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Soil energetics: A unifying framework to quantify soil functionality

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Abstract

Massive quantities of energy flow through soils during a year. Emerging views indicate that when supplied with abundant energy, soil biology acts as a self-organizing system as soil microbes forge their habitats into a porous, well-aggregated structure with high functionality. The flow of energy to power these self-organizing processes has not been accounted for in present soil models, which concentrate on static pools of soil organic matter (SOM) and carbon and their relationship to soil functionality. To address this, we introduce a new conceptual energetics framework that quantifies the net energy flows within a soil control volume (CV) using a suite of energetic components including mechanical, biogeochemical, and hydrological processes. This framework is presented at a conceptual level and can be expanded to more granular levels with further study. To assess its present capabilities, management systems of conventional-till (CT) and no-till (NT) corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotations and a grassland system (GS) were evaluated using the model. Net energy fluxes over a growing season were found to be negative for the CT, net zero for NT, and positive for GS. The energetics framework shows it can provide a first-order assessment of soil health and advise which management practices provide adequate supplies of energy to soil biology to effectively enhance soil functionality.

1 | INTRODUCTION

Soils are the foundation upon which agriculture is built, and soil management is at a crossroads in terms of being able to provide the functions necessary to support agriculture into the future (Hatfield et al., 2017). Some primary questions central to this goal are how can the functionality and resilience of soil be improved and what processes need to be considered to achieve these goals? Much focus traditionally has been

put on changing the soil by adding carbon into the soil to restore soil organic matter (SOM) and the associated functions of nutrient cycling, soil water holding capacity, and structural changes. Changes in these soil functions are often seen before changes SOM can be measured, and simply adding more organic material to a soil has not been shown to reliably result in heightened soil function. In a recent study, Williams and Plante (2018) proposed a bioenergetic framework for the quantitative assessment of SOM looking at changes in SOM formation and decomposition. Soil organic matter is treated as a continuum of organic material continuously processed by the decomposer community and with increasing oxidation

Abbreviations: CT, conventional till; CV, control volume; GS, grassland system; NT, no till; OM, organic matter; SOM, soil organic matter.

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and solubility protected from decomposition through mineral aggregation and adsorption. This approach also looked at how various food sources have different energy costs to access the energy in the food source, bringing ideas of energy consumption by microbes into the soil. Building on these concepts, Gunina and Kuzyakov (2015) drew a direct line from sugars exuded by plants into the soil to facilitate soil aggregation and structural formation via biogeochemical processes. These findings suggest that we should focus on energy inputs into the soil and efficiency of use for microbes as the drivers of microbial systems in the soil (Cotrufo et al., 2013; Chakrawal et al., 2021). As these microbial systems are directly responsible for the structuring of the soil, the role of energy inputs into the soil as the foundation piece of how soils begin to change functional states and store SOM opens as an area of investigation.

We propose that changes in soil, and eventual increases in carbon stocks in soil, occur when there is a net positive supply of energy into the soil to support biological systems capable of altering the soil structure. Additionally, mechanical models of soil breakdown processes, both from tillage and rainfall kinetics, have been expressed in energetic terms (Watts et al., 1996a; Gabet & Dunne, 2003; Papanicolaou et al., 2015), allowing for both soil formation and degradation processes to be incorporated into the same energetic formulation. Energetics principles have been used to describe relations and transformations in physical, chemical, and biological systems (Ksenzhek and Volkov, 1998; Smil, 2007; Tomlinson et al., 2014) but has not been defined for soil systems, let alone agricultural soil systems, where energetic flows are highly tied to management. Therefore, the goal of this paper is to present the concept of soil energetics as a framework to better understand changes in soil function and carbon dynamics. A series of equations are presented describing the flow of energy into and out of an agricultural soil system, and areas of future application and study are outlined.

2 | SOIL ENERGETICS IN AGRICULTURAL SYSTEMS

Soils are often described as having three parts that interact to form the complex matrix we know as soil. These parts are the physical, chemical, and biological parts of the soil system. Claims have been made for each of these three aspects to have controlling influence over soil properties and function. Organic matter (OM) is often pointed to for its physical and chemical properties in aiding in flocculation, water holding capacity, and nutrient holding capacity, all which are aspects of soil functionality (Hoffland et al., 2020). Aspects of physical structure are often cited as having proper proportions of clay, silt, and sand; soil pH; and clay mineralogy (Kemper & Rosenau, 1986). However, functional soils can be found with a wide range of proportions of constituent elements. Chemical

Core Ideas

- Net positive supplies of energy support biological systems capable of altering the soil structure.
- Management practices impact energy fluxes through tillage type and intensity and raindrop-induced erosion events.
- An energetic framework is proposed that is applied to three different management practices to assess energy balances.
- Seasonal net energy balances for conventional till, no till, and grassland system were negative, neutral, and positive, respectively.

aspects have often been theorized in the past with certain mineral balances being put forward as being necessary for proper soil function; however, soils lacking these balances are often observed to be functioning at high levels as well. In a review of the literature on the drivers of SOM changes that showed how different factors ranked in a hierarchical relationship, Wiesmeier et al. (2019) summarized that soil microbial activity was the most important factor across time and space scales in controlling soil dynamics. As energy sources for soil microbial systems determines the extent to which these systems can function, it is logical that the energy to supply to the soil has the controlling influence on soil dynamics.

We propose that the soil energetic balance is key to creating and maintaining soil functionality. Energy flowing into and out of the soil through plant exudates and the deposition of plant detritus is used for the creation and maintenance of the biological community. The biological community uses that energy for the creation and maintenance of the soil structure. A consideration of soil energetics and its relationship to the physical, chemical, and biological aspects of soil shows the interrelationship of these soil elements to one another, demonstrating in which circumstances the different parts of the soil system assume mechanistic control over the system (Figure 1).

The physiochemical aspect of the soil is composed of the parent material of the soil and its natural chemical state. This includes the texture, mineral composition, pH, salinity, and sodicity of the soil. These aspects of the soil change only with major additions or removal of material, whether from natural processes or human intervention. These provide the environment, or context, in which biology functions. The pH and the aerobic or anaerobic state of the soil dictate the respiration pathways available for energy to be processed in the soil. The parent material of the soil dictates the surface area in the soil for microbial life to exist (e.g., high clay soils vs. sandy soils). It has been observed that microbial diversity is highly dependent on the physiochemical state of the soil (Xu et al.,

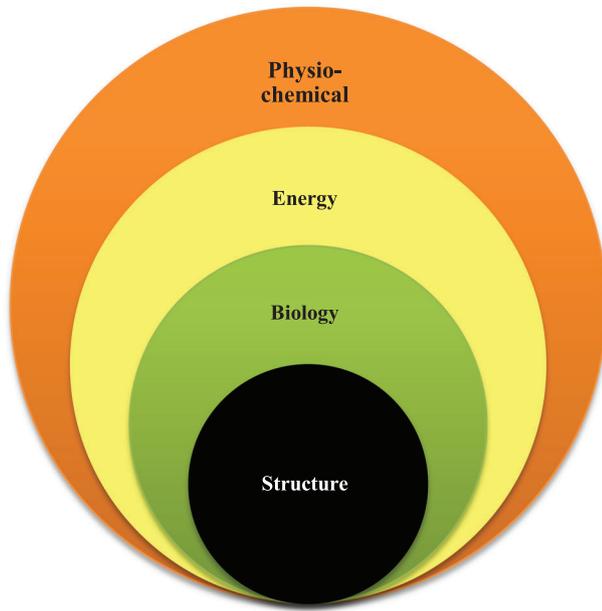


FIGURE 1 Concentric circles model of soil hierarchal interrelationship

2018). Additionally, these parent materials will naturally flocculate or deflocculate, effecting the amount of energy required by biological processes to aggregate sand, silt, and clay into stable aggregates. Structure beyond the natural propensities of the parent material to aggregate is not included our physiochemical category as fully structured soils are a result of biological activity and are therefore dependent on energy flow to create this structure.

The physiochemical state of the soil provides the context for how biology will function because of the chemical environment the biology is operating in. The amount of energy flowing into the soil, whether in the form of plant detritus, roots, root exudates, or deposition from human or natural processes such as spreading manures or erosion processes, determines the energy supply available for biology in the soil. This energy flow is affected by plant type, which is determined both by local climate and the physiochemical makeup of the soil. The amount of energy available for biology determines whether biology will be able to build the structure the soil to an optimal functional state, maintain the functional state, or result in decline of the functional state.

This framework provides a hierarchal structure in which the relationships among different parts of the soil systems are ordered and operate in predictable ways. The structure of the soil is the direct result of biology using energy to build structure. Biology relies on the energy supply provides by plant-derived photosynthate to operate. The physiochemical makeup of the soil determines what respiration pathways biology can run to use this energy and the textural environment the biology is dealing with to create the structure. The physio-

chemical makeup of the soil together with the broader climatic environment of a particular location determine the makeup of the plant community providing the photosynthate.

The hierarchal relationship between the different parts is clear in that although the physiochemical state of the soil effects how biology will function, biology does not have the ability to change the physiochemical state of the soil with the exception of longer time frames than are being treated in examining the relationship between energy flow and soil functionality. Also, the biology in the soil cannot directly increase the amount of energy flowing to it in a substantial way. Feedback loops in the hierarchal system do exist. As the structure of the soil becomes more aggregated, the functionality of the soil increases, resulting in increased vegetation growth and more photosynthate flowing into the soil. The functional limit of the soil is bounded by the ability of the soil to maintain a porous structure network, which impacts water, oxygen, and substrate transport and thus reaction and transformation processes.

The soil formation factors outlined by Jenny (1994) serves as a reminder that soil is formed through weathering of parent material, topography, climate, organisms, and time. The organism component of soil formation, in particular, the plant community growing in the soil, is the mechanism for the transfer of energy as primarily carbon-based compounds, such as sugar in the form of root exudates, into the soil. The exudation of simple sugars into soils by plants directly results in the buildup of soil aggregates through the creation of polysaccharides by microbiology that uses the simple sugars both as an energy source and a building block of the polysaccharides (Gunina & Kuzyakov, 2015) representing the other portion of the organismal component of soil formation.

2.1 | Conservation of energy and soil energetic aspects

This soil energetics framework adopts a generalized approach for mass balance models and uses the control-volume (CV) concept and transport across boundaries. The system is treated as an open, natural system within a fixed CV. The soil CV is fixed at a depth of 20 cm, as soil microbial abundance and diversity have been shown to be highest in the upper 10–20 cm and decline with depth (Aislabie et al., 2013). The soil CV builds upon the soil-active-layer concept (top 20 cm) and formulation presented in Papanicolaou et al. (2015), where a biogeochemical model was coupled with a transport model to simulate the redistribution of soil and OM along the downslope with updates to the soil active layer though additions and losses of material from erosion and deposition processes. This method also incorporates the effects of raindrop impact (kinetic energy) and runoff power (shear stress) from overland flow on the soil CV following approach by Gabet and Dunne

(2003). Lastly, the framework also incorporates the role of tillage-induced erosion and incorporation and translocation of soil and OM through mechanized tillage using methods proposed by Van Oost et al. (2005a).

Energy in agricultural systems derives from the sun as sunlight captured through photosynthesis converts radiation energy into chemical energy in glucose molecules (Oncley et al., 2007). Not all the solar radiation intercepted by the soil–plant canopy is used in photosynthesis. The net radiation per square unit of land surface is frequently determined using energy balance theorems to partition surface energy fluxes (Monteith & Szeicz, 1960; Sauer et al., 2007):

$$\Delta R_{\text{net}} = \left(\sum \text{LE} + \sum H + \sum G + \sum S + \sum E_{\text{photo}} \right) \Delta t \quad (1)$$

where, ΔR_{net} is the change in net radiation representing the amount of energy impinging on a canopy as a balance between incoming solar radiation and the amount reflected to the atmosphere and the incoming longwave radiation and the amount emitted back to the atmosphere (MJ m^{-2}). Expressing the other components as rates, LE represents the latent heat of evaporation ($\text{MJ m}^{-2} \text{d}^{-1}$), H is the sensible heat ($\text{MJ m}^{-2} \text{d}^{-1}$), G is the soil heat flux ($\text{MJ m}^{-2} \text{d}^{-1}$), S is the heat storage in the vegetation ($\text{MJ m}^{-2} \text{d}^{-1}$), E_{photo} is the energy for photosynthesis ($\text{MJ m}^{-2} \text{d}^{-1}$), and Δt , is the change in time (d^{-1}). Generally, the S and E_{photo} terms in Equation 1 are ignored because they represent a small amount of the energy used by a plant canopy when compared with other terms; however, in the consideration of energy utilization by a crop and in the soil, these terms become critical (Meyers & Hollinger, 2004).

The ΔE_{photo} (MJ m^{-2}) can be expanded to include the energy stored or exuded within plant shoots, E_{shoot} ($\text{MJ m}^{-2} \text{d}^{-1}$), roots, E_{root} ($\text{MJ m}^{-2} \text{d}^{-1}$), and exudates, E_{exud} ($\text{MJ m}^{-2} \text{d}^{-1}$), as well as the energy generated through autotrophic respiration processes, E_{resp} ($\text{MJ m}^{-2} \text{d}^{-1}$):

$$\Delta E_{\text{photo}} = \left(\sum E_{\text{shoot}} + \sum E_{\text{root}} + \sum E_{\text{exud}} + \sum E_{\text{resp}} \right) \Delta t \quad (2)$$

When dealing with grain cropping systems, the ΔE_{shoot} (MJ m^{-2}) has the grain portion removed during harvest, E_{grain} ($\text{MJ m}^{-2} \text{d}^{-1}$), while the remaining supply of residue, $E_{\text{resd,surf}}$ ($\text{MJ m}^{-2} \text{d}^{-1}$), from the combine is spread atop the soil surface:

$$\Delta E_{\text{shoot}} = \left(\sum E_{\text{grain}} + \sum E_{\text{resd,surf}} \right) \Delta t \quad (3)$$

The E_{root} and E_{exud} are confined within the soil CV, while the $E_{\text{resd,surf}}$ sits atop the soil CV as a potential input of energy until the residue is incorporated (transported) into the soil CV ($E_{\text{resd,soil}}$) through a tillage event or surface decay within the litter layer (Figure 2).

Combining Equations 2 & 3 allows the energetic components to be separated into internal and external sources:

$$\Delta E_{\text{photo}} = \left(\sum E_{\text{resd,soil}} + \sum E_{\text{root}} + \sum E_{\text{exud}} \right) \Delta t + \left(\sum E_{\text{resp}} + \sum E_{\text{grain}} + \sum E_{\text{resd,surf}} \right) \Delta t \quad (4)$$

where, the $E_{\text{resd,soil}}$, E_{root} , and E_{exud} components are in the first grouping, representing the internal flow of energy into the soil ($E_{\text{in soil}}$), while the E_{resp} , E_{grain} and $E_{\text{resd,surf}}$ components are in the second grouping and are considered external to the soil CV.

To apply an energy balance to the soil CV, both inputs ($E_{\text{in soil}}$) and outputs (losses) of energy from the soil need considered. Losses of energy from the soil CV ($E_{\text{out soil}}$) can be estimated using the following relation:

$$\Delta E_{\text{out soil}} = \left(\sum E_{\text{microb}} + \sum E_{\text{rain}} + \sum E_{\text{erod}} + \sum E_{\text{mgt}} \right) \Delta t \quad (5)$$

which consists of energy lost through biological processes associated with microbial activity, E_{microb} ($\text{MJ m}^{-2} \text{d}^{-1}$), hydrologic forces associated with raindrop impact, E_{rain} ($\text{MJ m}^{-2} \text{d}^{-1}$), water-driven erosion processes (detachment, mobilization, and transport), E_{erod} ($\text{MJ m}^{-2} \text{d}^{-1}$), and mechanized forces associated with tillage management, E_{mgt} ($\text{MJ m}^{-2} \text{d}^{-1}$).

Figure 3 provides a conceptual sketch highlighting the energetic components of a CT corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation within a typical, rain-fed, temperate agroecosystem in the U.S. Midwest. The top section of the schematic represents the energy inputs into the soil ($E_{\text{in soil}}$), while the bottom section represents the losses ($E_{\text{out soil}}$). The middle section of the schematic highlights some of the processes associated with management induced losses. Along the top of Figure 3 are the months of the year, and the size of the arrows represents the magnitude of energy flowing into and out of the soil CV.

Expanding on the loss terms, the energy that is entering the soil in the form of root exudates is quickly taken up and used by microbes. These compounds are either used for respiration by the microbe or for constituent matter or for making different polymers that effect soil aggregation (Gunina & Kuzyakov, 2015). The first main area of biological energy losses is the energy that is respired away (E_{microb}). Exudates and residue provide the carbon source that supports the growth and maintenance of microbial biomass communities (Ågren & Bosatta, 1996; Stockman et al., 2013). Microbial activity (decay processes) has been shown to be sensitive to soil temperature and moisture conditions and texture (Parkin et al., 2005). Soil CO_2 fluxes from microbial respiration have been found to double for every 10°C increase in soil

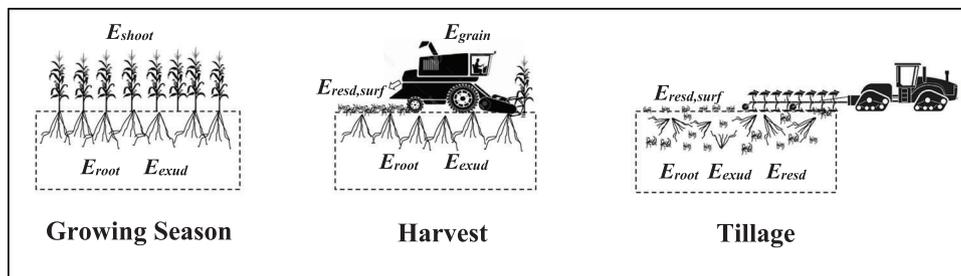


FIGURE 2 Schematic of energy components within the soil control volume (CV) impacted by different management practices. E_{shoot} , energy stored or exuded within plant shoots; E_{root} , energy stored or exuded within plant roots; E_{exud} , energy stored within plant exudates; E_{grain} , grain portion of energy removed during harvest; $E_{resd,surf}$, energy stored in surface residue; E_{resd} , energy supplied to the soil from residue

temperature (Haddix et al., 2011). Crop type has also been found to impact soil CO_2 fluxes, where Parkin et al. (2005) reported three times higher fluxes in corn systems than in soybean systems, in part, because of larger plant biomass and increased root activity (Anderson et al., 2004).

The E_{mgt} includes the mechanical energy applied to the soil through tillage operations. Primary tillage operations have been shown to range from 0.01 to 0.04 $MJ\ m^{-2}$ based on levels of tillage intensity, tillage depth, and soil conditions (Watts et al., 1996a). During tillage events, surface residue is incorporated into the soil, which increases microbial activity and enhances the biological oxidation of SOM (Van Oost et al., 2006). These events trigger a sharp spike in CO_2 from the soil ($E_{microb-spk}$), as the previously protected organic matter within aggregates are fractures and exposes to oxidation processes (Reicosky et al., 2005). Reicosky and Lindstrom (1993) reported that intensive tillage through a moldboard plow caused the soil surface area to increase by 50% after one event. Soil CO_2 fluxes in CT systems were 62–118% higher than NT fields based on tillage intensity and tillage depth (Sainju et al., 2008). The tillage-induced fluxes can become even more amplified during rainfall or irrigation events (Daly et al., 2008), as rapid rewetting of the soil enhances nutrient mineralization, and cycling causes a large pulse of CO_2 to be released from the soil (Miller et al., 2005). Further, tillage can also enhance erosion processes by disassociating soil aggregates, decreasing soil strength, and facilitating particle mobility under fluid forces (Rhoton et al., 2002; Van Oost et al., 2005b).

During a rainfall event, the kinetic energy of falling raindrops, E_{rain} , is transferred to the soil surface at varying magnitudes based on the mass of the drop and its corresponding terminal velocity (Carollo et al., 2017; Wacha et al., 2021). Rainfall intensity determines raindrop impact, which is the triggering mechanism for splash and detachment, while the resulting runoff mobilizes and transports the finer soil particles and residue across the landscape (Parsons & Stone, 2006; Beguería et al., 2015; Shanshan et al., 2018). Erosion events have been shown to significantly impact the persistence of

OM in agricultural soils (Berhe et al., 2012). Chaplot and Cooper (2015) showed that each year 18.9% of soil carbon stocks are removed in the top 5 cm by erosion. Surface residue cover and presence of a crop canopy have been shown to significantly decrease the transfer of energy via raindrop impact and dampen erosion losses (Al-Kaisi & Yin, 2005).

Although the inputs of energy into the soil may be well defined, outputs vary depending on many factors that are heavily influenced by management practices in agricultural systems. To define changes in energy with respect to time, ΔE ($MJ\ m^{-2}$), take the difference between inputs $E_{in\ soil}$ ($MJ\ m^{-2}\ d^{-1}$) and outputs $E_{out\ soil}$ ($MJ\ m^{-2}\ d^{-1}$) in the soil CV:

$$\Delta E = \left(\sum E_{in\ soil} - \sum E_{out\ soil} \right) \Delta t \quad (6)$$

2.2 | Energy flow rates into and out of the soil control volume

Capture of solar radiation by plants is a function of the leaf area of the plant, the extinction coefficient, and the incident solar radiation. This is a relatively simple yet complex process, and in this discussion the focus is on the amount of energy captured. The literature on light capture of plant canopies is voluminous and has been the effort of the world community to determine how crop canopies intercept solar radiation. The concept of radiation use efficiency provides the framework for light capture and conversion to biomass. Loomis and Amthor (1999) stated that C_4 plants would have a conversion efficiency of 4.0–5.8 $g\ MJ^{-1}$ of intercepted photosynthetically active radiation, while C_3 plants range between 1.5 and 2.0 $g\ MJ^{-1}$.

Let us consider at midday across the Midwest at the height of summer (day of year 221) on a sunny day (Figure 4a) where there would be $\sim 18.77\ MJ\ m^{-2}\ d^{-1}$ net incident solar radiation upon a crop canopy, and if 90% of the light is intercepted, there would be $16.89\ MJ\ m^{-2}\ d^{-1}$ of energy captured by the

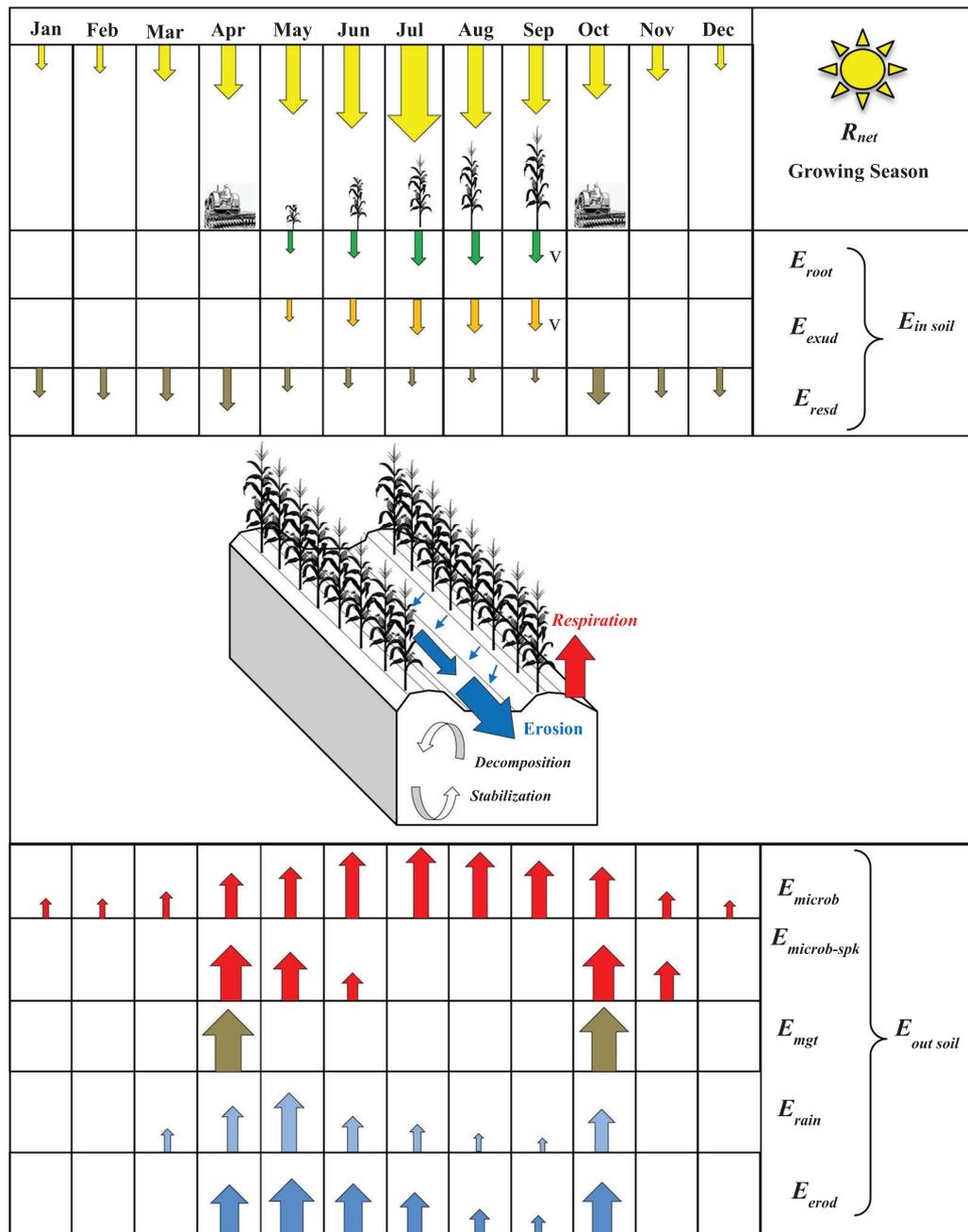


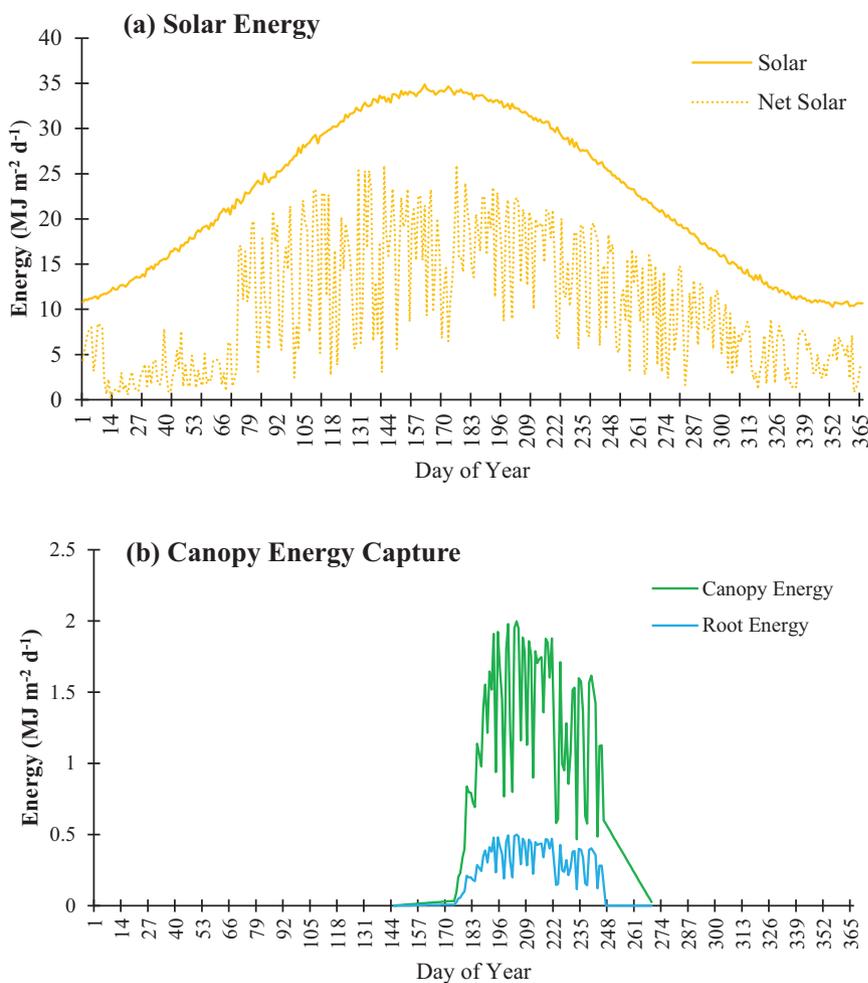
FIGURE 3 Conceptual diagram of energy components (inputs and outputs) within a high energy conventional row crop system. R_{net} , net radiation; E_{root} , energy stored or exuded within plant roots; E_{exud} , energy stored within plant exudates; E_{resd} , energy supplied to the soil from residue

crop canopy. This would be further reduced by the fact that ~90% of the intercepted energy, or $1.6 \text{ MJ m}^{-2} \text{ d}^{-1}$, is utilized in the process of evaporating water via transpiration (Hatfield et al., 1984). We can assume that early in the growing season that the root/shoot ratio (R/S) would be near 0.50, while during the grain-fill period the R/S ratio would be ~0.20. This equates to $0.80 \text{ MJ m}^{-2} \text{ d}^{-1}$ of energy being supplied to the roots during vegetative growth and $0.32 \text{ MJ m}^{-2} \text{ d}^{-1}$ during grain filling. By expanding the summary by Gunina and Kuzyakov (2015), based on observations by Kuzyakov and Domanski (2000) and Warembourg and Estelrich (2000),

approximately 15–40% of the E_{root} is being supplied to the soil as a root exudate. A conservative range in the E_{exud} for a maize canopy during the middle of summer is $0.048\text{--}0.128 \text{ MJ m}^{-2} \text{ d}^{-1}$ based on the amount of photosynthesis that occurs during the middle of the day. These values represent the upper limit of the potential amount of energy capable of flowing into the soil in this particular system.

As shown in Figure 4, these measurements integrated over an entire year are as such: total potential solar incoming is $8,291.05 \text{ MJ m}^{-2}$, available solar for a corn field is $3,800.41 \text{ MJ m}^{-2}$, intercepted solar by corn canopy is 974.96 MJ m^{-2} ,

FIGURE 4 Time series of energy from (a) potential incoming solar (solid orange line) and net solar (dashed orange line) and (b) energy intercepted by a corn canopy (green line) and energy transported to roots (blue line) for Ames, IA, in a typical year



97.50 MJ m⁻² is used for net primary production, and the portion into roots is 48.75 MJ m⁻². As 15–40% of the total energy transported to the roots is often exuded into the soil the total amount of energy from a corn crop in Ames, IA, that makes it into the soil as exudates would be in a range of 7.31–19.50 MJ m⁻².

For comparison, using the assumption by Dilly (2005), where soil carbon can be converted to energetic units using an energy equivalent of 2,877 kJ mol⁻¹ (Thauer, 1977; Odum & Odum, 2000), the total amount of latent energy present in the OM fraction of a soil at 3% OM is 83.36 MJ m⁻². Assuming a mineralization rate of 2% per year would mean there are 1.66 MJ m⁻² yr⁻¹ being utilized by the soil microbiology from OM in the soil. Adding the average of the range of values calculated above for energy entering the soil as root exudates (13.41 MJ m⁻² yr⁻¹) and accounting for the remaining 7.09 MJ m⁻² yr⁻¹ coming from detritus, then the breakdown of the 22.16 MJ m⁻² respired from the soil during the growing season is 7.5% from OM, 31.5% from detritus, and 60.54% from root exudates. This indicates over half of the energetics in the soil comes from the in-season deposition of root exudates through growing plants.

2.3 | Challenges in accounting for dynamic energy fluxes in a quasi-static system

As most of the total amount of energy used by microbes for soil processes comes from root exudates in the soil it may be asked how such a volume of energy has not been noticed or accounted for before in soil sampling and testing. This is due to the different time scales on which root exudates exist and soil sampling is done regardless of the time of year a sample is taken. Gunina and Kuzyakov (2015) state that the average amount of time a sugar molecule exuded by a plant exists in the soil before it is taken up by a microbe is 5 min. When collecting soil samples, cores are removed from their in situ environment and taken to labs for analysis. This collection process generally takes more than 5 min, and the soil microbes are still active in the sample while plants have been removed. Therefore, any sugar present at the taking of the sample is used before analysis begins. In the best-case scenario of having lab equipment present at the site, the sample is taken only the past 5 min of sugars will be present and would simply be pooled with the 'active' portion of the SOM in a tradition breakdown of the SOM present.

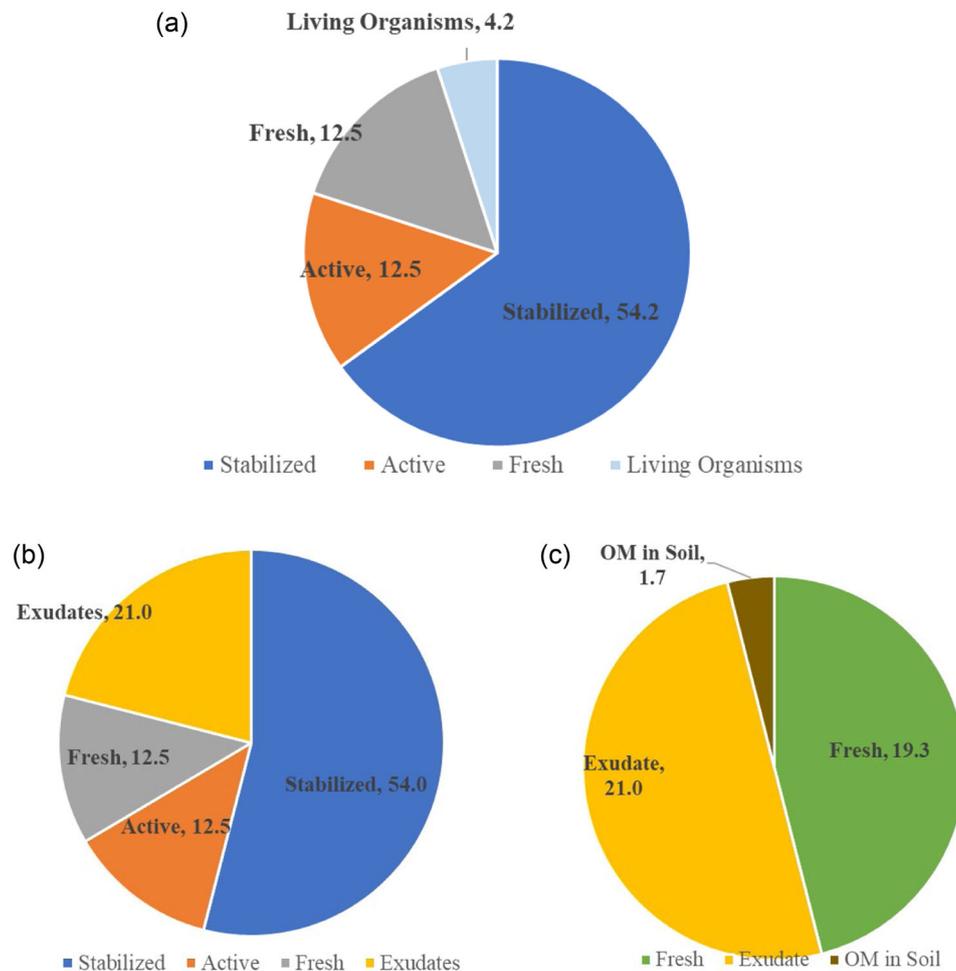


FIGURE 5 Pie charts highlighting the magnitudes of energy within a soil control volume (CV) including (a) energy breakdown by organic matter (OM) pools found within an instantaneous soil sample, (b) energy present within OM pools over a growing season, and (c) energy used over a growing season. All units are in MJ m^{-2}

Based on the calculation above, such a sample, at most, would contain $\sim 4.21 \times 10^{-3} \text{ MJ m}^{-2}$ if the sample contained the full CV. Compare this with the total energy value of SOM present in the sample of 83.36 MJ m^{-2} ; it is easy to see why this energy is not noticed. The exudates in a sample like this constitute only $5.04 \times 10^{-6}\%$ of the total energy in the active portion of the SOM (Figure 5a). Over the course of the year on a mixed grassland system in Iowa, the total amount of energy passing through the soil in the form of exudates was calculated based on net primary productivity as 21.00 MJ m^{-2} . This comprises 20.96% of the total energy present in the soil over the course of a year (Figure 5b). Grouping the SOM pools together as stated above, the percentage of energy utilized by microbes from the stable SOM pool is calculated as only 3.98%, the amount for detritus is 46.01%, and the amount from exudates is 50.01% (Figure 5c). In essence, the reason this energy has not been accounted for before is due to the instantaneous aspect of soil sampling methodology of a flux system as opposed to the integration of the flux over the course of a

growing season. If we hypothesize that surface residue (detritus) in this grassland system is confined mainly to the top 10 cm of the soil column, energy deeper than this is most likely almost solely from root exudates and root detritus.

3 | ANALYSIS OF SOIL ENERGETICS UNDER DIFFERENT MANAGEMENT SCENARIOS

Table 1 provides a summary of the assumptions and references used to estimate the net soil energetics under three different management scenarios, highlighting differences in $E_{\text{in soil}}$ and $E_{\text{out soil}}$ (Table 2). The management scenarios include a CT corn–soybean rotation, conservation till (NT) corn–soybean rotation, and a native warm-season GS in Iowa. For inputs ($E_{\text{in soil}}$), the harvest index and root/shoot ratio were used to partition the net primary production into E_{root} and potential E_{resd} . The E_{resd} was adjusted to capture the portion that would

TABLE 1 Assumptions and references used in estimating energy balances

Parameter	Units	Range	Management	Reference
Net primary production (NPP)	g carbon m ⁻²	1,400	Corn	Prince et al. (2001)
		450	Soybean	
		600	Grassland	
Root/shoot ratio (RS)	–	0.11–0.19	Soybean	Bray (1963); Allmaras et al. (1975); Anderson (1988); Silvius et al. (1977)
		0.15–0.23	Corn	
		0.87	Grassland	
Harvest index (HI)	–	0.50–0.54	Corn	Kiniry et al. (1997); Prince et al. (2001)
		0.42	Soybean	
		4.55	Grassland	
Soil respiration (SR)	g carbon m ⁻² d ⁻¹	2.4	Corn	Raich and Tufekciogul (2000)
		2.7	Soybean	
		900	Grassland	
Microbial biomass carbon (MBC)	mg kg ⁻¹	600	Corn–soybean	Carpenter-Boggs et al. (2003)
		60	Chisel plow	
		35	Field cultivator	
Tillage residue incorporation	%	65	Disc	Pikul et al. (2001); Logsdon (2013)

TABLE 2 Energetic components within conventional tilled (CT), no-till (NT), and grassland (GRASS) systems. All units are presented in MJ m⁻²

Component	CT		NT		GRASS Mixed grass
	Corn	Soybean	Corn	Soybean	
	MJ m ⁻²				
Inputs					
E_{exud}	10.1	11.3	10.1	11.3	21.0
E_{resd}	4.2	16.6	3.0	11.9	12.0
E_{root}	10.1	2.0	10.1	2.0	20.9
Total in ($E_{\text{in soil}}$)	24.4	29.8	23.2	25.1	53.8
Outputs					
E_{microb}	22.1	24.8	22.1	24.8	41.9
$E_{\text{mgt microb-spike}}$	3.1	3.5	0.0	0.0	0.0
E_{mgt} (primary tillage)	0.4	0.4	0.0	0.0	0.0
E_{mgt} (secondary tillage)	0.1	0.1	0.1	0.1	0.0
E_{rain}	10.8	10.8	3.1	3.1	1.5
E_{erod}	3.2	3.2	0.10	0.10	0.04
Total out ($E_{\text{out soil}}$)	39.7	42.8	25.4	28.1	43.4
Net (E_{net})	–15.3	–13.0	–2.3	–3.0	10.4
Net (E_{net}) 2-yr crop rotation	–28.3		–5.3		20.8

Note. E_{exud} , energy stored within plant exudates; E_{resd} , energy supplied to the soil from residue; E_{root} , energy stored or exuded within plant roots; E_{microb} , energy loss through biological processes associated with microbial activity; E_{mgt} , energy loss through mechanized forces associated with tillage management; $E_{\text{mgt microb-spike}}$, energy loss through enhanced respiration because of tillage; E_{rain} , energy loss through hydrologic forces associated with raindrop impact; E_{erod} , energy loss through water-driven erosion processes.

be transferred to the soil CV using assumptions of residue incorporation rates with respect to tillage type and surface decomposition (Table 1).

For outputs ($E_{\text{out soil}}$), the energy production from E_{microb} (MJ m^{-2}) was calculated using soil respiration rates and the energy gain from glucose mineralization using the relation by Wieser (1986):

$$E_{\text{microb}} (\text{MJ m}^{-2}) = \text{SR} (\text{moles CO}_2 \text{ m}^{-2}) \frac{2.87 \text{ MJ}}{6 \text{ moles CO}_2} \quad (7)$$

where, SR is the accumulated moles of CO_2 from soil respiration.

The increase in respiration because of spikes from tillage ($E_{\text{mgt microb-spike}}$) was estimated for just the CT system assuming a reported 14% increase in respiration in tilled systems (Sainju et al., 2008). The mechanical energy applied to the soil for primary ($E_{\text{mgt till1}}$) and secondary ($E_{\text{mgt till2}}$) were assigned values of 0.4 and 0.1 MJ m^{-2} , respectively, based on records by Watts et al. (1996b). For raindrop impact, E_{rain} , estimates by Carter et al (1974) were used and it was assumed that 0.72 MJ m^{-2} are supplied during 30 min of heavy rainfall (75 mm h^{-1}). Using that same energy relation, for a rain-fed system receiving 800 mm yr^{-1} , the E_{rain} would supply 15.4 MJ m^{-2} to the soil surface annually. Assigning residue and canopy surface covers of 30, 80, and 90% for the CT, NT, and GS, the throughfall E_{rain} supplied to the soil surface would equal 10.8, 3.1, and 1.5 MJ m^{-2} , respectively (Al-Kaisi and Yin, 2005). For E_{erod} , reported average annual erosion rates by Montgomery (2007) of 3.94, 0.12, and 0.053 mm yr^{-1} were selected for CT, NT, and GS, respectively. These rates were converted to energetic units under assumptions by Carter et al. (1992) and Odum & Odum (2000) that 22.6 MJ are lost in 1 kg of eroded soil carbon. This corresponds to an annual energy loss from erosion (E_{erod}) of 3.2 MJ m^{-2} for CT, 0.10 MJ m^{-2} for NT, and 0.043 MJ m^{-2} for GS systems.

The three systems analyzed fall into expected ranges for E_{net} based on has been observed for long-term soil degradation or soil building when these systems are employed on the landscape. The E_{exud} numbers used in this analysis are significantly higher than those calculated above using energy apportionment percentages. If those terms were to be used, it can easily be seen that the CT system becomes highly negative, and the NT system would be approaching a neutral state.

If we examine the carbon balance of different systems, then we can begin to develop the framework of energy availability. For example, Dold et al. (2016) showed that conventional corn–soybean production systems were carbon negative, while prairie systems were carbon positive. Shifting from conventional to reduced tillage changed the carbon dynamics from a carbon source to a carbon sink in the first year after conversion. These dynamics have been observed

in previous research with mixed results showing that changes often occurred in the upper portions of the soil profile but did not affect the carbon storage throughout the soil profile but with the overall conclusion that reduced tillage coupled with more diverse rotations had a positive impact on soil carbon balance (Havlin et al., 1990; Yang & Wander, 1999). The three systems analyzed fall into the expected ranges for E_{net} based on what has been observed in carbon dynamics (budgets) on similar systems. However, the energy apportioned throughout the soil profile is not well known at this time and should be of pivotal importance in further studies.

4 | ENERGY EFFICIENCY AND SUPPLY REFLECT FUNCTIONAL STATE OF SOIL

Soil structure is a product of microbial processes acting on the constituent elements of soil. Without these microbial processes, constituent elements would remain simply what they are to begin with—a collection of sand, silt, and clay lacking structure and therefore lacking the ability to provide the functions of water infiltration, holding, and supporting plant life. While soil carbon levels have often been pointed to as the indicators and drivers of this organization, Wiesmeier et al. (2019) provided a detailed assessment of the drivers of soil organic carbon change in the soil and found that microorganisms and fauna were the dominant systems responsible, placing the emphasis on microbial activity as opposed to the carbon levels themselves. Soil becomes organized as microbes take sugars exuded by plants and facilitate soil aggregation and structural formation processes (Gunina & Kuzyakov, 2015). Similar to the observation that plant growth can only occur when photosynthesis is greater than respiration, it would follow that growth of soil biological systems and their resultant impact on soil properties would only occur when there is sufficient energy in the soil volume to support these changes and maintenance.

Recall Equation 5 above, the microbial term, ΔE_{microb} (MJ m^{-2}), can be further expanded to account for processes associated with maintenance, E_{maint} ($\text{MJ m}^{-2} \text{ d}^{-1}$), growth, E_{growth} ($\text{MJ m}^{-2} \text{ d}^{-1}$), and work, E_{work} ($\text{MJ m}^{-2} \text{ d}^{-1}$):

$$\Delta E_{\text{microb}} = \left(\sum E_{\text{maint}} + \sum E_{\text{growth}} + \sum E_{\text{work}} \right) \Delta t \quad (8)$$

$$\Delta E_{\text{work}} = \left(\sum E_{\text{OM-bind}} + \sum E_{\text{agg}} \right) \Delta t \quad (9)$$

where, $E_{\text{OM-bind}}$ ($\text{MJ m}^{-2} \text{ d}^{-1}$) and E_{agg} ($\text{MJ m}^{-2} \text{ d}^{-1}$) represent energy used in structuring the soil. This term could be further expanded to account for other structure formation processes presently undefined. As the microbial community expends energy through work, soil aggregation increases and

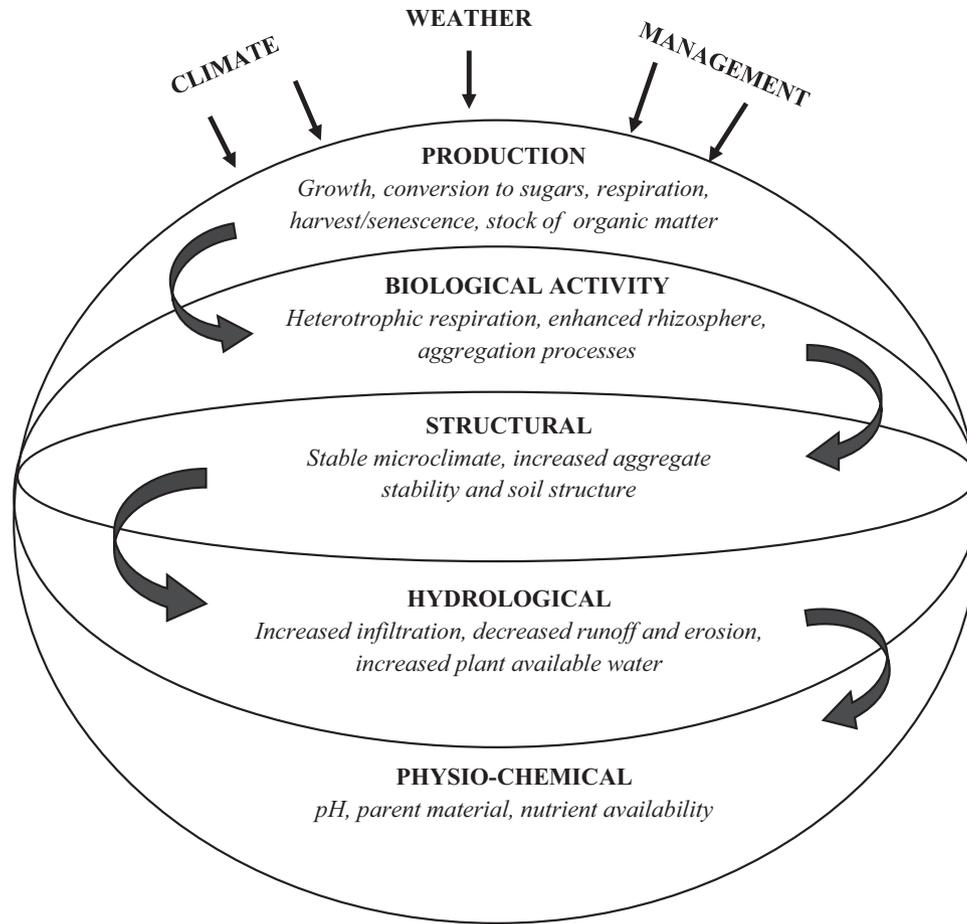


FIGURE 6 Diagram of interrelationship between biological, chemical, and physical systems in the soil including energetics

structure improves, which increases the functional state of the soil (F_{state}). To evaluate temporal changes in soil functionality (ΔF_{state}), soils can be assessed and compared at discrete points in time (t vs. $t-1$) through the following relation:

$$\Delta F_{\text{state}} = F_{\text{state},t} - F_{\text{state},t-1} \quad (10)$$

Changes in state (ΔF_{state}) are related to the total accessible energy used (E_{useable}) and the total energy used to maintain the functional state ($E_{\text{funct maint}}$). The following piecewise formulation can be used to predict negative (-) or positive (+) ΔF_{state} :

$$\Delta F_{\text{state}} = \begin{cases} -, & E_{\text{useable}} < E_{\text{funct maint}} \\ +, & E_{\text{useable}} > E_{\text{funct maint}} \end{cases} \quad (11)$$

Within the entire sequence of equations presented in this paper (Equations 1–11), there is a direct linkage between the energy captured in photosynthesis and exuded into the soil and changes in the functional state of the soil. By accounting for effects of different plants and cropping systems, tillage and other forms of disturbance, and microbial activity, it is possible to predict whether the energy entering the system is

enough to results in an increase of the functional state of the soil, if the soil will maintain its state, or if it will decrease. Using this sequence of equations, it is then possible to analyze how changes in plant cover, cropping system, and other agricultural practices will influence the functional state of the soil. Present soil models do not account for the dynamics of energy flux in real time and rely on correlations of SOM and carbon with microbial activity to predict changes in soil functionality unlike the model set forth here.

5 | CONCLUSIONS

The concept of soil energetics allows for a better understanding of soil processes by placing soil physical, biological, hydrological, and chemical processes into the interrelationships of these processes and in the framework of energy transfer. As is shown in Figure 6, the energy inputs, framed on weather and management variables for a specific location, determines the rate of biological activity. Biological activity has direct control of the physical and chemical state of the soil, which determines its hydrological capacities and the pH

and nutrient availability. The ability of microbes to change soil structure can directly influence the water dynamics of a soil long with potential erosive capacity of a precipitation event, and we can extend this impact into the weathering of parent materials or breakdown of plant residues touching all soil processes from short to long term. Soil energetics is a framework that provides an increased ability to quantify the changes that occur within soils because of management changes in a given environment.

Methods for maximizing the $E_{in\ soil}$ and minimizing $E_{out\ soil}$ are of primary importance for the future of agriculture and continued functionality of agricultural soils. By measuring how land use and management change the energetic balances in the soil, we can determine which agricultural systems and which plant combinations optimize the soil energetics chain. Soil energetics provides a framework for describing and predicting changes in soil functions and soil resilience—the two components of soil health. It therefore can provide a quantitative assessment of soil health and predict which management practices will be the most effective in building and maintaining it. Finally, by placing soil processes in the simple language of energy transfer, the ability of soil science to talk to the other disciplines is heightened, especially on issues such as carbon storage, environmental processing capacity, and the effects of agriculture on soils and surrounding ecosystems. This is a concept that requires further investigation to quantify the energy exchanges, flow of energy into the system, and the impact of energy dynamics on increasing or maintaining soil health.

Further studies into soil energetics and inquiries into the processes around the deposition and use of energy in the soil and its loss will increase our knowledge of soil processes and our ability to accurately predict changes in soils. The different ways in which $E_{in\ soil}$ and $E_{out\ soil}$ can be expanded present an outline of further studies into soil energetics to be undertaken to better understand and expand the usability of the concept. The E_{in} is dependent mainly on plants translocating sugars into the soils. How plants differ in this regard and how they make energetic ‘decisions’ is a major area to be investigated in plant physiology. Further application of such principles could lead to the breeding of special cover crops for agriculture that optimize energy placement into the soil. This also has bearing on pedology as the organism (O) term in the Jenny (1994) equation is directly influenced by energy flow. Differing levels of energy placement into the soil could theoretically affect biologically mediated soil weathering, the cycling and loss of nutrients from the upper soil profiles as a result of increased or decreased cycling through the biological pool, and how different plants increase or decrease the rate of soil formation because of differences in energy apportionment bearing directly on the study of pedology.

Expansion of the $E_{out\ soil}$ term requires investigation into how mechanical models of soil degradation can more accu-

rately quantify energy losses and may help to further the accuracy of such models. This term also has a great deal of bearing on how inputs of energy can be held in the soil for longer temporal periods, giving more information on the dynamics of carbon in the soil and the process of sequestration (Dold et al., 2021). Accumulations of carbon in the soil will only occur when the amount of energy flowing into the soil exceeds the amount needed to create and maintain functional soil properties. Therefore, the carbon balance in agricultural systems will ultimately be determined by the amount of energy available in excess of growth and maintenance needs.

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AUTHOR CONTRIBUTIONS

Kenneth Wacha: Conceptualization; Methodology; Writing-review & editing. Allen Philo: Conceptualization; Methodology; Writing-review & editing. Jerry L. Hatfield: Conceptualization; Methodology; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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