# Cover crop effects on soil temperature in a clay loam soil in southwestern Ontario

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ARTICLE

# Cover crop effects on soil temperature in a clay loam soil in southwestern Ontario

X.M. Yang, W.D. Reynolds, C.F. Drury, and M.D. Reeb

**Abstract:** Although it is well established that soil temperature has substantial effects on the agri-environmental performance of crop production, little is known of soil temperatures under living cover crops. Consequently, soil temperatures under a crimson clover and white clover mix, hairy vetch, and red clover were measured for a cool, humid Brookston clay loam under a corn–soybean–winter wheat/cover crop rotation. Measurements were collected from August (after cover crop seeding) to the following May (before cover crop termination) at 15, 30, 45, and 60 cm depths during 2018–2019 and 2019–2020. Average soil temperatures (August–May) were not affected by cover crop species at any depth, or by air temperature at 60 cm depth. During winter, soil temperatures at 15, 30, and 45 cm depths were greater under cover crops than under a no cover crop control (CK), with maximum increase occurring at 15 cm on 31 January 2019 (2.5–5.7 °C) and on 23 January 2020 (0.8–1.9 °C). In spring, soil temperatures under standing cover crops were cooler than the CK by 0.1–3.0 °C at 15 cm depth, by 0–2.4 °C at the 30 and 45 cm depths, and by 0–1.8 °C at 60 cm depth. In addition, springtime soil temperature at 15 cm depth decreased by about 0.24 °C for every 1 $\mathrm{Mg \cdot ha^{-1}}$ increase in live cover crop biomass. Relative to bare soil, cover crops increased near-surface soil temperature during winter but decreased near-surface soil temperature during spring. These temperature changes may have both positive and negative effects on the agri-environmental performance of crop production.

*Key words:* cover crops, crop residues, biomass, soil temperature, crop rotation.

**Résumé :** Bien qu'on sache depuis longtemps que la température du sol a des effets appréciables sur la performance agro-environnementale des cultures, la température du sol sous les cultures-abris est relativement mal connue. Pour y remédier, les auteurs ont mesuré la température du sol sous un mélange de trèfle rouge et de de trèfle blanc, de la vesce velue et du trèfle rouge dans un assolement maïs-soja-blé d'hiver/culture-abri poussant sur un loam argileux de Brookston humide. Les relevés ont été obtenus du mois d'août (après l'ensemencement de la culture-abri) au mois de mai suivant (avant destruction de la culture-abri) à une profondeur de 15, 30, 45 et 60 cm durant les périodes végétatives de 2018–2019 et 2019–2020. La température moyenne du sol (d'août à mai) n'a pas été affectée par l'espèce servant de couverture-abri, peu importe la profondeur. Elle n'a pas non plus été touchée par la température de l'air à la profondeur de 60 cm. En hiver, le sol de la parcelle sous la couverture-abri était plus chaud que sous celui de la parcelle témoin (PT) à 15, 30 et 45 cm de profondeur, l'élévation maximale ayant été enregistrée à 15 cm de profondeur, le 31 janvier2019 (2,5–5,7 °C) et le 23 janvier 2020 (0,8–1,9 °C). Au printemps, la température du sol sous la culture-abri était plus basse que celle du sol sous la PT, soit de 0,1–3,0 C à 15 cm de profondeur, de 0–2,4 °C à 30 et 45 cm de profondeur et de 0–1,8 °C à 60 cm de profondeur. Par ailleurs, au printemps, la température du sol enregistrée à 15 cm de profondeur a baissé d'environ 0,24 °C pour chaque hausse de 1 Mg de biomasse de culture-abri vivante par hectare. Comparativement au sol nu, la culture-abri augmente la température du sol près de la surface en hiver, mais la diminue au printemps. Ces variations pourraient avoir des effets positifs et négatifs sur la performance agro-environnementale des cultures. [Traduit par la Rédaction]

*Mots-clés :* culture-abri, résidus agricoles, biomasse, température du sol, assolement.

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## Introduction

Soil temperature is critical for crop production because it affects seed germination, seedling emergence, root growth, nutrient uptake, and plant development. Soil temperature is also environmentally important because it controls soil microbial communities that are closely linked to ecosystem functioning, such as greenhouse gas generation and carbon and nitrogen dynamics. A positive correlation between soil respiration and soil temperature is well established (Singh and Gupta 1977; Reich and Schlesinger 1992), and studies overwhelmingly show that warmer soils increase the decomposition of soil organic matter (Jenkinson and Ayanaba 1977; Lloyd and Taylor 1994; Trumbore et al. 1996; Dalias et al. 2001; Davidson and Janssens 2006; Sierra et al. 2015; Webb et al. 2016). Hence, elevated soil temperatures can exacerbate soil carbon dioxide efflux and global warming.

Soil temperature is affected by many factors including meteorological conditions, soil topography, soil water content, and plant canopy cover (Paul et al. 2004). No-tillage and cover cropping may change soil temperatures through the accumulation of crop residues and increased shading. Based on 11 cover crop versus no cover crop comparisons, Blanco-Canqui and Ruis (2020) concluded that soils under cover crops are cooler during the day and warmer at night and also warmer during winter and cooler during the rest of the year. Blanco-Canqui and Ruis (2020) further found that the difference in soil temperature between cover crops and no cover crops was larger during the spring than during the rest of the year, and that average springtime soil temperature was about 1 °C lower under cover crops. Lombardozzi et al. (2018) found that cover crops in central North America can increase wintertime temperature under snow by as much as 3 °C. Although a temperature increase from 25 to 26 °C increases soil respiration rate by only about 5%, an increase from 0 to 1 °C increases soil respiration by 22% (Lloyd and Taylor 1994). Hence, cover crops can potentially contribute appreciably to greenhouse gas emissions from soil, especially during the overwinter and early spring periods.

The impacts of land management on soil temperature have long been studied because a 1 °C difference in soil temperature can significantly affect crop growth, especially corn (Walker 1969; Barlow et al. 1977). An emerging issue with cover crops is that they can change soil temperatures relative to bare ground, which may in turn impact both crop productivity and global warming (Lombardozzi et al. 2018). Agricultural practices can affect the biogeophysical properties of the land surface by changing latent heat flux and albedo, which may in turn impact climate. For example, cover crops can increase latent heat flux, transpiration, and albedo compared to bare, snow-free land (Kaye and Quemada 2017). In addition, soil temperature is considered a key driver in soil organic carbon (SOC) dynamics in almost all SOC models (e.g., Campbell and Paustian 2015). Gregorich et al. (2017) demonstrated for temperate climates across southern Canada that soil temperature was the single most important factor controlling residue decay rates, easily superseding other soil properties, such as texture, cation exchange capacity, pH, and moisture. Their study further found that use of thermal time may advance the development of simplified soil carbon models by amalgamating the influences of many soil and climatic variables, some of which are not easily measured, into a single cumulative parameter based on readily available soil temperature data. For many cases in which soil temperature data are not accessible, an empirical equation for soil temperature based on air temperature could be helpful for estimating temperature effects in SOC models (Zheng et al. 1993).

Cooler soil under crop residue (e.g., no-till) relative to no residue (e.g., moldboard plow) is commonly observed, with the amount of temperature difference depending on the time of year and cropping history (Drury et al. 1999; Larney et al. 2003; Munoz-Romero et al. 2015). Burrows and Larson (1962) found at Ames, Iowa, that each 1.125 $\text{Mg}\cdot\text{ha}^{-1}$ of applied crop residue reduced the average soil temperature by 0.2 °C at the 10 cm depth during May and June. In recent years, more growers in Ontario are using cover crops in rotations for multiple benefits including improved soil stability (Dapaah and Vyn 1998), reduced weeds (O'Reilly et al. 2011), and increased overall soil nitrogen content in the following growing season (Vyn et al. 2000; O'Reilly et al. 2012; Coombs et al. 2017; Yang et al. 2019). A recent study in southwest Michigan showed that soil temperature was strongly associated with cover crop species, and that this in turn affected the efflux of carbon dioxide and nitrous oxide from the soil (Nguyen and Kravchenko 2021).

There is a general lack of information, however, on soil temperatures under living cover crops compared to no cover crops (bare ground) in different seasons. Accordingly, we measured soil temperature under three cover crops (crimson clover and white clover mix, CW; hairy vetch, HV; red clover, RC) and a no-cover crop control (CK) from August (after cover crop planting) until the following May (before cover crop termination for corn planting) for two cropping years in a corn–soybean–winter wheat/cover crop rotation in southern Ontario. The objective was to test two hypotheses regarding soil temperatures under live cover crops during the over-winter and spring periods: (*i*) soil temperatures under live cover crops differ from soil temperatures under no cover crop, and (*ii*) soil temperature is affected by the amount of live cover crop biomass.

## Materials and Methods

This field study was established in the summer of 2017 on a Brookston clay loam, which is a cool-humid poorly drained lacustrine soil (Orthic Humic Gleysol, Canadian

Soil Classification; mixed, mesic Typic Argiaquoll, USDA Soil Taxonomy), at the Honourable Eugene F. Whelan Experimental Farm, Agriculture and Agri-Food Canada, Woodslee, Ontario, Canada (42°13′ N; 82°45′ W). The average soil texture in the top 20 cm was 33% sand, 37% silt and 30% clay by weight, and average soil pH was 6.3. The 10-yr mean annual air temperature and mean annual precipitation were 9.4 °C and 877 mm, respectively. As surface slopes were <0.5%, soil erosion was negligible.

The experiment included three adjacent fields under a corn–soybean–winter wheat/cover crop rotation with every crop present each year. Shortly after winter wheat harvest, wheat stubble was disked, packed and legume cover crops were planted using an International grain drill (16 Jul. 2018; 30 Jul. 2019). The treatments included a CW treatment (*Trifolium incarnatum* L. mixed with *Trifolium repens* L., seeding rate = 12.5 +12.5 $kg{\cdot}ha^{-1}$), an HV treatment (*Vicia villosa* L. Roth, seeding rate = 25 $kg\ ha^{-1}$), an RC treatment (*Trifolium pratense* L., seeding rate = 12 $kg{\cdot}ha^{-1}$), and a CK treatment. Each field plot was 9.15 m wide (to allow 12 corn rows) by 30 m long, and the statistical design was a randomized complete block with four replicates. To estimate cover crop biomass accumulation, above-ground plant samples were collected (20 cm × 75 cm area, $n = 2$ per plot) after the first hard frost (late November), and again in the following spring (early May) just before cover crop termination for corn planting. The biomass was dried (60 °C) for two weeks, and then dry weight was measured. Fall and spring samples were collected because these cover crops are reasonably winter-hardy in southern Ontario (i.e., not winter-killed), and therefore resume growth after the spring thaw.

Soil temperature was measured hourly from cover crop planting (31 July 2018; 15 August 2019) to cover crop termination (5 May 2019; 15 May 2020) using Decagon 5TM/5TE sensors and EM-50 automated data loggers (Decagon Devices Inc., Pullman, WA, USA). The sensors were installed at four depths (15, 30, 45, 60 cm, $n = 4$ per depth per treatment) by hand-augering access holes, then backfilling. The data loggers were downloaded biweekly. The sensors were calibrated for the soil type in the lab using intact cores, and reported accuracy and resolution are ±1 and 0.1 °C, respectively (Decagon Devices, Inc., 5TE User's Manual, 2016). Each reported sensor reading was the average four different sensors, which we assume controls among-sensor errors and variability.

Soil temperature values were averaged on a field, season and monthly basis for each depth by cover crop combination, and also on a daily basis for both the coldest winter month and the month prior to cover crop termination. Regression was used to determine depthwise relationships between soil temperature and accumulated cover crop biomass in each plot. Analysis of variance was used to determine the significance of treatment main effects via the LSMeans procedure (SAS Institute, Cary, NC).

## Results

### Average monthly air and soil temperatures

The average monthly air temperature varied substantially during the cover crop growing periods (Figs. 1*a*, 1*b*). The lowest average monthly air temperatures were observed in January 2019 (−4.7 °C) and February 2020 (−1.5 °C), and the highest in August 2019 (22.9 °C) and August 2020 (21.6 °C). The average monthly air and soil temperatures correlated well at all depths, with change in soil temperature lagging behind the change in air temperature. In 2018–2019, there were no appreciable differences in average monthly soil temperature among cover crop species and the CK (Fig. 1*a*). In 2019–2020, however, higher soil temperatures occurred at 15 cm depth under cover crops relative to the CK during the winter months, and lower soil temperatures occurred at all depths under cover crops relative to the CK during May ($p < 0.05$) (Fig. 1*b*). Average soil temperature for the entire cover cropping season was similar in both cropping years, and the winter increase in temperature was offset by the decrease during the following spring. There were, however, higher soil temperatures during 2019–2020 than during 2018–2019, which reflected differences in air temperature between the two years (Table 1, Figs. 1*a*, 1*b*).

### Average daily air and soil temperatures

As the cover crops were seeded in July for both cropping seasons (after wheat harvest), their full canopies were not well established until mid to late September. Hence, cover crop effects on soil temperatures were generally not appreciable until the late fall–winter–early spring periods.

For the coldest month in 2019 (January), air temperature dropped from −7.5 °C on 28 January to −21 °C on 30 January, which caused daily soil temperature at 15 cm depth to decrease from −1.0 °C on 29 January to −7.4 °C on 31 January for CK, and from 0.2 °C at 28 January to −2.8 °C at 31 January for HV (Fig. 2*a*). The decrease in air temperature did not affect soil temperatures under CW and RC, however, and the 15 cm temperatures under CK and HV returned to previous levels after 3–4 days when air temperature increased. A similar but more muted pattern was evident at 30 cm depth, and no temperature responses occurred at the 45 and 60 cm depths (Fig. 2*a*). However, CK had a lower temperature from the end of January 2019 through to mid-February relative to CW (Fig. 2*a*).

For the coldest month in 2020, air temperature ranged from 4.3 to −11 °C during 15 January to 15 February (Fig. 2*b*). These higher air temperatures (relative to 2019) resulted in relatively higher soil temperatures (relative to 2019) at all soil depths, and below-zero soil temperature occurred only in CK and

**Fig. 1*a*.** Monthly average soil temperature at different depths and air temperature (1.2 m) from July 2018 to May 2019.

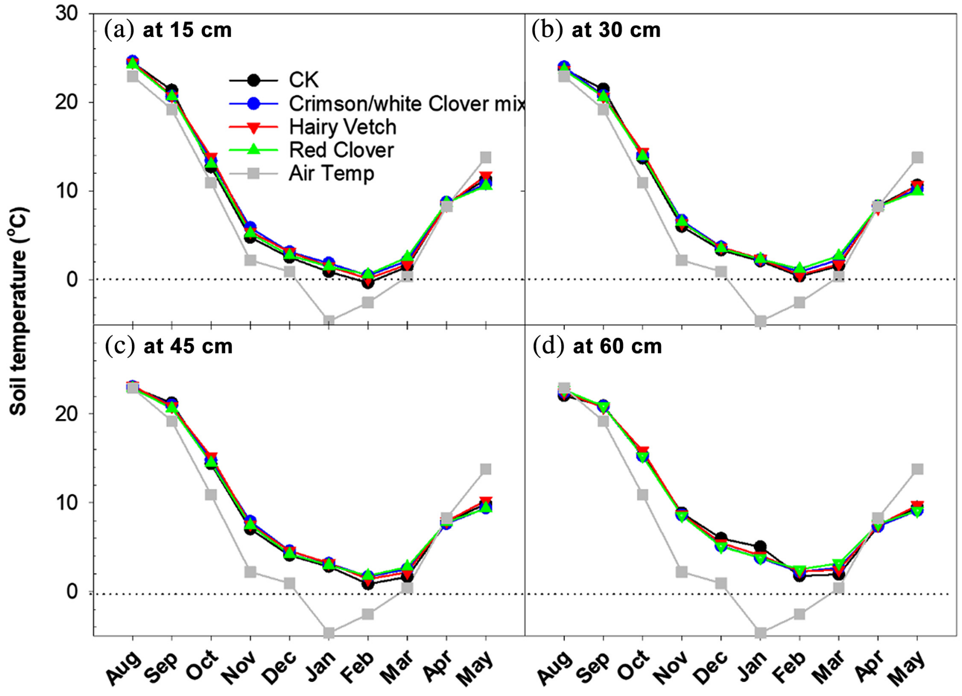
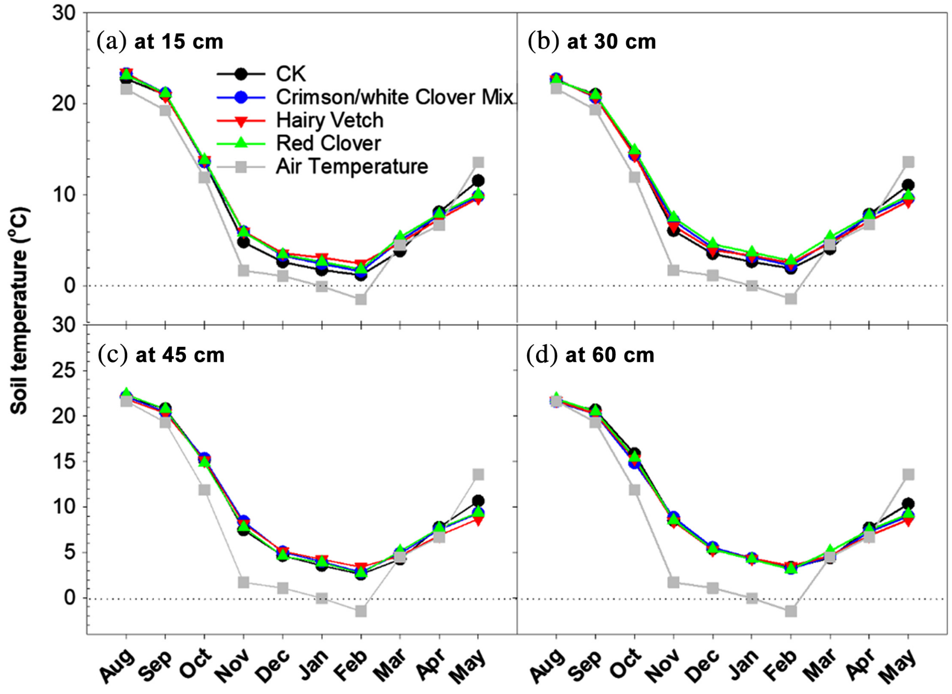


**Fig. 1*b*.** Monthly average soil temperature at different depths and air temperature (1.2 m) from August 2019 to May 2020.



only for a few days (21–23 January) (Fig. 2*b*). Unlike 2019, a sharp decrease in soil temperature occurred in the CK treatments following an air temperature drop; there was no clear drop in soil temperature during the coldest period of 2020, and an increase in soil temperature occurred for all treatments on 3 February 2020. The daily average soil temperature at 15 cm depth remained lower in the CK (0.4 °C) relative to other treatments (1.4–2.0 °C) for about 10 days, starting 21 January. A similar decrease in CK relative to the cover crops occurred at the 30 and 45 cm depths but to a reduced extent. At the 60 cm depth, soil temperature showed no cover crop effects or temporal fluctuations during the coldest month of 2020.

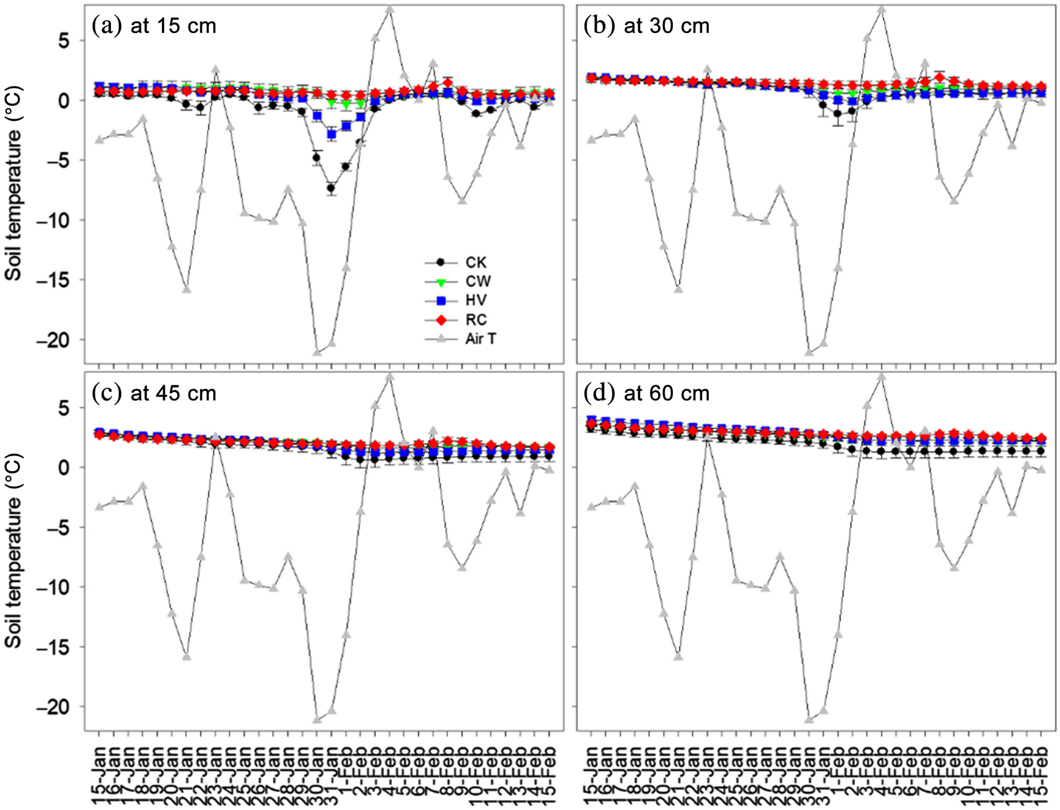
**Table 1.** Mean soil temperature (°C) during cover cropping period (August to May).[a]

| Soil depth | 15 cm | | 30 cm | | 45 cm | | 60 cm | |
|---|---|---|---|---|---|---|---|---|
| Year | 2018–2019 | 2019–2020 | 2018–2019 | 2019–2020 | 2018–2019 | 2019–2020 | 2018–2019 | 2019–2020 |
| CK | 8.8 | 9.1 | 9.1 | 9.5 | 9.3 | 9.9 | 9.9 | 10.2 |
| CW | 9.2 | 9.4 | 9.3 | 9.6 | 9.6 | 10.0 | 9.8 | 10.1 |
| HV | 9.2 | 9.5 | 9.2 | 9.5 | 9.6 | 9.9 | 10.0 | 9.9 |
| RC | 9.0 | 9.5 | 9.3 | 10.0 | 9.5 | 10.0 | 9.9 | 10.1 |
| Mean | 9.0a | 9.4b | 9.2a | 9.6b | 9.5a | 9.9b | 9.9a | 10.1a |
| | Pr > F | | Pr > F | | Pr > F | | Pr > F | |
| YR | 0.017 | | 0.001 | | 0.001 | | 0.256 | |
| TRT | 0.265 | | 0.076 | | 0.610 | | 0.937 | |
| YR × TRT | 0.830 | | 0.299 | | 0.595 | | 0.739 | |

**Note:** Cropping period overall means within a depth followed by a different lowercase letter were significantly different at $p < 0.05$. CK, no cover crop control; CW, crimson clover–white clover mix; HV, hairy vetch; RC, red clover; YR, year; TRT, treatment.

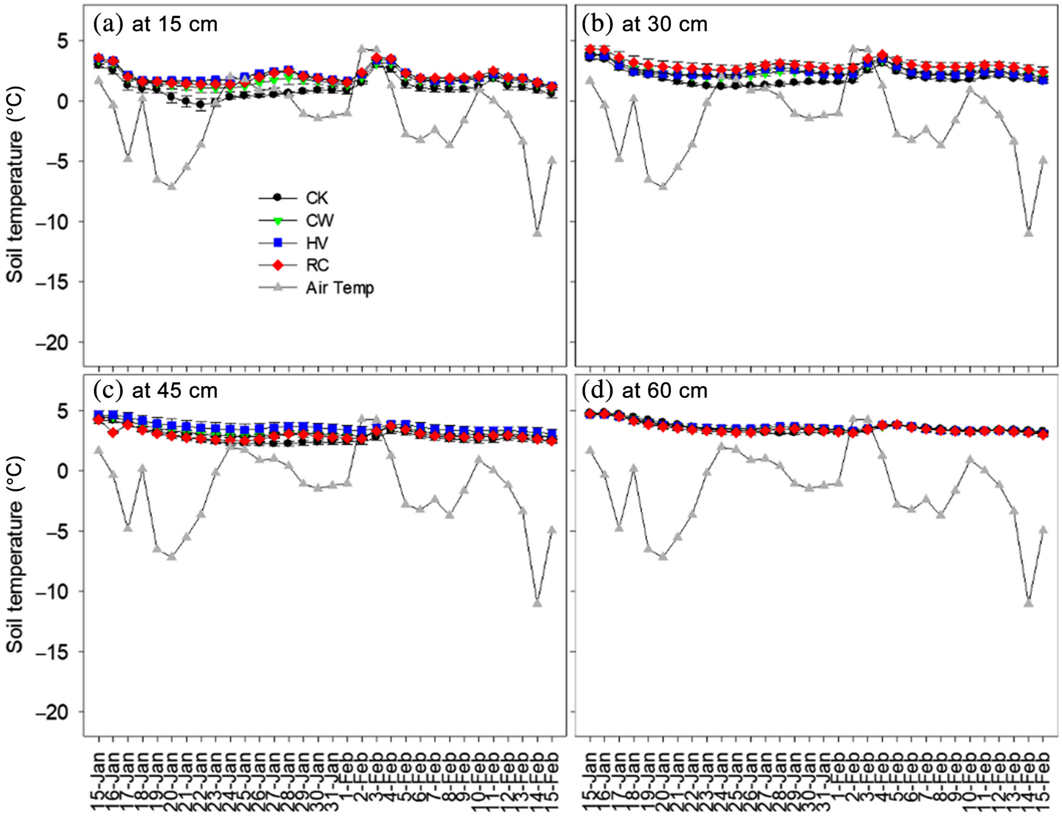
[a] Corresponding average air temperatures were 7.1 and 7.9 °C for 2018–2019 and 2019–2020, respectively.

**Fig. 2*a*.** Daily soil temperature at different depths and air temperature (1.2 m) from 15 January to 15 February 2019 (the period with the lowest air temperature).



Variability in daily average soil temperature increased with increasing air temperature at all soil depths in spring, and treatment differences were evident in late April until mid-May for both 2019 and 2020 (Figs. 3*a*, 3*b*). On 5 May 2019, the daily average soil temperature at 15 cm depth was lower for CW (11.1 °C) and RC (10.8 °C) than for CK (12.2 °C) and HV (12.1 °C) (Table 2). The same pattern occurred at the other depths but to a lesser degree (Fig. 3*a*). In 2020, separation in daily soil temperature among treatments started around 25 April, reached a maximum by 3 May for all soil depths, and persisted until the last measuring day, 15 May 2020 (Fig. 3*b*). On 15 May 2020, the daily average soil temperature at 15 cm was lower in all three cover crop treatments

**Fig. 2*b*.** Daily soil temperature at different depths and air temperature (1.2 m) from 15 January to 15 February 2020 (the period with the lowest air temperature).



(10.5–11.2 °C) than in the CK (13.5 °C) (Table 2). Lower daily soil temperature under the cover crops relative to CK also occurred at the deeper soil depths, being as much as 1.8–2.4 °C lower than CK on 15 May 2020 (Table 2). It is also worth noting that springtime daily average soil temperatures were periodically lower under HV than under CW and RC, despite all three crops having similar amounts of accumulated biomass. This may be due to greater sunlight reflectance and lower plant-air heat exchange in HV because of its numerous, closely spaced leaves and vine-like growth habit compared to greater-spaced broad leaves and erect to decumbent growth habit of CW and RC.

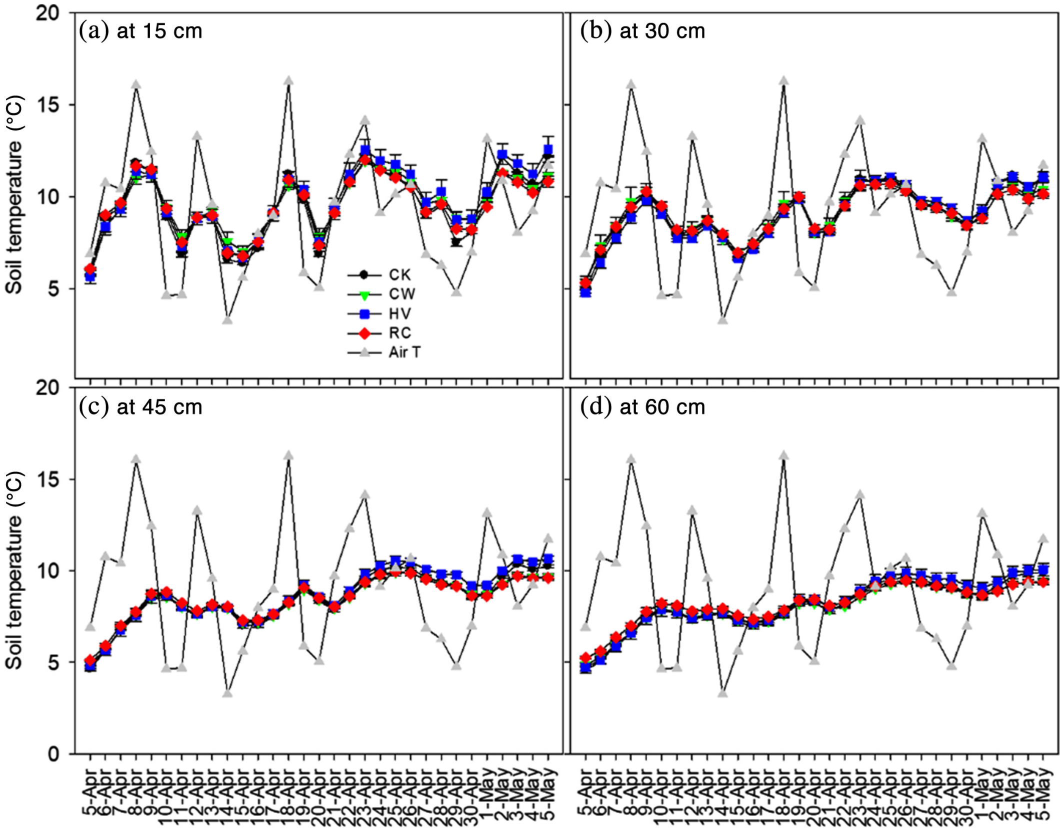
### Relationships between spring temperatures and cover crop biomass

Spring soil temperature shortly before cover crop termination decreased linearly with increasing accumulation of cover crop biomass (Mg·ha$^{-1}$) (Fig. 4). The coefficients of determination ($R^2$) ranged from 0.38 to 0.71; the *y*-axis intercepts (*a*, mean soil temperature when cover crop biomass is set zero) were 12.38 °C at 15 cm, 11.32 °C at 30 cm, 10.62 °C at 45 cm, and 9.73 °C at 60 cm; and the slope constants (*b*, model predict of soil temperature change for 1 unit (Mg·ha$^{-1}$) cover crop biomass change) were −0.24 to −0.19 for the top three depths, and −0.09 at 60 cm. It indicates that a 1 Mg·ha$^{-1}$ increase in cover crop biomass corresponded to −0.24 °C change in soil temperature at 15 cm depth, but only −0.09 °C change in soil temperature at 60 cm depth.

## Discussion

This study suggests that live cover crops and dead crop residues behave similarly with respect to their impacts on soil temperatures. For example, summer soil temperatures under both cover crops and residues are lower and less variable than those of bare soil (Bristow 1988; Blanco-Canqui and Ruis 2020), but higher than bare soil during the winter (Yang et al. 2018). In addition, the amount of surface residue retained influences the soil temperature regime (Larney et al. 2003), and surface temperature variations among residue and tillage treatments are due mainly to change in the amount of residue cover (Gupta et al. 1983; Larney et al. 2003; Blanco-Canqui and Lal 2009). In the study at Ames, Iowa, Burrows and Larson (1962) found that for each 1.125 Mg·ha$^{-1}$ of crop residue retained, average soil temperature was reduced by 0.2 °C at the 10 cm depth during May and June. Blanco-Canqui and Lal (2009) similarly observed in Ohio that each Mg·ha$^{-1}$ of retained corn stover reduced the soil temperature by 0.5 °C at the 10 cm depth during June–October. In this study, a 1 Mg·ha$^{-1}$ increase in live cover crop biomass resulted in a 0.24 °C drop in soil temperature at the 15 cm depth,

**Fig. 3*a*.** Daily soil temperature at different depths and air temperature (1.2 m) from 5 April to 5 May 2019, before cover crop termination and planting corn.



a 0.19–0.20 °C drop at the 30 and 45 cm depths, and a 0.09 °C drop at the 60 cm depth. Similar patterns likely occur because both cover crops and surface residues increase soil heat capacity by conserving soil moisture (Joyce et al. 2002), shade the soil surface from incident solar radiation, alter canopy heat balance, and lower thermal conductivity compared to bare soil (van Wijk et al. 1959; Horton et al. 1996; Johnson and Lowery 1985).

The results of this study are also consistent with other cover crop studies; notwithstanding the fact that such studies are very few in number. For example, Evans et al. (2016) and Teasdale and Daughtry (1993) found that cover crops can reduce diurnal changes in soil temperature; and Kahimba et al. (2008) reported that soils in the Canadian prairies under a cover crop were warmer in winter and thawed earlier in spring than soils without cover crop. It has also been speculated that cover crops may reduce extreme fluctuations in soil temperature, thereby potentially reducing abrupt fluctuations in wet-dry and freeze–thaw cycles (Blanco-Canqui and Ruis 2020).

Soil temperature varied with year and cover crop species. A substantial drop in soil temperature following a sharp decline in air temperature in late January 2019 occurred for HV, but not for CW and RC. We attribute this to HV winter-kill, given there was substantially less springtime biomass for HV (2.7 Mg·ha$^{-1}$) than for CW (6.2 Mg·ha$^{-1}$) and RC (6.5 Mg·ha$^{-1}$) (Fig. 5). The apparent biomass effect on soil temperature also occurred in spring 2019, when soil temperatures under HV were similar to CK but significantly higher than in CW and RC. The biomass effect on temperature appeared differently in spring 2020, however, with a greater temperature decrease in HV relative to the previous year, which was likely due to a dramatic increase in HV biomass from fall 2019 to spring 2020 (Fig. 5). These results support the Blanco-Canqui and Ruis (2020) postulation that cover crops reduce soil temperature during warm periods by intercepting and reflecting solar radiation, shading the surface, and reducing soil water evaporation; and that they also likely increase soil temperature during cold periods through the mulching–geothermal gradient effect.

## Conclusions

Both hypotheses were effectively supported: live cover crops caused soil temperature to be warmer in winter and colder in spring relative to no cover crop; springtime soil temperature changed linearly with amount of accumulated cover crop biomass.

Near-surface soil temperatures differed among cover crop species for both the coldest and warmest conditions

**Fig. 3*b*.** Daily soil temperature at different depths and air temperature (1.2 m) from 15 April to 15 May 2020, before cover crop termination and planting corn.

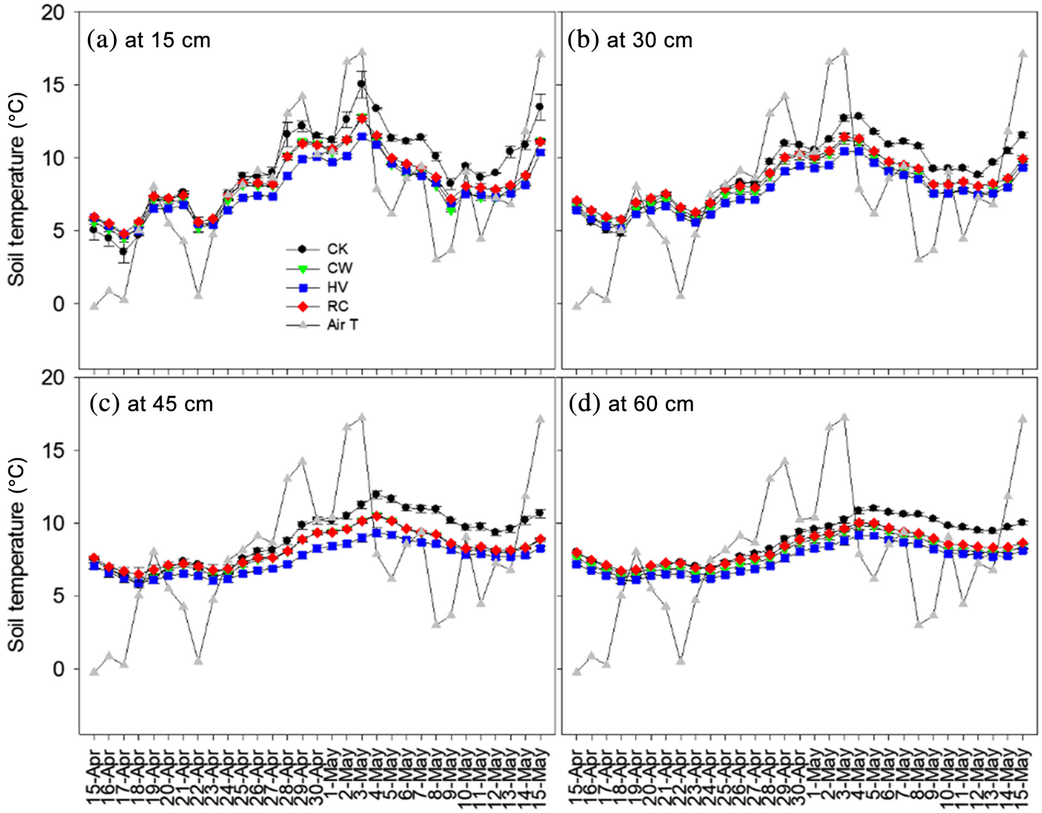


**Table 2.** Lowest and highest daily average soil temperatures (°C).

| Soil depth | 15 cm | | 30 cm | | 45 cm | | 60 cm | |
|---|---|---|---|---|---|---|---|---|
| Year | 2019 | 2020 | 2019 | 2020 | 2019 | 2020 | 2019 | 2020 |
| Lowest daily soil temperature occurred at 31 January 2019 and at 23 January 2020 | | | | | | | | |
| CK | −7.4c | −0.1c | −0.4a | 1.3b | 1.3a | 2.5b | 1.9a | 3.5a |
| CW | −0.3a | 0.7b | 0.6a | 2.0a | 1.8a | 3.0ab | 2.5a | 3.6a |
| HV | −2.8b | 1.8a | 0.5a | 2.1a | 1.7a | 3.6a | 2.8a | 3.6a |
| RC | 0.4a | 1.4ab | 1.3a | 2.7a | 2.0a | 2.7b | 2.8a | 3.4a |
| Mean | −2.0A | 1.0B | 0.5B | 2.0A | 1.7B | 2.9A | 2.5B | 3.5A |
| Highest daily soil temperature occurred at 5 May 2019 and at 15 May 2020 | | | | | | | | |
| CK | 12.2a | 13.5a | 11.0a | 11.5a | 10.2b | 10.7a | 9.9a | 10.0a |
| CW | 11.1b | 11.2b | 10.4a | 9.6b | 9.6c | 8.8b | 9.4a | 8.4bc |
| HV | 12.1a | 10.5b | 11.0a | 9.4b | 10.6a | 8.3c | 9.9a | 8.2c |
| RC | 10.8b | 11.1b | 10.2a | 9.5b | 9.6c | 8.9b | 9.4a | 8.6b |
| Mean | 11.5A | 11.4A | 10.6A | 10.0A | 10.0A | 9.1B | 9.6A | 8.7B |

**Note:** Treatment means followed by different lowercase letters in the same column of the same year were significantly different at $p < 0.05$. Overall means followed by different uppercase letters at the same depth were significantly different at $p < 0.05$.

during the cover crop growth cycle (i.e., from August of one year to May of the following year). This was likely due to differences in the amounts of cover crop biomass and cover crop species which intercepting and reflecting solar radiation, insulating the soil surface, and reducing soil water evaporation.

Near-surface soil temperature was consistently increased in winter and decreased in spring by red clover and the crimson clover and white clover mix. Hairy vetch, on the other hand, had inconsistent temperature effects, which we attribute to variable biomass accumulation stemming from its susceptibility to winter-kill in southern Ontario.

**Fig. 4.** The relationships between cover crop biomass and soil temperature in spring by terminating cover crop for corn planting.

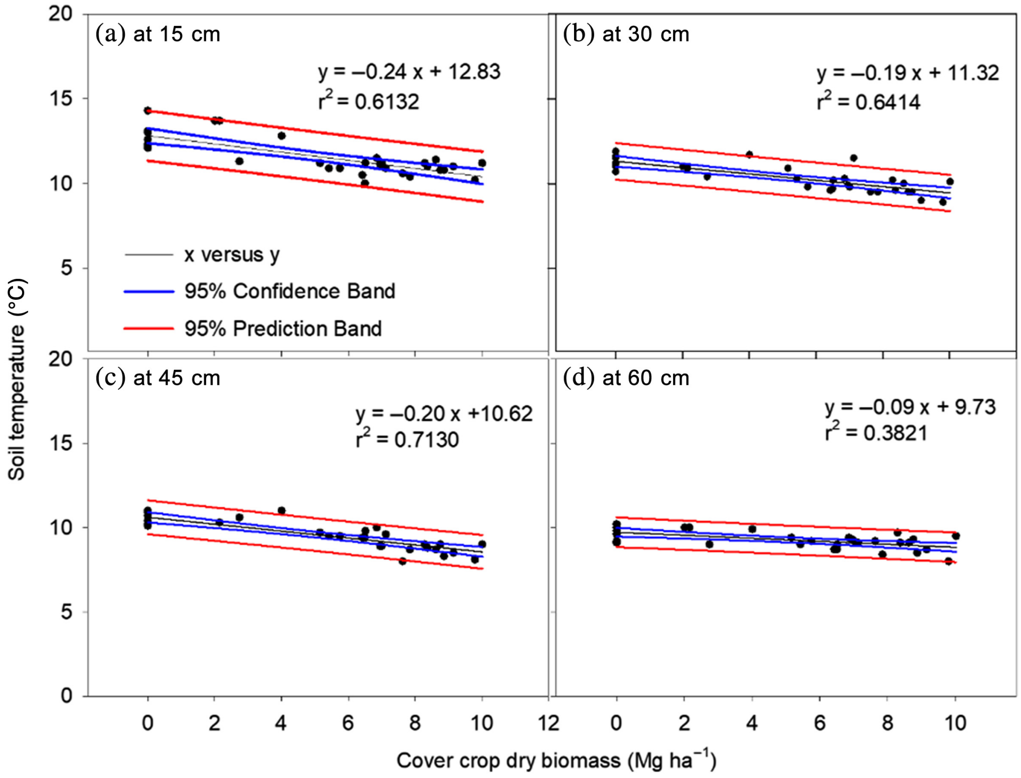
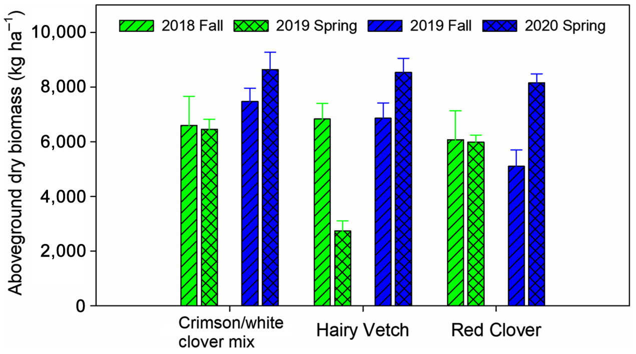


**Fig. 5.** Aboveground biomass in fall by freeze-up and in spring by spraying termination before corn planting.



Although lower spring and summer soil temperatures could assist accumulation (or slow loss) of soil carbon, they could also exacerbate crop diseases and (or) reduce seed germination, seedling emergence, early crop growth, and crop yield. Similarly, warmer soil temperatures in winter could assist overwinter survival of crop pests and diseases as well as survival of cover crops. In addition, the above effects could be enhanced substantially when cover cropping is combined with no-tillage on cool, humid soils. Hence, the temperature effects of cover cropping may be both positive and negative, and should therefore be considered carefully when interpreting soil biochemical processes, or developing agricultural best management practices.

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## References

Barlow, E.W.R., Boersma, L., and Young, J.L. 1977. Photosynthesis, transpiration, and lead elongation in corn seedlings at suboptimal soil temperature. Agron. J. **69**: 95–100. doi:10.2134/agronj1977.00021962006900010025x.

Blanco-Canqui, H., and Lal, R. 2009. Crop residue removal impacts on soil productivity and environmental quality, Crit. Rev. Plant Sci. **28**: 139–163.

Blanco-Canqui, H., and Ruis, S.J. 2020. Cover crop impacts on soil physical properties: A review. Soil Sci. Soc. Am. J. **84**: 1527–1576.

Bristow, K. L. 1988. The role of mulch and its architecture in modifying soil temperature. Aust. J. Soil Res. **26**: 269–280. doi:10.1071/SR9880269.

Burrows, W.C., and Larson, W.E. 1962. Effect of amount of mulch on soil temperature and early growth of corn. Agron. J. **54**: 19–23. doi:10.2134/agronj1962.00021962005400010007x.

Campbell, E.E., and Paustian, K. 2015. Current developments in soil organic matter modeling and the expansion of model application: A review. Environ. Res. Lett. **10**: 123004. doi:10.1088/1748-9326/10/12/123004.

Coombs, C., Lauzon, J.D., Deen, B., and Van Eerd, L.L. 2017. Legume cover crop management on nitrogen dynamics and yield in grain corn systems. Field Crops Res. **201**: 75–85. doi:10.1016/j.fcr.2016.11.001.

Dalias, P., Anderson, J.M., Bottner, P., and Coûteaux, M.M. 2001. Long-term effects of temperature on carbon mineralisation processes. Soil Biol. Biochem. **33**: 1049–1057.

Dapaah, H.K., and Vyn, T.J. 1998. Nitrogen fertilization and cover crop effects on soil structural stability and corn performance. Comm. Soil Sci. Plant Anal. **29**: 2557–2569. doi:10.1080/00103629809370134.

Davidson, E.A., and Janssens, I.A. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature **440**: 165–173. doi:10.1038/nature04514. PMID: 16525463.

Drury, C.F., Tan, C.S., Welacky, T.W., Oloya, T.O., Hamill, A.S., and Weaver, S.E. 1999. Red clover and tillage influence on soil temperature, water content, and corn emergence. Agron. J. **91**: 101–108. doi:10.2134/agronj1999.00021962009100010016x.

Evans, R., Lawley, Y., and Entz, M. H. 2016. Fall-seeded cereal cover crops differ in ability to facilitate low-till organic bean (Phaseolus vulgaris) production in a short-season growing environment. Field Crops Res. **191**: 91–100.

Gregorich, E.G., Janzen, H., Ellert, B.H, Helgason, B.L., Qian, B., Zebarth, B.J., et al. 2017. Litter decay controlled by temperature, not soil properties, affecting future soil carbon. Global Change Biol. **23**: 1725–1734. doi:10.1111/gcb.13502.

Gupta, S.C., Larson, W.E., and Linden, D.R. 1983. Tillage and surface residue effects on soil upper boundary temperatures. Soil Sci. Soc. Am. J. **47**: 1212–1218. doi:10.2136/sssaj1983.03615995004700060030x.

Horton, R., Bristow, K.L., Kluitenberg, G.J., and Sauer, T.J. 1996. Crop residue effects on surface radiation and energy balance — review. Theor. Appl. Climatol. **54**: 27–37. doi:10.1007/BF00863556.

Jenkinson, D. S., and Ayanaba, A. 1977. Decomposition of C-14-labeled plant material under tropical conditions. Soil Sci. Soc. Am. J. **41**: 912–915. doi:10.2136/sssaj1977.03615995004100050020x.

Johnson, M.D., and Lowery, B. 1985. Effect of three conservation tillage practices on soil temperature and thermal properties. Soil Sci. Soc. Am. J. **49**: 1547–1552. doi:10.2136/sssaj1985.03615995004900060043x.

Joyce, B.A., Wallender, W.W., Mitchell, J.P., Huyck, L.M., Temple, S.R., Brostrom, P.N., and Hsiao, T.C. 2002. Infiltration and soil water storage under winter cover cropping in California's Sacramento valley. Trans. ASAE **45**: 315–326.

Kahimba, F.C., Ranjan, R.S., Froese, J., Entz, M., and Nason, R. 2008. Cover crop effects on infiltration, soil temperature, and soil moisture distribution in the Canadian prairies. Appl. Eng. Agric. **24**: 321–333. doi:10.13031/2013.24502.

Kaye, J. P., and Quemada, M. 2017. Using cover crops to mitigate and adapt to climate change. A review. Agron. Sustain. Dev. **37**: 1–17.

Larney, F.J., Ren, T.S., McGinn, S.M., Lindwall, C.W., and Izaurralde, R.C. 2003. The influence of rotation, tillage and row spacing on near-surface soil temperature for winter wheat in southern Alberta. Can. J. Soil Sci. **83**: 89–98.

Lloyd, J., and Taylor, J. A. 1994. On the temperature dependence of soil respiration. Funct. Ecol. **8**: 315–323. doi:10.2307/2389824.

Lombardozzi, D. L., Bonan, G. B., Wieder, W., Grandy, A. S., Morris, C., and Lawrence, D. L. 2018. Cover crops may cause winter warming in snow-covered regions. Geophys. Res. Lett. **45**: 9889–9897. doi:10.1029/2018GL079000.

Munoz-Romero, V., Lopez-Bellido, L., and Lopez-Bellido, R.J. 2015. Effect of tillage system on soil temperature in a rainfed Mediterranean Vertisol. Intern. Agrophys. **29**: 467–473.

Nguyen, L.T.T., and Kravchenko, A.N. 2021. Effects of cover crops on soil CO2 and N2O emissions across topographically diverse agricultural landscapes in corn-soybean-wheat organic transition. Euro. J. Agron. **122**: 126189.

O'Reilly, K.A., Lauzon, J.D., Vyn, R.J., and Van Eerd, L.L. 2012. Nitrogen cycling, profit margins and sweet corn yield under fall cover crop systems. Can. J. Soil Sci. **92**: 353–365.

O'Reilly, K.A., Robinson, D.E., Vyn, R.J., and Van Eerd, L.L. 2011. Weed populations, sweet corn yield, and economics following fall cover crops. Weed Technol. **25**: 374–384.

Paul, K.I., Polglase, P.J., Smethurst, P.J., O'Connell, A.M., Carlyle, C.J., and Khanna, P.K. 2004. Soil temperature under forests: A simple model for predicting soil temperature under a range of forest types. Agr. Forest Meteorol. **121**: 167–182. doi:10.1016/j.agrformet.2003.08.030.

Reich, J.W., and Schlesinger, W.H. 1992. The global carbon dioxide flux in soil respiration and its relationship to climate. Tellus **44B**: 81–99.

Sierra, C.A., Trumbore, S.E., Davidson, E.A., Vicca, S., and Janssens, I. 2015. Sensitivity of decomposition rates of soil organic matter with respect to simultaneous changes in temperature and moisture, J. Adv. Model. Earth Syst. **7**: 335–356. doi:10.1002/2014MS000358.

Singh, J.S., and Gupta, S.R. 1977. Plant decomposition and soil respiration in terrestrial ecosystems. Bot. Rev. **43**: 449–528. doi:10.1007/BF02860844.

Teasdale, J. R., and Daughtry, C.S.T. 1993. Weed suppression by live and desiccated hairy vetch (Vicia villosa). Weed Sci. **41**: 207–212. doi:10.1017/S0043174500076074.

Trumbore, S. E., Chadwick, O. A., and Amundson, R. 1996. Rapid exchange between soil carbon and atmospheric carbon dioxide driven by temperature change. Science **272**: 393–396. doi:10.1126/science.272.5260.393.

van Wijk, W.R., Larson, W.E., and Burrows, W.C. 1959. Soil temperature and the early growth of corn from mulched and unmulched soil. Soil Sci. Soc. Am. Proc. **23**: 428–434.

Vyn, T.J., Faber, J.G., Janovicek, K.J., and Beauchamp, E.G. 2000. Cover crop effects on nitrogen availability to corn following wheat. Agron. J. **92**: 915–924. doi:10.2134/agronj2000.925915x.

Walker, J.M. 1969. One-degree increments in soil temperatures affect maize seedling behavior. Soil Sci. Soc. Am. Proc. **33**:729–736.

Webb, E.E., Schuur, E.A.G., Natali, S.M., Oken, K.L., Bracho, R., Krapek, J.P., et al. 2016. Increased wintertime $CO_2$ loss as a result of sustained tundra warming, J. Geophys. Res. Biogeosci. **121**: 249–265. doi:10.1002/2014JG002795.

Yang, X.M., Drury, C.F., and Reeb, M.R. 2018. No tillage had warmer over-winter soil temperatures than conventional tillage in a Brookston clay loam soils in Southwestern Ontario. Soil Sci. Soc. Am. J. **82**: 307–314. doi:10.2136/sssaj2017.05.0167.

Yang, X.M., Drury, C.F., Reynolds, W.D., and Reeb, M.R. 2019. Legume cover crops provide nitrogen to corn during a three-year transition to organic cropping. Agron. J. **111**: 3253–3264. doi:10.2134/agronj2018.10.0652.

Zheng, D.L., Hunt, E.R., Jr., and Running, S.W. 1993. A daily soil temperature model based on air temperature and precipitation for continental applications. Climate Res. **2**: 183–191. doi:10.3354/cr002183.