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Conservation agriculture and ecosystem services: An overview

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ABSTRACT

Conservation agriculture (CA) changes soil properties and processes compared to conventional agriculture. These changes can, in turn, affect the delivery of ecosystem services, including climate regulation through carbon sequestration and greenhouse gas emissions, and regulation and provision of water through soil physical, chemical and biological properties. Conservation agriculture can also affect the underlying biodiversity that supports many ecosystem services. In this overview, we summarize the current status of the science, the gaps in understanding, and highlight some research priorities for ecosystem services in conservational agriculture. The review is based on global literature but also addresses the potential and limitations of conservation agriculture for low productivity, smallholder farming systems, particularly in Sub Saharan Africa and South Asia. There is clear evidence that topsoil organic matter increases with conservation agriculture and with it other soil properties and processes that reduce erosion and runoff and increase water quality. The impacts on other ecosystem services are less clear. Only about half the 100+ studies comparing soil carbon sequestration with no-till and conventional tillage indicated increased sequestration with no till; this is despite continued claims that conservation agriculture sequesters soil carbon. The same can be said for other ecosystem services. Some studies report higher greenhouse gas emissions (nitrous oxide and methane) with conservation agriculture compared to conventional, while others find lower emissions. Soil moisture retention can be higher with conservation agriculture, resulting in higher and more stable yields during dry seasons but the amounts of residues and soil organic matter levels required to attain higher soil moisture content is not known. Biodiversity is higher in CA compared to conventional practices. In general, this higher diversity can be related to increased ecosystem services such as pest control or pollination but strong evidence of cause and effect or good estimates of magnitude of impact are few and these effects are not consistent. The delivery of ecosystem services with conservation agriculture will vary with the climate, soils and crop rotations but there is insufficient information to support a predictive understanding of where conservation agriculture results in better delivery of ecosystem services compared to conventional practices. Establishing a set of strategically located experimental sites that compare CA with conventional agriculture on a range of soil-climate types would facilitate establishing a predictive understanding of the relative controls of different factors (soil, climate, and management) on ES outcomes, and ultimately in assessing the feasibility of CA or CA practices in different sites and socioeconomic situations.

The feasibility of conservation agriculture for recuperating degraded soils and increasing crop yields on low productivity, smallholder farming systems in the tropics and subtropics is discussed. It is clear that the biggest obstacle to improving soils and other ES through conservation agriculture in these situations is the lack of residues produced and the competition for alternate, higher value use of residues. This limitation, as well as others, point to a phased approach to promoting conservation agriculture in these regions and careful consideration of the feasibility of conservation agriculture based on evidence in different agroecological and socioeconomic conditions.

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1. Introduction

Provision of food is a primary function and key ecosystem service (ES) of agriculture. There is growing recognition that agricultural systems are both dependent on ES that support production functions and a source of important agricultural and non-agricultural ES. Ecosystem services are categorized as provisioning, regulating, supporting, and cultural. The level of delivery of the different services is determined by a combination of ecosystem properties, including soils, vegetation, and climate and the resulting ecological processes (Fisher et al., 2009). Agricultural intensification aimed at increasing production can affect ecosystem components and processes. Intensification can disrupt many of the regulating and supporting ES, including nutrient cycling, climate regulation, regulation of water quality and quantity, pollination services, and pest control (Fig. 1; Power, 2010). It can also alter the biological diversity underpinning many of these ES. While some agricultural practices can decrease ES delivery (tradeoffs) others can enhance or maintain ES (synergies). Increasing food production at the expense of ESs can undermine agroecosystem sustainability including crop production.

Conservation agriculture (CA) is a system of agronomic practices that include reduced tillage (RT) or no-till (NT), permanent organic soil cover by retaining crop residues, and crop rotations, including cover crops. Together these practices aim to increase crop yields by enhancing several regulating and supporting ESs. Though CA was originally introduced to regulate wind and water erosion (Baveye et al., 2011), it is now considered to deliver multiple ES. This paper focuses on the effects of CA on selected ES such as climate regulation as related to soil carbon sequestration and greenhouse gas emissions and the provision and regulation of water and nutrients through modification of several soil properties and processes. The role of biodiversity, particularly soil functional diversity is also discussed, where possible. Pest and disease control and pollination are briefly mentioned. These ES were selected because they are the ones most likely affected by CA practices.

Conservation agriculture was originally designed as a response to the US Dust Bowl (Baveye et al., 2011). Since then, the adoption of CA has been rapid, particularly in North America, South America, and Australia (Derpsch and Theodor, 2009). It is primarily practiced on large-scale, mechanized farms, and requires large applications of herbicides to control weeds that are normally controlled by tillage. There are now concerted efforts that are promoting CA in smallholder systems in South Asia (Hobbs et al., 2008) and Sub Saharan Africa (Valbuena et al., 2012). Whether CA, which was designed in high-input systems in more temperate regions, can work and deliver ES in smallholder systems of the tropics and subtropics is unclear and warrants further consideration based on the evidence to date.

Over the past ten years numerous research papers and reviews have looked at the extent to which ES are generated through CA compared to conventional practices. Much of that research has focused on effects of RT and NT compared with conventional tillage (CT) where the effects of residue management and crop rotations are often confounded with tillage. Previous reviews indicate that CA can reduce water and wind erosion due to protection of the soil surface with residue retention and increased water infiltration and decreased runoff with NT (Verhulst et al., 2010). Benefits of CA on other ES including nutrient cycling, carbon sequestration, and pest and disease control are quite variable, from positive, to neutral or even negative depending on site-specific context, management, soil type, and climate.

This paper summarizes the state-of-knowledge of CA and ES and highlights the gaps and questions needed to provide a more predictive framework for ES delivered through CA. The summaries are based on the global literature including the growing literature on CA from smallholder farming systems, particularly Sub Saharan Africa and South Asia. The types of experiments installed for testing CA and comparing with conventional practices (tillage, residue removal or incorporation and monocultures) do not necessarily have the design required to separate the individual and combined effects of the different CA practices on ES. Comparisons often come from experiments that include one or two of the practices, with comparisons of tillage practices with residues being the most common. The approach we used examines each ES and how CA practices influence soil and plant processes and ES outcomes as described in Palm et al. (2007). We also discuss how ES relates to crop productivity, with an emphasis on situations where increasing regulating and supporting ESs do not compromise, but instead bolster, production functions.

2. Climate Regulation

The ES of climate regulation refers to processes that contribute to or mitigate the build-up of greenhouse gases (GHG) in the atmosphere or other factors, such as albedo, that contribute to global climate forcing (Millennium Ecosystem Assessment, 2005). The net potential of CA to contribute to climate regulation and serve as a global warming mitigation strategy depends on the direction and magnitude of changes in soil C, nitrous oxide (N_2O) and methane (CH_4) emissions associated with its implementation compared to conventional practices. Collectively this is assessed in terms of the global warming potential of the farming practices which are soil, climate and management dependent (Robertson and Grace, 2004). For example, if there is an increase in soil C that is greater than the combined increase in N_2O or CH_4 emissions (expressed as CO_2 equivalents), the net global warming potential decreases.

2.1. *Soil carbon sequestration*

Soil C sequestration refers to the increase in C stored in the soil by capturing atmospheric CO_2 as a result of changes in land use or management (Powlson et al., 2011b; West and Post, 2002). While CA was not initially conceived as a practice to sequester soil C, it is now considered as a potential technology to mitigate greenhouse gas emissions and has become a focus of CA research. Several reviews summarize the effects of the different component practices of CA on soil C stocks compared to conventional practices (Branca et al., 2011; Corsi et al., 2012; Gattinger et al., 2011; Govaerts et al., 2009; Grace et al., 2012; Lal, 2011; Luo et al., 2010; Ogle et al., 2012; Ogle et al., 2005; Six et al., 2002; West and Post, 2002). Though most studies report changes in soil C stocks or storage, an increase in soil C stocks does not necessarily represent sequestration or climate mitigation potential if there is not a net transfer of CO_2 from the atmosphere. As discussed by Powlson et al. (2011b), such situations relevant to CA are if residue retention results in increased C storage in the CA field but a reduction in soil C where the residue had been sourced. These factors are not usually considered in CA studies. In addition, some consider soil C sequestration as that C which is held in the more recalcitrant or protected forms and thus less susceptible to losses from decomposition (Powlson et al., 2011b; West and Post, 2002). Most studies however just report on the changes in the total C stored and not the changes in the recalcitrant fractions. As such we will refer to the changes in soil C reported in the studies to indicate the *potential* for CA to serve as a net sink of atmospheric CO_2.

2.1.1. *Factors and processes affecting soil carbon sequestration*

Simply put, soil C content is the balance between the C inputs and decomposition. Understanding and quantifying the factors and processes that determine C inputs and decomposition, however, is not simple but necessary to build the scientific evidence needed to