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Research Letter

Surface Energy Balance Partitioning in Tilled Bare Soils

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Core Ideas

- Following tillage, soil bulk density increased after rainfall.
- Increases in soil bulk density decreased the available energy for turbulent fluxes.
- Surface energy balances in tilled soils are affected by changes in bulk density.

Abstract: Surface energy balance (SEB) partitioning is critical to heat and water budgets at the soil–atmosphere interface. Tillage can alter SEB partitioning by initially decreasing soil bulk density (ρ_b), after which ρ_b increases with time due to rainfall and other factors. The objective of this study is to determine the effect of ρ_b changes on SEB partitioning. We measured SEB components for two 4-d periods (Period 1 and Period 2) at an early-tilled (T1) and late-tilled (T2) bare soil site. During Period 1, ρ_b, net radiation and soil heat flux were similar for T1 and T2, but evaporation was higher at T2. During Period 2, ρ_b was 0.11 g cm^{-3} larger at T2 than at T1. This resulted in a 7% higher soil heat flux at T2, which in turn caused 13% less evaporation. These results highlight the importance of considering dynamic ρ_b with time when determining SEB partitioning for tilled soils.

Energy distribution at the Earth's surface plays a significant role in global meteorological and hydrologic cycles. In agroecosystems, surface energy balance (SEB) partitioning affects seed germination, irrigation requirements, and water use efficiency (Gaudin et al., 2015; Hatfield and Prueger, 2015). Heat and water transfer at the soil–atmosphere interface is affected by soil bulk density (ρ_b), which may change with tillage and with wetting/drying cycles and reconsolidation following tillage. Better understanding of the ρ_b effects on net radiation (R_n) partitioning into soil heat flux (G), sensible heat flux (H), and latent heat flux (LE) is important (Evett et al., 2012; Ochsner et al., 2007), particularly as SEB models generally assume ρ_b to be static (Chen et al., 2014; Ogée et al., 2001).

Tillage reduces ρ_b, increases surface roughness, and destroys any existing surface crust. As larger porosities increase saturated hydraulic conductivity, wetted soil may dry at faster rates initially than if no disturbance had occurred (Potter et al., 1987). Such a decline in volumetric water content (θ_v), along with lower ρ_b , will reduce soil heat capacity, allowing the soil surface to more readily heat and cool (Richard and Cellier, 1998).

Following tillage, R_n tends to increase as greater surface roughness reduces albedo (Idso et al., 1975; Matthias et al., 2000). This increase in R_n may be dampened when lower θ_v increases albedo and larger surface temperatures increase outgoing longwave radiation (Richard and Cellier, 1998).

Greater R_n and larger thermal differences between the soil surface and deeper soil layers may enhance G (Azooz et al., 1997). However, reduced thermal conductivity due to lower θ_v may reduce G (Potter et al., 1987). Allmaras et al. (1977) observed that 0.07 m^3 m^{-3} lower θ_v and 10% greater porosity corresponded to 10% larger G for two tillage treatments. A third tillage treatment,

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Abbreviations: DOY, day of year; SEB, surface energy balance; T1, early-tilled site; T2, late-tilled site.

with similar porosity and θ_v, had 10% smaller G, which was attributed to greater macroporosity and surface roughness.

Greater R_n increases available energy for LE and H. Immediately following rainfall events, LE is therefore expected to be higher for tilled soils, causing a reduction in surface temperature and H (Schwartz et al., 2010). But as the soil dries out, LE may decline more quickly in tilled soils (Richard and Cellier, 1998). Schwartz et al. (2010) reported LE ranging from 0.2 to 2.3 and 0.3 to 1.1 mm d^{-1} on till and non-till sites, respectively. They attributed 53% of the difference to higher R_n and suggested that the larger LE at the till site could also be explained by less developed surface crusts.

Several studies have illustrated the difference in energy partitioning for tilled and non-tilled surfaces (Allmaras et al., 1977; Potter et al., 1987; Richard and Cellier, 1998). However, few studies have assessed how the four main SEB components behave with ρ_b dynamics and associated changes in field hydrology and soil thermal properties over time. In this study, our objective is to quantify the effect of increasing ρ_b with time on the partitioning of R_n to G, LE, and H at tilled bare soil surfaces.

Materials and Methods

Field Description

The field site was located at the Iowa State University Agronomy and Agricultural Engineering Research farm near Boone, IA (42.0173° N, 93.76161° W). The 76- by 38-m site was in a relatively level area on a Clarion loam soil (fine-loamy, mixed, superactive, mesic Typic Hapludoll). The field was divided along the short edge into a western half (early-tilled site [T1]) and an eastern half (late-tilled site [T2]). On day of year (DOY) 164 (13 June 2017), both halves were roto-tilled; on DOY 199 (18 July 2017), T2 was retilled to a ρ_b of about 0.96 g cm^{-3}.

Two periods of focus were selected. Period 1 (DOY 216–220; 4–8 August) began 17 d after the second tillage of T2, and Period 2 (DOY 262–265; 19–22 September) began 63 d following the second tillage of T2.

Field Measurements

Bulk density was determined by oven-drying three replicates of 250-cm^3 soil cores collected from the 0- to 5-cm layer immediately following tillage events and on 23 August and 19 September. A rain gauge (TE525, Texas Instruments) on T1 and T2 recorded the precipitation.

Net radiometers were placed at 1.25 m height above T1 and T2 (NR Lite 2, Kipp and Zonen), and two soil heat flux plates (PHF-03, Prede Co.) were installed at a depth of 0.06 m. Using the combination method (Sauer and Horton, 2005), soil heat storage was determined for the 0- to 0.06-m soil layer with Type T thermocouples placed at depths of 0.02, 0.04 and 0.06 m near each soil heat flux plate. An infrared thermometer (IRT, Apogee, Inc.) was used for surface temperature measurements. To calculate soil volumetric heat capacity (De Vries, 1963), soil volumetric water content was measured using four CS655 sensors (Campbell Scientific, Inc.) positioned horizontally at a depth of 0.03 m near each soil heat flux plate. All data were logged every second (CR3000, Campbell Scientific, Inc.) and saved as 30-min averages.

Soil water evaporation was measured using micro-lysimeters (Boast and Robertson, 1982). Measurements over Period 1 and Period 2 followed 4 d of rainfall totaling 34 mm and 26 mm, respectively. The micro-lysimeters were 10-cm-long and 10-cm-i.d. polyvinyl chloride columns with sharpened edges on one end. The columns were pressed into the soil to obtain intact core samples, capping the bottoms and then weighing the cores, before replacing them into the fields. Each day, core masses of three replicates per site were recorded where the evaporative water loss was equal to the mass difference. Samples were used for a maximum of 2 d as measurement accuracy is known to decrease after this period (Boast and Robertson, 1982). After converting micro-lysimeter evaporation to LE, H was determined as the residual of R_n, G, and LE.

Results and Discussion

At T1, ρ_b for the 0- to 5-cm layer amounted to 1.02 ± 0.03 g cm^{-3} on 16 June, following a 25-mm rain event with a peak intensity of 9 mm h^{-1}. On 17 July, ρ_b was 1.04 ± 0.01 g cm^{-3}, and on 19 September, it was 1.03 ± 0.02 g cm^{-3}. The period between the two tillage events was dry, with rainfall totaling 25 mm and maximum intensities <5 mm h^{-1}. At T2, ρ_b amounted to 1.05 ± 0.04 g cm^{-3} after a 1-h 27-mm rainfall event on 20 July, 1.04 ± 0.04 g cm^{-3} on 23 August, and 1.14 ± 0.02 g cm^{-3} on 19 September. Thus, during Period 1, following another 45 mm of rainfall after July 20, ρ_b was similar for T1 and T2, with values of about 1.04 and 1.05 g cm^{-3}, respectively. Period 2 started on 19 September with slightly larger ρ_b values at T2, following 91 mm of rainfall between the periods. While it was expected that the T1 ρ_b would be larger as there had been more time for the soil to consolidate, it may be that the extended dry period following the first tillage allowed T1 to develop a soil crust, making it less likely to be impacted by rain. T2 may also have had additional aggregates due to being tilled twice, making it more structurally unstable than T1.

Net Radiation and Soil Heat Flux

Daytime R_n was similar in T1 and T2 during Period 1 (11.8 and 11.9 MJ m^{-2} d^{-1}) when ρ_b was similar. There were also no observable differences in diurnal R_n patterns for the period (Fig. 1a). However, in Period 2, daytime R_n was 9.5 and 9.0 MJ m^{-2} d^{-1} for T1 and T2, respectively, with midday R_n peaking on average at 38 W m^{-2} lower in T2 (Fig. 1b). Greater R_n is common in low ρ_b soils and is usually attributed to larger surface roughness. If that is the case here, then T1, which was tilled before T2, somehow maintained greater surface roughness over time. Similar to R_n, diurnal G values of Period 1 in T1 and T2 were comparable. The θ_v was similar as well, with average daily values declining from 0.09 to 0.075 cm^3 cm^{-3} for both T1 and T2. The smallest G values occurred when the soil was wettest in the first days of each period but increased as the soil dried (Fig. 1a, 1b). Although R_n was on average 5% lower at T2 in Period 2, G was larger, as 7% more

R_n partitioned into G at T2 for the 4-d period. Average daily θ_v declined from 0.09 to 0.07 cm^3 cm^{-3} at T1 and from 0.11 to 0.09 cm^3 cm^{-3} at T2. It therefore appeared that the larger G in T2 was affected more by increased θ_v and thermal conductivity (Potter et al., 1987) than by reduced thermal gradients (Azooz et al., 1997).

Evaporation and Partitioning of Turbulent Fluxes

Evaporation rates on the initial day of Period 1 were 1.2 and 2.0 mm d^{-1} in T1 and T2, respectively (Fig. 1c). As the surface dried and LE declined, the differences between T1 and T2 diminished. These values corresponded to R_n partitioning fractions, as 19% more energy partitioned into LE at T2 than T1 in the initial 2 d of Period 1. These differences may be attributed to a less developed crust at T2, resulting in less soil surface resistance to vapor flow (Schwartz et al., 2010).

During Period 2 (when a larger ρ_b was observed at T2), T1 evaporated 0.7 mm (21%) and 0.3 mm (16%) more water than T2 on DOY 262 and 263, respectively (Fig. 1d). For these 2 d, 13% less R_n partitioned into LE at T2 compared with T1 for the initial 2 d, a 32% change from Period 1. As the soil surface dried, there was no clear difference in the percentage of R_n partitioned to LE. Evaporation is most pronounced when the surface is wet and soil surface evaporation is energy-limiting (Heitman et al., 2008; Xiao et al., 2011). In more recently tilled soils, larger LE is usually observed due to smaller ρ_b and a less developed surface crust, exposing available water (Richard and Cellier, 1998; Schwartz et al., 2010). Because surface crusts at T1 and T2 were noticeably similar in Period 2, the higher LE values at T1 may be attributed to differences in ρ_b. While differences of 0.11 g cm^{-3} ρ_b are rather small, it appears that the greater R_n and smaller G associated with the lower ρ_b may have increased available energy for LE at T1.

In Period 1 and 2, daytime H comparisons were opposite of LE, as was expected (Fig. 1e, 1f). During Period 1, partitioning of available energy to H/R_n increased daily from 36 to 56% and 8 to 42% at T1 and T2, respectively (Fig. 2a, 2c). In Period 2, H/R_n increased daily from 1 to 59% and −8 to 68% (Fig. 2b, 2d). A negative H at T1 for the first day of the period (DOY 262) corresponded to an LE fraction larger than the energy available at the T1 soil, indicating that wind may have contributed advective energy on this day (Todd et al., 2000).

Conclusion

In this study, we observed various degrees of increase in ρ_b with time following tillage. It appears that extended dry periods following tillage may improve structural stability of the soil. However, even slight increases in ρ_b can alter LE by 13%. Hence, when measuring and modeling SEB components, changes in ρ_b should be considered.

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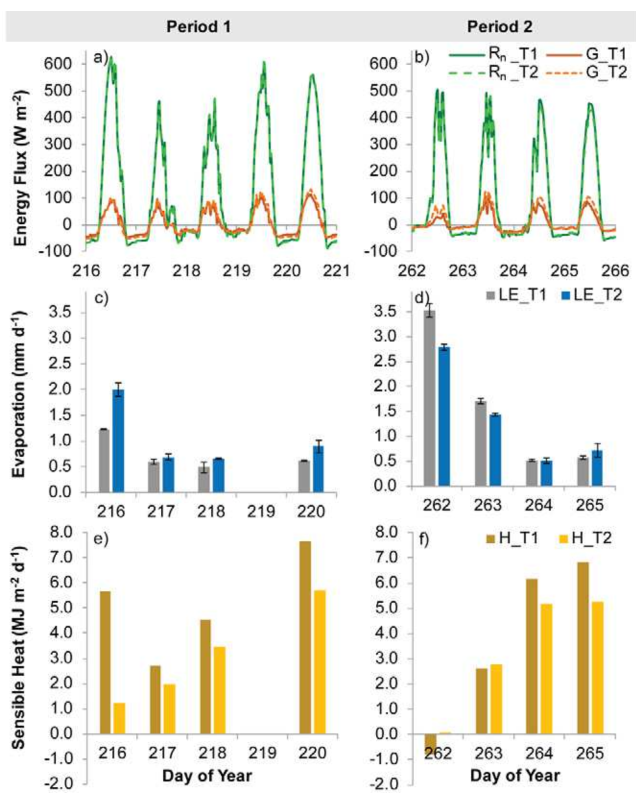

Fig. 1. Net radiation (R_n), soil heat flux (G), daytime micro-lysimeter evaporation (LE), and sensible heat flux (H) during (a,c,e) Period 1 (day of year [DOY] 216–220) and (b,d,f) Period 2 (DOY 262–265). T1, early-tilled site; T2, late-tilled site. Error bars indicate one standard error of the mean micro-lysimeter values (n = 3; for T2 on DOY 264–265, n = 2).

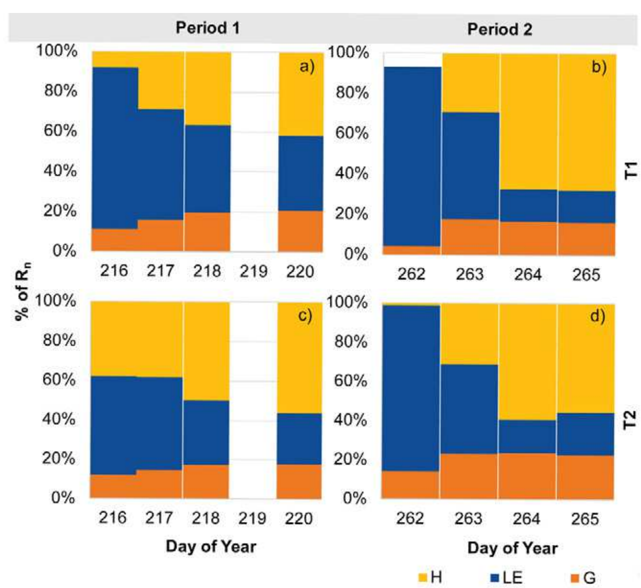

Fig. 2. Daytime percentages of net radiation (R_n) partitioned into soil heat flux (G), latent heat flux (LE) and sensible heat flux (H) for (a,b) early-tilled site (T1) and (c,d) late-tilled site (T2) during Period 1 (day of year [DOY] 216–220) and Period 2 (DOY 262–265).

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