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Research Paper

The adaptive capacity of maize-based conservation agriculture systems to climate stress in tropical and subtropical environments: A meta-regression of yields

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ABSTRACT

Conservation agriculture is widely promoted across sub-Saharan Africa as a sustainable farming practice that enhances adaptive capacity to climate change. The interactions between climate stress, management, and soil are critical to understanding the adaptive capacity of conservation agriculture. Yet conservation agriculture syntheses to date have largely neglected climate, especially the effects of extreme heat.

For the sub-tropics and tropics, we use meta-regression, in combination with global soil and climate datasets, to test four hypotheses: (1) that relative yield performance of conservation agriculture improves with increasing drought and temperature stress; (2) that the effects of moisture and temperature stress exposure interact; (3) that the effects of moisture and temperature stress are modified by soil texture; and (4) that crop diversification, fertilizer application rate, or the time since no-till implementation will enhance conservation agriculture performance under climate stress.

Our results support the hypothesis that the relative maize yield performance of conservation agriculture improves with increasing drought severity or exposure to high temperatures. Further, there is an interaction of moisture and heat stress on conservation agriculture performance and their combined effect is both non-additive and modified by soil clay content, supporting our second and third hypotheses. Finally, we found only limited support for our fourth hypothesis as (1) increasing nitrogen application rates did not improve the relative performance of conservation agriculture under high heat stress; (2) crop diversification did not notably improve conservation agriculture performance, but did increase its stability with heat stress; and (3) a statistically robust effect of the time since no-till implementation was not evident.

Our meta-regression supports the narrative that conservation agriculture enhances the adaptive capacity of maize production in sub-Saharan Africa under drought and/or heat stress. However, in very wet seasons and on clay-rich soils, conservation agriculture yields less compared to conventional practices.

1. Introduction

Maize yield gaps are high in sub-Saharan Africa, with yield trends stagnant or falling across large areas (Ray et al., 2012; van Ittersum et al., 2013). Closing these gaps and reversing yield declines is a priority, but greater sensitivity to drought may accompany increases in maize yield (Lobell et al., 2014). Drought stress and extreme temperatures interact in a synergistic fashion to reduce maize yields, as drought reduces maize's ability to cope with excessive heat (Lobell et al., 2011). Whilst arable agriculture across large areas of sub-Saharan Africa is already exposed to climate stress, climate change is predicted to further increase risks of both extreme temperatures and drought (Niang et al., 2014) and negative impacts on crop yields are expected (Schlenker and Lobell, 2010; Lobell et al., 2011). Recent projections suggest that there will be an increase in average air temperature of approximately 2.1 °C throughout sub-Saharan African maize growing

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regions by 2050 (Cairns et al., 2013). This has the potential to drastically reduce the production of major food crops, including maize and wheat (Lobell et al., 2008). At the same time, areas may be affected by an increased risk of extreme rainfall, potentially reducing crop production through waterlogging and leaching (Cairns et al., 2013; Niang et al., 2014).

In response to increasing threats to food security and livelihoods, the Food and Agriculture Organization of the United Nations (FAO) developed the framework of climate-smart agriculture (Palombi and Sessa, 2013; Lipper et al., 2014). In this framework, a farming technology is considered climate-smart when it meets three complementary criteria: (1) it sustainably increases agricultural productivity; (2) it adapts and builds resilience to climate change; and (3) it creates opportunities to reduce greenhouse gas emissions and sequester carbon (Lipper et al., 2014). A range of agricultural systems have been considered climate-smart, including conservation agriculture, agroforestry, improved cereal-legume systems, alternate wetting and drying in rice, improved rangeland management, targeted fertilizer application and drought tolerant germplasm (Rosenstock et al., 2016; Thierfelder et al., 2017). These systems require scrutiny to establish whether they meet climate-smart criteria and if they still deliver benefits under increasingly variable climates (Thierfelder et al., 2015c, 2017; Powlson et al., 2016).

African governments and institutions have started advocating and promoting climate-smart agriculture. Its scaling-up has become a central component of the development agenda to increase production, food security and climate change adaptation (Andersson and D'Souza, 2014; Whitfield et al., 2015). Conservation agriculture is an especially important form of climate-smart agriculture (Richards et al., 2014) defined by three key principles (Kassam et al., 2009; Wall et al., 2014): (1) direct planting of crops with minimum soil disturbance, (2) permanent soil cover by crop residues or cover crops, and (3) crop rotation or association (crop diversification). It offers a range of key benefits and ecosystem services that are associated with climate adaptation such as increased water infiltration, reduced evaporation of soil moisture, reduced soil erosion and run-off, and the ability to plant early (Thierfelder et al., 2017). Conservation agriculture systems may sequester carbon and reduce greenhouse gas emissions under optimal conditions, but the results from southern Africa are often variable and inconclusive depending on the context (Cheesman et al., 2016; Kimaro et al., 2016; Powlson et al., 2016).

Given the increasing emphasis on conservation agriculture in sub-Saharan Africa, an important research gap is that its yield benefits have not been systematically assessed under climate stress for different soils and land management situations. Understanding the importance of context to conservation agriculture yields is essential because African farming systems are complex varying between different contexts (Richards et al., 2014).

Meta-analyses comparing yields from conservation vs. conventional agriculture have typically explored climate, management, or soil effects using simplistic categorical approaches, for example contrasting high and low rainfall or soil texture classes (Rusinamhodzi et al., 2011; Corbeels et al., 2014a; Pittelkow et al., 2015). These syntheses have shown that the yield performance of conservation agriculture compared to conventional practices improves (1) on well-drained soils (Rusinamhodzi et al., 2011; Corbeels et al., 2014b; Nyamangara et al., 2014), (2) in dry environments (Rusinamhodzi et al., 2011; Ogle et al., 2012; Wall et al., 2014; Pittelkow et al., 2015), (3) with increased time since reduced or no-till implementation (Rusinamhodzi et al., 2011; Brouder and Gomez-Macpherson, 2014; Corbeels et al., 2014b; Thierfelder et al., 2015a), (4) with increasing nitrogen fertilizer application rate (Rusinamhodzi et al., 2011; Corbeels et al., 2014b), and (5) with crop diversification (Rusinamhodzi et al., 2011; Pittelkow et al., 2015). However in all these previous studies, the effects of climate have only been explored by grouping results into broad precipitation categories (Rusinamhodzi et al., 2011; Corbeels et al., 2014b; Pittelkow et al., 2015). Given the diverse combinations of climates, soils and socio-economic conditions found across sub-tropical farming environments, this use of broad categorical approaches is inadequate.

Another research gap is a lack of knowledge about the effects of heat stress on the relative yields of conservation agriculture and ploughed tilled systems. In African maize-growing areas, yield reductions associated with increasing temperatures have been found to be were exacerbated by drought, with yields declining in a non-linear fashion (Lobell et al., 2011). Further, the interaction of soil and management variables with climate stress conditions has not been quantified.

In this study, we provide the first assessment of the adaptive capacity of conservation agriculture to heat and water stress, including interactions with management and soil. Using a novel combination of field data, geospatial soil data, and historical climate data, we used meta-regression to compare maize yields from conservation agriculture (continuous soil surface cover and no-tillage or minimal tillage) and conventional agriculture (substantial soil disturbance through tillage and minimal permanent soil cover).

We tested four hypotheses: (1) the relative yield performance of conservation agriculture improves with increasing drought severity or exposure to high temperatures; (2) the effects of moisture stress and exposure to high temperatures on the relative yield performance of conservation agriculture is non-linear rather than additive (i.e. they will interact); (3) the relative yield performance of conservation agriculture under climate stress (moisture or heat) is affected by soil texture; and (4) fertilizer application rate, the time since no-till implementation, and crop diversification are expected to enhance the relative yield performance of conservation agriculture, in particular under drought and/or heat stress.

2. Materials and methods

2.1. Data collection

2.1.1. Meta-dataset

To maximise search efficiency, conservation agriculture or no-till studies were collated from datasets compiled for existing syntheses (Table A.1). These were found using a Web of Science search on 10/01/2016, using the terms 'tillage', 'no till', 'zero till', 'direct drill', or 'conservation ag*' in the article title and 'review' or 'meta-analysis' or 'synthesis' in the article topic. Any further syntheses cited in these publications were also considered. This gave a total of 715 independent studies for screening from three global analyses (Nyamangara et al., 2014; Farooq and Siddique, 2015), including one meta-analysis of 643 studies (Pittelkow et al., 2015), three African analyses (Bayala et al., 2012; Corbeels et al., 2014a; Wall et al., 2014) and one analysis focussing on smallholders (Brouder and Gomez-Macpherson, 2014). The studies from previous syntheses were updated with recent publications using a Web of Science search. The search used the terms "tillage", 'no till', 'zero till', 'direct drill', or 'conservation ag*' in the article title, 'yield' in the article topic, and covered the period 01/01/2014 to 17/02/2016. These studies were then screened as per the criteria of Pittelkow et al. (2015): (1) studies had to be field experiments containing side-by-side comparisons of no-till and conventional tillage practices; (2) no-till treatments consisted of nil or extremely limited tillage immediately before crop establishment for a given growing season (reduced-tillage treatments such as strip-tillage were rejected); (3) crop yields were reported; (4) the location of the experiment was stated; and (5) other than differences in residue, crop rotation or intercrop management, confounding effects between treatments were negligible. Studies were rejected if it was unclear whether factors in (5) differed between treatments. As the absence of tillage as a weed or pest control strategy generally requires changes in herbicide and pesticide management under no-till (Farooq et al., 2011), differences between treatments in herbicide pesticide management were acceptable. If multiple types of tillage were presented in a study, the deepest and/or