Differential gas exchange and soil microclimate dynamics under biodegradable plastic, polyethylene, and paper mulches

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Highlights

- *Gas exchange and soil microclimate dynamics under biodegradable plastic, polyethylene, and paper mulches were assessed.*
- *Elevated CO_2 levels were observed near planting holes of plastic mulches (both biodegradable and polyethylene).*
- *The plastic mulches inhibited O_2 exchange, but not to a level that could impair plant growth.*
- *Polyethylene mulch conserved soil water better than biodegradable plastic and paper mulches.*

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See the online Appendix for additional material.

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Abstract

Biodegradable plastic mulch is potentially a suitable alternative to conventional polyethylene mulch because of the limited disposal options of the latter. However, biodegradable plastic mulch must perform better or comparably to polyethylene mulch to be widely adopted. Gas exchange and soil microclimate are important factors impacted by the use of plastic mulch, which in turn have implications on crop productivity. A controlled-environment study was established in a greenhouse to assess gas exchange and soil microclimate dynamics under biodegradable plastic, polyethylene, and paper mulches with and without planting holes, as well as the impact of the mulches on the growth of sweet corn (*Zea mays*). A no-mulch condition was included as control. In addition, we monitored CO_2 concentrations in the vicinity of planting holes (chimney effect) in a greenhouse and agricultural field conditions under sweet corn production. The plastic mulches (both biodegradable plastic and polyethylene mulches) decreased the soil O_2 concentration to a minimum of 181-183 mmol mol^{-1}, and when compared to the no-mulch, the plastic mulches reduced water loss within 50 days by 35-68 mm. The paper mulch inhibited light penetration more than did the plastic mulches. There was an increase in the CO_2 concentration at 2.5 cm above the planting holes in the plastic mulches compared to that under the no-mulch. The plastic mulches (both biodegradable plastic and polyethylene mulches) decreased the soil growth of sweet corn, possibly, because the canopy height of sweet corn was more than 15 cm within a few days after planting. Overall, the plastic mulches did not reduce O_2 concentration below 100 mmol mol^{-1}, the minimum level at which plant growth becomes impaired. Also, the often reported improved growth of sweet corn from plastic mulching could be attributable to other factors, such as weed control, reduced water loss, and early season soil warming, rather than elevated CO_2 concentrations and fluxes in the vicinity of planting holes.

Introduction

Plastic mulch is an important product for agricultural crop production. Plastic mulch is mostly made of polyethylene, but environmental implications resulting from disposal problems make biodegradable plastic mulch a potentially more suitable alternative. Besides the disposal advantage, biodegradable plastic mulch must at least perform comparably to polyethylene mulch and be cost-competitive in order to be widely adopted (Hayes *et al*., 2019; Sintim and Flury, 2017). In addition, biodegradable plastic mulches designed to biodegrade in the soil can be tilled into the soil after usage, saving labour costs associated with the removal and disposal of conventional polyethylene mulches (Chen *et al*., 2019; Goldberger *et al*., 2019; Sintim *et al*., 2020).

Weed control is an important benefit to the use of plastic mulch, especially in organic agriculture, where the use of herbicides and pesticides is restricted (Bond and Grundy, 2001; Rajablariani *et al*., 2015). Black plastic mulch controls weeds by inhibiting light penetration; thus, clear plastics are not usually preferred in areas where weed control by occlusion is the objective (Bond and Grundy, 2001). Under water-deficient environments, plastic mulch can conserve water by reducing evaporative water losses (Kara and Atar, 2013; Rajablariani *et al*., 2015; Saglam *et al*., 2017; Xu *et al*., 2015; Zhang *et al*., 2018). In a meta-analysis of 266 peer-reviewed publications, the use of plastic mulch in China was found to increase crop yield by 24.3% and water use efficiency by 27.6% (Gao *et al*., 2019). Saglam *et al*. (2017) indicated that under a plastic cover, soil drying is mainly due to root water uptake and evaporation from non-covered alleyways. The use of plastic mulches also tends to increase soil temperature, which is useful for early planting, especially in cold environments (Brown *et al*., 1990; Ghimire *et al*., 2018; Lamont, 1993; Moreno and Moreno, 2008).

The increase in soil water content and temperature from plastic mulching stimulates microbial activities, leading to elevated soil CO_2 concentrations (Bandopadhyay *et al*., 2018; Shen *et al*., 2016; Yu *et al*., 2016). More importantly, plastic mulch restricts CO_2 diffusion at the soil surface, which allows the gas to build up and escape at elevated concentrations through holes punched for planting. The process is commonly termed as 'chimney effect', and is often regarded as one of the factors leading to improved crop growth from plastic mulching (Lamont, 1993; Marr, 1993; Retamales and Hancock, 2012; Soltani *et al*., 1995; Tarara, 2000). However, the positive impact of CO_2 chimney effects on crop growth has not been experimentally proven in the literature.

Soltani *et al*. (1995) evaluated CO_2 chimney effects under watermelon (*Citrullus lanatus*) production. The authors sampled air from planting holes of plastic mulch at 10 cm height above the holes and analyzed for CO_2 concentration. Soltani *et al*. (1995) found that CO_2 concentration under the plastic mulch was almost twice (0.6 mmol mol^{-1}) the ambient CO_2 concentration, but the air sampled 10 cm above the plastic mulch had a CO_2 concentration equivalent to the ambient CO_2 concentration. Based on the observation, Soltani *et al*. (1995) surmised that the elevated CO_2 concentrations in the planting holes may have been beneficial during the early stages of seedling growth on a calm day. Soltani *et al*. (1995) measured the CO_2 concentration under both calm and windy weather conditions but did not assess the diurnal fluctuations in CO_2 concentration. Besides the wind, CO_2 emissions can be affected by other atmospheric conditions, such as temperature, solar radiation, and precipitation. Also, routine farm operations, such as irrigation and fertiliser application, can affect CO_2 concentration in the soil. In contrast to the assertion of Soltani *et al*. (1995) that elevated CO_2 concentration from plastic mulching may be beneficial to plant growth in the early season, there are concerns that plastic mulch may actually lead to a low supply of O_2 in the soil and impede biological activities (Kim *et al*., 2017; Steinmetz *et al*., 2016). However, it is possible that planting holes through the mulches could allow adequate passage of ambient O_2 into the soil. Also, non-covered alleyways could be a channel for gas exchange. In addition, various mulch products have different physicochemical properties, which in turn affect their functionality. Therefore, the objective of this study was to determine how gas exchange and soil microclimate dynamics are affected by biodegradable plastic, polyethylene, and paper mulches and the subsequent impact on the growth of sweet corn.

Materials and methods

Mulch treatments

Commercial biodegradable plastic mulch (Organix), polyethylene mulch, and paper mulch were tested, including a no-mulch as the control treatment. The mulches tested in this study were the same as those used in a companion study of a long-term field assessment (Ghimire *et al*., 2018; Sintim *et al*., 2021) to complement the findings of the studies. Table 1 provides the major constituents and physicochemical properties of the mulches. The experiment entailed two sets of every mulch in four replications each, with one set being intact and the other having planting holes of 2 cm radius, through which sweet corn was planted. Moreover, we also included two sets of no-mulch treatments in four replications each, where sweet corn was later planted in one set. Thus, we had a treatment factor of eight levels with four replications.

Table 1. Manufacturers, major constituents, and physicochemical properties of the different mulches used in the study.

Mulches	Manufacturer	Major constituents	Colour	Thickness (μm)	Elongation (%)	Apparent weight (g m^{-2})	Carbon content (%)	Biobased content (%)
Organix	Organix Solutions, Bloomington, MN	BASF ecovio® grade M2351 (blend of PLA and PBAT)	Black	20	273	19.2	51.4	10-20
Paper	Sunshine Paper Co., Aurora, CO	Cellulose	Brown	479	6.4	109	46.0	100
Polyethylene	Filmtech, Allentown, PA	Linear low density polyethylene	Black	47	578	22.5	82.9	<1

Mesocosm construction and soil processing

The mesocosms were built from two plastic buckets (Gamma Seal Lid 2.0, Gamma Plastics Company, San Diego, CA) (Figure 1). Each bucket was equipped with two rubber gaskets, one adapter ring, and one O-ring lid. Two sampling ports at 6.5 cm and 13.5 cm depths from the top were installed on one bucket by drilling holes and inserting rigid Tygon tubings (polyethylene liner with ethyl vinyl acetate shell, 1/4 and 1/8 inch, BEV-A-LINE IV PC/IV-NVC/L-N/T-N/F, United States Plastic Corp., Lima, OH) to the center of the bucket. The end of the tubing inside the bucket was covered with a Teflon membrane (PTFE membrane, Aspire Laminated, hydrophobic, polypropylene backer, 5.0 micron, Lot Nr. BBTN415011-9, Stelitech Corp., Kent, WA, USA) to restrict water but allow gas exchange, and the other end of the tubing outside the bucket was closed with a septum. The bottom of the second bucket was cut off, and we also installed a sampling port at 6.5 cm depth from the top of the bucket.

We sampled soils from the top 20 cm of field plots at the Puyallup Research and Extension Center of Washington State University, Puyallup, WA (47°11'37'N,122°19'52'W). The soil was a sandy loam (63% sand, 31% silt, and 6% clay), classified as a Briscot Series, coarse-loamy, mixed, superactive, nonacid, mesic fluvaquentic Endoaquepts. The soils were air-dried, mixed thoroughly, and sieved through a 6-mm sieve. Samples of the air-dried soils were taken, and water content was determined by oven drying at 105°C for 48 h. In addition, we collected four subsamples of the air-dried soil samples for chemical analyses (Table 2). All analyses were performed following standard soil testing procedures (NCERA, 2015) by the American Agricultural Laboratory, McCook, NE, except the CO_2-C measured by the Solvita CO_2 burst method (Woods End Laboratories, 2016) in Puyallup, WA.

Based on the known water content of the air-dried soil, water was added to obtain a gravimetric water content of 0.155 g g^{-1}, which was 70% of the field capacity of the soil. The soils were then mixed with a mechanical shaker for 10 mins and immediately packed into mesocosms at 1.0 g cm^{-3} bulk density. Each bucket was filled with the processed soil, as described above, and a HOBO Pendant Temperature/Light Data Logger (Onset Computer Corp., Bourne, MA) was placed on the soil surface to record temperature and light illuminance every 15 min. The mulches were then laid on top of the soil and the HOBO sensors. The planting holes were aligned at the centre of the bucket for buckets that received mulches with planting holes. The adapter ring was screwed onto the bucket, sandwiching the mulch, and the second bucket (with cut-off bottom) was inserted on top of the adapter ring. We used a plumber's putty to make an air-tight seal between the mulches and the two buckets. The top bucket could be sealed with a screwable O-ring lid with an inlet valve (Figure 1). The mesocosms were placed in a greenhouse and kept open always to equilibrate with ambient conditions, except during gas measurements.

Gas and water measurements in the mesocosms

Initial gas readings started 4-6 h post mulch installation. Soil

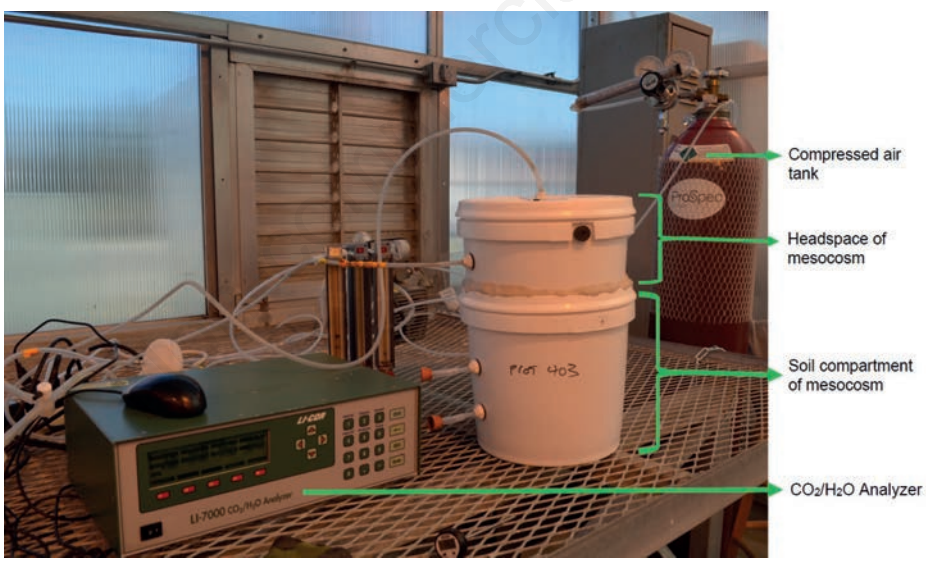

Figure 1. Mesocosm setup and simultaneous measurement of CO_2 and H_2O concentrations over time in the headspace of experimental mesocosm. A schematic of the mesocosm is provided in Figure S1.

Table 2. Characteristics of the soil used for the greenhouse experiment. All data were measured by the American Agricultural Laboratory, McCook, NE, except CO_2-C, that was measured by the Solvita test method in Puyallup, WA.

Property	Organic matter (g kg^{-1})	CO_2-C (mg kg^{-1})	Soil pH	EC dS m^{-1}	CEC cmol kg^{-1}	Nitrate-N mg kg^{-1}	P mg kg^{-1}	K mg kg^{-1}	Ca mg kg^{-1}	Mg mg kg^{-1}	Na mg kg^{-1}
Mean	29.5	80.4	5.53	0.42	10.6	53.0	492	242	663	92.3	31.8
Standard dev.	0.6	6.77	0.05	0.04	0.59	1.07	6.45	9.46	34.0	7.46	5.32

EC, electrical conductivity; CEC, cation exchange capacity; P, available phosphorus; K, Ca, and Mg, exchangeable potassium, calcium, and magnesium, respectively. Values of the mean and standard deviation are aggregates of four replications.

CO_2 concentration and CO_2 and water vapor (H_2O) diffusive fluxes were measured with LI-7000 CO_2/H_2O Analyzer (LI-COR, Inc., Lincoln NE). For soil CO_2 concentration measurements, 2 mL of air, representing the dead volume of the Tygon tubings, was first extracted with a hypodermic needle from the sampling port and discarded. The process was followed by sampling 3 mL of air and injecting it into a stream of CO_2-free air to obtain a peak concentration value as described by the manufacturer (LI-COR, 2007). By conversion, the 3 mL of air was drawn from a radius of 1.2 cm of the soil. We developed a calibration curve with CO_2 standards 0, 0.4, 1.5, 2.5, 5, 10, and 50 mmol mol^{-1}.

CO_2 and H_2O diffusive fluxes were measured following the non-steady state chamber method (Hutchinson and Livingston, 2002; Shahzad *et al*., 2019). For these measurements, the O-ring lid was screwed tightly onto the mesocosm. The Tygon tubing outlet of the top bucket was connected to the inlet valve of the gas analyser. In contrast, the inlet valve on the O-ring lid was connected to the outlet valve of the gas analyzer (Figure 1). The internal pump of the gas analyser was turned on, using a flow rate of 117.5 mL min^{-1}, to circulate air from the mesocosm headspace through the instrument sample chamber and back into the mesocosm headspace. The CO_2 and H_2O concentrations were measured simultaneously every second for two minutes. The first 30 seconds of the measurements were discarded, and then the rate of increase of the CO_2 and H_2O concentrations were determined from a linear model. The temperature in the mesocosm headspace was recorded immediately after the two minutes period. The CO_2 and H_2O diffusive fluxes were calculated from the CO_2 and H_2O concentrations following Rolston (1986).

The O_2 concentration was measured with a QRAE 3 gas sensor (RAE Systems, San Jose, CA). The sensor was calibrated with 30 mL O_2 standards (0, 100, 180 mmol mol^{-1}) and ambient air, assumed to be 209 mmol mol^{-1}. Soil O_2 concentration was then measured from 30 mL air, representing a 2.5 cm radius of the soil, sampled from the sampling ports with a hypodermic needle. Gas measurements, as described above, were made on days 0, 1, 2, 5, 10, 15, and 20. Day 0 represents the measurements taken 4-6 hr post mulch installation. The mesocosms were left open, except during CO_2 and H_2O diffusive flux measurements (closed for 2 min). The mesocosms were weighed every time gas measurements were taken to calculate the loss of soil moisture. Also, the mesocosms were rearranged randomly within a block at two-days intervals to ensure the mesocosms received similar microclimate conditions. The greenhouse was shaded with a black shade cloth to prevent direct transmittance of solar radiation that could induce wide variation in the temperature of the mesocosms.

Calculation of CO_2 and H_2O diffusion coefficients

The diffusive flux and soil CO_2 concentration data were used to calculate the diffusion coefficients of the soil by rearranging the equation for Ficks Law (Jury and Horton, 2004):

$$D_{\mathrm{no}} = -J_{\mathrm{g}} \frac{L_{\mathrm{no}}}{\Delta C} \quad (1)$$

where J_g is the diffusive gas flux, L_{no} is the soil depth (6.5 cm), and C is the gas concentration. The H_2O concentration in the soil was not measured, but we assumed a relative humidity of 99.9%. For comparison, CO_2 and H_2O diffusion coefficients of the soil derived with different methods (Marshall, 1959; Millington and Quirk, 1960; Moldrup *et al*., 1997, 1996; Penman, 1940) are provided in Table S1. We calculated CO_2 and H_2O diffusion coefficients of the mulches considering a two-layer system: mulch (top) and soil (bottom) layers. We assumed that the gases flow perpendicular to the layers. The CO_2 and H_2O diffusion coefficients of the mulches (D_m) were then calculated based on the resistance in series approach as follows (Jury and Horton, 2004):

$$D_{\mathrm{m}} = \frac{L_{\mathrm{m}}}{\frac{L_{\mathrm{no}}}{D_{\mathrm{no}}} + \frac{\Delta C}{J_{\mathrm{g}}}} \quad (2)$$

where L_m is the thickness of the mulch.

Cultivation of sweet corn in the mesocosm

Seeds of sweet corn, cultivar Temptation, were disinfected in 70% ethanol for 1 min and rinsed several times with deionized water. The seeds were pre-germinated in a Petri dish for 60 hrs by sandwiching between two-layer moistened filter papers and wrapped in aluminum foil. Pre-germinated seeds were planted in the mesocosms at 3-cm depth on day 20 after the gas measurements had been taken. We transplanted three seedlings per mesocosm and then thinned to two seedlings per mesocosm after five days. The plants were irrigated frequently by drip irrigation to maintain the moisture content at 60% to 80% field capacity of the soil. Thus, each mesocosm received different irrigation amounts depending on the actual water loss. The plants were supplied with 168 kg N ha^{-1}, 21 kg P ha^{-1}, and 62 kg K ha^{-1} *via* one-time fertigation. We planted sweet corn in one set of the no-mulch mesocosms and the mesocosms that had mulches with planting holes. The other set of the no-mulch mesocosm received irrigation and fertigation, but it was not planted to sweet corn.

The mesocosms were subjected to gas and water measurements, as described previously, on days 0, 1, 5, 15, and 30 after planting sweet corn. After 30 days of planting, we measured the plant height, leaf area, root biomass, shoot biomass, and the circumference of the shoots. Plant height was measured from the soil surface to the highest point on the plant, and the shoot circumference was measured from the center of the plant. Leaf area was measured by placing the leaves uniformly on a white surface and taking photographs. ImageJ software (Rasband, 2014) was then used to digitise the photographs and measure the total area. The shoot and root biomass were measured by oven drying at 60°C for 48 h. The roots were sampled by gently sieving the soil through a 2 mm sieve and then washing several times with deionised water.

Monitoring chimney effect

The chimney effect was monitored during sweet corn production in the mesocosms in the greenhouse and also under field conditions. The field was an experimental site under sweet corn production at the Northwestern Washington Research and Extension Center, Washington State University, Mount Vernon, WA (48°43’24’N,122°39’09’W). The field had been used to evaluate different mulches for four continuous growing seasons in a companion study [pie pumpkin (*Cucurbita pepo*) in 2015 and 2016, and sweet corn in 2017 and 2018] (Ghimire *et al*., 2018; Sintim *et al*., 2021). CO_2 measurements were made in 2018 (September 25-29), and the sweet corn plants were at the grain-filling stage at the time of the measurement. The mulches tested in the greenhouse study were the same as those being tested in the field.

Portable infrared CO_2 sensors (CO_2 Monitor and Data Logger, CO_2 Meter, Ormond Beach, FL, USA) were placed over the planting holes at 2.5 cm height above the ground in both greenhouse and field, with the addition of sensors placed at 15 cm height above the Organix and polyethylene mulches in the greenhouse study. The sensors were installed at two replications per mulch treatment in the field and one replication per mulch treatment at the different installation heights in the greenhouse. The sensors were set to simultaneously measure CO_2 concentration and temperature every five minutes. Ambient CO_2 concentration in the field was monitored by placing one portable infrared CO_2 sensor close to a weather station located about 100 m away from the field plots. The portable sensor was placed at ~91 cm above the ground. The ambient CO_2 concentration in the greenhouse was also measured by placing one portable infrared CO_2 sensor at ~61 cm above the ground.

Statistical analyses

Repeated measure analyses were performed for the gas concentration and diffusive flux data, and analysis of variance for a randomized complete block design for the water loss and diffusion coefficient data, using the 'lme4' package in R (Bates *et al*., 2015). For the repeated measure analyses, mulch treatment was considered as between factor variable, and time was considered as within factor variable. In addition, assumptions of normality of residuals, homoscedasticity, and sphericity were tested. Correction for sphericity was performed for the gas concentration and diffusive flux data using the Greenhouse-Geisser correction method, whereas the water loss and diffusion coefficient data were transformed using the Box-Cox transformation method. Mean separations were performed using the least squares means and the Tukey multiple comparison procedure was adjusted. The significance level of all analyses was assessed at P=0.05.

Results and discussion

Soil CO_2 and O_2 concentrations in the mesocosms before planting sweet corn

CO_2 and O_2 concentrations in the mesocosms sampled over time at 6.5 cm and 13.5 cm depths before planting sweet corn are shown in Figure 2. The results showed significant effects of mulching on the soil CO_2 and O_2 concentrations at both sampling depths (P-value<0.001). The CO_2 concentration in the bottom soil layer was greater than in the top, which is consistent with the expected CO_2 concentration gradient between the atmosphere and soil (Oh *et al*., 2005). The CO_2 concentration in the soil sampled at both depths increased rapidly under the two plastic mulches without planting holes on day 1, but then it decreased gradually thereafter (Figure 2A and B; Table S2). The Organix and polyethylene mulches both increased the soil CO_2 concentration to a similar peak (13 mmol mol^{-1} to 15 mmol mol^{-1}), but the CO_2 concentration declined to a greater extent in the former. Conversely, we observed a general decline in the soil CO_2 concentration under the plastic mulches with planting holes and the no-mulch and paper mulch following a peak at day 0. Thus, the planting holes reduced the build-up of soil CO_2 in the plastic mulches, with a peak soil CO_2 concentration of 4.90 mmol mol^{-1} to 5.77 mmol mol^{-1}. The soil CO_2 concentration in the no-mulch peaked at 2.8 mmol mol^{-1}.

In contrast to soil CO_2 concentration, the soil O_2 concentration under Organix and polyethylene mulches without planting holes decreased significantly within the first day of installation (Figure 2C and D; Table S3). Then the soil O_2 concentration increased from 183-184 mmol mol^{-1} on day 1 to 199-204 mmol mol^{-1} on day

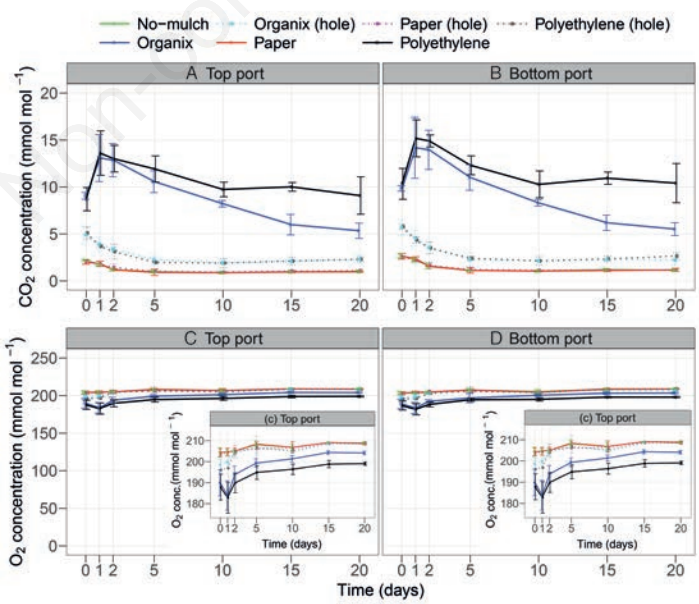

Figure 2. Soil CO_2 (A, B) and O_2 (C, D) concentrations as a function of time in the greenhouse study before planting sweet corn. Day 0 refers to the first measurements taken 4-6 h after mulch placement. The inserts show O_2 concentrations plotted on a magnified scale for a detailed view. The top and bottom ports refer to measurements taken at 6.5 cm and 13.5 cm below the top of the mesocosm, respectively. Errors indicate the standard deviation of the mean (n=4). Error bars are slightly offset from the x-axis for visibility.

20. Planting holes reduced the inhibition of plastic mulches on soil O_2, particularly in the Organix, where the soil O_2 concentration was similar to that of the no-mulch and paper mulch. The observed differences in CO_2 and O_2 concentrations among the mulches on day 0 are likely due to the slight delay, about 4 to 6 h, from when the mulches were installed to when the first measurements were taken. Results of the CO_2 and O_2 concentrations indicate that microorganisms consumed the organic matter in the soil, using O_2 and releasing CO_2 (Hobbie and Hobbie, 2013; Tate, 2000; Yoshitake *et al*., 2007). The results are consistent with the initial increase in CO_2 concentration and the decline in O_2 concentration. The build-up of CO_2 was fast, reaching maximum concentration within one day. This was attributable to the mixing of the soil that induced microbial activities. As energy and nutrient sources become depleted, microbial activities also decline (Ölinger *et al*., 1996; Yoshitake *et al*., 2007). This led to reduced CO_2 concentration after the initial increase and an increase in the O_2 concentration from the influx of O_2 in the atmosphere. The soil O_2 concentrations under the no-mulch and paper mulch became comparable to ambient O_2 concentration (209 mmol mol^{-1}) after 15 days.

Soil CO_2 and O_2 concentrations in the mesocosms after planting sweet corn

Sweet corn was planted after 20 days of mulch installation. At planting, the soil CO_2 concentration in the two plastic mulches was greater than that observed under the no-mulch and paper mulch (Figure 3A and B; Table S4). There was an increase in the soil CO_2 concentration in all plots one day after the first irrigation, except under the polyethylene mulch. The CO_2 concentration increased by 29%, 19%, 25%, and 0.6% in the no-mulch, paper mulch, Organix, and polyethylene mulch, respectively. However, subsequent irrigation did not induce any effect on the CO_2 concentration. Fertigation, which occurred after the initial irrigations, induced a greater impact on the CO_2 concentration. The CO_2 concentration in the soil increased by 53%, 52%, 60%, and 89% in the no-mulch, paper mulch, Organix, and polyethylene mulch, respectively. The results suggested that there was a carbon source available for consumption by microorganisms, but limited nutrients inhibited the microbial respiration.

Yoshitake *et al*. (2007) evaluated carbon and nitrogen limitations to microbial respiration. The authors observed that adding glucose caused a marginal increase in microbial respiration rate, whereas the application of ammonium nitrate had no significant effect. However, the simultaneous addition of both carbon and nitrogen caused an almost eightfold increase in the microbial respiration rate (Yoshitake *et al*., 2007). At 30 days after transplanting sweet corn, we observed an increase in the soil CO_2 concentration in the no-mulch plots with plants compared to the no-mulch plots without plants (1.88 *vs* 1.12 mmol mol^{-1} in the top port and 2.06 *vs* 1.10 mmol mol^{-1} in the bottom port; Figure 3A and B; Table S4), albeit it was not statistically significant. The marginal increase in CO_2 concentration in the former could reflect root respiration. Besides microbial respiration, root respiration is another important source of CO_2 concentration in the soil (Kou *et al*., 2007; Oh *et al*., 2005). However, the plants were likely still too small after 30 days of transplanting to elevate CO_2 concentrations in soil significantly.

Significant differences were observed in the soil O_2 concentration on days 0 and 15 after planting (Figure 3C and D; Table S5). Day 15 reflects 24 h after fertigation, which tended to cause a general decline in the soil O_2 concentration in the plastic mulches. There were no differences in the soil O_2 concentration between the no-mulch plots without plants and the no-mulch plots with plants, indicating that the sweet corn had a minimal impact on O_2 concentrations.

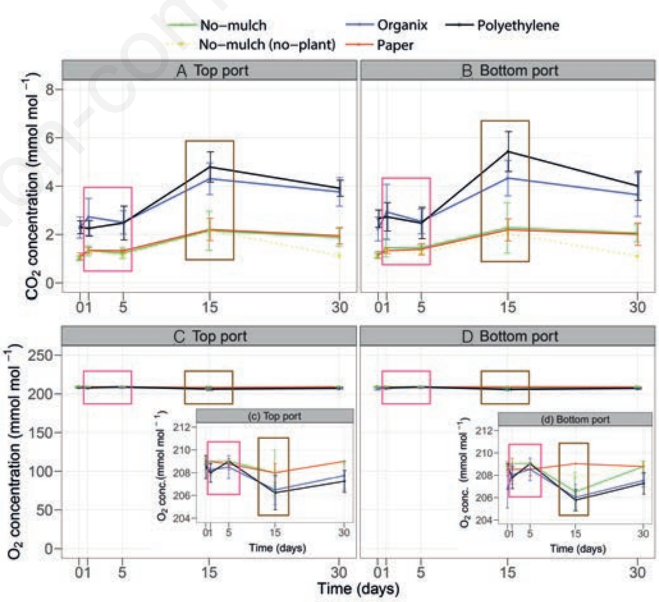

Figure 3. Soil CO_2 (A, B) and O_2 (C, D) concentrations as a function of time in the greenhouse study after planting sweet corn. Day 0 refers to the day sweet corn was transplanted. The inserts show O_2 concentrations plotted on a magnified scale for a detailed view. Pink rectangles enclosing data points indicate the data was measured 24 h after irrigation and the brown rectangles indicate the data was measured 24 h after fertigation with 168 kg N ha^{-1}, 21 kg P ha^{-1}, and 62 kg K ha^{-1}. The top and bottom ports refer to measurements taken at 6.5 cm and 13.5 cm below the top of the mesocosm, respectively. Errors bars are the standard deviations of the mean (n=4). Error bars are slightly offset from the x-axis for visibility.

CO_2 and H_2O diffusive fluxes across the soil-atmosphere boundary

CO_2 diffusive flux increased rapidly across the polyethylene mulch without planting hole on day 1 and then remained fairly constant thereafter (Figure 4A and Table S6). Under the Organix without planting hole, the CO_2 diffusive flux increased rapidly on day 1, remained relatively constant until day 10, and then declined after that. The initial increase in diffusive flux reflects a build-up of CO_2 concentration in the soil, which caused an increase in the CO_2 concentration gradient. This is more obvious in the Organix, where the CO_2 concentration decreased more rapidly after the initial increase (Figure 2A and B). As a result, the CO_2 diffusive flux also decreased. CO_2 diffusive flux across the plastic mulches with planting holes decreased rapidly until day 5, and then remained fairly constant thereafter (Figure 4A). On day 0, the CO_2 diffusive fluxes across the plastic mulches with planting holes were generally greater than across the respective plastic mulches without planting holes. The observation supports that the planting holes did indeed reduce the buildup of CO_2 above the soil but under the plastic mulches. The CO_2 diffusive fluxes in the no-mulch and paper mulch decreased rapidly until day 2, more slowly from day 2 to day 5, and then remained relatively constant after that. Overall, the CO_2 diffusive fluxes across the no-mulch and paper mulch were greater than across the plastic mulches, with and without planting holes. Zhang *et al*. (2015) reported greater CO_2 flux across no-mulch as compared to plastic mulch (0.19 *vs* 0.16 g CO_2 m^{-2} h^{-1}), consistent with the results of our study. A similar observation was made by Okuda *et al*. (2007), who reported CO_2 fluxes of 0.16 and 0.10 g CO_2 m^{-2} h^{-1} for no-mulch and polyethylene mulch, respectively. However, other studies have reported higher CO_2 flux across polyethylene mulch when compared to that across no-mulch (Zhang *et al*., 2017). In a greenhouse study, Shahzad *et al*. (2019) observed greater CO_2 flux across no-mulch than across polyethylene mulch at day 0 (0.78 *vs* 0.14 g CO_2 m^{-2} h^{-1}). However, on day 16, the CO_2 flux across the no-mulch was lower than the CO_2 flux across the polyethylene mulch (0.16 *vs* 0.24 g CO_2 m^{-2} h^{-1}) (Shahzad *et al*., 2019).

The H_2O diffusive fluxes across the no-mulch and paper mulch were similar but greater than across the plastic mulches, with and without planting holes. The H_2O diffusive flux across Organix was generally greater than that across the polyethylene mulch (Figure 4B and Table S6). In addition, the H_2O diffusive fluxes across the plastic mulches with planting holes were greater than across the respective plastic mulches without planting holes. The results indi-

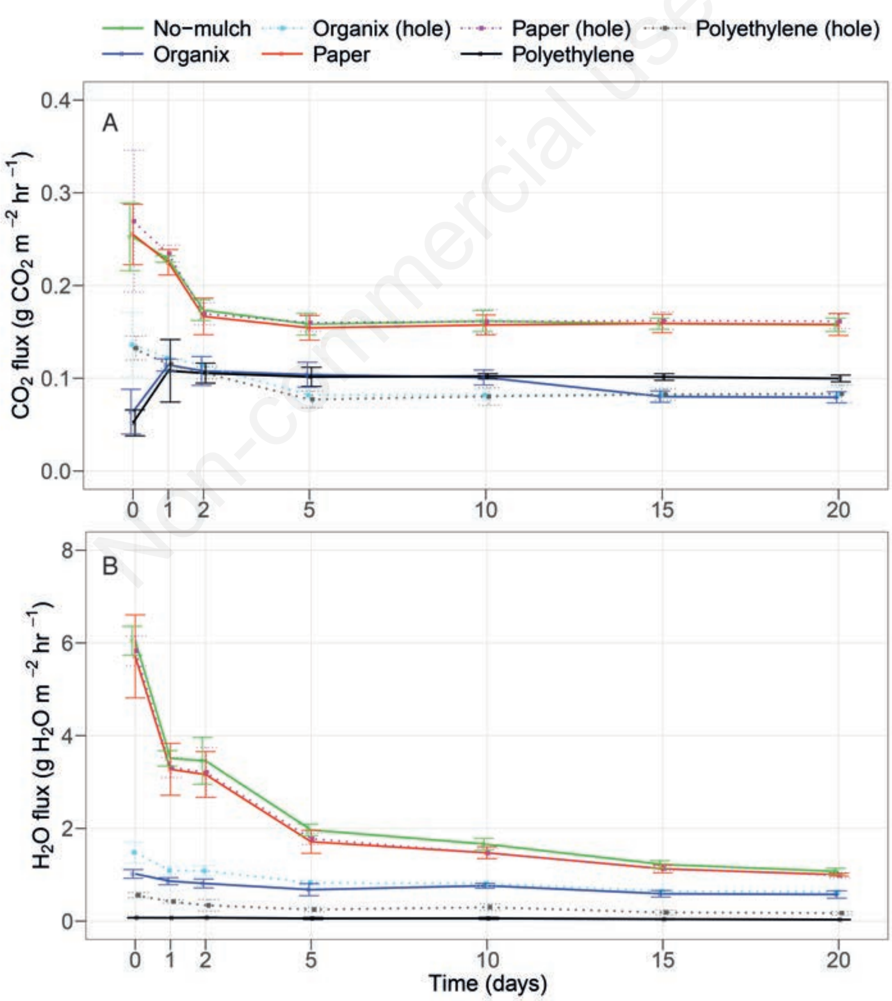

Figure 4. CO_2 and H_2O diffusive fluxes of the mulch treatments as a function of time in the greenhouse before planting sweet corn. Day 0 refers to the first measurements taken 4-6 h after mulch placement. Error bars indicate the standard deviation of the mean (n=4). Error bars are slightly offset from the x-axis for visibility.

cate that the polyethylene mulch was more efficient in reducing evaporative water losses compared to Organix, which could partly be attributed to the thickness of the mulches. The polyethylene mulch had a thickness of 25.4 μm, and the thickness of Organix was 17.8 μm.

CO_2 and H_2O diffusion coefficient of mulches

Table 3 shows the calculated CO_2 and H_2O diffusion coefficients of the mulches or soil (*i.e.*, the no-mulch treatment) on days 0 and 1 after mulch installation in the mesocosms. In general, the CO_2 diffusion coefficient of the soil on day 1 was greater compared to that observed on day 0. The diffusion coefficients of CO_2 in the air are much greater than in water, reported to be 0.16 cm^{-2} s^{-1} and 1.67×10^{-5} cm^{-2} s^{-1}, respectively, at 20°C (Lide, 2005). Thus, the greater CO_2 diffusion coefficient of the soil on day 1 compared to what was observed on day 0 could partly be attributable to the loss of water after one day that increased the air-filled porosity of the soil. In contrast, the H_2O diffusion coefficient of the soil was generally greater on day 0 than on day 1 (Table 3), which was because the H_2O concentration in the soil was not directly measured, but we assumed a relative humidity of 99.9%. We calculated the diffusion coefficients of the mulches by a two-layer system, assuming the diffusion coefficients of the soil layer under the mulches are similar to the diffusion coefficient of the no-mulch. This assumption is likely true for day 0, but the no-mulch lost some water after one day. Thus, the diffusion coefficients of the mulches calculated for day 0 are more representative.

The CO_2 diffusion coefficient of polyethylene mulch was similar to that of Organix. The paper mulch had a significantly higher CO_2 diffusion coefficient than the plastic mulches, but it was significantly lower when compared to that of the soil. The H_2O diffusion coefficient was greatest in the soil and least in the plastic mulches. Also, the CO_2 and H_2O diffusion coefficients of the plastic mulches with planting holes were higher than those observed in the plastic mulches without planting holes, albeit most of the differences were not statistically significant. Shahzad *et al*. (2019) reported the CO_2 diffusion coefficient of polyethylene mulch without a planting hole to be 2.23×10^{-6} cm^{-2} s^{-1} and that for bare soil to be 4.08×10^{-2} cm^{-2} s^{-1}. These values are higher than those observed in our current study, likely due to the addition of compost in the study by Shahzad *et al*. (2019).

Soil water conservation in the greenhouse study

Total water loss before planting sweet corn was greatest in the no-mulch and paper mulch, followed by the Organix (with and without planting holes), and then the polyethylene mulch (with and without planting holes) (Figure 5A). This order is consistent with the H_2O diffusive flux measurements. There were no differences in the total water loss between the plastic mulches with planting holes and the total water loss under the respective plastic mulches without planting holes. The results suggest that the planting holes had minimal effects on soil water loss. Actually, the polyethylene mulch with a planting hole even lost less water compared to the Organix without a planting hole. After 30 days of planting sweet corn, the total water loss was 58.3, 20.2, 52.7, and 12.6 mm for the no-mulch, Organix, paper mulch, and polyethylene mulch, respectively (Figure 5B). These values were considerably greater than the respective plots that were not planted to sweet corn (48.7, 6.1, 8.0, and 0.4 mm, respectively, for the no-mulch, Organix, paper mulch, and polyethylene mulch) (Figure 5C). The results are partly due to transpiration and because the plots with planting holes received supplemental water by irrigation, which increased the potential for water loss. However, the no-mulch plots without plants received the same amount of supplemental water by irrigation as the no-mulch plots with plants. Thus, the greater total water loss of the latter compared to the former (a difference of 9.6 mm) reflects water loss by transpiration. Also, the greater water loss in the no-mulch with plants than in the paper mulch with plants suggests that the paper mulch conserved soil water to some extent.

Light illuminance, temperature, and calculated thermal time in the greenhouse study

Light illuminance was greatest in the no-mulch, followed by Organix, polyethylene mulch, and then the paper mulch (Figure 6A). The light did not penetrate the paper mulch at all, with light illuminance of 0 lux. The paper mulch was brown but 13 and 9 times thicker than the Organix and polyethylene mulch, respectively. Photosynthetic photon flux density (PPFD) of 100-200 μmol m^{-2} s^{-1} can sustain the normal growth of several plants, but PPFD as low as 17 μmol m^{-2} s^{-1} can still induce growth (Paz *et al*., 2019; Pons and Poorter, 2014). Thus, the least light illuminance through the paper mulch makes it the most effective in preventing weed growth unless there is a premature breakdown of the mulch in the field. Ghimire *et al*. (2018) evaluated the effects of different biodegradable plastic mulches under pie pumpkin production at different locations, including no-mulch, paper mulch, and polyethylene mulch as controls. The authors observed that at the Knoxville, TN location, the weed nutsedge (*Cyperus sp.* L.) grew and penetrated all the plastic mulches but did not grow under the paper mulch. Anzalone *et al*. (2010) also reported that paper mulch performs

Table 3. CO_2 and H_2O diffusion coefficients of the mulches and soil (*i.e.*, no-mulch) calculated using flux measurements and the concentration gradients between the top sampling port and the atmosphere in the greenhouse.

Mulch	CO_2 diffusion coefficient (cm^2 s^{-1})		H_2O diffusion coefficient (cm^2 s^{-1})	
	Day 0	Day 1	Day 0	Day 1
No-mulch	$(1.45\pm0.32)\times10^{-2d}$	$(1.84\pm0.13)\times10^{-2e}$	$(8.15\pm0.42)\times10^{-2d}$	$(5.15\pm0.23)\times10^{-2d}$
Organix	$(2.05\pm0.72)\times10^{-7a}$	$(2.59\pm0.48)\times10^{-7a}$	$(40.1\pm3.82)\times10–^{7b}$	$(38.1\pm3.96)\times10^{-7ab}$
Organix (hole)	$(9.66\pm4.05)\times10^{-7ab}$	$(10.7\pm2.84)\times10^{-7bc}$	$(60.1\pm1.05)\times10^{7b}$	$(49.7\pm4.52)\times10^{-7b}$
Paper	$(1.00\pm0.33)\times10^{-4c}$	$(1.04\pm0.47)\times10^{-4d}$	$(4.39\pm1.09)\times10^{-4c}$	$(2.76\pm0.78)\times10^{-4c}$
Paper (hole)	$(1.34\pm1.21)\times10^{-4c}$	$(1.09\pm0.38)\times10^{-4d}$	$(4.48\pm0.37)\times10^{-4c}$	$(2.77\pm0.29)\times10^{-4c}$
Polyethylene	$(2.60\pm1.16)\times10^{-7ab}$	$(3.23\pm0.77)\times10^{-7ab}$	$(3.86\pm0.42)\times10^{-7a}$	$(4.07\pm0.45)\times10^{-7a}$
Polyethylene (hole)	$(12.1\pm2.83)\times10^{-7b}$	$(15.1\pm1.67)\times10^{-7c}$	$(30.6\pm3.05)\times10–^{7ab}$	$(25.4\pm2.16)\times10^{-7ab}$

Within measurement variable and sampling time, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparison ($P<0.05$). Values represent the mean ± standard deviation (n=4).

better than polyethylene and biodegradable plastic mulches in terms of weed control. These observations can be explained by the absence of light penetration in the paper mulch, rendering paper mulch most effective for weed control. However, paper mulch can be prone to ripping, particularly where paper contacts the soil and under windy conditions (Ghimire *et al*., 2018; Harrington and Bedford, 2004).

The temperature was similar among the different mulch treatments at the initial stages until shortly after planting sweet corn, where temperatures under the no-mulch and paper mulch became lower than temperatures under the plastic mulches (Figure 6B). The temperature was relatively higher in the paper mulch compared to the no-mulch, but lower when compared to those of the plastic mulches. The greenhouse in this study was shaded, so we expected to see similar temperatures across the mulch treatments, which was indeed the case from the initial mulch installation until planting sweet corn. However, the no-mulch and paper mulch had more significant water loss so we provided more irrigation in order to maintain the soil water content between 60 to 80% field capacity. Perhaps, the frequent irrigation could have induced a larger evaporative cooling effect in the no-mulch and paper mulch. Under field conditions, plastic mulches were reported to induce greater soil temperature than no-mulch, particularly before planting and during the early growing season (Brown *et al*., 1990; Lamont, 1993; Moreno and Moreno, 2008; Sintim *et al*., 2019). However, Sintim *et al*. (2019) noted that the differences in soil temperature between plastic and no-mulch conditions diminished later in the growing season as the plant canopy developed and the mulches became shaded.

Chimney effect under greenhouse and field conditions

The CO_2 concentrations and temperatures measured during sweet corn production in the greenhouse and under field conditions are shown in Figure 7. The ambient data of the field is not available after September 27 because of sensor failure. We observed fluctuations in the diurnal CO_2 concentrations, with higher values observed in the evenings and early mornings, whereas lower values were observed during the day for both greenhouse and field measurements. Diurnal fluctuation of atmospheric CO_2 concentration is a common occurrence and has been reported in various parts of the world (Guha and Ghosh, 2010; Idso *et al*., 2002; Imasu and Tanabe, 2018). According to Idso *et al*. (2002), the controlling factors of diurnal atmospheric CO_2 concentration include: i) air temperature inversions at night and in the early morning, where the inversions trap vehicular-generated CO_2 near the ground, thereby increasing the CO_2 concentration; and ii) solar-induced convective mixing during the mid-day period, which dilutes CO_2 concentration near the ground.

Under greenhouse conditions, the CO_2 chimney effect (*i.e.*, elevated CO_2 concentrations) was observed at 2.5 cm above the planting holes in the polyethylene mulch (Figure 7A). The effects were consistently pronounced after October 29, corresponding to when the plants received nutrients via fertigation. As already noted, fertigation induced microbial activities that elevated the CO_2 concentrations in the soil. In addition, root respiration could have also led to increased CO_2 concentrations in the soil. Under field conditions, the CO_2 chimney effect was observed at 2.5 cm above the planting holes in both Organix and polyethylene mulches, with the effect being more obvious in Organix (Figure 7B). No CO_2 chimney effect was observed at 15 cm above the

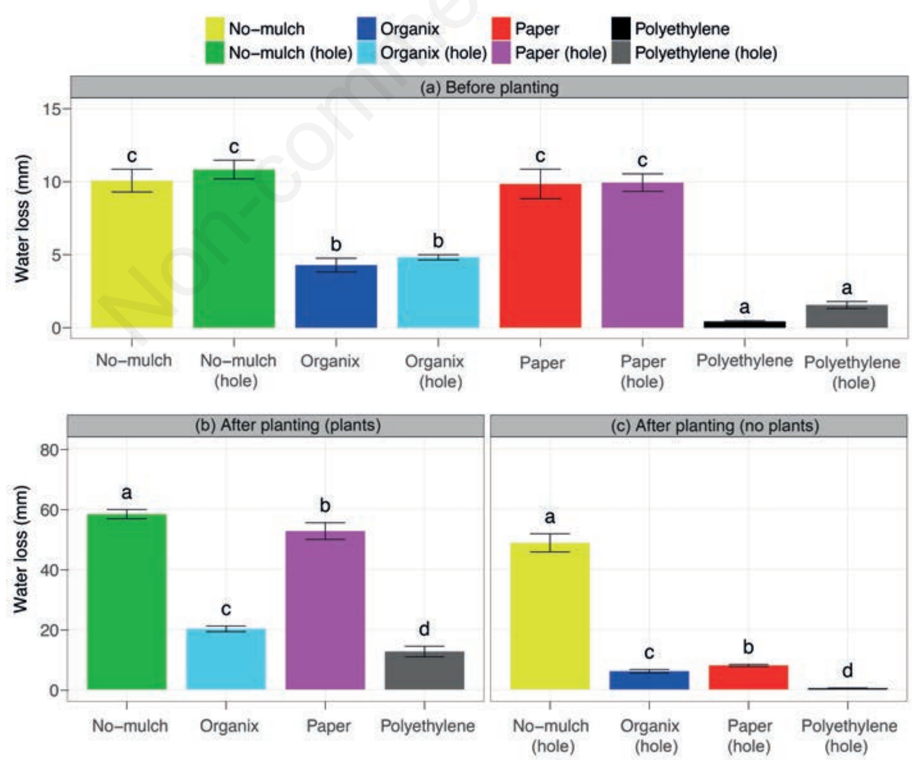

Figure 5. Cumulative water loss in the greenhouse (A) within the first 20 days before transplanting sweet corn and (B) 30 days after transplanting sweet corn. Within each sup-plot, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparison (P<0.05). Values represent the mean ± standard deviation (n=4).

planting holes in the plastic mulches in the greenhouse.

Greenhouse temperatures measured at 2.5 cm above the no-mulch were lower than temperatures measured at 2.5 cm above the paper mulch and plastic mulches (Figure 7C). In addition, greenhouse temperatures measured at 15 cm above the plastic mulches were higher than temperatures measured at 2.5 cm above the plastic mulches. Ambient temperatures measured in the greenhouse were higher than those measured at 2.5 cm above the no-mulch, but lower than those measured above the paper mulch and plastic mulches. Under field conditions, the ambient temperatures were generally lower compared to temperatures measured at 2.5 cm above the no-mulch and plastic mulches (Figure 7D). The temperatures measured during the day at 2.5 cm above the ground tended to be highest in the polyethylene mulch, followed by Organix, and then the no-mulch. However, temperatures above the mulches were similar during the evenings.

Our results indicate that plastic mulch affects the gas and microclimate dynamics of the soil and the immediate atmosphere. We determined that the effect was negligible at 15-cm height, likely due to convective mass transfer in the greenhouse. Convective mass transfer is expected to be much higher under field conditions, further reducing the height in which the chimney effect could be noticeable. The results of our study are, therefore, consistent with the results of Soltani *et al*. (1995), who observed the CO_2 chimney effect near the surface of plastic mulches but not at 10 cm above the plastic mulches. The greater chimney effect of Organix over polyethylene mulch in the field could be attributed to differences in the history of the field. The field reflects the effects of different mulches used for four continuous growing seasons. Sintim *et al*. (2019) initially determined that the plots under Organix had greater CO_2-C (measured by the Solvita CO_2 burst method) than the plots under polyethylene mulch (82.6 mg kg^{-1} *vs* 72.4 mg kg^{-1}).

Growth parameters of sweet corn cultivated in the mesocosms

Mulch effects on the growth parameters of sweet corn after 30 days in the greenhouse are shown in Table 4. We did not observe significant differences between the mulches in all the measured growth parameters. Plastic mulches have been shown to increase grain and sweet corn growth cultivated in field conditions, especially under water-deficient environments (Kara and Atar, 2013; Rajablariani *et al*., 2015; Xu *et al*., 2015; Zhang *et al*., 2018). In this study, we evaluated the growth of sweet corn in a controlled environment in a greenhouse. We ensured soil water content remained between 60% to 80% of field capacity to avoid water stress. Also, the greenhouse was slightly shaded, which prevented direct transmittance of solar radiation. More importantly, we adequately controlled weeds, a major factor that results in better crop growth by mulching (Rajablariani *et al*., 2015).

Overall, the results indicate that the impact of the chimney effect induced by the plastic mulches on sweet corn growth was minimal. This is consistent with the observation that the chimney effect was only noticeable at 2.5 cm above the mulch surface but not at 15 cm above the mulch surface. As the canopy height of the sweet corn was more than 15 cm within a few days after planting, no effect on plant growth would be expected. However, the chimney effects could, perhaps, positively impact a different crop with lower canopy height.

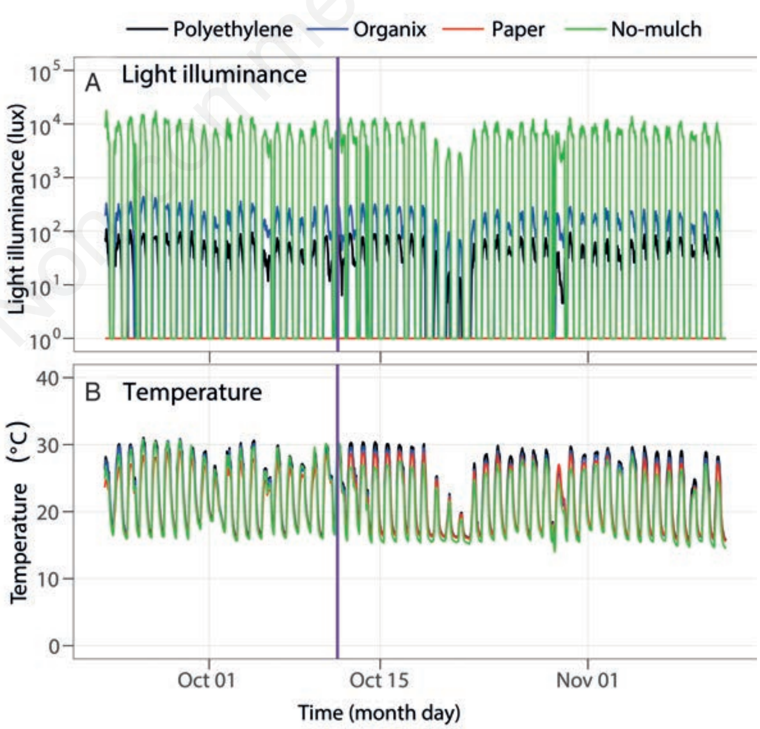

Figure 6. A) Light illuminance and (B) temperature at the soil surface or directly underneath the mulches during the greenhouse study. The vertical purple line indicates when sweet corn was planted. The time tick marks correspond to midnight (00:00 h) for the corresponding day. Assuming the light source was solar radiation, then 122 lux is ~1 W m^{-2}. Also, 122 lux will be ~1 μmol m^{-2} s^{-1} of photosynthetic photon flux density.

Conclusions and implications

Plastic mulching increased the soil CO_2 concentration, but planting holes in the plastic mulches decreased the peak soil CO_2 concentration by 62% to 71%. On the contrary, plastic mulch decreased the soil O_2 concentration to a minimum of 181 mmol mol^{-1} to 183 mmol mol^{-1}. The value is well above 100 mmol mol^{-1}, the minimum O_2 concentration in which plant growth becomes impaired (Hanslin *et al*., 2005). Organix conserved soil moisture better than the no-mulch and paper mulch but not as much as polyethylene mulch. We observed that the impact of the planting hole on soil water loss was minimal compared to the impact on CO_2 and O_2 dynamics.

The paper mulch inhibited light penetration the most, followed by polyethylene mulch, Organix, and then no-mulch. The results make paper mulch the most effective in controlling weeds, as long as its integrity stays intact. There was evidence of a chimney effect at 2.5 cm above the plastic mulches, but it was not discernible at 15 cm height. Thus, we did not observe a significant impact on the growth of sweet corn. Improved growth of sweet corn from plastic mulching could, therefore, be attributable to other factors, such as weed control, reduced water loss, and early season soil warming.

References

Anzalone A, Cirujeda A, Aibar J, Pardo G, Zaragoza C, 2010. Effect of biodegradable mulch materials on weed control in processing tomatoes. Weed Technol. 24:369-77.

Bandopadhyay S, Martin-Closas L, Pelacho AM, DeBruyn JM, 2018. Biodegradable plastic mulch films: impacts on soil microbial communities and ecosystem functions. Front. Microbiol. 9:1-7.

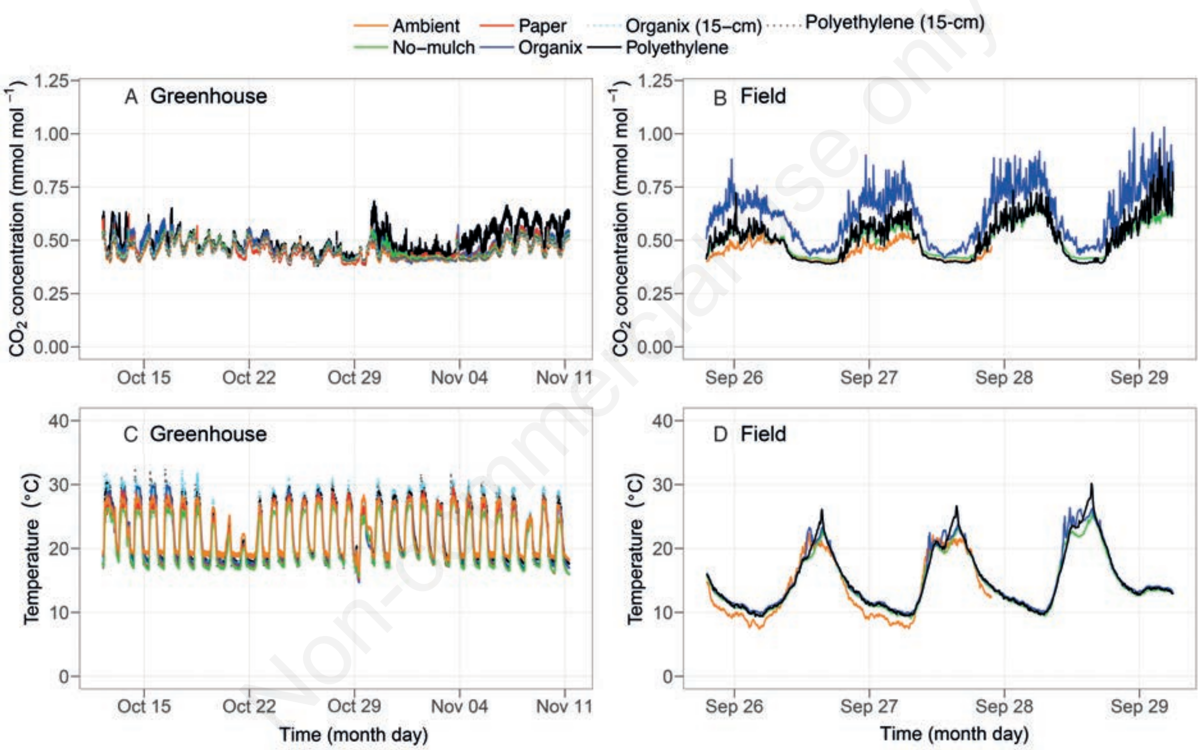

Figure 7. CO_2 concentration and temperature measured during sweet corn production in the greenhouse (A, C) and under field conditions in Mount Vernon, WA (B, D). The sensors were positioned 2.5 cm above ground, except for the greenhouse study, where additional sensors were positioned at 15 cm above the Organix and polyethylene mulches. Ambient refers to sensors installed at a weather station (located about 100 m away from the experimental field) or in the greenhouse at 91 cm and 61 cm above the ground, respectively. The time tick marks correspond to midnight (00:00 h) for the corresponding day.

Table 4. Mulch effects on the growth parameters of sweet corn after 30 days in the greenhouse.

Mulch	Plant height (cm)	Leaf area (cm^2)	Shoot biomass (g)	Root biomass (g)	Stem circumference (cm)
No-mulch	54.8±3.9^a	536±28^a	1.9±0.2^a	0.35±0.02^a	21.9±1.1^a
Organix	56.7±3.7^a	554±25^a	1.9±0.2^a	0.36±0.02^a	23.0±1.8^a
Paper	55.7±4.2^a	597±35^a	2.2±0.3^a	0.40±0.03^a	23.5±1.8^a
Polyethylene	54.7±2.1^a	575±47^a	2.1±0.2^a	0.39±0.02^a	22.9±1.6^a
P-value	0.727	0.145	0.200	0.05	0.399

Within every growth parameter, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparison ($P<0.05$). Values represent the mean ± standard deviation (n=4).

Bates D, Maechler M, Bolker B, Walker S, 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67:1-48.

Bond W, Grundy AC, 2001. Non-chemical weed management in organic farming systems. Weed Res. 41:383-405.

Brown JE, Stevens C, Khan VA, Hochmuth GJ, Splittstoesser WE, Granberry DM, Early BC, 1990. Development in plastics for soil solarization, in: Soil Solarization. Proceedings of the First International Conference on Soil Solarization, FAO Plant Production And Protection Paper 109, Rome, Italy.

Chen K-J, Marsh TL, Tozer PR, Galinato SP, 2019. Biotechnology to sustainability: consumer preferences for food products grown on biodegradable mulches. Food Res. Int. 116:200-10.

Gao H, Yan C, Liu Q, Ding W, Chen B, Li Z, 2019. Effects of plastic mulching and plastic residue on agricultural production: a meta-analysis. Sci. Total Environ. 651:484-92.

Ghimire S, Wszelaki AL, Moore JC, Inglis DA, Miles C, 2018. The use of biodegradable mulches in pie pumpkin crop production in two diverse climates. HortSci. 53:288-94.

Goldberger JR, DeVetter LW, Dentzman KE, 2019. Polyethylene and biodegradable plastic mulches for strawberry production in the United States: experiences and opinions of growers in three regions. Horttechnology 1-10.

Guha T., Ghosh P. 2010. Diurnal variation of atmospheric CO2 concentration and $\delta^{13}C$ in an urban atmosphere during winter-role of the Nocturnal Boundary Layer. J. Atmos. Chem. 65:1-12.

Hanslin HM, Sæbø A, Bergersen O, 2005. Estimation of oxygen concentration in the soil gas phase beneath compost mulch by means of a simple method. Urban For. Urban Green. 4:37-40.

Harrington KC, Bedford TA, 2004. Control of weeds by paper mulch in vegetables and trees. New Zeal. Plant Prot. 57:37-40.

Hayes DG, Anunciado MB, Debruyn JM, Bandopadhyay S, Schaeffer S, English M, Ghimire S, Miles C, Flury M, Sintim HY, 2019. Biodegradable plastic mulch films for sustainable specialty crop production. In: T.J. Gutiérrez (Ed.), Polymers for agri-food applications. Springer, Cham, Switzerland, pp. 183-213.

Hobbie JE, Hobbie EA, 2013. Microbes in nature are limited by carbon and energy: the starving-survival lifestyle in soil and consequences for estimating microbial rates. Front. Microbiol. 4:324.

Hutchinson GL, Livingston GP, 2002. Soil-atmosphere gas exchange. In: Methods of Soil Analysis, Part 4, Physical Methods. Science Society of America, Madison, WI, pp. 1159-1182.

Idso SB, Idso CD, Balling RC, 2002. Seasonal and diurnal variations of near-surface atmospheric CO_2 concentration within a residential sector of the urban CO_2 dome of Phoenix, AZ, USA. Atmos. Environ. 36:1655-60.

Imasu R, Tanabe Y, 2018. Diurnal and seasonal variations of carbon dioxide (CO2) concentration in urban, suburban, and rural areas around Tokyo. Atmosphere (Basel). 367:1-10.

Jury WA, Horton R, 2004. Soil physics, 6th ed. John Wiley & Sons, New York, United States.

Kara B, Atar B, 2013. Effects of mulch practices on fresh ear yield and yield components of sweet corn. Turkish J. Agric. For. 37:281-7.

Kim GW, Das S, Hwang HY, Kim PJ, 2017. Nitrous oxide emissions from soils amended by cover-crops and under plastic film mulching: fluxes, emission factors and yield-scaled emissions. Atmos. Environ. 152:377-88.

Kou T, Zhu J, Xie Z, Hasegawa T, Heiduk K, 2007. Effect of elevated atmospheric CO2 concentration on soil and root respiration in winter wheat by using a respiration partitioning chamber. Plant Soil 299:237-49.

Lamont WJ, 1993. Plastic mulches for the production of vegetable crops. Horttechnology 3:35-9.

LI-COR, 2007. Measuring small volumes of CO2 with the LI-7000. Li-COR Biosciences, Lincoln, NE, USA.

Lide DR, 2005. CRC handbook of chemistry and physics. Internet Version, CRC Press, Boca Raton, FL, USA. Available from: https://doi.org/10.5860/choice.41-4368

Marr CW, 1993. Plastic mulches for vegetables. No. MF-1091, Kansas State University, Manhattan, KS, USA.

Marshall TJ, 1959. The diffusion of gases through porous media. J. Soil Sci. 10:79-82.

Millington RJ, Quirk JP, 1960. Transport in porous media. In: F.A. Van Baren (Ed.), Transactions of the 7th International Congress of Soil Science. Vol. 1. Elsevier, Amsterdam, The Netherlands, p. 97-106.

Moldrup P, Kruse CW, Yamaguchi T, Rolston DE, 1996. Modeling diffusion and reaction in soils. I. A diffusion and reaction corrected finite difference calculation scheme. Soil Sci. 161:347-54.

Moldrup P, Olesen T, Rolston DE, Yamaguchi T, 1997. Modeling diffusion and reaction in soils: VII. Predicting gas and ion diffusivity in undisturbed and sieved soils. Soil Sci. 162:632-40.

Moreno MM, Moreno A, 2008. Effect of different biodegradable and polyethylene mulches on soil properties and production in a tomato crop. Sci. Hortic. (Amsterdam). 116:256-63.

NCERA, 2015. Recommended chemical soil test procedures for the North Central Region. North Central Regional Res. Publ. No. 221 ed. North Central Extension and Research Activity, Madison, WI, USA.

Oh N-H, Kim H-S, Richter DD, 2005. What regulates soil CO2 concentrations? A modeling approach to CO2 diffusion in deep soil profiles. Environ. Eng. Sci. 22:38-45.

Okuda H, Noda K, Sawamoto T, Tsuruta H, Hirabayashi T, Yonemoto JY, Yagi K, 2007. Emission of N2O and CO2 and uptake of CH4 in soil from a Satsuma Mandarin orchard under mulching cultivation in Central Japan. J. Japanese Soc. Hortic. Sci. 76:279-87.

Ölinger R, Beck T, Heilmann B, Beese F, 1996. Soil respiration. In: Methods in Soil Biology. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 93-110.

Paz M, Fisher PR, Gómez C, 2019. Minimum light requirements for indoor gardening of lettuce. Urban Agric. Reg. Food Syst. 4:1-10.

Penman HL, 1940. Gas and vapour movements in the soil: I. The diffusion of vapours through porous solids. J. Agric. Sci. 30:437-62.

Pons TL, Poorter H, 2014. The effect of irradiance on the carbon balance and tissue characteristics of five herbaceous species differing in shade-tolerance. Front. Plant Sci. 5:1-14.

Rajablariani HR, Sheykhmohamady M, AghaAlikhani M, 2015. Growth of sweet corn and weeds in response to colored plastic mulches. J. Adv. Agric. Technol. 2:42-5.

Rasband WS, 2014. ImageJ. U.S. National Institutes of Health, Bethesda, MD, USA.

Retamales JB, Hancock JF, 2012. Blueberries. Crop production science in horticulture series; No. 21. CAB International, Wallingford, UK.

Rolston DE, 1986. Gas flux. In: A. Klute (Ed.), Methods of soil analysis, Part 1, Physical and mineralogical methods. Soil Science Society of America, American Society of Agronomy, Madison, WI, United States, pp. 1103-1119.

Saglam M, Sintim HY, Bary AI, Miles CA, Ghimire S, Inglis DA, Flury M, 2017. Modeling the effect of biodegradable paper and plastic mulch on soil moisture dynamics. Agric. Water Manag. 193:240-50.

Shahzad K, Bary AI, Collins DP, Chalker-Scott L, Abid M, Sintim HY, Flury M, 2019. Carbon dioxide and oxygen exchange at the soil-atmosphere boundary as affected by various mulch materials. Soil Tillage Res. 194:104335.

Shen Y, Chen Y, Li S, 2016. Microbial functional diversity, biomass and activity as affected by soil surface mulching in a semiarid farmland. PLoS One 11:e0159144.

Sintim HY, Bandopadhyay S, English ME, Bary A, Liquet y González JE, DeBruyn JM, Schaeffer SM, Miles CA, Flury M, 2021. Four years of continuous use of soil-biodegradable plastic mulch: impact on soil and groundwater quality. Geoderma 381:114665.

Sintim HY, Bandopadhyay S, English ME, Bary AI, DeBruyn JM, Schaeffer SM, Miles CA, Reganold JP, Flury M, 2019. Impacts of biodegradable plastic mulches on soil health. Agric. Ecosyst. Environ. 273:36-49.

Sintim HY, Bary AI, Hayes DG, Wadsworth LC, Anunciado MB, English ME, Bandopadhyay S, Schaeffer SM, DeBruyn JM, Miles CA, Reganold JP, Flury M, 2020. In situ degradation of biodegradable plastic mulch films in compost and agricultural soils. Sci. Total Environ. 727:138668.

Sintim HY, Flury M, 2017. Is biodegradable plastic mulch the solution to agriculture's plastic problem? Environ. Sci. Technol. 51:1068-9.

Soltani N, Anderson JL, Hamson AR, 1995. Growth analysis of watermelon plants grown with mulches and rowcovers. J. Am. Soc. Hortic. Sci. 120:1001-9.

Steinmetz Z, Wollmann C, Schaefer M, Buchmann C, David J, Tröger J, Muñoz K, Frör O, Schaumann GE, 2016. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? Sci. Total Environ. 550:690-705.

Tarara JM, 2000. Microclimate modification with plastic mulch. HortSci. 35:169-80.

Tate RL, 2000. Soil microbiology. John Wiley & Sons, Inc., New York, NY, USA.

Woods End Laboratories, 2016. Soil CO2-burst official Solvita instructions. Woods End Laboratories, Inc., Mt Vernon, ME, USA.

Xu J, Li C, Liu H, Zhou P, Tao Z, Wang P, Meng Q, Zhao M, 2015. The effects of plastic film mulching on maize growth and water use in dry and rainy years in Northeast China. PLoS One 10: e0125781.

Yoshitake S, Sasaki A, Uchida M, Funatsu Y, Nakatsubo T, 2007. Carbon and nitrogen limitation to microbial respiration and biomass in an acidic solfatara field. Eur. J. Soil Biol. 43:1-13.

Yu Y, Zhao C, Stahr K, Zhao X, Jia H, 2016. Plastic mulching increased soil CO2 concentration and emissions from an oasis cotton field in Central Asia. Soil Use Manag. 32:230-9.

Zhang F, Li M, Qi J, Li F, Sun G, 2015. Plastic film mulching increases soil respiration in ridge-furrow maize management. Arid L. Res. Manag. 29:432-53.

Zhang F, Li M, Zhang W, Li F, Qi J, 2017. Ridge–furrow mulched with plastic film increases little in carbon dioxide efflux but much significant in biomass in a semiarid rainfed farming system. Agric. For. Meteorol. 244-245, 33-41.

Zhang F, Zhang W, Qi J, Li F-M, 2018. A regional evaluation of plastic film mulching for improving crop yields on the Loess Plateau of China. Agric. For. Meteorol. 248:458-68.