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Review and classification of indicators of green water availability and scarcity

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Abstract

Research on water scarcity has mainly focused on blue water (surface- and groundwater), but green water (soil moisture directly returning to the atmosphere as evaporation) is also scarce, because its availability is limited and there are competing demands for green water. Crop production, grazing lands, forestry and terrestrial ecosystems are all sustained by green water. The implicit distribution or explicit allocation of limited green water resources over competitive demands determines which economic and environmental goods and services will be produced and may affect food security and nature conservation. We need to better understand green water scarcity to be able to measure, model, predict and handle it. This paper reviews and classifies around 80 indicators of green water availability and scarcity and discusses the way forward to develop operational green water scarcity indicators that can broaden the scope of water scarcity assessments.

1 Introduction

Freshwater is a renewable resource that is naturally replenished over time when moving through the hydrological cycle (Oki and Kanae, 2006; Hoekstra, 2013). Precipitation forms the input of freshwater on land. Subsequently, it takes the blue or the green pathway back to the ocean and atmosphere before eventually returning as precipitation again (Falkenmark, 2003; Falkenmark and Rockström, 2006, 2010). The water that runs off to the ocean via rivers and groundwater is called the blue water flow. The green water flow is formed by the water that is temporarily stored in the soil and on top of vegetation and returns to the atmosphere as evaporation instead of running off (Hoekstra et al., 2011). As suggested by (Savenije, 2004), we use in this paper the term evaporation (instead of the often used term evapotranspiration) to refer to the vapour flux from land to atmosphere, which includes soil evaporation, evaporation of intercepted water, transpiration and in some cases (e.g. rice or swamp vegetation)

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open-water evaporation. About three-fifth of the precipitation over land takes the green path and two-fifth the blue path (Oki and Kanae, 2006).

Both blue and green water flows are made productive for human purposes. Blue water is used for industrial and domestic purposes and irrigation in agriculture. Green water sustains crop production, grazing lands, forestry and terrestrial ecosystems (Rockström, 1999; Rockström et al., 1999; Savenije, 2000; Gerten et al., 2005). These systems provide food, fibres, biofuels, timber and livestock products and other ecosystem services humans benefit from (Millennium Ecosystem Assessment, 2005; Gordon et al., 2010).

Although freshwater is renewable, this does not mean that its availability is unlimited. In fact, freshwater is also a finite resource (Hoekstra, 2013). Over a certain period, there falls a certain amount of precipitation. This limits both blue and green water availability in time. Human society cannot appropriate more water than is available. The finiteness of freshwater in combination with the various competing demands for water, makes water a scarce resource.

Water scarcity is becoming increasingly important for multiple reasons. The growing world population leads to rising demands for food, energy and other water-consuming goods and services (Hejazi et al., 2014; WWAP, 2015). Moreover, people's diets are changing toward more livestock-based products, due to rising incomes and continuing urbanization (Molden, 2007). Such diets are more water and land intensive (Erb et al., 2009; Kastner et al., 2012; Odegard and van der Voet, 2014). Policies towards more energy production from biomass create additional pressure on water and land (Hejazi et al., 2014). On top of this, a changing climate with increased variability and more extremes (IPCC, 2013) amplifies water scarcity (WWAP, 2014).

Given that green and blue water resources are limited and there are competing demands for both, green water as well as blue water are scarce. Therefore, it is surprising that research and debate on water scarcity have been, and still are, mainly focused on blue water (Vörösmarty et al., 2000, 2010; Rijsberman, 2006; Wada et al., 2011; Hoekstra et al., 2012; WWAP, 2014, 2015). Although the importance of green water has

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increasingly gained acceptance since Falkenmark (1995) drew attention to it in the mid-1990s (Savenije, 2000; Rockström, 2001; Rijsberman, 2006; Liu et al., 2009; Hanasaki et al., 2010; Hoekstra and Mekonnen, 2012), the notion of green water scarcity is only limitedly addressed in literature (Falkenmark et al., 2007; Falkenmark, 2013a, b). While the need to incorporate green water in water scarcity indicators and assessments has already been expressed since the beginning of this millennium (Savenije, 2000; Rockström, 2001; Rijsberman, 2006; Falkenmark and Rockström, 2006), only a few attempts have been made so far in the form of combined green-blue water scarcity assessments (Rockström et al., 2009; Gerten et al., 2011; Kummu et al., 2014) (discussed in detail in Sect. 3.2).

Green water scarcity refers to the competition over limited green water resources and allocation over competing demands. This allocation occurs mostly implicit and indirect, since generally it is land that is been allocated to a certain use. This indirectness of allocation, together with the absence of a price, makes green water scarcity invisible in our economy. This does not mean, though, that green water resources are not scarce, since using green water for one purpose makes it unavailable for another purpose. We need to measure how scarce green water is in order to answer questions like: can we produce enough food, feed, fibres, bioenergy and forestry products with limited availability of water resources and suitable land? and; how can we do so without compromising natural ecosystems and other sectors that put a claim on water and land resources? For studying these crucial questions, a sole assessment of blue water scarcity is insufficient.

Therefore, it is due time that more attention is given to green water scarcity and how we can measure it. This paper reviews and classifies indicators of green water availability and scarcity and discusses the way forward to develop operational green water scarcity indicators. First, we discuss the multiple dimensions of water availability and scarcity and sharpen the scope of this review (Sect. 2). Next, we classify and review green water availability and scarcity indicators (Sect. 3). Finally, we draw conclusions and discuss future research directions (Sect. 4).

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2 Multiple aspects of water availability and scarcity

The concepts of water availability and scarcity are examined in Sects. 2.1 to 2.4. We will reflect on these concepts in broad terms, not yet focussing on green water. In Sect. 2.5 we detail the scope of the indicators discussed in this paper.

2.1 Water availability and scarcity

A straightforward definition of water scarcity is: "an excess of water demand over available supply" (FAO, 2012). Various other definitions of water scarcity exist that aim to be more inclusive:

"An imbalance between supply and demand of freshwater in a specified domain (country, region, catchment, river basin, etc.) as a result of a high rate of demand compared with available supply, under prevailing institutional arrangements (including price) and infrastructural conditions." (FAO, 2015)

"When an individual does not have access to safe and affordable water to satisfy her or his needs for drinking, washing or their livelihoods we call that person water insecure. When a large number of people in an area are water insecure for a significant period of time, then we can call that area water scarce." (Rijsberman, 2006)

Considering these definitions, we can conclude that water scarcity is not something that is experienced by a single person on a particular moment (day or week). Rather, it is experienced by a larger community within a certain geographic area (e.g. catchment or country) and relates to larger time-scales (months or years).

The concept of scarcity describes a relation between humans and nature (Baumgärtner et al., 2006). Nevertheless, we can distinguish water scarcity mainly caused by natural conditions of low water availability from scarcity mainly induced by a large human demand relative to natural availability. The latter can also occur in naturally water abundant areas (Pereira et al., 2002).

Until now we have spoken about physical water scarcity, referring to the situation where there is insufficient water to meet human demand. If human, institutional and

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financial capital limit access to the water, the term economic water scarcity applies (Seckler et al., 1999; Molden, 2007). In a broader sense, Ohlsson (2000) defines social resource scarcity as the situation in which social resources required to successfully adapt to physical water scarcity fall short.

2.2 Relative and absolute water scarcity

According to economic theory, water is a scarce good, because it carries opportunity costs, which are the benefits foregone from possible alternative uses of the water (FAO, 2004). This is a form of "relative scarcity" based on the assumption of substitutability of goods (Baumgärtner et al., 2006). Water can be scarce in the relative sense also in water-abundant areas, because allocating water to purpose A implies it cannot be allocated to purpose B. In other words, water for purpose A is scarce in relation to water for other purposes. In common language we are inclined to say that at some times water is scarce and at other times it is not. In economic sense, water is always scarce; the degree of water scarcity can vary though, it can even be zero if alternative uses and thus competition is absent.

We speak of "absolute scarcity" when according to Baumgärtner et al. (2006) "scarcity concerns a non-substitutable means for satisfaction of an elementary need and cannot be levied by additional production". This means that in an area with a limited amount of water resources (that cannot be increased), at a certain level of consumption, water for elementary purposes (e.g. drinking and food production) will no longer be substitutable with water use for less essential purposes. In this case, there is "absolute scarcity" of water. Whether water is scarce in the absolute or relative sense thus depends on the degree of water scarcity: relative water scarcity turns into absolute scarcity when the boundaries of water exploitation are approached.

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2.3 Blue and green water

Freshwater essentially stems from precipitation, which partitions into green and blue water (Falkenmark and Rockström, 2006, 2010). As discussed in the introduction of this paper, water availability and scarcity can pertain to both blue or green water resources, separately or in combination (Falkenmark, 2013b).

2.4 Water quantity and quality

Water scarcity is not only a function of the quantity of the water resource in relation to the demand, but also the quality of the resource in relation to the required quality for its end-purpose (Pereira et al., 2002). If there is sufficient water available for a certain purpose, but it is polluted to such an extent that it is not usable for that purpose, then water can be considered scarce as long as the means are not available for cleaning the water to a desirable level. Pollution of water resources can thus aggravate water scarcity (FAO, 2012).

2.5 Scope of the review and classification

This paper focuses on green water, water quantity and physical water scarcity and treats both green water availability and scarcity. In the next section, we consider indicators within this scope, including indicators of aridity, agricultural and meteorological drought, vegetation drought, soil moisture and integrated green-blue water scarcity. The focus of this paper implies that several concepts and indicators fall outside the scope of the classification. Concepts and indicators focusing on blue water that are out of scope are:

– Hydrological drought: concerns the effects of dry periods on surface- and subsurface hydrology and is therefore related to blue water. Examples of associated indicators are: Surface Water Supply Index (Shafer and Dezman, 1982); Palmer

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Hydrological Drought Index (Karl, 1986); several indicators reviewed by Smakhtin (2001).

- Blue water scarcity: measures human demand for blue water resources vs. blue water availability and is thus purely about blue water. Examples of associated indicators are: the water crowding indicator (Falkenmark et al., 1989), the withdrawal-to-discharge ratio (Vörösmarty et al., 2000), Water Poverty Index (Sullivan et al., 2003); Water Stress Indicator (Smakhtin et al., 2004); Water Stress Index (Pfister et al., 2009); Dynamic Water Stress Index (Wada et al., 2011); Blue Water Scarcity (Hoekstra et al., 2012). Note that some of these indicators also incorporate more than only physical elements of water scarcity (e.g. Water Poverty Index).

Concepts related to broader forms of water scarcity than physical water scarcity that are out of scope are:

- Socio-economic drought: concerns imbalances in supply and demand of economic goods due to the physical characteristics of drought (Wilhite and Glantz, 1985; American Meteorological Society, 2013) with effects on the economy and society. American Meteorological Society (2013) mentions the following effects: loss of income from lower crop yields; reduced spending in rural communities; health issues; mass migration.

- Social resource scarcity: see Sect. 2.1.

Furthermore, the review and classification in this paper excludes indicators that measure drought by combining multiple drought indicators (classified individually) and sometimes other information such as land-use maps. Examples of such indicators are the U.S. Drought Monitor (Svoboda et al., 2002) and the Vegetation Drought Response Index (Brown et al., 2008).

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3 Green water availability and scarcity indicators

We have identified around eighty indicators of green water availability and scarcity, which we classify into the following categories:

1. Green water availability indicators show whether green water availability is low or high and are insensitive to actual water demand. In other words, when the water demand increases, indicator values will not change. Within this category we distinguish *absolute* and *relative* green water availability indicators:

   a. Absolute green water availability indicators measure actual conditions of green water availability (in an absolute sense).

   b. Relative green water availability indicators measure actual conditions of green water availability compared to conditions that are perceived as "normal", which is often defined as the climate-average or median value of the variable of interest.

Note that this distinction between absolute and relative indicators is unrelated to and different from the concepts of relative and absolute scarcity earlier discussed in Sect. 2.2.

2. Green water scarcity indicators incorporate elements of both water availability and demand and therefore respond – in contrast to green water availability indicators – to changes in water demand as well. We distinguish three different options to measure green water scarcity conceptually (explanation in Sect. 3.2):

   a. Green water crowding.

   b. Green water requirements for self-sufficiency vs. green water availability.

   c. Actual green water consumption vs. green water availability.

In this paper, the term "demand" occurs in two different contexts with different meaning and hence requires some clarification. When we speak of "demand" in relation to

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the concept of green water scarcity, we refer to the human demand for green water, associated with the production of biomass for human purposes. In the discussion of agricultural drought indicators in Sect. 3.1, the term "crop moisture/evaporation/water demand" is used to refer to the water needs of the crop for non-water limited growth.

3.1 Green water availability indicators

Indicators of green water availability fall apart in indicators that do so in absolute sense or in the sense of relative to normal conditions. These two categories are treated in the next two subsections, respectively. Descriptions of various specific green water availability indicators that fall in the two categories are included in Appendices A and B, respectively. The indicator acronyms used in this section are defined in these appendices.

3.1.1 Absolute green water availability indicators

Indicators in this category measure green water availability in a certain area (or location) and period (or moment) in an absolute sense. We find here indicators of aridity, agricultural drought, soil moisture and agricultural suitability. Aridity indicators are solely based on climatic variables, while the others incorporate variables related to the soil and vegetation (or crop) as well. Agricultural drought indicators measure green water availability set against crop water demand for non-water limited growth. Absolute soil moisture indicators provide a "direct" measure of the amount of soil moisture available. Lastly, land classifications based on agricultural suitability under rain-fed conditions indirectly measure if green water availability is sufficient for the production of certain crops, by taking into account climate, soil and topographic conditions and the requirements of the crop.

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Aridity indicators

Aridity is seen as a permanent feature of a climate, consisting of low average annual precipitation and low soil moisture availability (Pereira et al., 2002; Heim, 2002; Kallis, 2008). As such, one can say that an aridity map shows the preconditions for vegetation (Falkenmark and Rockström, 2004). Aridity indicators are usually based on long-term average comparisons of precipitation vs. potential evaporation, temperature or saturation deficit, whereby the latter two were often used in the 20th century as proxies for potential evaporation due to lack of data. Aridity indicators are reviewed by Walton (1969), Wallén (1967) and more recently by Stadler (2005).

Two indicators we classify as aridity indicators require a note. First, Peixoto and Oort (1992) take the long-term average ratio of actual (instead of potential) evaporation over precipitation as a measure of aridity (ER). Second, the SCMD by Wilhelmi et al. (2002) shows the probability of seasonal crop moisture deficiency based on a combination of long-term precipitation records and area-weighted evaporation of the mixture of crops grown in the study area. Wilhelmi and Wilhite (2002) apply the SCMD to assess agricultural drought vulnerability in Nebraska. We classify the SCMD here under the aridity indicators, because like most aridity indicators, it measures precipitation vs. evaporation and is calculated for a historical time-period, thus representing a long-term average.

Agricultural drought indicators

According to the World Meteorological Organization (1975), agricultural drought indicators "indirectly express the degree to which growing plants have been adversely affected by an abnormal moisture deficiency", which may be the result of an unusually small moisture supply or an unusually large moisture demand (World Meteorological Organization, 1975). Formulated differently by Sivakumar (2010): "Agricultural drought depends on the crop evapotranspiration demand and the soil moisture availability to meet this demand."

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Therefore, the bulk of agricultural drought indicators measure crop available water compared to crop water needs for non-water limited growth (i.e. potential evaporation) and are usually applied on a daily, weekly, monthly or seasonal basis (Woli et al., 2012). Some indicators only look at the difference between actual and potential transpiration (e.g. DTx and WDI).

Drought is typically a relative-to-normal phenomenon as will be discussed in Sect. 3.1.2. Agricultural drought indicators, which measure actual relative to potential evaporation, are "relative" indicators in another way, though. They do not compare actual with "normal" conditions. Instead, they compare moisture supply with a crop water demand in the ideal case of non-water limited growth. Therefore these indicators actually measure absolute green water availability (actual evaporation), set against this crop water demand. In fact, these indicators say more about the demand for blue water (irrigation) to ensure non-water limited crop growth than they do about green water availability.

Here, three indicators need an extra note. Both the DSI by Mu et al. (2013) and the GrWSI by Wada (2013) compares the actual to potential evaporation ratio with the long-term average of this ratio. Therefore, these indicators are in essence relative indicators according to our classification. However, they are classified as agricultural drought indicators because they, like most of the others, measure actual to potential evaporation. The name of the GWSI by Nunez et al. (2013) suggests that it is a green water scarcity indicator. Nevertheless, we classify it as an agricultural drought indicator, because it measures actual moisture supply vs. crop-specific reference evaporation, albeit on a larger time-scale (three-year crop rotation) than most other agricultural drought indicators.

Absolute soil moisture indicators

Several indicators provide a measure of the absolute amount of soil moisture available at a given location and moment (or summed over a period), be it on the basis of field measurements (e.g. SMIX, SMI) and/or modelling of the soil water balance (e.g.

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Avg-GWS and SD-GWS) or remote sensing data (e.g. TVDI, MPDI). Many of these indicators have been introduced and applied as indicators of agricultural drought (e.g. ADD, SMDI, SMIX, SMI), analysing the correlation between soil moisture availability and crop yields. Therefore, they are typically calculated on intra-annual time-scales.

Agricultural suitability under rain-fed conditions

Maps that classify land according to agricultural suitability under rain-fed conditions (green water only) are indirect measures of green water availability in the absolute sense. Up to date, two global studies have made such land suitability classifications for rain-fed crop production for climate-average temperature and precipitation conditions and taking into account various soil parameters and terrain slope: GAEZ (IIASA/FAO, 2012) and GLUES (Zabel et al., 2014). Both studies classify lands as "not suitable", "marginally suitable", "moderately suitable" or "highly suitable". This classification shows where the climate, soil and topographic conditions are more or less suitable for agricultural production with green water only. In other words, where aridity maps show the preconditions for vegetation in general (Falkenmark and Rockström, 2004), these maps show the preconditions for rain-fed crop production, therein considering soil and terrain parameters in addition to climate.

3.1.2 Relative green water availability indicators

Indicators in this category measure green water availability relative to a "normal" condition and are usually calculated on intra-annual scales. As opposed to aridity, drought is often defined as a condition relative to what is perceived as a "normal" amount of precipitation or balance between precipitation and evaporation (World Meteorological Organization, 1975; Wilhite and Glantz, 1985). Droughts are often termed temporary, uncertain and difficult to predict features characterized by lower-than-average precipitation (Pereira et al., 2002; Heim, 2002; Kallis, 2008; Mishra and Singh, 2010; FAO, 2015). Therefore, indicators of meteorological drought and vegetation drought are clas-

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sified into the category of relative green water availability indicators. Meteorological drought indicators are based on climatic variables; vegetation drought indicators measure the impact of relatively low green water availability on vegetation. Indicators that measure soil moisture in a relative sense are included in this category as well.

Drought indicators have been reviewed by Keyantash and Dracup (2002) and Mishra and Singh (2010) and those indicators applied in the US by Heim (2002) and Hayes (2007).

Meteorological drought indicators

Meteorological drought indicators are based on climate factors. They fall apart in indicators that are solely based on precipitation (e.g. SPI) and those that consider both precipitation and potential evaporation (e.g. PDSI, RDI, SPEI). These indicators show whether there is relatively little precipitation or whether the normal balance between precipitation and evaporation is distorted.

Vegetation drought indicators

Vegetation drought indicators show the impact of relatively low green water availability by measuring the greenness of vegetation relative to historical observations of greenness. Hence, they reflect whether vegetation is deviating from regular conditions. Since the vegetation drought indicators we have identified are all based on remote-sensing observations, the indicators do not show whether deviations are caused by relatively dry weather (i.e. meteorological drought) or by other factors influencing vegetation growth (e.g. plant diseases or human interference such as pruning and clearing).

Relative soil moisture indicators

In contrast to the absolute soil moisture indicators discussed in Sect. 3.1.1, these indicators measure the moisture conditions at a given location relative to a normal condition. Identified examples are the PZI, SMAI and SD. They are also considered suitable for measuring agricultural droughts (Keyantash and Dracup, 2002; Narasimhan and Srinivasan, 2005).

3.2 Green water scarcity indicators

As put forward in Sect. 2, water scarcity pertains to a situation with a high water demand compared to water availability, which is experienced by a community (numerous people) within a certain geographic area (e.g. catchment or country) over a significant period of time (months or years). We can then define green water scarcity as *the degree of competition over limited green water resources, whereby the demand for green water resources to sustain the production of a desirable level of biomass-based products within a certain geographic area is somehow compared to the available green water resources in space and time*.

Since production of biomass-based products (food, fibres, biofuels, timber) generally takes place in cycles of one year (or more in case of perennials and forestry), this definition of green water scarcity incorporates the "significant period of time" element in the imbalance between green water availability and demand. Furthermore, limited production of biomass-based products affects numerous people, both producers and consumers.

As opposed to the indicators discussed in Sect. 3.1, indicators of green water scarcity thus need to include a measure of green water demand, associated with the production of biomass for human purposes, compared to green water availability. In other words, they should measure green water availability in relation to human needs for green water: crop production, grazing lands, forestry. Note that the term "green water availability" here refers to the part of the green water flow available for biomass production for human purposes (in space and time); it thus excludes green water flows that are effectively unavailable, for instance green water flows in unsuitable areas (e.g. because of steep slopes) or green water flows in cold parts of the year unsuitable for growth.

We distinguish three different options to measure green water scarcity conceptually:

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a. *Green water crowding*: per capita available green water resources in an area compared to a global average threshold representing the amount of green water required to sustain a person's "standard consumption pattern of biomass-based products".

b. *Green water requirements for self-sufficiency vs. green water availability*: green water requirements for producing the consumed biomass-based products within a certain geographic area, assuming self-sufficiency within the geographic area, compared to the green water resources in the geographic area.

c. *Actual green water consumption vs. green water availability*: actual green water consumption in a certain geographic area (associated with the actual production of biomass for human purposes) compared to green water availability in the area. This type of indicator thus acknowledges the possibility of virtual water trade as opposed to assuming self-sufficiency as in the previous two types of indicators.

In Sects. 3.2.1 and 3.2.2, we discuss existing indicators that measure aggregated green-blue water scarcity and reflect on how these indicators could be adapted to measure green water scarcity according to above-mentioned options (a) and (b). In Sect. 3.2.3, we elaborate upon a comprehensive indicator of the third form of measuring green water scarcity that has yet to be brought into practice. The challenges for operationalization of these green water scarcity indicators are discussed in Sect. 3.2.4.

3.2.1 Green water crowding

Rockström et al. (2009) introduced a combined green-blue water shortage index, which compares the sum of green and blue water availability with a global average threshold of 1300 $m^3 cap^{-1} yr^{-1}$. This threshold represents the green and blue water requirements for sustaining a global average "standard diet". When green-blue water availability drops below the threshold, this indicates a shortage of green-blue water re-

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sources. The green-blue water shortage index is an indicator of water crowding, similar to Falkenmark's blue-water focused water crowding indicator (Falkenmark et al., 1989).

Similar to the indicator by Rockström et al. (2009), an indicator of green water crowding could be defined as the per capita available green water resources in an area compared to a global average threshold representing the amount of green water required to sustain a person's "standard consumption pattern". We intentionally speak here of a consumption pattern, because green water is not only required to produce food, but also to produce other biomass-based products humans consume, such as fibres, biofuels and forestry products. As such, the measure of green water requirements we propose here is broader than the definition of a "standard diet" according to Rockström et al. (2009) (and Gerten et al., 2011; Kummu et al., 2014), which only pertains to water requirements for food production.

Rockström et al. (2009) define green water availability as "the soil moisture available for productive vapour flows from agricultural land". Technically, they calculate green water availability as actual evaporation from existing cropland and permanent pasture, reduced by a factor 0.85 that accounts for minimum evaporation losses that are unavoidable in agricultural systems (Rockström et al., 2009). This definition is dependent on the extent of agricultural land and excludes available green water on lands that are currently uncultivated, but have potential to be used productively in a sustainable manner.

3.2.2 Green water requirements for self-sufficiency vs. green water availability

Gerten et al. (2011) and later Kummu et al. (2014) elaborated on the work by Rockström et al. (2009). Instead of using a global average, Gerten et al. (2011) calculate the green-blue water requirements for sustaining a "standard diet" on the national level based on local crop water productivities and compare this with the sum of green and blue availability in each country of the world. The resulting green-blue water scarcity indicator, computed for each country, is defined as the ratio between green-blue water availability and green-blue water requirements for producing the standard diet. They

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define green water availability similar to Rockström et al. (2009), but a bit more conservative: they do not assume year-round evaporation from areas covered with perennial "other" crops (excl. the major food crops) they parameterized as perennial grass (Gerten et al., 2011).

Whereas the studies by Rockström et al. (2009) and Gerten et al. (2011) are based on climate-averages, Kummu et al. (2014) apply the green-blue water scarcity indicator by Gerten et al. (2011) on a year-by-year basis to account for inter-annual climate variability on the scale of food producing units, the scale at which demand for water and food is assumed to be managed according to the authors. Kummu et al. (2014) measure the frequency of years in which green-blue water availability falls short of green-blue water requirements, on which they base their classification of green-blue scarcity: no scarcity; occasional scarcity (subdivided in four levels); or chronic scarcity.

The green-blue water scarcity indicator shows the potential of a geographic area (e.g. country or food producing unit) to reach food self-sufficiency and reflects its dependency on trade in agricultural commodities and associated virtual water (Kummu et al., 2014). A similar indicator for green water could show an area's green water demand for self-sufficiency in producing biomass-based products for sustaining the "standard consumption pattern" to green water availability in the area.

For the potential green water scarcity indicators discussed in Sects. 3.2.1 and 3.2.2, a more comprehensive definition of green water availability is advised than the one applied by Rockström et al. (2009), Gerten et al. (2011) and Kummu et al. (2014). An example of a more comprehensive definition is discussed in the following section.

3.2.3 Actual green water consumption vs. green water availability

The green water scarcity indicator by Hoekstra et al. (2011) compares the actual green water consumption in an area associated with the actual biomass production pattern (hence considering virtual water trade as opposed to assuming self-sufficiency) with green water availability in the area. Green water scarcity is defined as the ratio of the

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total green water footprint in a catchment x in a period t (e.g. a year) over green water availability.

The sum of green water footprints equals all actual evaporation (E_{act}) related to biomass production for human purposes (i.e. agriculture and forestry) excluding the part of the vapour flow that originates from blue water resources (irrigation). Green water availability is defined as total E_{act} over the catchment minus E_{act} from land reserved for natural vegetation (so called "environmental green water requirement") and minus E_{act} from land that cannot be made productive, e.g. in areas or periods of the year that are unsuitable for crop growth (Hoekstra et al., 2011). In fact, green water availability defined like this, represents the maximum sustainable green water footprint in the catchment and period under consideration. Hence, the green water scarcity ratio shows the extent to which the green water footprint has reached its maximum sustainable level. Of course, this definition can also be applied to other geographical units than a catchment.

The definition of green water availability by Hoekstra et al. (2011) is more comprehensive than the one used by Rockström et al. (2009), Gerten et al. (2011) and Kummu et al. (2014). However, this is also the reason why the indicator has not been made operational yet. Difficulties remain in estimating the amount of land that needs to be reserved for nature and when and where the green water flow (E_{act}) cannot be made productive (Hoekstra et al., 2011). These challenges are discussed in the following section.

Furthermore, this indicator does not overcome the problem of dealing with the productivity of green water use (Rockström et al., 2009). Transpiration is a productive form of green water use, contributing to biomass production, while other components of the evaporative flow are regarded as unproductive (Rockström, 2001; Rockstrom et al., 2007; Savenije, 2004). Rockstrom et al. (2007) express this in a ratio of transpiration to evaporation, which Rockström et al. (2009) call the transpiration efficiency, when they apply the ratio at the country level (in fact they reduce evaporation with a factor 0.85, see Sect. 3.2.1). The transpiration efficiency is complementary to the green water scarcity indicator by Hoekstra et al. (2011). A green water scarcity assessment based on both will give insight into the *severity* of green water scarcity: areas that are considered highly green-water scarce, but have a low transpiration efficiency, may have options to improve the latter and thereby yields, which may lower the green water scarcity.

3.2.4 Challenges for operationalization of green water scarcity indicators

Operationalization of green water scarcity indicators faces three major challenges, particularly regarding the quantification of green water availability.

First, the determination of which areas and periods of the year the green water flow can be used productively is not straightforward. Absolute green water availability indicators, in particular land classifications of agricultural suitability, can provide insight in the availability of green water in the spatial dimension. Relative green water availability indicators can enrich the picture by showing which areas are prone to large inter- and intra-annual variations in green water availability, making these areas less suitable for (certain types of) biomass production. To estimate which part of the green water flow can be used productively in time, advanced crop growth models (like APSIM (McCown et al., 1995; Holzworth et al., 2014), AquaCrop (Steduto et al., 2009), CropSyst (Stöckle et al., 2003), EPIC (Jones et al., 1991) or SWAP/WOFOST, van Dam et al., 2008) can be used to simulate water-limited yields and actual evaporation for various cropping periods and different types of soil, crop and agricultural water management (e.g. adding blue water in the form of deficit irrigation during a dry spell, might make it possible for the crop to survive and use the green water flow later in the year productively).

Second, estimating green water consumption of forestry is difficult, because it entails separation of production forest evaporation into green and blue parts. This is problematic, because trees generally root so deep that, by means of capillary rise, they directly take up water from groundwater (blue) in addition to the soil moisture (green) (Hoekstra, 2013).

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Third, research is required to determine the environmental green water requirements, i.e. the green water flow that should be preserved for nature, similar to the environmental flow requirements for blue water. Key here is the identification of areas that need to be reserved for nature and biodiversity conservation. It is known that the current network of protected areas is insufficient to conserve biodiversity (Rodrigues et al., 2004a, b; Venter et al., 2014; Butchart et al., 2015) and that attention should be paid to conservation of biodiversity in production landscapes that are shared with humans (Baudron and Giller, 2014). The 11th Aichi Biodiversity Target is to expand the protected area network, which currently has a terrestrial coverage of about 14.6 % (Butchart et al., 2015), to at least 17 % terrestrial coverage by 2020 (Convention on Biological Diversity, 2010). However, to properly assess the limitations to green water availability, spatially explicit information on the additional areas to be preserved is required. The best-available data regarding this is recently published work by Montesino Pouzols et al. (2014). These authors have mapped global and national priority areas for expansion of the protected area network on 0.2° spatial resolution and assessed associated conservation gains (Montesino Pouzols et al., 2014; Brooks, 2014).

4 Conclusions and future research

In this paper we have reviewed and classified around eighty indicators of green water availability and scarcity. This list of indicators is extensive, but not exhaustive. Nevertheless, we are confident to have identified the most widely used and cited indicators.

The number of green water availability indicators by far outnumbers the existing green water scarcity indicators. This reflects that the concept of green water scarcity is still largely unexplored. Indicators of green-blue water crowding and scarcity have been developed by Rockström et al. (2009), Gerten et al. (2011) and Kummu et al. (2014). These have potential to be tailored to measure green water crowding and green water requirements for self-sufficiency vs. green water availability. The green water scarcity indicator by Hoekstra et al. (2011) measures actual green water consumption vs. green

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water availability, but has not yet been operationalized due to several challenges discussed in Sect. 3.2.4. The biggest challenge is to determine which part of the green water flow can be made productive in space and time. Application of both absolute and relative green water availability indicators will provide insight in which areas the green water flow can be made productive for human purposes. Simulations with crop growth models for different management strategies can be used to assess which parts of the year the green water flow can be made productive.

Future research should be aimed at overcoming these challenges to make the green water scarcity indicators discussed in this paper operational. We also encourage the development of additional definitions of green water scarcity indicators to the ones discussed here. The conceptual definition of green water scarcity we introduced in Sect. 3.2 can be a starting point for this.

Despite scientific obstacles on the way, it is time that the scope of water scarcity assessments is broadened to include green water. We hope that this paper is a stepping stone towards this goal by bringing structure in the large pool of green water availability indicators and discussing the way forward to develop operational green water scarcity indicators. Practitioners and scholars might also find the classification of indicators provided in this paper insightful and helpful for choosing the indicator that suits their purpose.

Appendix A: Absolute green water availability indicators

Absolute green water availability indicators are included in Tables A1 to A4. Often used symbols in this Appendix: E_{act} = actual evaporation; E_{pot} = potential evaporation; $E_{pot,\,c}$ = crop-specific potential evaporation; $E_{pot,\,ref}$ = potential evaporation of FAO reference crop; P = precipitation; S = soil moisture; T = air temperature; Tr_{act} = actual transpiration; Tr_{pot} = potential transpiration.

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Appendix B: Relative green water availability indicators

Relative green water availability indicators are included in Tables B1 to B4. Often used symbols in this Appendix: E_{pot} = potential evaporation; $E_{pot,\,ref}$ = potential evaporation of FAO reference crop; P = precipitation; NDVI = Normalized Difference Vegetation Index.

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References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements, FAO, Rome, 1998.

Alley, W. M.: The Palmer drought severity index – limitations and assumptions, J. Clim. Appl. Meteorol., 23, 1100–1109, doi:10.1175/1520-0450(1984)023<1100:tpdsil>2.0.co;2, 1984.

American Meteorological Society: Drought: An Information Statement of the American Meteorological Society, American Meteorological Society, Boston, USA, 2013.

Anderson, M. C., Norman, J. M., Mecikalski, J. R., Otkin, J. A., and Kustas, W. P.: A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 1. Model formulation, J. Geophys. Res.-Atmos., 112, D10117, doi:10.1029/2006jd007506, 2007a.

Anderson, M. C., Norman, J. M., Mecikalski, J. R., Otkin, J. A., and Kustas, W. P.: A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 2. Surface moisture climatology, J. Geophys. Res.-Atmos., 112, D11112, doi:10.1029/2006jd007507, 2007b.

Bates, C. G.: Climatic characteristics of the Plains Region, in: Possibilities of Shelterbelt Planting in the Plains Region, edited by: Silcox, F. A., United States Government, Washington, D.C., 83–110, 1935.

Baudron, F. and Giller, K. E.: Agriculture and nature: trouble and strife?, Biol. Conserv., 170, 232–245, doi:10.1016/j.biocon.2013.12.009, 2014.
Baumgärtner, S., Becker, C., Faber, M., and Manstetten, R.: Relative and absolute scarcity of nature: assessing the roles of economics and ecology for biodiversity conservation, Ecol. Econ., 59, 487–498, doi:10.1016/j.ecolecon.2005.11.012, 2006.
Bergman, K. H., Sabol, P., and Miskus, D.: Experimental indices for monitoring global drought conditions, 13th Annual Climate Diagnostics Workshop, Cambridge, MA, 31 October–4 November, 190–197, 1988.
Bhalme, H. N. and Mooley, D. A.: Large-scale droughts/floods and monsoon circulation, Mon. Weather Rev., 108, 1197–1211, doi:10.1175/1520-0493(1980)108<1197:lsdamc>2.0.co;2, 1980.
Blumenstock, G.: Drought in the United States Analyzed by Means of the Theory of Probability, USDA Technical Bulletins, Washington D.C., USA, 1942.
Brooks, T. M.: Conservation: mind the gaps, Nature, 516, 336–337, doi:10.1038/516336a, 2014.
Brown, J. F., Wardlow, B. D., Tadesse, T., Hayes, M. J., and Reed, B. C.: The Vegetation Drought Response Index (VegDRI): a new integrated approach for monitoring drought stress in vegetation, Gisci. Remote Sens., 45, 16–46, doi:10.2747/1548-1603.45.1.16, 2008.
Budyko, M. I.: The Heat Balance of the Earth's Surface, Teplovoi balans zemnoi poverkhnosti. English, U.S. Dept. of Commerce, Weather Bureau, Washington, 259 pp., 1958.
Butchart, S. H. M., Clarke, M., Smith, R. J., Sykes, R. E., Scharlemann, J. P. W., Harfoot, M., Buchanan, G. M., Angulo, A., Balmford, A., Bertzky, B., Brooks, T. M., Carpenter, K. E., Comeros-Raynal, M. T., Cornell, J., Ficetola, G. F., Fishpool, L. D. C., Fuller, R. A., Geldmann, J., Harwell, H., Hilton-Taylor, C., Hoffmann, M., Joolia, A., Joppa, L., Kingston, N., May, I., Milam, A., Polidoro, B., Ralph, G., Richman, N., Rondinini, C., Segan, D. B., Skolnik, B., Spalding, M. D., Stuart, S. N., Symes, A., Taylor, J., Visconti, P., Watson, J. E. M., Wood, L., and Burgess, N. D.: Shortfalls and solutions for meeting national and global conservation area targets, Conservation Letters, 1–9, doi:10.1111/conl.12158, 2015.
Byun, H.-R. and Wilhite, D. A.: Objective quantification of drought severity and duration, J. Climate, 12, 2747–2756, doi:10.1175/1520-0442(1999)012<2747:OQODSA>2.0.CO;2, 1999.
Capot-Rey, R.: Une carte de l'indice d'aridité au Sahara français, Bulletin de l'Association de géographes français, 73–76, 216–217, 1951.
de Martonne, E.: Nouvelle carte mondial de l'indice d'aridité, Ann. Geogr., 288, 241–250, 1942.

Du, L., Tian, Q., Yu, T., Meng, Q., Jancso, T., Udvardy, P., and Huang, Y.: A comprehensive drought monitoring method integrating MODIS and TRMM data, Int. J. Appl. Earth Obs., 23, 245–253, doi:10.1016/j.jag.2012.09.010, 2013.

Erb, K.-H., Haberl, H., Krausmann, F., Lauk, C., Plutzar, C., Steinberger, J. K., Müller, C., Bondeau, A., Waha, K., and Pollack, G.: Eating the Planet: Feeding and fuelling the world sustainably, fairly and humanely – a scoping study, Social Ecology Working Paper 116, Institute of Social Ecology, Vienna, 2009.

Falkenmark, M.: Land-Water Linkages: A Synopsis. Land and Water Integration and River Basin Management, Food and Agriculture Organization of the United Nations, Rome, 15–16, 1995.

Falkenmark, M.: Freshwater as shared between society and ecosystems: from divided approaches to integrated challenges, Philos. T. R. Soc. B, 358, 2037–2049, doi:10.1098/rstb.2003.1386, 2003.

Falkenmark, M.: Water security – the multiform water scarcity, in: Water Security: Principles, Perspectives and Practices, edited by: Lankford, B. B. K., Zeiton, M., and Conway, D., Earthscan, London, 64–79, 2013a.

Falkenmark, M.: Growing water scarcity in agriculture: future challenge to global water security, Philos. T. R. Soc. A, 371, 20120410, doi:10.1098/rsta.2012.0410, 2013b.

Falkenmark, M. and Rockström, J.: Balancing Water for Humans and Nature: The New Approach in Ecohydrology, Earthscan, London, 2004.

Falkenmark, M. and Rockström, J.: The new blue and green water paradigm: breaking new ground for water resources planning and management, J. Water Res. Pl.-ASCE, 132, 129–132, doi:10.1061/(asce)0733-9496(2006)132:3(129), 2006.

Falkenmark, M. and Rockström, J.: Building water resilience in the face of global change: from a blue-only to a green-blue water approach to land-water management, J. Water Res. Pl.-ASCE, 136, 606–610, 2010.

Falkenmark, M., Lundqvist, J., and Widstrand, C.: Macro-scale water scarcity requires micro-scale approaches – aspects of vulnerability in semi-arid development, Nat. Resour. Forum, 13, 258–267, 1989.

Falkenmark, M., Berntell, A., Jägerskog, A., Lundqvist, J., Matz, M., and Tropp, H.: On the Verge of a New Water Scarcity: A Call for Good Governance and Human Ingenuity, SIWI, Stockholm, Sweden, 2007.

FAO: Early Agrometeorological Crop Yield Assessment, Food and Agriculture Organization of the United Nations, Rome, 1986.

HESSD
12, 5519–5564, 2015

FAO: Economic Valuation of Water Resources in Agriculture: From the Sectoral to a Functional Perspective of Natural Resource Management, Food and Agriculture Organization of the United Nations, Rome, 2004.

FAO: Coping with Water Scarcity: An Action Framework for Agriculture and Food Security, Food and Agriculture Organization of the United Nations, Rome, 2012.

FAO AQUASTAT Glossary: available at: http://www.fao.org/nr/water/aquastat/data/glossary/search.html?lang=en, (last access: 2 March 2015), 2015.

Gao, B.: NDWI – a normalized difference water index for remote sensing of vegetation liquid water from space, Remote Sens. Environ., 58, 257–266, doi:10.1016/S0034-4257(96)00067-3, 1996.

Gerten, D., Hoff, H., Bondeau, A., Lucht, W., Smith, P., and Zaehle, S.: Contemporary "green" water flows: simulations with a dynamic global vegetation and water balance model, Phys. Chem. Earth, 30, 334–338, doi:10.1016/j.pce.2005.06.002, 2005.

Gerten, D., Schaphoff, S., and Lucht, W.: Potential future changes in water limitations of the terrestrial biosphere, Climatic Change, 80, 277–299, doi:10.1007/s10584-006-9104-8, 2007.

Gerten, D., Heinke, J., Hoff, H., Biemans, H., Fader, M., and Waha, K.: Global water availability and requirements for future food production, J. Hydrometeorol., 12, 885–899, doi:10.1175/2011jhm1328.1, 2011.

Ghulam, A., Qin, Q., Teyip, T., and Li, Z.-L.: Modified perpendicular drought index (MPDI): a real-time drought monitoring method, ISPRS J. Photogramm., 62, 150–164, doi:10.1016/j.isprsjprs.2007.03.002, 2007a.

Ghulam, A., Qin, Q., and Zhan, Z.: Designing of the perpendicular drought index, Environ. Geol., 52, 1045–1052, doi:10.1007/s00254-006-0544-2, 2007b.

Gocic, M. and Trajkovic, S.: Drought characterisation based on water surplus variability index, Water Resour. Manag., 28, 3179–3191, doi:10.1007/s11269-014-0665-4, 2014.

Gommes, R. A. and Petrassi, F.: Rainfall Variability and Drought in Sub-Saharan Africa Since 1960, Agrometeorology series working paper, FAO, Research and Technology Development Division, Agrometeorology Group, Rome, 1994.

Gordon, L. J., Finlayson, C. M., and Falkenmark, M.: Managing water in agriculture for food production and other ecosystem services, Agr. Water Manage., 97, 512–519, doi:10.1016/j.agwat.2009.03.017, 2010.

HESSD
12, 5519–5564, 2015

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Gu, Y., Brown, J. F., Verdin, J. P., and Wardlow, B.: A five-year analysis of MODIS NDVI and NDWI for grassland drought assessment over the central Great Plains of the United States, Geophys. Res. Lett., 34, L06407, doi:10.1029/2006GL029127, 2007.
Hanasaki, N., Inuzuka, T., Kanae, S., and Oki, T.: An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model, J. Hydrol., 384, 232–244, doi:10.1016/j.jhydrol.2009.09.028, 2010.
Hargreaves, G. H.: The evaluation of water deficiencies, Age of Changing Priorities for Land and Water, Spokane, USA, 26–28 September, 273–290, 1972.
Hayes, M.: Drought Indices, Intermountain West Climate Summary, Western Water Assessment, Colorado, USA, 2007.
Heim, R. R.: A review of twentieth-century drought indices used in the United States, B. Am. Meteorol. Soc., 83, 1149–1165, 2002.
Hejazi, M., Edmonds, J., Clarke, L., Kyle, P., Davies, E., Chaturvedi, V., Wise, M., Patel, P., Eom, J., Calvin, K., Moss, R., and Kim, S.: Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework, Technol. Forecast. Soc., 81, 205–226, doi:10.1016/j.techfore.2013.05.006, 2014.
Hiler, E. A. and Clark, R. N.: Stress day index to characterize effects of water stress on crop yields, Transactions of the American Society of Agricultural Engineers, 14, 757–761, 1971.
Hoekstra, A. Y.: The Water Footprint of Modern Consumer Society, Routledge, London, UK, 2013.
Hoekstra, A. Y. and Mekonnen, M. M.: The water footprint of humanity, P. Natl. Acad. Sci. USA, 109, 3232–3237, doi:10.1073/pnas.1109936109, 2012.
Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., and Mekonnen, M. M.: The Water Footprint Assessment Manual: Setting the Global Standard, Earthscan, London, 2011.
Hoekstra, A. Y., Mekonnen, M. M., Chapagain, A. K., Mathews, R. E., and Richter, B. D.: Global monthly water scarcity: blue water footprints versus blue water availability, Plos One, 7, e32688, doi:10.1371/journal.pone.0032688, 2012.
Holzworth, D. P., Huth, N. I., deVoil, P. G., Zurcher, E. J., Herrmann, N. I., McLean, G., Chenu, K., van Oosterom, E. J., Snow, V., Murphy, C., Moore, A. D., Brown, H., Whish, J. P. M., Verrall, S., Fainges, J., Bell, L. W., Peake, A. S., Poulton, P. L., Hochman, Z., Thorburn, P. J., Gaydon, D. S., Dalgliesh, N. P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, F. Y., Wang, E., Hammer, G. L., Robertson, M. J., Dimes, J. P., Whitbread, A. M., Hunt, J., van Rees, H., McClelland, T., Car-

HESSD
12, 5519–5564, 2015

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berry, P. S., Hargreaves, J. N. G., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S., and Keating, B. A.: APSIM – evolution towards a new generation of agricultural systems simulation, Environ. Modell. Softw., 62, 327–350, doi:10.1016/j.envsoft.2014.07.009, 2014.

Huete, A., Justice, C., and Liu, H.: Development of vegetation and soil indices for MODIS-EOS, Remote Sens. Environ., 49, 224–234, doi:10.1016/0034-4257(94)90018-3, 1994.

Hunt, E. D., Hubbard, K. G., Wilhite, D. A., Arkebauer, T. J., and Dutcher, A. L.: The development and evaluation of a soil moisture index, Int. J. Climatol., 29, 747–759, doi:10.1002/joc.1749, 2009.

IIASA/FAO: Global Agro-Ecological Zones (GAEZ v3.0), IIASA/FAO, Laxenburg, Austria/Rome, Italy, 2012.

IPCC: Summary for policymakers, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P. M., Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–29, 2013.

Isard, S. A., Welford, M. R., and Hollinger, S. E.: A simple soil moisture index to forecast crop yields, Phys. Geogr., 16, 524–538, doi:10.1080/02723646.1995.10642569, 1995.

Jackson, R. D., Idso, S. B., Reginato, R. J., and Pinter, P. J.: Canopy temperature as a crop water-stress indicator, Water Resour. Res., 17, 1133–1138, doi:10.1029/WR017i004p01133, 1981.

Jenny, H.: Factors of Soil Formation: A System of Quantitative Pedology, Dover Publication Inc., New York, 1941.

Jones, C. A., Dyke, P. T., Williams, J. R., Kiniry, J. R., Benson, V. W., and Griggs, R. H.: EPIC: an operational model for evaluation of agricultural sustainability, Agr. Syst., 37, 341–350, doi:10.1016/0308-521X(91)90057-H, 1991.

Kallis, G.: Droughts, Annu. Rev. Env. Resour., 33, 85–118, doi:10.1146/annurev.environ.33.081307.123117, 2008.

Karl, T. R.: The sensitivity of the Palmer drought severity index and Palmer's Z-index to their calibration coefficients including potential evapotranspiration, J. Clim. Appl. Meteorol., 25, 77–86, doi:10.1175/1520-0450(1986)025<0077:TSOTPD>2.0.CO;2, 1986.

Kastner, T., Rivas, M. J. I., Koch, W., and Nonhebel, S.: Global changes in diets and the consequences for land requirements for food, P. Natl. Acad. Sci. USA, 109, 6868–6872, doi:10.1073/pnas.1117054109, 2012.

HESSD

12, 5519–5564, 2015

Keetch, J. J. and Byram, G. M.: A drought index for forest fire control, USDA Forest Service Research Paper SE-38, Southeastern Forest Experiment Station, Asheville, NC, 33 pp., 1968.
Keyantash, J. and Dracup, J. A.: The quantification of drought: an evaluation of drought indices, B. Am. Meteorol. Soc., 83, 1167–1180, doi:10.1175/1520-0477(2002)083<1191:TQODAE>2.3.CO;2, 2002.
Kincer, J. B.: The seasonal distribution of precipitation and its frequency and intensity in the United States, Mon. Weather Rev., 47, 624–631, doi:10.1175/1520-0493(1919)47<624:TSDOPA>2.0.CO;2, 1919.
Kogan, F. N.: Remote-sensing of weather impacts on vegetation in nonhomogeneous areas, Int. J. Remote Sens., 11, 1405–1419, 1990.
Kogan, F. N.: Droughts of the late 1980s in the United-States as derived from NOAA polar-orbiting satellite data, B. Am. Meteorol. Soc., 76, 655–668, doi:10.1175/1520-0477(1995)076<0655:dotlit>2.0.co;2, 1995.
Kogan, F. N.: Operational space technology for global vegetation assessment, B. Am. Meteorol. Soc., 82, 1949–1964, doi:10.1175/1520-0477(2001)082<1949:OSTFGV>2.3.CO;2, 2001.
Köppen, W.: Grundriss der Klimakunde: Zweite, verbesserte Auflage der Klimate der Erde, Walter de Gruyter and Co, Berlin and Leipzig, 1931.
Kummu, M., Gerten, D., Heinke, J., Konzmann, M., and Varis, O.: Climate-driven interannual variability of water scarcity in food production potential: a global analysis, Hydrol. Earth Syst. Sci., 18, 447–461, doi:10.5194/hess-18-447-2014, 2014.
Lang, R.: Verwitterung und Bodenbildung als Einführung in die Bodenkunde, Schweizerbart Science Publishers, Stuttgart, Germany, 1920.
Liu, J., Zehnder, A. J. B., and Yang, H.: Global consumptive water use for crop production: the importance of green water and virtual water, Water Resour. Res., 45, W05428, doi:10.1029/2007wr006051, 2009.
Marcovitch, S.: The measure of droughtiness, Mon. Weather Rev., 58, 113–113, doi:10.1175/1520-0493(1930)58<113:TMOD>2.0.CO;2, 1930.
Marletto, V., Zinoni, F., Botarelli, L., and Alessandrini, C.: Studio dei fenomeni siccitosi in Emilia-Romagna con il modello di bilancio idrico CRITERIA, RIAM, 9, 32–33, 2005.
McCown, R. L., Hammer, G. L., Hargreaves, J. N. G., Holzworth, D., and Huth, N. I.: APSIM: an agricultural production system simulation model for operational research, Math. Comput. Simulat., 39, 225–231, doi:10.1016/0378-4754(95)00063-2, 1995.

McGuire, J. K. and Palmer, W. C.: The 1957 drought in the eastern United States, Mon. Weather Rev., 85, 305–314, doi:10.1175/1520-0493(1957)085<0305:TDITEU>2.0.CO;2, 1957.
McKee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration to time scales, Proceedings of the 8th Conference on Applied Climatology, 17–22 January, Anaheim, USA, 179–183, 1993.
McQuigg, J.: A simple index of drought conditions, Weatherwise, 7, 64–67, doi:10.1080/00431672.1954.9930323, 1954.
Meyer, S. J., Hubbard, K. G., and Wilhite, D. A.: A crop-specific drought index for corn: 1. Model development and validation, Agron. J., 85, 388–395, 1993.
Middleton, N. J. and Thomas, D. S. G.: World Atlas of Desertification, Arnold, London, 1992.
Middleton, N. J. and Thomas, D. S. G.: World Atlas of Desertification, Arnold, London, 1997.
Millennium Ecosystem Assessment: Ecosystems and Human Well-Being: Synthesis, World Resources Institute, Washington, D.C., 2005.
Mishra, A. K. and Singh, V. P.: A review of drought concepts, J. Hydrol., 391, 204–216, doi:10.1016/j.jhydrol.2010.07.012, 2010.
Molden, D.: Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture, Earthscan/International Water Management Institute, London, UK/Colombo, Sri Lanka, 2007.
Montesino Pouzols, F., Toivonen, T., Di Minin, E., Kukkala, A. S., Kullberg, P., Kuustera, J., Lehtomaki, J., Tenkanen, H., Verburg, P. H., and Moilanen, A.: Global protected area expansion is compromised by projected land-use and parochialism, Nature, 516, 383–386, doi:10.1038/nature14032, 2014.
Moran, M. S., Clarke, T. R., Inoue, Y., and Vidal, A.: Estimating crop water-deficit using the relation between surface-air temperature and spectral vegetation index, Remote Sens. Environ., 49, 246–263, doi:10.1016/0034-4257(94)90020-5, 1994.
Mu, Q., Zhao, M., Kimball, J. S., McDowell, N. G., and Running, S. W.: A remotely sensed global terrestrial drought severity index, B. Am. Meteorol. Soc., 94, 83–98, doi:10.1175/bams-d-11-00213.1, 2013.
Munger, T. T.: Graphic method of representing and comparing drought intensities, Mon. Weather Rev., 44, 642–643, doi:10.1175/1520-0493(1916)44<642:GMORAC>2.0.CO;2, 1916.

Myneni, R. B., Tucker, C. J., Asrar, G., and Keeling, C. D.: Interannual variations in satellite-sensed vegetation index data from 1981 to 1991, J. Geophys. Res.-Atmos., 103, 6145–6160, doi:10.1029/97jd03603, 1998.

Narasimhan, B. and Srinivasan, R.: Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring, Agr. Forest Meteorol., 133, 69–88, doi:10.1016/j.agrformet.2005.07.012, 2005.

Nunez, M., Pfister, S., Anton, A., Munoz, P., Hellweg, S., Koehler, A., and Rieradevall, J.: Assessing the environmental impact of water consumption by energy crops grown in Spain, J. Ind. Ecol., 17, 90–102, doi:10.1111/j.1530-9290.2011.00449.x, 2013.

Odegard, I. Y. R. and van der Voet, E.: The future of food – scenarios and the effect on natural resource use in agriculture in 2050, Ecol. Econ., 97, 51–59, doi:10.1016/j.ecolecon.2013.10.005, 2014.

Ohlsson, L.: Water conflicts and social resource scarcity, Phys. Chem. Earth Pt. B, 25, 213–220, 2000.

Oki, T. and Kanae, S.: Global hydrological cycles and world water resources, Science, 313, 1068–1072, doi:10.1126/science.1128845, 2006.

Palmer, W. C.: Meteorological Drought, US Department of Commerce, Washington D.C., USA, 1965.

Palmer, W. C.: Keeping track of crop moisture conditions, nationwide: the new crop moisture index, Weatherwise, 21, 156–161, doi:10.1080/00431672.1968.9932814, 1968.

Peixoto, J. P. and Oort, A. H.: Physics of Climate, American Institute of Physics, New York, 1992.

Pereira, L. S., Cordery, I., and Iacovides, I.: Coping with water scarcity, UNESCO, Paris, Technical Documents in Hydrology, Report No. 58, 2002.

Perez-Mendoza, H. A., Jaime Zuniga-Vega, J., Zurita-Gutierrez, Y. H., Fornoni, J., Solano-Zavaleta, I., Hernandez-Rosas, A. L., and Molina-Moctezuma, A.: Demographic importance of the life-cycle components in sceloporus grammicus, Herpetologica, 69, 411–435, 2013.

Peters, A. J., Walter-Shea, E. A., Ji, L., Vina, A., Hayes, M., and Svoboda, M. D.: Drought monitoring with NDVI-based standardized vegetation index, Photogramm. Eng. Rem. S., 68, 71–75, 2002.

Pfister, S., Koehler, A., and Hellweg, S.: Assessing the environmental impacts of freshwater consumption in LCA, Environ. Sci. Technol., 43, 4098–4104, doi:10.1021/es802423e, 2009.

HESSD
12, 5519–5564, 2015

Review and classification of indicators of green water availability and scarcity

J. F. Schyns et al.

Rickard, D. S.: The occurrence of agricultural drought at Ashburton, New Zealand, New Zeal. J. Agr. Res., 3, 431–441, doi:10.1080/00288233.1960.10426627, 1960.
Rijsberman, F. R.: Water scarcity: fact or fiction?, Agr. Water Manage., 80, 5–22, doi:10.1016/j.agwat.2005.07.001, 2006.
Rockström, J.: On-farm green water estimates as a tool for increased food production in water scarce regions, Phys. Chem. Earth Pt. B, 24, 375–383, doi:10.1016/s1464-1909(99)00016-7, 1999.
Rockström, J.: Green water security for the food makers of tomorrow: windows of opportunity in drought-prone savannahs, Water Sci. Technol., 43, 71–78, 2001.
Rockström, J., Gordon, L., Folke, C., Falkenmark, M., and Engwall, M.: Linkages among water vapor flows, food production, and terrestrial ecosystem services, Conserv. Ecol., 3, 5, 1999.
Rockström, J., Lannerstad, M., and Falkenmark, M.: Assessing the water challenge of a new green revolution in developing countries, P. Natl. Acad. Sci. USA, 104, 6253–6260, doi:10.1073/pnas.0605739104, 2007.
Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., and Gerten, D.: Future water availability for global food production: the potential of green water for increasing resilience to global change, Water Resour. Res., 45, W00A12, doi:10.1029/2007wr006767, 2009.
Rodrigues, A. S. L., Akcakaya, H. R., Andelman, S. J., Bakarr, M. I., Boitani, L., Brooks, T. M., Chanson, J. S., Fishpool, L. D. C., Da Fonseca, G. A. B., Gaston, K. J., Hoffmann, M., Marquet, P. A., Pilgrim, J. D., Pressey, R. L., Schipper, J., Sechrest, W., Stuart, S. N., Underhill, L. G., Waller, R. W., Watts, M. E. J., and Yan, X.: Global gap analysis: priority regions for expanding the global protected-area network, Bioscience, 54, 1092–1100, doi:10.1641/0006-3568(2004)054[1092:ggaprf]2.0.co;2, 2004a.
Rodrigues, A. S. L., Andelman, S. J., Bakarr, M. I., Boitani, L., Brooks, T. M., Cowling, R. M., Fishpool, L. D. C., da Fonseca, G. A. B., Gaston, K. J., Hoffmann, M., Long, J. S., Marquet, P. A., Pilgrim, J. D., Pressey, R. L., Schipper, J., Sechrest, W., Stuart, S. N., Underhill, L. G., Waller, R. W., Watts, M. E. J., and Yan, X.: Effectiveness of the global protected area network in representing species diversity, Nature, 428, 640–643, 2004b.
Saleska, S. R., Didan, K., Huete, A. R., and da Rocha, H. R.: Amazon forests green-up during 2005 Drought, Science, 318, 612–612, 2007.
Sandholt, I., Rasmussen, K., and Andersen, J.: A simple interpretation of the surface temperature/vegetation index space for assessment of surface moisture status, Remote Sens. Environ., 79, 213–224, doi:10.1016/S0034-4257(01)00274-7, 2002.

Savenije, H. H. G.: Water scarcity indicators; the deception of the numbers, Phys. Chem. Earth Pt. B, 25, 199–204, doi:10.1016/s1464-1909(00)00004-6, 2000.
Savenije, H. H. G.: The importance of interception and why we should delete the term evapotranspiration from our vocabulary, Hydrol. Process., 18, 1507–1511, doi:10.1002/hyp.5563, 2004.
Schuol, J., Abbaspour, K. C., Yang, H., Srinivasan, R., and Zehnder, A. J. B.: Modeling blue and green water availability in Africa, Water Resour. Res., 44, W07406, doi:10.1029/2007wr006609, 2008.
Seckler, D., Barker, R., and Amarasinghe, U.: Water scarcity in the twenty-first century, Int. J. Water Resour. D, 15, 29–42, doi:10.1080/07900629948916, 1999.
Shafer, B. A. and Dezman, L. E.: Development of a surface water supply index (SWSI) to assess the severity of drought conditions in snowpack runoff areas, 50th Annual Western Snow Conference, Reno, Nevada, 19–13 April, 164–175, 1982.
Sivakumar, M. V. K.: Agricultural Drought – WMO Perspectives, WMO/UNISDR Expert Group Meeting on Agricultural Drought Indices, Murcia, Spain, 2010.
Sly, W. K.: A climatic moisture index for land and soil classification in Canada, Can. J. Soil Sci., 50, 291–301, doi:10.4141/cjss70-040, 1970.
Smakhtin, V., Revenga, C., and Döll, P.: A pilot global assessment of environmental water requirements and scarcity, Water Int., 29, 307–317, doi:10.1080/02508060408691785, 2004.
Smakhtin, V. U.: Low flow hydrology: a review, J. Hydrol., 240, 147–186, doi:10.1016/S0022-1694(00)00340-1, 2001.
Stadler, S. J.: Aridity indexes, in: Encyclopedia of World Climatology, edited by: Oliver, J. E., Springer, Heidelberg, 89–94, 2005.
Steduto, P., Hsiao, T. C., Raes, D., and Fereres, E.: AquaCrop – the FAO crop model to simulate yield response to water: I. Concepts and underlying principles, Agron. J., 101, 426–437, doi:10.2134/agronj2008.0139s, 2009.
Stöckle, C. O., Donatelli, M., and Nelson, R.: CropSyst, a cropping systems simulation model, Eur. J. Agron., 18, 289–307, doi:10.1016/S1161-0301(02)00109-0, 2003.
Sullivan, C. A., Meigh, J. R., and Giacomello, A. M.: The water poverty index: development and application at the community scale, Nat. Resour. Forum, 27, 189–199, doi:10.1111/1477-8947.00054, 2003.

HESSD
12, 5519–5564, 2015

Svoboda, M., LeComte, D., Hayes, M., Heim, R., Gleason, K., Angel, J., Rippey, B., Tinker, R., Palecki, M., Stooksbury, D., Miskus, D., and Stephens, S.: The drought monitor, B. Am. Meteorol. Soc., 83, 1181–1190, 2002.
Thornthwaite, C. W.: The climates of North America: according to a new classification, Geogr. Rev., 21, 633–655, 1931.
Thornthwaite, C. W.: An approach toward a rational classification of climate, The Geographical Review, 38, 55–94, 1948.
Transeau, E. N.: Forest centers of eastern America, Am. Nat., 39, 875–889, 1905.
Tsakiris, G. and Vangelis, H.: Establishing a drought index incorporating evapotranspiration, European Water, 9, 3–11, 2005.
Tsakiris, G., Pangalou, D., and Vangelis, H.: Regional drought assessment based on the Reconnaissance Drought Index (RDI), Water Resour. Manag., 21, 821–833, doi:10.1007/s11269-006-9105-4, 2007.
Tucker, C. J.: Red and photographic infrared linear combinations for monitoring vegetation, Remote Sens. Environ., 8, 127–150, doi:10.1016/0034-4257(79)90013-0, 1979.
UNESCO: Bioclimatic Map of the Mediterranean Zone: Ecological Study of the Mediterranean Zone, Explanatory Notes, Arid Zone Research, 21, edited by: FAO and UNESCO, UNESCO-FAO, Paris, 1963.
van Dam, J. C., Groenendijk, P., Hendriks, R. F. A., and Kroes, J. G.: Advances of modeling water flow in variably saturated soils with SWAP, Vadose Zone J., 7, 640–653, doi:10.2136/vzj2007.0060, 2008.
Venter, O., Fuller, R. A., Segan, D. B., Carwardine, J., Brooks, T., Butchart, S. H. M., Di Marco, M., Iwamura, T., Joseph, L., O'Grady, D., Possingham, H. P., Rondinini, C., Smith, R. J., Venter, M., and Watson, J. E. M.: Targeting global protected area expansion for imperiled biodiversity, PLoS Biol., 12, e1001891, doi:10.1371/journal.pbio.1001891, 2014.
Verdin, J. and Klaver, R.: Grid-cell-based crop water accounting for the famine early warning system, Hydrol. Process., 16, 1617–1630, doi:10.1002/hyp.1025, 2002.
Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index, J. Climate, 23, 1696–1718, doi:10.1175/2009JCLI2909.1, 2009.
Vörösmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B.: Global water resources: vulnerability from climate change and population growth, Science, 289, 284–288, doi:10.1126/science.289.5477.284, 2000.

HESSD
12, 5519–5564, 2015

Review and classification of indicators of green water availability and scarcity

J. F. Schyns et al.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R., and Davies, P. M.: Global threats to human water security and river biodiversity, Nature, 467, 555–561, doi:10.1038/nature09440, 2010.

Wada, Y.: Human and climate impacts on global water resources, PhD, Department of Physical Geography, Utrecht University, Utrecht, 2013.

Wada, Y., van Beek, L. P. H., Viviroli, D., Duerr, H. H., Weingartner, R., and Bierkens, M. F. P.: Global monthly water stress: 2. Water demand and severity of water stress, Water Resour. Res., 47, W07518, doi:10.1029/2010wr009792, 2011.

Wallén, C. C.: Aridity definitions and their applicability, Geogr. Ann. A, 49, 367–384, doi:10.2307/520903, 1967.

Walton, K.: The Arid Zones, Transaction Publishers, New Jersey, USA, 1969.

Wanders, N., van Lanen, H. A. J., and van Loon, A. F.: Indicators for drought characterization on a global scale, WATCH Technical Report No. 24, Wageningen University, Wageningen, the Netherlands, 2010.

Wilhelmi, O. V. and Wilhite, D. A.: Assessing vulnerability to agricultural drought: a Nebraska case study, Nat. Hazards, 25, 37–58, doi:10.1023/a:1013388814894, 2002.

Wilhelmi, O. V., Hubbard, K. G., and Wilhite, D. A.: Spatial representation of agroclimatology in a study of agricultural drought, Int. J. Climatol., 22, 1399–1414, doi:10.1002/joc.796, 2002.

Wilhite, D. A. and Glantz, M. H.: Understanding: the drought phenomenon: the role of definitions, Water Int., 10, 111–120, doi:10.1080/02508068508686328, 1985.

Woli, P., Jones, J. W., Ingram, K. T., and Fraisse, C. W.: Agricultural Reference Index for Drought (ARID), Agron. J., 104, 287–300, doi:10.2134/agronj2011.0286, 2012.

World Meteorological Organization: Drought and Agriculture: Report of the CAgM Working Group on the Assessment of Drought, Technical Note No. 138, Geneva, Switzerland, 1975.

Wu, H., Hubbard, K. G., and Wilhite, D. A.: An agricultural drought risk-assessment model for corn and soybeans, Int. J. Climatol., 24, 723–741, doi:10.1002/joc.1028, 2004.

WWAP: The United Nations World Water Development Report 2014: Water and Energy, UNESCO, Paris, 2014.

WWAP: The United Nations World Water Development Report 2015: Water for a Sustainable World, UNESCO, Paris, 2015.

HESSD

12, 5519–5564, 2015

Review and classification of indicators of green water availability and scarcity

J. F. Schyns et al.

Yao, Y., Liang, S., Qin, Q., and Wang, K.: Monitoring drought over the conterminous United States using MODIS and NCEP Reanalysis-2 Data, J. Appl. Meteorol. Clim., 49, 1665–1680, doi:10.1175/2010jamc2328.1, 2010.
Zabel, F., Putzenlechner, B., and Mauser, W.: Global agricultural land resources – a high resolution suitability evaluation and its perspectives until 2100 under climate change conditions, PLoS ONE, 9, e107522, doi:10.1371/journal.pone.0107522, 2014.

HESSD
12, 5519–5564, 2015

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Table A1. Aridity indicators.

Name	Acronym	Formula/Description	Reference
Rainfall-evaporation ratio	RER	$\frac{P}{E_{ow}}$ E_{ow} = open water evaporation	Transeau (1905)
Rain Factor	RF	$\frac{P}{T}$	Lang (1920)
Koloskov Index	KI	$\frac{P}{\sum T}$ Sum over vegetative period	Koloskov (1925) as cited by World Meteorological Organization (1975)
de Martonne's Aridity Index	dM-AI	$\frac{P}{T+10}$	de Martonne (1926) as cited by Thornthwaite (1931), Budyko (1958) and de Martonne (1942)
Precipitation-Saturation deficit ratio	PDR	$\frac{P}{D}$ D = mean annual atmospheric saturation deficit	Meyer (1926) as cited by Thornthwaite (1931) and Budyko (1958)
Reichel's Aridity Index	R-AI	$\frac{N \times P}{T+10}$ N = number of rainy days	Reichel (1928) as cited by Perez-Mendoza et al. (2013)
Marcovitch's Index	MI	$0.5L^2 \times \left(\frac{100}{P}\right)^2$ L = the total number of two or more consecutive days above 90° Fahrenheit for the months of Jun, Jul, Aug, and Sep; Total P for those months.	Marcovitch (1930)
Shostakovich Index	SI	$\frac{P}{T}$ P during vegetative period; mean T over this period	Shostakovich (1932) as cited by Jenny (1941)
Emberger's Aridity Index	E-AI	$\frac{100P}{(M+m)(M-m)}$ M = mean temperature of the warmest month; m = mean temperature of the coldest month	Emberger (1932) as cited by Wallén (1967)
Precipitation Effectiveness Index	PE	$\sum_{n=1}^{12} 10 \frac{P_n}{E_{pot_n}}$	Thornthwaite (1931)
Hydrothermal coefficient	HC	$\frac{P}{\sum T\vert_{T>10\,°C}}$	Selianinov (1930, 1937) as cited by Budyko (1958) and World Meteorological Organization (1975)
Köppen classification	KC	Threshold for classifying area as semi-arid: $P = 2(T + 14)$ (summer rainfall) $P = 2T$ (winter rainfall) Threshold for classifying area as arid: $P = T + 14$ (summer rainfall) $P = T$ (winter rainfall) P = annual precipitation amount in $cm\,yr^{-1}$; T = mean annual temperature in °C.	Köppen (1931)
Aridity Coefficient	AC	$f_{lat} \times (T_{max} - T_{min}) \times \left(\frac{P_{max}-P_{min}}{P_{avg}}\right)$ f_{lat} = latitude factor; T_{max} = temperature of the long-term mean warmest month; T_{min} = temperature of the long-term mean coldest month; P_{max} = largest annual precipitation amount on record; P_{min} = smallest annual precipitation amount on record; P_{avg} = average annual precipitation amount on record	Gorczynski (1940)
Modified de Martonne Aridity Index	MdM-AI	$\frac{1}{2}\left(\frac{P}{T+10} + \frac{12P_d}{T_d+10}\right)$ P_d = precipitation in the driest month; T_d = temperature in the driest month	de Martonne (1942)
Popov's Aridity Index	P-AI	$\frac{P_{eff}}{2.4(t-t')r}$ P_{eff} = annual amount of precipitation available to plants; r = factor depending on day length; $t - t'$ = annual mean wet bulb depression in °C.	Popov (1948) as cited by World Meteorological Organization (1975)

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Table A1. Continued.

Name	Acronym	Formula/Description	Reference
Moisture Index; Aridity Index; Humidity Index	I_m; I_a; I_h	$I_a = \frac{100d}{E_{pot}}$ $I_h = \frac{100s}{E_{pot}}$ $I_m = I_h - 0.6 I_a$ where d is a water deficiency when $P < E_{pot}$ and s is a water surplus when $P > E_{pot}$. I_m is an overall measure of the moisture conditions of a region, giving more weight to I_h, since s in one season can partially compensate for d in another season.	Thornthwaite (1948)
Capot-Rey's Aridity Index	CR-AI	$\frac{1}{2}\left(\frac{100P}{E_{pot}} + \frac{12P_w}{E_{pot,w}}\right)$ P_w = precipitation of the wettest month of the year (in cm month^{-1}); $E_{pot,\,w}$ = potential evaporation of the wettest month of the year (in cm month^{-1})	Capot-Rey (1951)
Radiational Index of Dryness	RID	$\frac{R}{L \times P}$ R = mean annual net radiation; L = latent heat of vaporization of water	Budyko (1958)
Gaussen Classification	GC	$P \leq 2T$	UNESCO (1963)
Sly's Climatic Moisture Index	SCMI	$\frac{P}{P+S+I}$ I = irrigation requirement for non-water limited growth. P and I during growing season. S at start of growing season. The index is made purely climatic by fixed assumptions on the non-climatic factors.	Sly (1970)
Moisture Availability Index	MAI-H	$\frac{P_{dep}}{E_{pot}}$ P_{dep} = dependable precipitation, which is the precipitation amount with a specified probability of occurrence	Hargreaves (1972)
Evaporation ratio	ER	$\frac{E_{act}}{P}$	Peixoto and Oort (1992)
UNEP's Aridity Index	AI	$\frac{P}{E_{pot}}$	Middleton and Thomas (1992, 1997)
Seasonal Crop Moisture Deficiency	SCMD	Probability of seasonal crop moisture deficiency based on a combination of long-term precipitation records and area-weighted E_{act} of the mixture of crops grown in the study area. Although most crops studied by Wilhelmi et al. (2002) are considered well-watered ($E_{act} = E_{pot,\,c}$), for wheat and grasses E_{act} is estimated as the E_{act} associated with a certain threshold yield, representing so called critical crop water requirements (Wilhelmi et al., 2002).	Wilhelmi et al. (2002); Wilhelmi and Wilhite (2002)

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Table A2. Agricultural drought indicators.

Name	Acronym	Formula/Description	Reference
Bova's Drought Index	BDI	$\frac{10(S+P)}{\sum T}$ S (in mm) of the top 100 cm of soil at the beginning of the growing season; P during growing season; sum of T from the first day T is above 0 °C.	Bova (1941) as cited by World Meteorological Organization (1975)
Moisture Adequacy Index	MAI	$\frac{P+S}{E_{pot}}$	McGuire and Palmer (1957)
Water Requirement Satisfaction Index	WRSI	$\frac{E_{act}}{E_{pot} \times K_c}$ K_c = crop coefficient that accounts for the difference in evaporation between the considered crop and a reference grass surface. WRSI is usually evaluated as sum over the growing season.	FAO (1986); Verdin and Klaver (2002)
Crop Water Stress Index	CWSI	$1 - \frac{E_{act}}{E_{pot}}$	Jackson et al. (1981); Moran et al. (1994)
Evaporative Stress Index	ESI	Idem to CWSI.	Anderson et al. (2007a, b); Yao et al. (2010)
Water Stress ratio	WS	$\frac{E_{pot}-E_{act}}{E_{pot}}$ In fact, idem to CWSI.	Narasimhan and Srinivasan (2005)
Crop Moisture Index	CMI	Abnormal evaporation deficit, defined as the difference between E_{act} and climatologically expected weekly evaporation. Whereby the latter is the normal value adjusted up or down according to the departure of the week's temperature from normal (Wilhite and Glantz, 1985).	Palmer (1968)
Stress Day Index	SDI	Product of a stress day factor (SD) that measures the degree and duration of plant water deficit and a crop susceptibility factor (CS), which is specific for the crop species and growth stage, indicating a crop's susceptibility to water deficit. Various definitions of SD are proposed based on Tr_{act} and Tr_{pot} and/or leaf and soil water potential.	Hiler and Clark (1971)
Crop-Specific Drought Index	CSDI	$\prod_{i=1}^{n} \left(\frac{\sum E_{act}}{\sum E_{pot,\,c}} \right)_i^{\lambda_i}$ Index i depicts the crop growth stage. Exponent λ_i expresses the relative sensitivity of the crop to moisture stress during stage i. Meyer et al. (1993) initially developed the CSDI for corn. Later on, the index was also applied for soybean, wheat and sorghum (Wu et al., 2004).	Meyer et al. (1993)
Integrated transpiration deficit	DTx	$\sum_{i=1}^{x} \left(\mathrm{Tr}_{pot} - \mathrm{Tr}_{act} \right)$ Transpiration deficit that has been built up during a period of x days before.	Marletto et al. (2005)
Actual to potential canopy conductance	$\mathrm{L_{TA}}$	$\frac{g_{act}}{g_{pot}}$ Ratio of actual to potential canopy conductance. It describes the extent to which transpiration and photosynthesis are co-limited by soil water deficits (Gerten et al., 2007).	Gerten et al. (2005, 2007)
Water Deficit Index	WDI	$1 - \frac{\mathrm{Tr}_{act}}{\mathrm{Tr}_{pot}}$	Woli et al. (2012)
Agricultural Reference Index for Drought	ARID	$1 - \frac{\mathrm{Tr}_{act}}{E_{pot,\,ref}}$	Woli et al. (2012)
MODIS Global Terrestrial Drought Severity Index	DSI	Standardized sum of the standardized ratio of E_{act} to E_{pot} and the standardized Normalized Difference Vegetation Index (NDVI). The latter only during the snow-free growing season.	Mu et al. (2013)

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Table A2. Continued.

Name	Acronym	Formula/Description	Reference
Green Water Scarcity Index	GWSI	$\frac{\min(P_{eff}, E_{pot,c})}{P_{eff}}$ Ratio of the green water consumption of a three-years crop rotation (in $m^3 m^{-2} rotation^{-1}$) over the effective precipitation during the same period (P_{eff} in $m^3 m^{-2} rotation^{-1}$). P_{eff} represents infiltrated precipitation as a proxy for crop-available green water. Green water consumption is defined as the minimum of P_{eff} and $E_{pot,c}$. Therefore, the index is 1 if $P_{eff} \leq E_{pot,c}$ and ranges from 0 to 1 if $P_{eff} > E_{pot,c}$. It measures to which extent available green water during the three-year period was sufficient to meet the evaporative demand of the crop rotation during that period.	Nunez et al. (2013)
Green Water Stress Index	GrWSI	$\frac{E_{act}/E_{pot}}{\overline{E_{act}}/\overline{E_{pot}}}$	Wada (2013)

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Table A3. Absolute soil moisture indicators.

Name	Acronym	Formula/Description	Reference
Antecedent Precipitation Index	API	$k \times \text{API}_{i-1} + P_i$ API on day i is calculated by multiplying API of the previous day with a factor k (e.g. 0.9) and adding the P during day i. By combining the amount and timing of precipitation, the index is a proxy for available soil moisture.	McQuigg (1954)
Agricultural Drought Day	ADD	$\sum_{i=1}^{L} \text{day}\Big\vert_{\theta \leq \theta_{wp}}$ L = length of the period considered	Rickard (1960)
Kulik's drought indicator	KU	$\sum \text{day}\vert_{S<S_{thres}}$ S in tilled layer of soil (top 20 cm).	Kulik (1958) as cited by World Meteorological Organization (1975)
Keetch-Byram drought index	KBDI	The amount of net precipitation (precipitation minus evaporation) that is required to fill up the soil moisture to field capacity.	Keetch and Byram (1968)
Soil Moisture Drought Index	SMDI	$\sum_{i=1}^{365} S$	Hollinger et al. (1993) as cited by Byun and Wilhite (1999)
Soil Moisture Index	SMIX	$\int_{t1}^{t2}\int_{l1}^{l2} S\text{d}l\text{d}t$ $t1$ and $t2$ are usually start and end of growing seasons (authors also take $t2$ somewhat before end of the cropping period); $l1$ and $l2$ are the soil depths over which integration takes place; $l1$ is the soil surface and $l2$ represents the rooting depth, which depends on the crop type and stage of growth.	Isard et al. (1995)
Water stress coefficient	K_s	$\frac{S_{tot}-S_{depl}}{(1-p)\times S_{tot}}$ S_{tot} = total available soil water in the root zone (mm); S_{depl} = root zone depletion (mm); p = part of total available soil water in the root zone that a crop can extract from the root zone without suffering from water stress.	Allen et al. (1998)
Temperature – Vegetation Dryness Index	TVDI	Surface soil moisture availability based on an empirical parameterisation of the relationship between Normalized Difference Vegetation Index (NDVI) and land surface temperature (LST) derived from satellite observations.	Sandholt et al. (2002)
Modified Perpendicular Drought Index	MPDI	Soil moisture and vegetation status on the basis of near-infrared and red spectral reflectance space.	Ghulam et al. (2007a, b)
Average green water storage availability	Avg-GWS	Long-term average number of months in which $S > 1\,\text{mm}\,\text{m}^{-1}$.	Schuol et al. (2008)
Standard deviation of green water storage availability	SD-GWS	Standard deviation of the number of months in which $S > 1\,\text{mm}\,\text{m}^{-1}$.	Schuol et al. (2008)
Soil Moisture Index	SMI	$-5 + 10\frac{\theta-\theta_{WP}}{\theta_{FC}-\theta_{WP}}$ θ = volumetric soil moisture content ($\text{cm}\,\text{m}^{-1}$); θ_{WP} = volumetric soil moisture content at wilting point ($\text{cm}\,\text{m}^{-1}$); θ_{FC} = volumetric soil moisture content at field capacity ($\text{cm}\,\text{m}^{-1}$).	Hunt et al. (2009)

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Table A4. Agricultural suitability under rain-fed conditions.

Name	Acronym	Formula/Description	Reference
GAEZ crop-specific suitability under rain-fed conditions	GAEZ	Crop-specific suitability under rain-fed conditions is based on estimates of agro-ecologically attainable yields. First, agro-climatically attainable yields are determined based on a water balance approach that calculates E_{act} and additionally considers crop water requirements and a crop's sensitivity to water stress during the various stages of growth to calculate a yield reduction factor due to water limitations. Second, agro-climatically attainable yields are further reduced by agro-edaphic constraints.	IIASA/FAO (2012)
GLUES crop-specific suitability under rain-fed conditions	GLUES	Crop-specific suitability under rain-fed conditions is based on a fuzzy logic approach with crop-specific membership functions, which reflect the crop's requirements during the growing period. Yield estimates are not provided by the GLUES methodology.	Zabel et al. (2014)

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Table B1. Meteorological drought indicators based on precipitation only.

Name	Acronym	Formula/Description	Reference
Days of rain	DoR	$\sum \text{day}\|_{P<P_{thres}}$	Munger (1916); Kincer (1919); Blumenstock (1942)
Percent of average precipitation	PoAP	$\frac{P}{\bar{P}}$	Bates (1935); Hoyt (1936) as cited by World Meteorological Organization (1975)
Foley Drought Index	FDI	Cumulative deficiency (excess) of P in certain month (period) compared to the long-term average P for that month (period), expressed in thousands of annual P.	Foley (1957) as cited by World Meteorological Organization (1975) and Keyantash and Dracup (2002)
Rainfall Anomaly Index	RAI	$\pm 3\frac{P-\bar{P}}{\overline{P_{ext}}-\bar{P}}$ $\overline{P_{ext}}$ = average of the 10 most extreme precipitation amounts on record (largest for positive and smallest for negative anomalies). Can be calculated on weekly, monthly or annual time scale (Wanders et al., 2010).	Van Rooy (1965) as cited by Keyantash and Dracup (2002)
Deciles	–	In which decile of a long-term record of precipitation events a certain precipitation event falls.	Gibbs and Maher (1967) as cited by Wilhite and Glantz (1985)
Bhalme and Mooley Drought Index	BMDI	The percentage departure of monthly rainfall from the long-term mean weighted by the reciprocal of the coefficient of variation.	Bhalme and Mooley (1980)
Standardized Precipitation Index	SPI	Precipitation deviation for a normally distributed probability density with a mean of zero and standard deviation of one.	McKee et al. (1993)
National Rainfall Index	NRI	National average of annual precipitation weighed according to the long-term average precipitation of all individual stations in a country.	Gommes and Petrassi (1994)
Effective Drought Index	EDI	Ratio of the difference between effective precipitation (EP, calculated from equations based on precipitation) and its 5 day running mean over the standard deviation of this difference.	Byun and Wilhite (1999)
Precipitation Condition Index	PCI	$\frac{P-P_{min}}{P_{max}-P_{min}}$ P inputs refer to monthly amounts.	Du et al. (2013)

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Table B2. Meteorological drought indicators based on precipitation and a measure of potential evaporation.

Name	Acronym	Formula/Description	Reference
Palmer Drought Severity Index	PDSI	Accumulated weighted differences between actual precipitation and precipitation requirement of evaporation (Wilhite and Glantz, 1985).	Palmer (1965); Alley (1984)
Reconnaissance Drought Index	RDI	Standardized ratio of P to E_{pot} based on a lognormal distribution.	Tsakiris and Vangelis (2005); Tsakiris et al. (2007)
Standardized Precipitation Evapo-transpiration Index	SPEI	Standardized difference between P and E_{pot} based on a log-logistic distribution.	Vicente-Serrano et al. (2009)
Water Surplus Variability Index	WSVI	Standardized difference between P and $E_{pot,\,ref}$ based on a logistic distribution.	Gocic and Trajkovic (2014)

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Table B3. Vegetation drought indicators.

Name	Acronym	Formula/Description	Reference
Normalized Difference Vegetation Index Anomaly	NDVIA	$\mathrm{NDVI}-\overline{\mathrm{NDVI}}$	Tucker (1979); Myneni et al. (1998)
Vegetation Condition Index	VCI	$\frac{\mathrm{NDVI}-\mathrm{NDVI}_{min}}{\mathrm{NDVI}_{max}-\mathrm{NDVI}_{min}}$ NDVI_{min} = a location's minimum observed NDVI value during the study period; NDVI_{max} = a location's maximum observed NDVI value during the study period	Kogan (1990, 1995)
Vegetation Health Index	VHI	$a \cdot \mathrm{VCI} + b \cdot \mathrm{TCI}$ a = coefficient quantifying share of VCI contribution in the combined condition; b = coefficient quantifying share of TCI contribution in the combined condition; TCI = Temperature Condition Index; VCI = Vegetation Condition Index	Kogan (2001)
Standardized Vegetation Index	SVI	NDVI deviation for a normally distributed probability density with a mean of zero and standard deviation of one.	Peters et al. (2002)
Normalized Difference Water Index Anomaly	NDWIA	Adaptation of NDVI (Gao, 1996) compared to its multi-year mean.	Gu et al. (2007)
Enhanced Vegetation Index Anomaly	EVIA	EVI anomaly. EVI is an improvement over NDVI, which keeps sensitivity over densely vegetated areas (Huete et al., 1994).	Saleska et al. (2007)
Percent of Average Seasonal Greenness	PASG	$\frac{\mathrm{SG}}{\overline{\mathrm{SG}}} \times 100\,\%$ SG = seasonal greenness, defined as accumulated NDVI above background NDVI during a specified period.	Brown et al. (2008)

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Table B4. Relative soil moisture availability indicators.

Name	Acronym	Formula/Description	Reference
Soil water Deficit	SD (and SMDI)	Difference between mean weekly and long-term median S, divided by the difference between long-term minimum (maximum) and median S.	Narasimhan and Srinivasan (2005)
Palmer Z-index (a.k.a. Palmer moisture anomaly index)	PZI	Moisture anomaly for the current period from the climate-average moisture conditions for that period.	Palmer (1965); Alley (1984)
Soil Moisture Anomaly Index	SMAI	$\frac{\theta-\overline{\theta}}{\overline{\theta}} \times 100\,\%$ θ = volumetric soil moisture content	Bergman et al. (1988)

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