Chapter 19
Ecohydrology of Agroecosystems: Interactions Between Local and Global Processes

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1 Introduction

Agriculture is central for both human and natural systems globally and particularly within drylands (D'Odorico et al. 2013), providing numerous benefits to human welfare by ensuring incomes and food security for rural communities. Yet agricultural practices have induced widespread modifications to drylands, through large-scale alterations of water and nutrient cycles (see Chaps. 11 and 12) as well as through the conversion of native ecosystems to (generally less biodiverse) rangelands and croplands. These tradeoffs present a formidable challenge for people reliant on dryland agroecosystems as they seek to meet the food demand of growing and increasingly affluent populations, in order to enhance their domestic food supply. Climate change, by increasing temperatures and potential evapotranspiration rates and enhancing the frequency and duration of dry spells, may further exacerbate these tradeoffs, by negatively affecting crop yields and their stability and water availability (Challinor et al. 2014; Lobell et al. 2008). In particular for these vulnerable and vast agricultural areas, it is clear that current trends and practices in food production and consumption are unsustainable, with wide agreement that humanity's rate of resource use exceeds the rate at which those resources (e.g., soils, soil nutrients, water stocks) can be generated by the Earth system (Hoekstra

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and Wiedmann 2014; Jaramillo and Destouni 2015; Steffen et al. 2015). Dryland nations must therefore develop solutions that consider the potential co-benefits and tradeoffs across multiple food security, environmental, and economic dimensions (e.g., Davis et al. 2017b; DeFries et al. 2016; Davis and Olayide 2018).

Globally, the vast majority of anthropogenic consumptive water use supports agricultural production (Hoekstra and Mekonnen 2012). The linkages between agriculture and water are particularly strong in drylands, where precipitation occurs intermittently and is often insufficient to prevent crop water and heat stress. If left unaddressed, these stressed conditions can substantially reduce crop yields and negatively affect local food security and economic output. To prevent this, farmers often employ supplementary irrigation from surface and groundwater sources to enhance and stabilize yields (e.g., Leng 2017; Neumann et al. 2010; Osborne and Wheeler 2013; Oweis et al. 1998; Troy et al. 2015). Because areas of dryland agriculture also often coincide with low-yielding croplands, the expansion of irrigation use is often promoted as means to close the crop yield gap (Mueller et al. 2012) and to increase the food self-sufficiency of many developing, import-dependent nations (Davis et al. 2014b). While this approach may offer promise from a perspective focused solely on crop production and food supply, increased reliance on irrigation will enhance local demands for water. This may be problematic in dryland regions, i.e., those regions where natural availability of renewable water is already low. Thus, the question to be reconciled by sustainability and food security policies in dryland regions is whether additional water resources are and will be adequately available in low-yielding areas (e.g., Davis et al. 2017b) and, if so, how to avoid their injudicious use (e.g., Pradhan et al. 2015). It is thus essential to ensure that efforts to increase production match the location and timing of resource availability (see, e.g., Brauman et al. 2016; Davis et al. 2017b; Hoekstra et al. 2012; Mekonnen and Hoekstra 2016).

Here, we revisit the inherently coupled global and local aspects of agricultural production, with a focus on drylands. First, we examine the global drivers of food demand and briefly explore how international food trade can act as a telecoupling mechanism that links individual consumer choices with (sometimes geographically distant) environmental impacts of food production within dryland regions. Second, we investigate how the impacts of these production decisions have induced water-stressed conditions within dryland regions and led to the proliferation of human-made “anthropogenic drylands”. Third, we summarize the local conditions with which farmers must contend at the field level and the strategies they employ to cope with the high variability in water availability. Fourth, we highlight the bidirectionality by which global influences may be manifested in local cropping decisions as well as how local conditions can influence large-scale food supply and food security. We conclude by arguing that policies aimed at food system sustainability in dryland systems must not only take into consideration the local and global processes that influence food production decisions but also seek to enhance resilience and redundancy within agroecosystems.

2 Global Issues

Food demand continues to rise as a result of demographic growth and increasing affluence (Alexandratos and Bruinsma 2012; Tilman et al. 2011). While rising household incomes have pulled 123 million people in developing countries out of undernourishment between 1990 and 2015 alone (Alexandratos and Bruinsma 2012), substantial deficiencies persist in many parts of the developing world—where much of the world's drylands occur—with roughly one in seven people receiving inadequate protein and calories and even more lacking access to important micronutrients (FAO 2009; Godfray et al. 2010; Davis and Olayide 2018). Thus, the double burden of malnutrition persists, with developing countries facing challenges of nutritious and equitable food supply and access (D'Odorico et al. 2019) and other nations dealing with issues of overconsumption have become commonplace elsewhere (Alexandratos and Bruinsma 2012).

The rising affluence of households has allowed for dietary shifts that include larger quantities of animal products. These changes in demand have led to a growing fraction of crops diverted away from direct human consumption, with roughly half of the world's crop calories used as inputs to support the livestock sector (Davis and D'Odorico 2015; FAOSTAT 2017). The combination of growing demand for animal products and shifts within the livestock sector away from extensive production (e.g., rangelands) toward more feed-intensive (but efficient) products and systems (e.g., industrial chicken and pig production) has increased competition for crop use between human food and feed (Steinfeld et al. 2006; Thornton 2010; Davis and D'Odorico 2015). These transitions have had important implications for rural communities within dryland systems, many of which rely on rangeland-fed livestock as an important source of income and nutrition. Recent and rapid growth in crop-based biofuel demand has also compounded the pressure placed on crop production and its supporting land and water resources (Rulli et al. 2016; OECD-FAO 2017). Large amounts of water and other natural resources also support extensive food waste and losses at each step in the food supply chain, with distinct regional patterns (Gustavsson et al. 2011; Kummu et al. 2012; West et al. 2014).

A tripling of crop production and a 2.5-fold increase in the supply of animal products supported massive population growth over the past half-century (FAOSTAT 2017). This Green Revolution was possible due to the increased availability of high-yielding crop varieties, the diffusion of which minimized the need for agricultural expansion but led to a heavy dependence on external resource inputs such as fertilizer, pesticide, and irrigation. These unprecedented efforts prevented widespread famine and the massive conversion of natural systems but led to important tradeoffs for nutrition and environmental impacts (e.g., water resource depletion, overapplication of fertilizers, use of marginal or sloped lands, reduced biodiversity) (Pingali 2016). These rapid transitions in agricultural practices across many parts of the world have meant that the global food system is now one of humanity's most extensive modifiers of natural systems (Davis et al. 2018a). Agricultural lands (i.e., croplands, pastures, and rangelands) now cover a third of the planet's ice-free land (Ramankutty et al. 2008). Agriculture also constitutes most of humanity's consumptive water use (Postel et al. 1996; Hoekstra and Mekonnen 2012), has led to a doubling of reactive nitrogen in the environment due to synthetic fertilizer use (Schlesinger 2009), and contributes 19–29% of humanity's greenhouse gas emissions through processes like flood irrigation, fertilizer denitrification, ruminant digestion, and land use change (Vermeulen et al. 2012). The average environmental footprint of an individual has also increased with time due to shifts in diets toward animal-based (and more resource-intensive) products (Kastner et al. 2012; Mekonnen and Hoekstra 2012; West et al. 2014). However, by consuming many plant products that are directly inedible to humans, livestock convert biomass from sources like grasses and hays into animal tissue and serve as important sources of key nutrients like protein and iron. Animal production continues to transition away from land-intensive systems to systems that are capital- and input-intensive, leading to important environmental tradeoffs between improving efficiency in land use and GHG emissions and increasing water and nitrogen per unit of animal production, mainly to support feed production (Davis et al. 2015a).

The global food system supports unprecedented levels of production, consumption, and resource use (Davis and Olayide 2018). Growing globalization and interconnectedness are also increasingly important features of this system, with one in four food calories traded internationally and the vast majority of nations food trade dependent (D'Odorico et al. 2014; Davis et al. 2014b). Globalization has also meant that food supply chains have become more complex, with the production of primary crops, processed goods, and animal products all potentially occurring in places that are geographically distant from the final consumer (e.g., Davis et al. 2015a). How a nation chooses to interact with international market has important implications for the overall stability and resilience of its food supply. On one hand, trade can be used as a mechanism to support populations beyond the capacity of locally available resources, including water (e.g., Suweis et al. 2015). Further, it can help to stabilize domestic food supply in places where climate conditions and resource availability are relatively variable. On the other hand, an overreliance on food imports exposes countries to exogenous economic or environmental shocks (e.g., D'Odorico et al. 2010; Puma et al. 2015; Suweis et al. 2015). International food trade has also served to separate the environmental impacts of production from places of consumption, though exporting countries tend to require less water per unit of food item produced (Chapagain et al. 2006). While this has led to global water savings (compared to a situation where each country locally produces its own food), there are still numerous instances where attractive economic conditions incentivize exporting countries to overexploit their water resources. For dryland countries with limited water availability, making the decision to bear the environmental costs of production will likely have important implications for the (un)sustainable use of freshwater resources (e.g., leading to groundwater overdraft). As the processes of globalization and trade continue to separate consumers from the production impacts of their choices (Dalin et al. 2017; DeFries et al. 2010; Lenzen et al. 2012; Weinzettel et al. 2013), there is an increased likelihood of these tradeoffs between economic benefit and environmental impact.

To enhance the resilience of their food systems, countries continue to employ a variety of food security mechanisms including self-sufficiency policies and strategic reserves for key staple crops, fertilizer and irrigation subsidies, and, increasingly, direct investment in foreign agricultural lands and resources, a phenomenon commonly referred to as the global land rush (Deininger 2013; Rulli et al. 2013; Dell'Angelo et al. 2017). Two main factors have facilitated this surge in the leasing and acquisitions of lands in the Global South—and within many of the world's drylands—since the start of the century. First, in an effort to promote rural development, enhance agricultural productivity, and ease the path for agricultural technology transfers, many countries in the Global South welcomed direct investments in their agricultural lands. Second, events like the 2008 global food crisis left import-reliant countries wary of reliability of international markets, and in response, investors from these nations sought to increase the pool of agricultural resources under their control by acquiring large tracts of agricultural land in the developing world (Davis et al. 2015b). Yet there is mounting evidence that these investments often do not achieve their stated development and food security goals (e.g., De Schutter 2011; von Braun and Meinzen-Dick 2009) while also often producing a suite of social and environmental consequences (see e.g., Davis et al. 2015c; D'Odorico et al. 2017).

These realized and potential impacts place at risk the livelihoods, food security, and resource access of many local communities of targeted investment areas within drylands. Recent work estimated that these large-scale land acquisitions could potentially disrupt the incomes of more than 12 million people globally (Davis et al. 2014a). In addition, the commercialization of agriculture within land can rapidly increase demand for freshwater and prevent smallholders from continuing to access water resources (Rulli and D'Odorico 2013; Rulli et al. 2013) as well as jeopardize food supplies in targeted regions by facilitating exports (Rulli and D'Odorico 2014). For dryland agroecosystems, identifying mechanisms that support yield enhancements, that facilitate the transfer of technologies, and that secure land tenure for local communities and informal land users will be essential for advancing global and local food security, promoting poverty alleviation, enhancing food system resilience, and ensuring the sustainable and equitable use of available (and often limited) water resources (Davis and Olayide 2018).

These complex and interacting phenomena have enhanced crop demands for various uses, linked consumers to pools of resources that are geographically distant, and increased the pressure on (and in certain circumstances the unsustainable use of) land and water resources. These various influences have resulted in the emergence and expansion of "anthropogenic drylands," where the water demands of agriculture and other human uses exceed the availability of renewable freshwater resources (Brauman et al. 2016; Mekonnen and Hoekstra 2016). As discussed below, these human-made drylands often coincide with hydrologic drylands, so that they can enhance scarcity in already water-stressed regions and compound the challenges that dryland nations face with regard to food security, sustainability, and climate change.

3 Anthropogenic Drylands

Currently, two-fifths (42%) of the world's croplands are located within natural drylands (Fig. 19.1, inset). These areas account for 35% of major crop production globally and provide enough calories to feed 2.3 billion people (Davis et al. 2017b; IIASA/FAO 2012). Despite their importance to food production in many regions—the US High Plains, Brazil, Argentina, Australia, and much of sub-Saharan Africa—these vast areas are also subject to relatively high natural variability in precipitation (e.g., Nicholson 2011). To cope with the inherent unpredictability of freshwater availability in these regions, many farmers rely on irrigation to avoid crop water stress and prevent reductions in crop yields (see Sect. 4 below). Within dryland agroecosystems, irrigated areas are (expectedly) more productive, as they constitute 32% of dryland cropped areas yet contribute 61% of crop production from these regions. Globally, irrigation consumption in dryland agroecosystems currently accounts for 79% of the total irrigation (blue) water footprint but contributes only half (50%) of the crop production from the world's irrigated lands (Davis et al. 2017b; IIASA/FAO 2012). Thus, dryland irrigated systems also appear to use water much less efficiently than non-dryland irrigated areas.

This inefficient water use in dryland agroecosystems is in sharp contrast to a defining quality of dryland systems—that of limited water availability—and may be the result of nonlinearities in rates of evapotranspiration and water loss or of the need to cope with highly variable freshwater resources by planting crops with lower but more reliable yields. From a sustainability perspective, the additional water demands

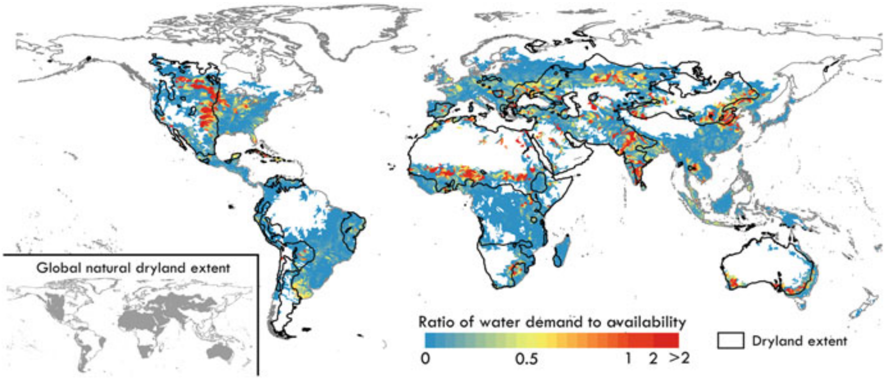

Fig. 19.1 Global distribution of natural and "anthropogenic" drylands. Natural dryland extent is shown in gray in the inset map and outlined in black in the larger map. These areas are defined as those places where the aridity index (i.e., the ratio of average annual precipitation and total annual potential evapotranspiration) is less than 0.65 (see Chap. 1). We define "anthropogenic drylands" as those areas where annual consumptive water demand exceeds the annual renewable water availability (as defined in Brauman et al. 2016), i.e., those areas where the ratio of water demand to availability is greater than or equal to 1. Data on natural dryland extent came from Sorensen (2007); and data on consumptive water demand and renewable water availability came from Davis et al. (2017c)

from agriculture in these areas can impose stress on local resources and, if maintained over time, can lead to the creation of “anthropogenic drylands” where the water demands of humanity exceed what is locally available and readily renewable (i.e., independent of total water availability). For the purposes of this overview, we define “anthropogenic drylands” as croplands where consumptive water demand is greater than long-term average rate of renewable water availability (i.e., a ratio greater than 1; Brauman et al. 2016; Davis et al. 2017b). This definition means that our estimates of the water stress ratio tend to be low, as we do not subtract environmental flow requirements (i.e., set some of the volume of available water aside for nature) from overall water availability. As apparent in Fig. 19.1, “anthropogenic drylands” are widespread across current croplands. They occur both within naturally occurring drylands (warm colors inside thick black lines) and outside of them, in places that are relatively abundant in terms of water resources but can become water-stressed due to unsustainable agricultural water (warm colors outside the regions enclosed by the thick black lines). “Anthropogenic drylands” disproportionately occur within dryland agroecosystems, with 90% of the world’s water-stressed cropland sub-basins (i.e., where water demand exceeds annual availability) occurring in dryland regions. Indeed, they currently constitute 337 Mha (or 11%) of croplands within natural dryland areas. In addition to these places where human water demands may exceed availability throughout the year, other croplands may also produce seasonal “anthropogenic drylands” where, for instance, the major cropping season of an area induces unsustainable demand for only part of the year. It is therefore the location as well as the timing of water demand that dictate not only the persistence of “anthropogenic drylands” throughout a year but also the suite of potential options for moving toward food system sustainability in a given place.

Many of the countries in which natural drylands occur also have large crop yield gaps—the difference between current and attainable yields (Mueller et al. 2012)—and rely heavily on food imports to meet domestic demand (FAOSTAT 2017). These places are faced with an apparent dilemma: the need to enhance crop yields and food security through the addition of irrigation and fertilizers and the desire to ensure the sustainable, long-term availability of their freshwater resources. Given the high population growth expected in many of these places in the coming decades (UN-DESA 2015), these seemingly conflicting goals portend the substantial expansion of “anthropogenic drylands,” with greater volumes of water required to meet immediate and rapidly growing food demand. Recent research however indicates that these food security and sustainability goals need not be mutually exclusive and that soil and water management strategies can help to conserve freshwater resources and substantially enhance crop productivity (e.g., Brauman et al. 2013; Jägermeyr et al. 2016).

4 Local Dimension: Crop Yields and Water Consumption and Their Variability

The emergence of “anthropogenic drylands” is ultimately dictated by the aggregate over large areas of individual decisions taken by farmers. Thus, the potential for ensuring sustainable agroecosystems is fundamentally a question of the feasibility of water conservation and use strategies at the local scale, via selection of the crop(s), crop variety, management practice, and irrigation strategy. For example, crop replacements have the potential to reduce water stress in some locations (e.g., in India, the African Sahel, and the Murray-Darling Basin; see Fig. 4 in Davis et al. 2017c). Shifting from annual crops to perennial (naturally deep rooted) crops may allow better exploiting the available soil water but is expected to require more irrigation to meet the larger plant water demands and support similar yields (Vico and Brunsell 2018). The introduction of a second crop per year—a potential positive for food security—may require the implementation of irrigation during the dry season in tropical seasonally dry regions, potentially generating an “anthropogenic dryland,” as seen with winter wheat in northern India (Davis et al. 2018b). Water requirements for irrigation—and their interannual variability—can impact local and regional water balances, with serious implications for water resource management. Knowledge of current and future water needs is necessary to anticipate future requirements (e.g., Thomas 2008). Taken together, yield and water use determine the water use efficiency of a crop (i.e., its water footprint)—a relevant aspect in dryland agriculture, where achieving “more crop per drop” is critical for future water-food sustainability (Brauman et al. 2013).

Identifying the most suitable solutions under local pedoclimatic conditions is not trivial, because of the randomness of precipitation and temperatures; the complex interactions between crops and growing conditions, particularly, climatic extremes; as well as local cultural practices, dietary preferences, economic and political landscapes, and perception of risk (George 2014; Thornton et al. 2014). These challenges exercise important influence on farming decisions, where farmers must consider not only a crop’s average yield and its sensitivity to stresses but also the crop’s water requirements for irrigation as well as the reliability and availability of freshwater resources. Yield and yield stability directly affect both the profitability of agriculture and food security.

The aspect of variability is particularly relevant for dryland systems, where the interannual variability of growing conditions, yields, water requirements for irrigation, and water use efficiency are potentially large. When assessing the feasibility and sustainability of local food production strategies, a focus on average growing conditions may produce misleading expectations (Fishman 2016). Experimentally, only long-term observations allow an understanding of the outcomes under many different climatic conditions, including extreme ones. However, such experiments are few in number, geographically sparse, and do not readily allow the exploration of future climate scenarios. Furthermore, concurrent changes in management or trends in climatic conditions make their interpretation difficult.

Models offer a complementary approach, suitable for moving beyond available observations and for exploring scenarios pertaining to different climatic conditions or management choices. To this end, a number of models have been developed to describe crop yields and water requirements. While they vary in complexity and focus, they are generally based on coupling the soil water balance with a crop development module and resolved at the hourly or daily time scale (e.g., Boote et al. 2013; Mekonnen and Hoekstra 2011; Siebert and Doll 2010). The simplest model considers direct coupling of crop development and plant water availability, based only on one soil layer where most of the crop roots are located. Formally, this can be written as (see also Chap. 2)

$$nZ_\mathrm{r}\frac{\mathrm{d}s(t)}{\mathrm{d}t} = P(t) + I(s(t), t) - ET(s(t)) - LQ(s(t)). \tag{19.1}$$

$$\frac{\mathrm{d}b(t)}{\mathrm{d}t} = g(b(t), s(t)). \tag{19.2}$$

where $s(t)$ is the soil moisture; n is the soil porosity; Z_r is the depth of the soil layer where most of the roots are located; P and I are the inputs via precipitation and irrigation (if any); ET and LQ are the losses via evapotranspiration rate and superficial runoff and deep percolation, respectively; $b(t)$ is the crop biomass per unit ground area; and $g(b(t), s(t))$ is the biomass growth rate, which in general depends on existing biomass and soil water availability and, possibly, on other growing conditions (temperature, developmental stage, nutrient availability, and the occurrence of disturbances such as pests). The timing and depth of irrigation applications depend on local conditions and irrigation strategy employed. Irrigation may be scheduled due to temporal constraints on water access or driven by declining soil moisture ("demand-based" irrigation). Further, irrigation may aim at maintaining the crop under well-watered conditions (stress avoidance irrigation), or a certain level of water stress may be considered acceptable (deficit irrigation; English 1990; Geerts and Raes 2009). The amount of water supplied by each irrigation application typically depends on the irrigation technique employed, and decreases from more traditional irrigation techniques (e.g., flood or furrow irrigation) to more effective but also increasingly expensive techniques (from center pivots to drip or micro-spray irrigation; see Cuenca 1989; Kruse et al. 1990; Vico and Porporato 2011a, b). Required inputs to the model are standard climatic data (chiefly precipitation and temperature), as well as information on soil features and management practices. As such, models permit the exploration of the effects of crop choice and variety selection (affecting the amount and timing of water requirements and the feasibility of rainfed agriculture and deficit irrigation), as well as management practices (e.g., those affecting the soil water holding capacity). The evapotranspiration rate is often estimated based on climate data, e.g., via the Penman-Monteith equation for a standard crop, and then modified by empirically determined coefficients to describe specific crops (Allen et al. 1998). Crop growth is generally modeled either directly from light interception and radiation use efficiency, transpiration, and water productivity or, more mechanistically, based on a description of leaf level activity scaled up to the canopy level (e.g., Keating et al. 2003; Steduto et al. 2009). The effects of unfavorable growing conditions like water stress are often incorporated by empirical functions reducing the crop growth, thus capturing the reduction in carbon uptake via photosynthesis caused by limited access to water. Knowledge of the crop biomass at a specific stage and allometric relations allow the determination of the approximate marketable yield, based on the crop-specific harvest index. Beyond the coupled soil moisture and plant biomass balances, additional aspects that crop models can explicitly consider are plant and soil nitrogen balance, soil salt dynamics (and hence the effects of salinization), and specific descriptions of biomass allocation to different organs, coupled to a description of developmental stage.

While these models effectively represent soil water balance, crop development, and yield formation, in their most detailed forms, they require many parameters, some of which of difficult estimation. Further, they are computationally intensive, as they explicitly simulate the seasonal course of soil moisture and crop growth. This is a major drawback when attempting to study the effects of the fluctuations and unpredictability of growing conditions (e.g., rainfall) in detail. An alternative approach to these detailed models is represented by extensions to managed ecosystems of the ecohydrological stochastic approaches developed for natural ecosystems (e.g., Laio et al. 2001; Milly 2001; Rodriguez-Iturbe and Porporato 2004; Rodriguez-Iturbe et al. 1999; see also Chap. 2). In this context, the soil moisture dynamic in Eq. (19.1) is assumed to be driven by stochastic precipitation events, occurring according to a Poisson process (i.e., with exponentially distributed intervals between two subsequent precipitation events). Event depths are considered exponentially distributed. Evapotranspiration rates are assumed to be at their maximum when soil moisture is at or above a crop- and soil-specific threshold (corresponding to the point of incipient stomatal closure, s^*) and to be linearly reduced below that threshold. Other losses (i.e., superficial runoff and deep percolation) are idealized as occurring instantaneously (when interpreted at the daily time scale) when soil moisture exceeds field capacity. These approaches have also been extended to include demand-based irrigation—where a fixed amount of water is provided whenever soil moisture reaches a preset level (Vico and Porporato 2011a)—and have been coupled to a minimalist crop growth model (Vico and Porporato 2013). The crop growth during the main growing period—from soon after emergence to when the vegetative growth tapers off during the reproductive phase—is described in a simplified form (Monteith 2000). At a first approximation, crop development proceeds unhampered when soil moisture is above the point of incipient stomatal closure, s^*, and at a reduced rate below that point. The crop growth rate in Eq. (19.2) is thus modeled as

$$g(b(t), s(t)) = \begin{cases} g_+ & s \geq s^* \\ g_- & s < s^* \end{cases}, \qquad (19.3)$$

with g_+ and g_- representing the growth rates under well-watered and water-stressed conditions, where well-watered and water-stressed conditions are inferred from the soil moisture dynamics of Eq. (19.1). While this description is an extreme simplification of the complex mechanisms driving plant activities and growth, it serves well the objective of determining the crop biomass and ultimately the final marketable yield. The probability distribution of the durations of well-watered and water-stressed conditions and the intervals between subsequent irrigations are not known, but numerical simulations shows that they are approximately exponentially distributed under realistic parameter choices (Vico and Porporato 2013). Conversely, the average durations of these periods are known analytically, as a function of soil and vegetation parameters and the precipitation regime (see Porporato et al. (2001) and Vico and Porporato (2010) for details). With these simplifications, the crop growth can be idealized as a dichotomic process. It thus becomes possible to analytically obtain the temporal evolution of the probability density function of the crop biomass during the main growth season and, by means of the harvest index, the final marketable yield. The probability distribution of applied irrigation totals can be obtained analytically too, as a function of the soil moisture crossing properties. We focus here on the case of demand-based traditional irrigation, i.e., it is assumed that a fixed amount of water is applied instantaneously (at the daily time scale) whenever soil moisture reaches a predefined threshold. For realistic parameter values, such irrigation applications occur at exponentially distributed intervals, with the shortest interval corresponding to the time necessary for evapotranspiration to remove the fixed amount of water provided at each application. Hence, irrigation applications occur according to a dead-time corrected Poisson process, and the probability distribution of seasonal irrigation totals can be obtained analytically (Cantor et al. 1975; Vico and Porporato 2013). Producing distributions for yield and applied irrigation volume ultimately provides a means to quantify not only their average values but also their variability, as a function of key aspects of the system: soil features, plant features and response to water stress, and management practices.

An example application of this approach is reported in Fig. 19.2, summarizing the average and standard deviation of seasonal precipitation totals (Fig. 19.2a), yield (Fig. 19.2b) and, for irrigated agriculture, required water volumes to meet the irrigation demands (Fig. 19.2c). Seasonal rainfall totals increase along the curves as indicated by the increasing sizes of the dots (dots of the same size correspond to the same amount of precipitation in all plots). The idealized description of the precipitation occurrence is such that the standard deviation of rainfall amounts increases with rainfall totals, although not linearly (Fig. 19.2a). A more complex pattern is observed for yield and irrigation applications. As expected, average yield increases, and irrigation applications decrease with rainfall totals. Conversely, the variability of both yield and water requirements is low under both dry and wet conditions (Fig. 19.2b, c). Under dry conditions, yield is driven by crop water use and management choice, and the variability in rainfall amount is low. At the other extreme, rainfall is sufficient to ensure well-watered conditions for the crop in all but a few years, so that yield variability is minimized and irrigation applications are generally infrequent. Within this general framework, irrigation can increase yields

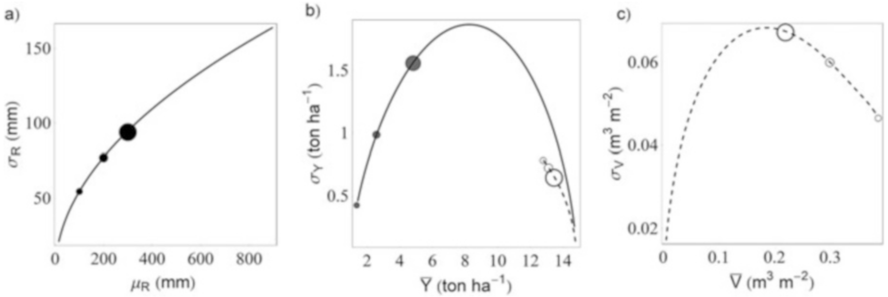

Fig. 19.2 Propagation of variability from rainfall to yields and irrigation water requirements using the example of maize. (**a**) Average μ_R and standard deviation σ_R of seasonal precipitation totals, as they change with average precipitation frequency; the average event depth is set at 15 mm. (**b**) Corresponding average μ_Y and standard deviation σ_Y of crop yield for rainfed agriculture (solid line) and deficit traditional irrigation (dashed line). (**c**) For irrigated agriculture, corresponding average μ_V and standard deviation σ_V of total seasonal irrigation requirements. Total seasonal average rainfall increases along all the curves, as indicated by the increasing sizes of the dots (from small to large dot, 100, 200, and 300 mm/seas, corresponding, respectively, to annual rainfall totals of 365, 730, and 1095 mm/year). All the other parameters are presented in Vico and Porporato (2013)

and reduce their variability relative to rainfed agriculture (dashed vs. solid line in Fig. 19.2b). The variability injected into the system by unpredictable rainfall is however transferred to the water requirements for irrigation (Fig. 19.2c). These results are in agreement with those obtained with both global data analyses and local, more detailed modeling approaches, showing that the variability in irrigation water requirements is lowest in dryer regions (Haddeland et al. 2006; Wisser et al. 2008). Irrigation significantly reduces the impact of climatic conditions (Troy et al. 2015) by buffering against the impacts of water stress and warming on crop yields (Hsiao 1973; Lobell and Gourdji 2012).

The relations in Fig. 19.2 exemplify the effects of the inherent nonlinearities of ecohydrological processes, which amplify the fluctuations and intermittency of external conditions (in this case the rainfall regime) in dryland systems. Also, they point to the existence of multiple tradeoffs, among yield and its stability and water requirements and their stability. At the local scale, for a given set of climatic conditions, large and stable yields can be achieved at the cost of high and variable irrigation requirements. In other words, efforts to ameliorate local “anthropogenic drylands” may have detrimental effects on yields and yield stability and hence on local food security or on economic benefits of food export. Across climates, the most stable yields occur in drier locations, but for those yields to be sufficiently high, large volumes of additional water become necessary, with implications for regional water availability, environmental flows, and ecosystem functioning. As such, shifting the production to more mesic locations, wetter seasons, or more water efficient crops would globally reduce water requirements for irrigation. Additional tradeoffs may need consideration when evaluating the sustainability of local water management for agriculture, beyond those relative to local demands for crop yields and water availability. Irrigation applications may affect percolation rates and groundwater recharge but also lead to groundwater level declines (Scanlon et al. 2010, 2012). Water quality must also be considered, both when evaluating the feasibility of using low quality water for irrigation (Assouline et al. 2015) and for preventing issues of secondary salinization. These biophysical factors play an important role in shaping the cropping decisions of each farmer in dryland agroecosystems. Of equal importance are the economic, social, and policy landscapes—shaped by both local and global influences—in which these decisions occur. These local–global linkages are essential to consider when developing effective strategies for enhancing both food security and water sustainability within dryland agroecosystems.

5 Local–Global Interactions

The processes discussed in the above sections point to the inherent coupling between local and global scales. All of the dynamics at play within the global food system are ultimately manifested as benefits or consequences at the local scale, and these local conditions and decisions affect the global food demand and supply. Figure 19.3 summarizes the key interactions between and within these scales, highlighting the role of environmental conditions, markets, and governmental policies.

Demographic growth, shifting diets, resource availability, and economic conditions dictate global food demand and ultimately shape the prices that a farmer can obtain for each crop. This produces an important feedback between global food demands and local production choices (and the resource use to support them). With the majority of global food production coming from smallholders (Leah et al. 2016), the influence of these global–local linkages will have important implications for rural livelihoods, for resilience and agrobiodiversity, and for the sustainable development of dryland nations. However, the majority of dryland cultivated areas are currently rainfed, and smallholders may not have adequate financial capital to access improved agricultural technologies and infrastructure (such as irrigation). Without interventions from government institutions, the expected increases in rainfall variability and in the frequency of extreme climatic events under climate change will make it increasingly difficult for farmers to avoid crop losses and will have important consequences for food and nutrition security within dryland nations. Governments and other actors can aid in minimizing the risks to farmers through a number of interventions, including improved access to irrigation and drought-resistant crop varieties, promotion of index insurance, and the facilitation of income diversification. Local initiatives may also support the implementation of management strategies aimed at enhancing soil water holding capacity, thus potentially reducing water (and nutrient) losses via deep percolation (Jägermeyr et al. 2016). While all these measures may implicate the local water balance, irrigation has the largest potential effect. Hence, expanding access to irrigation should not compromise efforts at sustainable water use or produce new “anthropogenic drylands” (Rosa et al. 2018). Overall, the strategies adopted by governments and farmers will be what prevent (or facilitate)

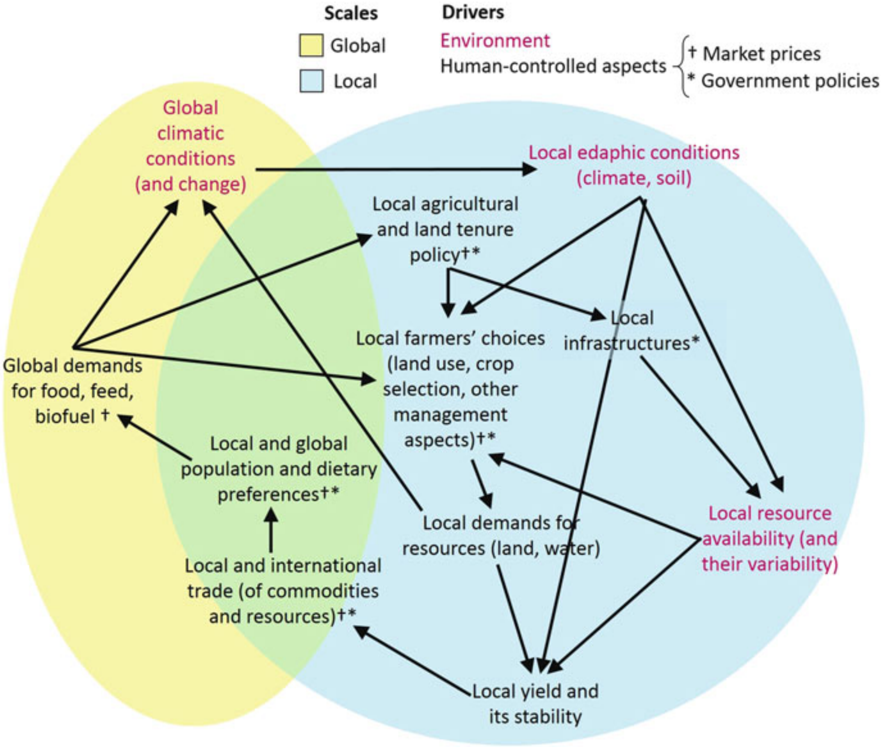

Fig. 19.3 Feedbacks between global and local scales within dryland agroecosystems. This schematic representation shows the interacting factors of food production, consumption, trade, and resource availability and use

the endurance or emergence of "anthropogenic drylands." Tools like the one discussed in Sect. 4 permit assessing the local implications of different strategies and allow for a quantitative exploration of the inherent tradeoffs between production, water requirements, and the efficient use of resources, explicitly including the key management aspects.

The ongoing emergence of "anthropogenic drylands" is compelling evidence that sustainability goals related to food security and the environment continue to be in discord. The mounting effects of climate change and variability and ever-growing food demand promise to produce conditions of water scarcity in global drylands more extensively and more frequently (Veldkamp et al. 2016). Dryland nations that export food items absorb the environment costs of production in exchange for economic benefits. These transactions will require re-evaluation under ongoing global environmental change (O'Bannon et al. 2014; Suweis et al. 2013). This is especially true for those countries whose willingness to export has had local negative effects on resource availability, for example, by contributing to groundwater depletion and inadequate environmental flows (Dalin et al. 2017). Ultimately, the extent to which dryland nations can move toward sustainable and resilient management of their food and water systems will have knock-on effects for the rest of the global food system. Countries will need to decide where on the spectrum from complete food self-sufficiency to total import reliance they will achieve the best opportunities for ensuring food security and water sustainability in the face of rising environmental variability and food demand. By assessing their exposure to both local and distant economic and environmental shocks and by quantifying the nutritional, environmental, and economic aspects of domestic food production systems, countries in dryland regions can begin developing informed, holistic, and science-based sustainability solutions.

6 Conclusion

Locally, water stress—and the creation of “anthropogenic drylands”—occurs as a direct result of the crops that farmers choose to plant (Sect. 4). These decisions are heavily influenced by global and local dietary preferences, economic conditions, and local knowledge (Davis and Olayide 2018). The various linkages between production and consumption are a key aspect of solution development when seeking to ensure food system sustainability and resilience, rural livelihood development, and responsible water use within dryland agroecosystems (Fig. 19.3). The ever-growing crop needs and a changing (and increasingly variable) climate demand that strategies toward increasing food production in drylands integrate multiple sustainability goals aimed at promoting food security and nutrition, sustainable water use, and climate resilience. Matching food security goals with sustainable water use begins by identifying low-yielding (and often water-scarce) cropland areas (e.g., Davis et al. 2017b) and determining whether water availability can be expected to meet the demands of crop yield gap closure (Rosa et al. 2018). In this way decision-makers can ensure that places of increased crop production within drylands match the spatial and temporal availability of water resources (e.g., Brauman et al. 2016; Davis et al. 2017b; Hoekstra et al. 2012; Mekonnen and Hoekstra 2016). For dryland systems, in particular, these efforts at sustainability also mean quantifying both the availability and variability of local water resources (Sect. 4). A baseline knowledge on the volume and variability of water resources and demand as well as the benefits or impacts of different management strategies will better enable decision-makers to develop science-based solutions that incorporate multiple economic and socio-environmental considerations.

To this end, solutions aimed at enhancing food production and avoiding unsustainable water use should seek to incorporate future uncertainties in precipitation variability and freshwater availability in dryland agroecosystems. In sub-Saharan Africa and many other parts of the world, there remains a large potential to increase crop yields through improved irrigation and fertilizer access (Mueller et al. 2012; van Ittersum et al. 2016), offering dryland agriculture a host of opportunities to both increase the average and stability of crop supply (Fig. 19.2). In addition, there remains a large potential for many places to transition to double-cropping systems, subject to water availability (Ray and Foley 2013). By selectively enhancing crop productivity where and when water resources are relatively abundant, dryland nations can develop diverse strategies to better cope with current and future climatic stress. This potential to intensify agriculture offers promise for reducing the reliance of many dryland nations on food imports (FAOSTAT 2017; van Ittersum et al. 2016), though the question of how high-yielding crop varieties and agricultural technologies can best be diffused to these areas of persistent low productivity remains a complex challenge (Pingali 2012). Given the inherently high variability in precipitation within dryland agroecosystems, efforts to maximize yields may help to mitigate issues of yield stability, as long as shocks to production do not overwhelm the buffering capacity of trade and strategic reserves. How each dryland nation deals with this tradeoff between system redundancy and efficiency will be dictated by the specific conditions with which they must cope and will be central in determining the sustainability of their water and food systems (e.g., Suweis et al. 2015).

There are various opportunities by which dryland countries can achieve co-benefits for crop production and water use. These strategies include the management of irrigation and soil resources (Jägermeyr et al. 2016), increasing the cropland areas dedicated to more nutritious and water use-efficient crops (Davis et al. 2017a, b) and selectively expanding irrigation infrastructure based on water availability (Rosa et al. 2018). While these potential solutions offer promise for aligning goals of food security and water sustainability, there is still a need to understand the various economic, social, and environmental factors that shape farmer cropping choices and how these decisions collectively influence food supply and water resource use. All of this demonstrates the utility of multidimensional approaches for achieving sustainable dryland food systems—approaches that consider the outcomes of a particular intervention across agriculture, nutrition, livelihoods, and the environment—and reasserts the need to develop solution-oriented science that links with the information needs of decision-makers in dryland countries. By examining the potential co-benefits or tradeoffs between food production, water use, and a host of other outcomes deemed important by local stakeholders, decision-makers can tailor strategies that best ensure the long-term sustainability of agricultural systems in drylands areas.

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