**The problem:**

Climate change is expected to increase the incidence and severity of extreme precipitation and drought events (Luber and McGeehin, 2008; Meehl et al., 2007), meaning its impacts on rain-fed agriculture will be substantial (Urban et al., 2012). Increasing soil organic matter (SOM) is frequently promoted as essential to improving soil health and as an agricultural strategy to mitigate these climate impacts (Iglesias et al., 2012). This suggestion is based on the positive relationship between SOM and soil water holding capacity (WHC). In a seminal article, Hudson (1994) demonstrated a strong, positive relationship between SOM content in soils and their water content at both field capacity and permanent wilting point. Saxton and Rawls (2006) similarly demonstrated the positive impact of SOM on WHC using the Soil Characterization Database from the USDA. This relationship is possibly explained by the demonstrated impact of organic matter content on the formation of water stable aggregates (Oades, 1984; Tisdall and Oades, 1982), which provide soils with structure and pore spaces capable of retaining water even under vapor pressure deficits, such as those induced by drought and increased evapotranspiration.

This positive relationship between SOM and soil water dynamics implies that by increasing SOM producers may reduce inter-annual yield variability and improve yield resilience by mitigating yield losses during adverse weather, and a handful of studies have demonstrated a connection between SOM and yield stability empirically. Using yield data between the years 1949 and 1998 from several sites across an SOM gradient in China, Pan et al. (2009) found that yield variability across time, measured as coefficient of variation, was lower at sites with higher SOM content. Similarly, using historic yield data from the US Department of Agriculture (USDA) and soil data extracted from the USDA’s spatial soils dataset (SSURGO), Williams et al. (2016) found that areas with higher estimated soil WHC had improved corn yield stability and decreased risk of low yields in bad weather years.

**The need for more evidence:**

These different lines of evidence suggest that the nearly ubiquitous recommendation to farmers to increase SOM is sound and likely a good strategy to mitigate against the impacts of extreme weather. But since these recommendations rely on a limited number of studies, it’s often hard to separate the impacts of SOM on soil water dynamics and yields from other soil properties or direct management impacts. For example, increasing SOM may have dramatically different impacts depending on soil texture, and conservation tillage may be improving soil water dynamics more via direct impacts, such as maintaining soil macro-aggregates, than via increases to SOM.

Since the effects of agricultural management changes on SOM are often modest, managers need to know to what extent efforts to build SOM through local management changes will translate to improved soil water dynamics on their specific soil types or if a focus on particular practices rather than SOM targets is more advisable. Similarly, building on existing evidence to understand what practices best reduce yield variability and how SOM contributes to those reductions could be important to prioritizing goals.

**Our approach:**

To address this need we employed a data-driven approach that leveraged existing databases and meta-analysis techniques to separate the effects of SOM from management across multiple contexts. By drawing on data and results from several different soil studies that span cropping systems and soil types, we can make conclusions that are more broadly applicable rather than assuming the results of a few studies are applicable to other potentially unrelated systems. This type of work could help to develop real, actionable decision support information for farmers and land managers faced with making decisions about how to develop healthy, resilient cropping systems in the face of a changing climate.

**The study:**

*1. Analysis of USDA soil characterization database:*

The USDA’s Soil Characterization Database includes information on several representative soil types across the United States, with laboratory data on a variety of soil characteristics. Saxton and Rawls (2006) used the database to create a series of regression equations relating different soil properties, such as soil texture, to soil water characteristics. We conducted an analysis of the USDA National Cooperative Soil Survey’s Soil Characterization Database similar to that performed by Saxton and Rawls (2006) but with a more explicit focus on SOM and on providing interpretive detail that is accessible to the public.

USDA staff at the National Cooperative Soil Survey provided us with a comprehensive database from all states in the USDA’s North Central region. Of this database there were \_\_\_ samples that included all the necessary data for us to complete our planned analysis. Samples included soils from different layers of \_\_\_ unique pedons taken in USDA sampling efforts and representing a range of different soil types. Each of these samples was analyzed for total soil carbon content, sand content, silt content, clay content, and water content at a pressure of -15 bar. In addition, we were able to identify the most likely soil order for each sample using the GPS location of each sample and SoilGrids, a global soil information system/map. We analyzed how soil carbon impacted water content while accounting for the effects of soil texture.

*Why permanent wilting point?:*

Water content at a pressure of -15 bar is recognized as being equivalent to water content of a soil when permanent wilting point is reached in the field. The difference between water content at field capacity and permanent wilting point is often described as plant available water and is a more functional measure of soil water supply. However, water content at permanent wilting point is often correlated with plant available water and is arguably also representative of soil water supply under extreme weather conditions.

*Results:*

Our analysis indicated that across different soil types in the USDA North Central region, increasing soil carbon content positively impacted water content at permanent wilting point, regardless of the impacts soil texture, and this pattern was true across soil orders (Figure 1). In our analysis, for every increase in soil carbon of 0.2% there was an increase in water retention at permanent wilting point of ~0.15%. While this impact may seem relatively modest, it provides strong evidence that across a variety of soils the impact of soil carbon on water retention is positive. Further work to contextualize these impacts and better understand how they translate to real-world outcomes for farmers will require soil water modeling efforts.



Figure : Water retention increases with increasing soil carbon content across different soil types.

*2. Meta-analysis of literature relating conservation practices and SOM/SOC to water infiltration:*

To complement to our analysis of the Soil Characterization Database, we conducted a meta-analysis of literature relating soil organic carbon (SOC), soil organic matter (SOM), and conservation agriculture practices to water infiltration, a key measure of soil water dynamics and resiliency of soils. We compiled an extensive bibliography of papers with data on soil water infiltration and soil organic matter. We were assisted by Dr. Andrea Basche, previously of the Union of Concerned Scientists, who recently completed a similar analysis and generously shared her bibliography with us. This bibliography includes 79 different papers in which researchers compared infiltration rates of different conservation agriculture practices (i.e. conservation tillage, cover cropping, etc.) against conventional controls. In this collection of papers, a subset of 22 papers also included paired measurements of SOM/SOC. We extracted all infiltration rate and SOM/SOC data from these papers and categorize data points based on whether or not they represented a specific conservation agriculture practice. This approach allowed us examine the relative impacts of changes in SOM/SOC induced by introducing a conservation agriculture practice against the more direct possible impacts of said practices.

*Results:*

An initial analysis of our dataset revealed that across the board confirmed that across the board SOM/SOC content positively impacted water infiltration rates. When evaluating individual conservation agriculture practices, results differed. Conservation tillage and cover cropping had non-significant direct impacts on infiltration rates and in many instances actually decreased infiltration rates relative to conventional practices. But in cases where introducing these practices led to increases in SOM/SOC, infiltration rates generally increased (Figure 2). In contrast, introducing organic amendments or residues very rarely decreased infiltration rates and often had direct impacts on infiltration rates regardless of how they changed overall SOM/SOC stocks, although the direct impacts of these practices essentially replicate the impacts of increasing SOM/SOC stocks via conservation practices. These analyses indicate that the impacts of conservation agriculture practices on important soil water dynamics are context-dependent. Introducing conservation tillage or cover cropping does not necessarily guarantee improvements, but if in introducing those practices farmers can reasonably expect to increase SOM/SOC, improvements to infiltration rates are likely to follow.



Figure : Conservation tillage induced changes in SOC often improve IR, but improvements are not universal.

*Further work:*

In the process of compiling the papers and extracting data we used in this analysis we realized there were other soil bio-physical and structure variables that were frequently reported in the literature, as well. As a follow-up, we conducted a number of other searches looking for agricultural field studies with paired observations of SOM/SOC with measures of soil aggregation, porosity, and water holding capacity. Initial searches generated over 800 possible papers that we are currently reading and filtering with the intention of replicating the same data-driven, meta-analysis approach.

*3. Meta-analysis of long-term cropping systems trials*:

Papers reporting on long-term cropping systems trials (5+ years) provide valuable data that can be leveraged to answer questions about the relative impacts of conservation tillage and SOM/SOC stocks on resiliency of yields. These trials are often designed using treatments that span a management intensity gradient that creates differences in SOM/SOC after several years. For this analysis, we compiled an extensive bibliography of papers from long-term cropping systems trials. We focused on extracting all yield data in order to calculate metrics of yield variability and resilience, as well as any data on soil carbon that appears in the same papers or related papers from the same experiment. We extracted a total of 8300 yield observations from 87 different papers reporting on long-term yield trials and found sufficient soil carbon data on a subset of 21 of those 87 trials. Using these yield data we derived a metric called minimum yield potential (MYP), a measure of how well a cropping system performs in adverse conditions based on long-term yield patterns. This metric allowed us to test the relative impacts of improvements in SOM/SOC and conservation practices on yield stability and resilience.

*Results:*

Analyzing results from the full set of 87 papers revealed that different conservation agriculture practices have differing impacts on yield stability and resilience. Conservation tillage does not increase MYP but introducing organic amendments or crop rotations can. When analyses were reduced to the subset of papers for which we could find SOM/SOC data, there was only a sufficient number of studies to examine the practices of conservation tillage and organic amendments. But results regarding tillage and organic amendments remained the same when we included data on the relative impacts of introducing these practices on SOM/SOC. Tillage induced changes in SOM/SOC were insufficient to improve MYP in our analysis, while organic amendment induced changes in SOM/SOC had significant positive impacts on MYP. These results may be due to the fact that in our dataset, conservation tillage did not generally increase SOM/SOC and when it did, increases were modest at best (Figure 3). In contrast, organic amendments, unsurprisingly, had strong impacts on SOM/SOC.



Figure : Conservation tillage had insufficient impacts on SOM/SOC to impact MYP.