperature typically associated with global warming. Mean annual temperatures in Pennsylvania, USA, are expected to increase by ~3 °C over the next century (Shortle et al. 2015). With warming, autumn soil nutrient mineralization should be higher, and high nutrient leaching can occur in this region when soils with elevated inorganic N become recharged with water each autumn (Finney et al. 2016a). Cover crops can help adapt to autumn warming by taking up N that is mineralized to prevent a warming-induced increase in autumn nutrient leaching. Currently, autumn cover cropping in much of the Mid-Atlantic, USA, is constrained by the small planting window between cash crop (maize, soybeans) harvest and the onset of cold temperatures. Warming should increase this window, making it easier to establish cover crops that realize substantial autumn biomass to prevent leaching of mineralized N. Furthermore, species choices are currently very limited for late-planted cover crops because of cold autumn temperatures (Murrell et al. 2017) and warming could substantially increase the diversity and associated adaptive management capabilities of cover crops in this region. For instance, warming may enable selection of deep-rooted species that are more effective at preventing leaching from the whole soil profile (Thorup-Kristensen and Rasmussen 2015).

In hotter regions, such as our Spain case, cover crops may modulate extremes in soil temperature. While it is known that cover crop residues modulate temperatures, there is surprisingly little information on how standing cover crops affect soil temperature. We would expect that cover crops reduce the amplitude of diel temperature variation because of the increased boundary layer effect of the canopy (compared to bare soil), but we found only one study (Dabney et al. 2001) documenting this effect. Additional research is needed to quantify cover crop effects on soil temperatures and how this might affect adaptation to climate change. Based on studies to date, warming is expected to enhance the main ecosystem services provided by the cover crops by increasing cover crop growth. Soil cover and biomass are mainly driven by the accumulation of degree days and the time of the frost-free period (Ramírez-García et al. 2015a). Warmer autumn temperatures will enhance soil cover and allow cover crops to reach minimum threshold values for erosion control (>30 % soil cover) before freezing. In addition, the larger cover crop biomass will provide thicker crop residue mulch and enhance water conservation, soil organic matter inputs, and weed suppression.

3.4 Adaptation summary

Unlike mitigation, adaptation is not something we can simply evaluate with a greenhouse gas budget. Thus, our discussion of adaptation is more qualitative than our discussion of mitigation and it draws on more nuanced local knowledge. Based on lessons learned from two contrasting systems, it is clear that cover crops can confer the capacity to adapt to extreme rain events that overlap with the cover crop growth period. Likewise, warming may cause higher soil N mineralization rates to overlap with the cover crop growth period and cover cropping may be an adaptive management tool to reduce N leaching in these circumstances. Cover crop kill dates and mulching can be used to adapt to drought by adjusting cover crop water use and reducing soil evaporation, respectively. Cover crops that increase infiltration and rooting depth are also potential drought adaptation strategies. However, cover crops can decrease adaptive capacity by creating small transition windows for cover crop termination and planting that can inhibit cash crop establishment. In other cases, such as warming in temperate climate regions, climate change can also increase autumn planting windows, decreasing associated management risks, and providing more options for species that can provide desired functions. While our cases represent very common uses of cover crops, some interesting themes fell outside the scope of our review and warrant further analysis, including grazing cover crops, harvesting cover crops as biofuels, and cover cropping between perennial crops or in flooded rice.

In addition, we note that it is more than just the presence or absence of cover crops that can be used as an adaptation strategy. Cover crop species selection provides flexibility in cover crop function that increases adaptive potential. Multispecies mixes themselves could be more stable under variable climate if species that vary in their environmental tolerances are intentionally planted together (Tribouillois et al. 2015). In Pennsylvania, we have experimented with this approach, and while it can work, it is also challenging to design mixes that are not dominated by the most competitive species (Finney et al. 2016b, Murrell et al. 2017). One interesting effect we have observed is that grasses in mixtures can serve as nurse plants that increase legume survival in very cold winters (Murrell et al. 2017). In Aranjuez, Spain, after experimenting with several species and seeding ratios, we found that a biculture of barley and vetch could decreased the risk of pre-emptive competition for water and N (with cash crops) and maintain the potential for nitrate leaching control if the killing date was used to adapt to varying environmental conditions (Alonso-Ayuso et al. 2014). Thus, well-designed, locally-tailored cover crop mixtures may increase the adaptive capacity of yield and N losses to climate change more so than monocultures.

From the economic adaptation perspective, introducing cover crops in a crop rotation could lead to extra direct or indirect costs for the farm. Direct costs are the incremental costs, relative to a fallow field, including the cost of seeds, planting, or termination. Indirect costs are related to hindering the establishment of the subsequent cash crop by slow soil warming or pre-emptive water and nutrient competition. A detailed description of the costs can be found in the study conducted in central Spain by Gabriel et al. (2013). But introducing cover crops may also have some economic benefits for the farm. For example, maize yields after cover crops are often higher than yields after fallow; an average of 850 kg ha^{-1} after a vetch cover crop and of 300 kg ha^{-1} after barley in our Spain case study. Fertilizer savings, particularly after legumes, and selling the cover crops as animal feed in years with high biomass may be additional incomes. The product and commodity prices vary from region to region and depend on inter-annual fluctuations so it is hard to calculate a general and reliable economic budget. In the Spain case study, replacing the fallow with a cover crop increased the economic benefit in 67 and 50 % of the study years for vetch and barley, respectively. Selling the cover crop as forage or grazing in good years could increase the benefit associated with cover crops. In the mid-term, cover cropping is a win-win strategy as it increases farm benefits and provides ecosystem services. Still, many farmers are reluctant to adopt this practice because it requires additional labor and expertise, and in the short term, may entail a risk of reducing farm benefits. If opportunities for climate change mitigation and adaptation offered by cover cropping are to be promoted, farmer education or subsidies might be required to incentivize this strategy initially.

4 Conclusions

There are many good reasons to plant cover crops, and most of them have been well known for centuries. More recently, there has been elevated interest in how the more traditional benefits of cover cropping interact with climate change. By reviewing for the first time all of the climate change mitigation factors that might be altered by cover cropping, we found that cover crop adoption should mitigate greenhouse gas-based climate change by ~116 g CO_2 e/m^2/year for non-legumes and by ~135 g CO_2 e/m^2/year for legumes. The main sources of variation in these values are soil C sequestration rates and fertilizer credits for cover crops, both of which should be active areas for future research. We also made the first calculations of CO_2 e due to cover crop effects on albedo and found that for typical plant and soil albedo combinations, albedo changes increase the mitigation potential from cover cropping by 12 to 46 g CO_2 e/m^2/year at two case study sites. Based on these preliminary calculations, we suggest that additional research is warranted to define the common combinations of soil, plant, and residue albedos in relation to snow duration and depth. Our analysis of research from two contrasting regions also showed that management of cover crop species and their planting and killing dates should aid adaptation to extreme rain events, drought, and warming. However, there may be cases when cover crop water use or field operations associated with cover crops could decrease adaptive capacity, and local knowledge of these risks will need to be taken into account.

Our review suggests that cover crops should be included in the portfolio of agricultural practices that could be used to mitigate climate change. Cover cropping is not a mitigation panacea; even widespread adoption might mitigate 10 % of agricultural greenhouse gas emissions. Yet, its mitigation potential is comparable to other practices (e.g., no till), and cover cropping can also be an adaptive management tool to maintain yields and minimize N losses as the climate changes. Despite these benefits, we are not necessarily advocating that cover crops be planted primarily for the purposes of climate change mitigation or adaptation. Instead, we think the most important conclusion from our analysis is that there appear to be few tradeoffs between traditional benefits of cover cropping and the benefits for climate change. Farmers and policymakers can expect cover cropping to simultaneously benefit soil quality, water quality, and climate change adaptation and mitigation.

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