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Tradeoffs between water requirements and yield stability in annual vs. perennial crops

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ABSTRACT

Population growth and changes in climate and diets will likely further increase the pressure on agriculture and water resources globally. Currently, staple crops are obtained from annuals plants. A shift towards perennial crops may enhance many ecosystem services, but at the cost of higher water requirements and lower yields. It is still unclear when the advantages of perennial crops overcome their disadvantages and perennial crops are thus a sustainable solution. Here we combine a probabilistic description of the soil water balance and crop development with an extensive dataset of traits of congeneric annuals and perennials to identify the conditions for which perennial crops are more viable than annual ones with reference to yield, yield stability, and effective use of water. We show that the larger and more developed roots of perennial crops allow a better exploitation of soil water resources and a reduction of yield variability with respect to annual species, but their yields remain lower when considering grain crops. Furthermore, perennial crops have higher and more variable irrigation requirements and lower water productivity. These results are important to understand the potential consequences for yield, its stability, and water resource use of a shift from annual to perennial crops and, more generally, if perennial crops may be more resilient than annual crops in the face of climatic fluctuations.

1. Introduction

The 2030 Agenda for Sustainable Developmental Goals calls for 'zero hunger' and 'sustainable consumption and production', while at the same time preserving life on land and in water, clean water, and acting to limit climate change (United Nations 2015). Among other steps, meeting these goals will require sufficient and stable yields, produced in a sustainable way.

Currently, intensive agriculture relies primarily on annual crops (Meyer et al., 2012; Monfreda et al., 2008; Raun and Johnson 1999). A shift from annual to perennial crops has been advocated as a way to enhance the sustainability of crop production, because perennial plants have the ability to provide a number of diverse ecosystem services (Batello et al., 2014; Cox et al., 2006; Crews 2005; DeHaan et al. 2005; Glover et al., 2010b; Kantar et al., 2016; Pimentel et al., 2012). Perennial crops cover the soil throughout the year, have low tillage requirements beyond the establishment year, and have larger belowground biomass than annual crops. As a result, with respect to annual crops, perennials reduce soil erosion and water and nutrient losses, may achieve higher nutrient- and water-uptake efficiencies, and may enhance soil carbon sequestration (Culman et al., 2013; Randall and Mulla 2001; Zan et al., 2001). Furthermore, perennial crops improve soil biological, physical and chemical properties, e.g., by sustaining a larger microbial biomass and a more diverse nematode population (Culman et al., 2013; DuPont et al., 2014; Glover et al., 2010a).

Beyond the provisioning of ecosystem services, sustainable agriculture must ensure yield production with an effective use of available resources, in terms of arable lands (i.e., providing adequate yields per unit cultivated areas), water, and nutrients. Regarding yields, perennial plants tend to allocate less resources to reproduction structures, prioritizing instead storage structures for extended survival (Bazzaz et al., 1987; Bloom et al., 1985). This pattern emerges also among most of the newly developed perennial cereal crops (perennial wheat and perennial rice; Hayes et al., 2012; Larkin et al., 2014; Murphy et al., 2009; Pogna et al., 2014; Sacks et al., 2003, 2006, 2007; Scheinost et al., 2001), particularly among those varieties exhibiting a higher survival after the first year (Vico et al., 2016). This resource allocation pattern is problematic when seeds represent the sought product, as in grain crops. Nevertheless, perennial plants tend to be larger than their annual counterparts. This is a clear advantage when aiming at biomass production (e.g., for biofuels or feed) but may also partially counterbalance the lower allocation to seed when considering seed yields, as in grain

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crops. Recent estimates suggest that perennial cereals could provide average seed yields comparable to the annual ones, should they achieve a biomass increase over the years similar to those of some other existing perennial grasses (Vico et al., 2016).

Water is already in scarce supply in many regions. Climate change, with warmer temperatures and more frequent dry spells, may further exacerbate water scarcity. Crop water requirements and use patterns are thus key aspects for future sustainable agriculture. Perennial crops are generally considered more drought tolerant than annual ones (Glover et al., 2010b; van Tassel et al. 2014). Indeed, perennial plants, by allocating more resources below ground, may develop more extensive rooting systems, accessing deeper soil layers and thus resources not available to annual plants. Furthermore, developing deeper and denser rooting systems enhances plant tolerance to dry periods (Canadell et al., 1996; Chaves et al., 2002), by buffering against fluctuations in water availability. Perennial crops may thus have an advantage during dry periods and result in more stable yields because of their access to deeper water stores. This is a key aspect to ensure stable yields under future conditions, when more intermittent precipitation and higher temperatures may lead to more frequent or more severe periods of water scarcity. At the same time, the larger transpiring biomass typical of perennial plants may result in higher gross plant water needs, thus accelerating soil moisture depletion and potentially exposing the plants to more frequent water stress than annuals. This raises the question if the extended rooting system typical of perennial plants is sufficient to meet the higher water demands potentially generated by a larger transpiring biomass and buffer against dry spells, or will additional irrigation be required? Additionally, can perennial grain crops lead to 'more crop per drop', despite their lower allocation of resources to seeds?

Answers to these questions are a necessary step to ensure that the advocated shift from annual to perennial crops truly enhances the sustainability of crop production system, not only in terms of yields and provision of a diverse set of ecosystem services, but also for an effective use of available water resources in the face of future, more variable and potentially drier climates. So far, this issue has not been investigated in detail, either experimentally or via modeling. Most of the existing assessments of yields and water use do not compare annual and perennial crops. Those that do so focus on bioenergy crops and compare crops with very different genetic background (e.g., corn or soybean vs. miscanthus or switchgrass). The only exception to date is Culman et al., (2013), where a two-year field comparison of annual and perennial wheat showed that perennial wheat had lower yields than annual wheat and resulted in lower or comparable soil moisture levels. This result is suggestive of a higher water use and lower water use efficiency of perennial wheat. To address this knowledge gap, here we combine the results of an extensive meta-analysis of annual and perennial plant traits and a stochastic model of crop yield accounting for the randomness in precipitation. We quantify yields and their variability, water productivity and irrigation water requirements in annual and perennial plants. The goals are i) to identify the climatic conditions under which perennial crops with specific traits allow for higher or more stable yields, lower water requirements and a more efficient use of water than annual crops and when, conversely, annual crops are preferable; and ii) to define the key traits that perennial crops must possess in order to be sustainable also with respect to yield, yield stability, and efficient water use.

2. Methods

Informed decisions on the viability of annual vs. perennial crops under certain environmental and management conditions require quantitative knowledge on their performances in terms of productivity and sustainability. To this aim, we compare annual and perennial crops grown under the same soil and environmental conditions. A minimalist, stochastic model coupling the dynamics of plant-available soil moisture, crop development, and yield formation (Section 2.1) is parameterized for prototype annual and perennial crops (Section 2.2). Their performances are contrasted with reference to several metrics of productivity and sustainability, and their year-to-year variability (Section 2.3). To focus on the potential differences in performance deriving from expected life span and the associated plant traits, annuals and perennials are assumed to be subjected to the same management practices. In addition, different climatic scenarios are explored.

2.1. Crop development and yield and the soil water balance

To limit parameter requirements, we employ a minimalist description of crop development and yield formation. We focus on the crop development during the main growing season of duration T_{main}, i.e., the period starting a few days after emergence (or when sustained growth is resumed after the winter) and ending when biomass growth rate tapers off and resources start to be allocated to reproductive and storage structures. During this period, the crop biomass growth is largely independent of the existing biomass (i.e., the growth is approximately linear; Monteith 2000). With an extreme simplification of the complex processes driving plant growth during the main growing season and focusing on water as the most limiting factor, it is assumed that plant growth occurs at rate g_+ when water availability is adequate; conversely, when water is limited, the growth rate decreases to g_- (Vico and Porporato 2013). The alternation of periods of well-watered and water-stressed conditions drives the accumulation of biomass during the main growing season and, in turn, the final yield. In turn, the plant biomass at the end of the main growing season provides the starting point for a simple yet robust estimate of the final yield, exploiting the concept of harvest index (*HI*, representing the fraction of the final plant biomass corresponding to the marketable yield). More details on the description of the crop development model are reported in the Appendix A1.

The alternation of periods of well-watered and water-stressed conditions is determined by the soil moisture balance (Laio et al., 2001), extending over the ecohydrologically active rooting zone of depth Z_r, where most of the roots are located. The plant-available soil moisture averaged over Z_r, $s(t)$, is driven by the inputs via precipitation (and irrigation, if any) and the losses via actual evapotranspiration, surficial runoff, and deep percolation. Rainfall pattern is summarized via the average frequency of rainfall events, λ, and the average depth of rainfall events, α. The actual evapotranspiration rate, in turn, depends on the plant-available soil moisture, linearly declining from ET_{max} under well-watered conditions (corresponding to soil moisture levels above the threshold of incipient plant water stress, s^*) to 0, when no more water is available to plants. For irrigated agriculture, an efficient, demand-based deficit irrigation (English and Raja 1996) strategy is considered, where irrigation is supplied whenever plant-available soil moisture is depleted to a pre-set level $\tilde{s}$, below the threshold s^* (Vico and Porporato 2011). Because a demand-based irrigation strategy is implemented, the rainfall pattern also affects the frequency of irrigation applications and hence the total irrigation water requirements: for example, water requirements are lower in wetter climates. More details on the soil moisture balance and the irrigation strategy are reported in the Appendix A1.

This simple description of the coupled plant-available soil moisture, crop development and yield formation allows an analytical solution to the probability density functions of crop biomass (and hence final yield) and, for irrigated agriculture, seasonal irrigation requirement (Vico and Porporato 2013). This analytical approach allows for the full accounting of the unpredictability of rainfall events without requiring computationally heavy Monte Carlo simulations. The results are summarized in the form of averages and standard deviations of the key random variables (yields and irrigation requirements for irrigated agriculture). They can be readily obtained via integration of the probability density functions (see Section A2 in the Appendix). Knowledge