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Farming strategies to fuel bioenergy demands and facilitate essential soil services

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ABSTRACT

Perennial lignocellulosic biomass and food crop residues have traditionally been important resources used internally on-farm. However given the growing outlook with advanced biofuel conversion technologies, such biomass sources might be of competing greater value if sold off the farm into the bioenergy feedstock stream. Inputs of carbon embedded in above-ground plant biomass are a key biological energy source for the soil surface — a zone of great importance in the success of food–feed–fiber production and ecological processes essential to environmental quality. This review of literature looks at how above-ground plant biomass contributes to soil properties and processes, water conservation and quality, on-farm forage availability, and as a harvestable biofuel component. Competing needs for this resource could cause serious environmental or economic consequences without sufficient knowledge of their potential impacts. Perennial forages and crop residues are critical for providing surface cover to protect soils against erosion and for providing the organic inputs to support below-ground ecosystem communities, properties, and processes. The amount of biomass required to maintain soil organic matter and various ecosystem services linked to this key soil property may, in many cases, exceed that needed for simple erosion control. Consequences of continuous residue harvest could be detrimental or minor, depending on the climatic and edaphic conditions, as well the type of cropping system and tillage management employed. Achieving a balanced outcome will require scientific evidence of in-field effects, a collective vision for designing landscapes of appropriate functional capacity, and well-designed government policies for crop residue and perennial biomass utilization schemes to contribute to a sustainable agricultural approach.

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1. Introduction

Agriculture is often viewed as an industry — one that requires an enormous amount of dedicated mental and physical work tending to land and animals to be able to produce food, feed, fiber, and fuel for the world's population. Agriculture is a business that yields economic return from rightful investment. Agriculture can also be described as a culture of living with nature — having to realize the limits of ourselves and the environment, while extending the possibilities of our imagination to discover new approaches to harvesting the enormous solar influx and momentum that it provides to material and nutrient flows. In addition, the vocation of agriculture often imparts spiritual and ethical feelings for wise use of inherited resources and fostering sustainability for future generations. These diverse views are not necessarily disparate and distinct, as agriculturalists meld these approaches daily into

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different expressions of their world view. All perspectives are valuable in their own, but more valuable when taken together. The challenge of agricultural research is to respect each perspective so that wise decisions can be made accordingly.

The success of agriculture depends on two central themes — productivity and sustainability. Productivity can be achieved within a short time period by manipulating all necessary components for success, but the high cost and limited availability of labor and inputs may limit success year in and year out. Sustainability addresses the economic and ecological balances of time, costs, and resource use efficiency, as well as fitness of the operation within a community (e.g., infrastructure support) and within a personal perspective (e.g., cultural or religious beliefs). Along with air, water, and the sun, the soil is a primary ingredient for agricultural success. How we manage the soil to achieve its potential, therefore, determines the success of agriculture.

The objective of this paper is to review some of the biophysical issues facing agriculturalists in designing a future to foster sustainable food, feed, fiber, and fuel production with a particular emphasis on the dynamic properties of soils as environmental guideposts. Soil organic C is a central component of many dynamic soil properties, and therefore, the primary focus is on its change in quantity and quality, as well as management implications on its features over time. Designing agricultural landscapes with biofuel production should capture win–win strategies rather than settle for trade-off strategies.

2. Carbon cycling and ecosystem services

Carbon is a keystone element closely associated with the global cycling of N and other macro-nutrients. With plant materials containing a relatively stable concentration of C (38–45%), plant productivity is a large driver of C flows worldwide. With ~800 Pg (10^{15} g) of C in the atmosphere as CO_2 and 1500 Pg of C in soil as organic matter, the stock of C in plant biomass does not appear very large at 550 Pg, but the fluxes of C into and out of plant biomass are highly dynamic at 60 Pg yr^{-1} (Morgan et al., 2010), and therefore, of enormous significance in the C cycle. Rising concentration of atmospheric CO_2 during the past century is of great concern due to the strong impact of radiatively-active trace gasses [also called greenhouse gasses (GHGs)] on the potential to warm the planet, and concomitantly disrupt the hydrologic cycle by altering rainfall patterns and weather extremes (SWCS, 2007; Walthall et al., 2012). Three of the most important GHGs related to agricultural activities are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Atmospheric concentration of CO_2 increased at a rate of 4.3 Pg yr^{-1}, primarily due to burning of fossil-fuels and industrial activities (8.6 Pg yr^{-1}) and land-use change (0.9 Pg yr^{-1}), while the ocean absorbed 2.5 Pg yr^{-1} and terrestrial sinks were 2.8 Pg yr^{-1} (Le Quéré et al., 2014).

Since 1750, atmospheric concentration of CO_2 has increased 31%, concentration of CH_4 has increased 151%, and concentration of N_2O has increased 17% (IPCC, 2001). In the USA, agriculture contributes a relatively small fraction (6.1%) of the total burden for the country, which was estimated as 1.9 Pg C yr^{-1} (in CO_2 equivalence from all sources) in 2008 (USDA, 2011). Understanding the linkages between GHG dynamics and agricultural land-use activities will help society (1) strengthen its resolve to take appropriate and necessary actions to avoid devastating climate-induced impacts and (2) design effective mitigation and adaptation strategies to bolster ecosystem functioning and overcome human-induced land degradation.

Reducing net GHG emissions in agriculture is possible by (1) reducing fossil fuel combustion and becoming more energy efficient, (2) relying more on low-C energy sources, such as capturing solar energy, generating wind power, and harvesting biofuels, (3) sequestering C in soil, (4) applying the right amount and form of N at the right time and in the right place to reduce N_2O emissions, and (5) avoiding cultivation of crops on wetland soils and offering ruminant animals high-quality forages to avoid CH_4 emissions. Agricultural systems that capture as much solar energy as possible and then transform this organically bound energy into food, fiber, feed, or fuel are highly desirable. The key to making this capture strategy work as effectively as possible though is to (a) minimize the fossil-fuel C needed for its production and (b) limit the release of C from this stored resource back to the atmosphere as CO_2.

Sequestration of C in soil can be achieved with a variety of conservation agricultural systems. Conservation agricultural approaches aim to achieve high production without degrading the environment. These approaches rely on three basic principles that can be applied globally: (1) minimize soil disturbance consistent with sustainable production, (2) maximize soil surface cover by managing crops, pasture, and crop residues, and (3) stimulate biological activity through crop rotations, cover crops, and integrated nutrient and pest management. Conservation agricultural systems are not recipes, since each unique environmental and sociological setting will require a unique set of practices that need to be optimized to achieve desired goals. Conservation approaches will likely draw significantly from related concepts of sustainable intensification (Tilman et al., 2011; Garnett et al., 2013) and holistic management (Savory and Buttefield, 1999). The approach of conservation agriculture gives these other concepts a set of practical tools to implement in different situations to balance production and environmental quality.

Sequestering C in soil as organic matter is not only a viable strategy to reduce C emissions from the atmosphere, but is also essential in improving the quality of soil so that it can function fully to provide a wide range of essential ecosystem services. Soil organic matter plays a vital role in:

1. Soil fertility, by slowly supplying N and many other essential elements and molecules to plants through mineralization/immobilization turnover;
2. Water cycling, by contributing to soil aggregation, water-holding capacity, and infiltration;
3. Soil biodiversity, by providing the C and energy sources needed for soil biological community development;
4. Environmental detoxification, by supplying chemical bonds, physical support, and biological activity; and
5. Biogeochemical cycling, by storing and delivering many globally important elements interacting through the atmosphere, hydrosphere, lithosphere, and biosphere.

Soil organic C is a vital component of ecosystem properties, processes, and functions (Robinson et al., 2009, 2013). Soil and its surface organic C concentration are intimately linked with many important ecosystem services, including provisioning, supporting, and regulating services (Franzluebbers, 2010b). It has highly relevant physical, chemical and biological features, which give soil organic C deserved attention as a key indicator of soil quality, i.e., how soil management affects the functioning of soil (Doran et al., 1994). Attributes of soil organic C that affect soil and ecosystem properties include a range of (1) physical characteristics, including dark color of organic matter that alters thermal properties (i.e., absorbing heat), low solubility that ensures organic matter inputs are retained and are not rapidly leached from the soil profile, high water retention that absorbs several times its mass of water and indirectly retains water through its effect on pore geometry and soil structure, and stabilization of soil structure by binding mineral particles to form water-stable aggregates and improve water infiltration into the surface soil; (2) chemical characteristics, including high cation-exchange capacity, in which a high charge enhances retention of nutrient cations, such as Al, Fe, Ca, Mg and NH_4, high pH buffering capacity that avoids large swings in pH to keep acidity/alkalinity in a more acceptable range for plants, chelation of metals into complexes to enhance dissolution of minerals, enhance availability of P, reduce losses of micronutrients and reduce toxicity, and enhanced biodegradation of xenobiotics to alter biodegradability, activity, and persistence of pesticides and other organic contaminants, such as antibiotics and endocrine-disrupting chemicals; and (3) biological characteristics, including as a reservoir of metabolic energy embedded in organic