Increase in staple crop production and yield stability for sub-Saharan Africa through supplemental irrigation and associated water needs

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Abstract

The majority of sub-Saharan African (SSA) agriculture is rainfed and has low and variable yields. Supplemental irrigation (SI) might be a solution to increase yields and yield stability. The goal of this study is to quantify the potential effect of large-scale implementation of supplemental irrigation on crop yields throughout SSA as well as on the temporal variability of crop yields and the irrigation water volumes required.

In this study we defined SI strategies as having the highest marginal water productivity (MWP) ($\frac{\Delta Y}{\Delta ET}$) . Strategies in this study consist of an separate irrigation threshold and amount for the vegetative, flowering and yield formation crop stage. We used the crop model AquaCrop to determine robust SI strategies for four staple crops: maize, sorghum, cassava and wheat. Potential SI strategies that have a high MWP in many locations and years were taken as being a robust SI strategy.

Implementation of these robust strategies without limitations increase average, currently rainfed, yields by 22, 54, 30 and 33% for maize, sorghum, cassava and wheat respectively and reduce the interannual coefficient of variation of yield of said crops by 73, 70, 74 and 72%. The water use associated with this is 33, 83, 70 and 97 mm of evapotranspiration of irrigation water for respectively maize, sorghum, cassava and wheat.

Limiting the implementation of SI to locations with sufficient amounts of available water changes the increase in yield to 15, 25, 28 and 19% for maize, sorghum, cassava and wheat respectively and reduce the interannual coefficient of variation of yield of said crops by 70, 43, 32 and 36%. The water use associated with this is 17, 31, 63 and 52 mm of evapotranspiration of irrigation water for respectively maize, sorghum, cassava and wheat.

Large scale implementation of SI has the potential to severely increase yields and yield stability for SSA staple crops and might be part of a solution for food security for SSA in the future.

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1 Introduction

1.1 Malnutrition, growing populations and climate change

Sub-Saharan Africa (SSA), consisting of whole Africa except for Egypt, Libya, Tunisia, Algeria, Morocco and Western Sahara (UNSD, 2003) severely suffers from malnutrition with a total of 23.2% of the population having insufficient food (FAO et al, 2018) and is for a large part dependent on agriculture for it economy (FAO, 2016). One of the causes for the malnutrition are the very low yields for many crops when compared to the world average (FAO, 2019a) and large annual variability in these yields (GYGA, 2018).

Part of the cause of these low and variable yields lies in the absence of a green revolution in the 1960's and 1970's (Rockstrom et al., 2007) and in the nature of the local climate. Low annual rainfall is not necessarily a problem, but irregular occurrence of rainfall events is (Sivakumar & Wallace, 1991). This is the case for the large amount of savannah regions of SSA (Beck et al., 2018), with highly erratic precipitation (Falkenmark & Rockström, 2004) and the occurrence of periods of no precipitation during dry spells, often in critical crop growth stages (Barron et al., 2003).

According to medium population projections (UN, 2017) the population of SSA will increase from the 1.0 billion in 2017 to 2.2 billion in 2050 and 4.0 billion in 2100, which, combined with the United Nations goal to eradicate hunger by 2030 (UN, 2016), requires large increase in food supply. Furthermore, climate change will increase consecutive dry days for SSA (Tebaldi et al., 2006) and change worldwide precipitation and temperature patterns (IPCC, 2014b). This will affect the world's crop yields and increase interannual variability in yields (IPCC, 2014a) with African agriculture being hit especially hard with reductions between 5 and 22% for major crops (Knox et al., 2012; Schlenker & Lobell, 2010), with local changes even larger due to large spatial differences in the changes throughout SSA (IPCC, 2014a). To keep up with increased population and a changing climate, solutions are required in SSA agriculture.

Since 20 to 40% of the gap between actual yields and potential yields can be explained by limitations in water (GYGA, 2018; van Bussel et al., 2015; van Ittersum et al., 2013), there is great potential in the use of irrigation for improving and stabilizing yields. The mostly smallholder farmers (<5 ha) in SSA don't have the resources to invest in full irrigation (Falkenmark & Rockström, 2004) and large amount of water are required which are not available everywhere, but supplemental irrigation (SI) (Fox et al., 2005) through water harvesting (Fox & Rockström, 2003; Ngigi et al., 2005) is an affordable and appropriate solution (Rockström et al., 2007).

1.2 Supplemental irrigation

Supplemental irrigation is adding or ensuring a limited amount of water (Oweis & Hachum, 2006), to an essentially rainfed crop that would normally produce some yield (Oweis & Hachum, 2012). This is done during the critical and most sensitive crop growth stages (Oweis & Hachum, 2009) when rainfall fails to provide sufficient moisture (Oweis, 1997) for normal crop growth. The goal of SI is not to provide moisture-stress-free conditions (Rockström et al., 2007) but rather to substantially improve and stabilize yield or even prevent complete yield loss (Caliandro & Boari, 1996).

This study will use the following definition:

"The addition of **small amounts** of irrigation water during **critical crop growth stages** to improve, stabilize and secure harvests **when rainfall fails to provide** sufficient moisture."

A range of literature (Caliandro & Boari, 1996; Nangia et al., 2018; Oweis & Hachum, 2012), field (Fox & Rockström, 2003; Magaia et al., 2017; Muluneh et al., 2017; T. Oweis et al., 1999) and modelling studies (Chukalla et al., 2015; Giménez et al., 2016; Magaia et al., 2017; Manivasagam & Nagarajan, 2015; Muluneh et al., 2017; Pandey et al., 2013) on SI in Africa, the Middle East and India have shown the potential for improved yields (20 to 138 % increase from rainfed situation) and reduced interannual variability (decrease of coefficient of variation of circa 10-15%) at low water usage (60-120 mm).

These studies are all small scale studies (up to 200 km^2) with limited differences in soil and climate and therefore lack crucial information about applicability and usefulness for large and diverse areas such as SSA. The different studies use arbitrary, not quantifiable, descriptions of SI strategies leading to a large range of different strategies being called SI but meaning completely different things with respect to amount and timing of irrigation. This makes it difficult to pick suitable strategies for general or specific purposes.

The goal of this study is to quantify the potential effect of large-scale implementation of supplemental irrigation on crop yields throughout SSA as well as on the temporal variability of crop yields and the irrigation water volumes required. We use an innovative method to determine good SI strategies as a function of the crop and location, aiming at maximizing marginal irrigation water productivity.

1.3 Scope

The majority of agriculture in SSA is rainfed, with a total of 95% this is the most of any continent (Rockström et al., 2007). These rainfed locations are of interest for implementation of SI, while currently irrigated areas are not. Therefore we have only looked at implementation on the currently rainfed locations.

This study will focus on four crops, namely: maize, sorghum and cassava which are the three crops with the highest rainfed surface area in SSA (Portmann, Siebert, & Döll, 2010) and wheat which provides most calories in SSA after maize (FAO, 2019a).

To catch the variability in climatic variables this study was performed on climatic data for the years 1986-2015. For this study a spatial resolution of 5x5 arcminutes was used, with some input data being coarser at a resolution of 30x30 arcminutes.

2 Methods

In this study we define SI strategies as the strategies resulting in the highest marginal water productivity (MWP). Finding a strategy with a high MWP for a specific location, year and crop is difficult since it requires data on ET and Y over the whole range from rainfed to fully irrigated crops. We use a model to find the ET and Y values of potential strategies for a selection of 70 to 100 representative locations, based on soil and climate characteristics, in SSA. The outcomes of these experiments were plotted on an ET-Y diagram for each combination of crop, location and year to find the strategies within 95% of the maximum MWP. The reasoning behind this is explained in chapter 2.1, Quantification of a supplemental irrigation strategy.

To obtain the whole range of potential strategies we have to incrementally increase the water added over a growing season with the extra complication that this extra water can be added at different moments in time, each affecting the yield in a different way, making the amount of possible strategies endless. To limit the endless range of possible strategies we used previous research to find many potential SI strategies. We then found the strategies that are within the 95% MWP range frequently and select them as robust SI strategies. To ensure that this robustness holds for different situations we checked that the robust SI strategies are also in the 95% MWP range frequently for groups of locations and years categorised based on soil and climate. The exact methodology of how this was done in this study is laid out in chapter 2.2, Characteristics of robust supplemental irrigation strategies.

We selected three robust strategies, which were then used as our SI strategy for SSA and used as input for our model. The output from this model and a reference rainfed scenario was used to compare yields, interannual variability in yields and evapotranspiration (ET) of irrigation water between currently rainfed and SI on currently rainfed crops. Limitations on implementation of SI were imposed based on water availability. This is explained further in 2.3 ,The potential of supplemental irrigation in sub-Saharan Africa.

2.1 Quantification of a supplemental irrigation strategy

SI aims at improving yields with the addition of only small amounts of water. Here, we define SI more specifically as a form of irrigation that gives the largest increase in yield for the increase in water, i.e. the highest MWP. This differs from full irrigation, which aims at optimizing production per unit of land (tonne/ha) and deficit irrigation, which aims at optimizing production per unit of water (tonne/ha) (Hoekstra, 2013).

Evapotranspiration, the loss of water to the atmosphere, consists of evaporation and transpiration. Evaporation is non-beneficial loss of water while transpiration directly contributes to crop growth in a linear relationship (Falkenmark & Rockström, 2004; Oweis & Hachum, 2006). Crop growth shows a particular relation between ET and yield. At the start of the growing season evaporation is the only loss of water and transpiration is negligible (Falkenmark & Rockström, 2004; Zhang & Oweis, 1999). Once the crop has germinated, started its growth and development of leaves, transpiration starts increasing and with more growth the influence of evaporation starts decreasing due to increased shading and the linear relationship starts showing (Falkenmark & Rockström, 2004; Oweis & Hachum, 2006; Rockstrom et al., 2007). After a while deviation from this line happens due to deep percolation, runoff and non-beneficial ET (T. Oweis & Hachum, 2006).

When following this increase in ET with respect to yield we can see a s-curve forming. Were other studies, such as Fereres & Soriano (2006) show only the right part containing deficit and full irrigation strategies we are interested in the whole curve as shown in Figure 1. The location of the different forms of irrigation strategies on this ET-Y curve is shown in SI figure 1. By taking the derivative of this line we find the MWP-curve, from which we can derive the point with the highest MWP. Since there might be many strategies very close to, and no strategies at, the exact peak we consider all strategies that are within 95% of the maximum MWP as a SI strategy. The MWP-curve and subsequentially selected SI strategies are visualised in Figure 1.

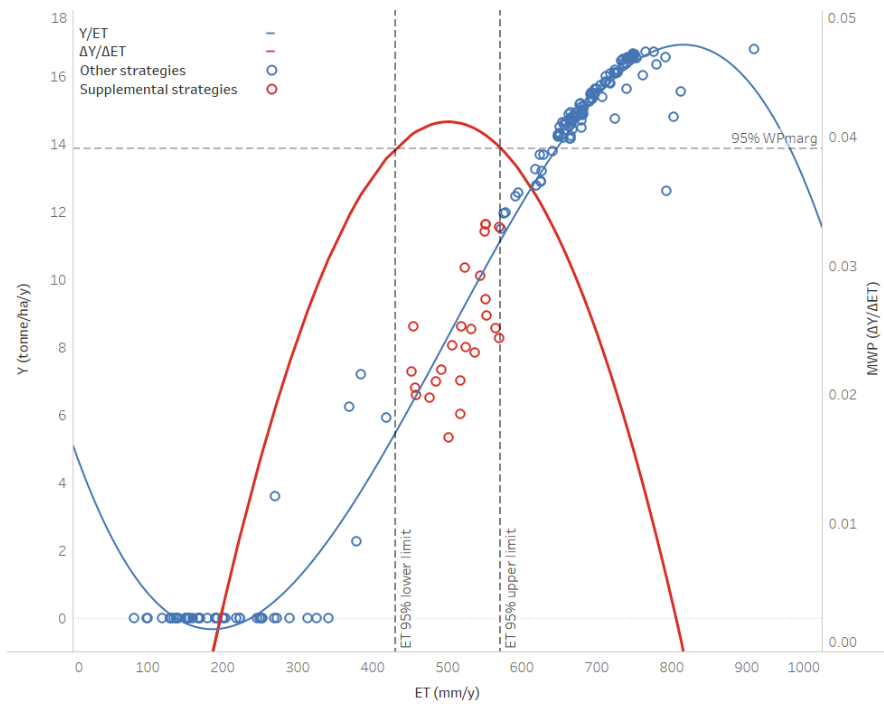

Figure 1: The evapotranspiration-yield curve (blue line), fitted on data points (red and blue dots), and the marginal water productivity curve (red line), derived from the ET-Y curve, are shown. Supplemental irrigation strategies are shown as red dots and have a marginal water productivity of at least 95% of the maximum; based on modelled data for maize in southern Mauritania in the year 2002, location shown in SI figure 2.

To obtain the different points in our ET-Y diagram and find the characteristics of a SI strategy we care about the way water interacts with crop growth for specific locations. Therefore, we used the water-driven crop growth model AquaCrop (Raes et al., 2009; Steduto et al., 2009) to model and test irrigation strategies.

AquaCrop uses a soil-water balance to calculate soil-water depletion which determines when and to what extent crops experience certain water stresses. Important factors in this are readily available water (RAW) and total available water (TAW). Where RAW is the difference between field capacity (FC), the maximum amount of water that can be retained by the soil against gravitational forces (Raes et al., 2018), and the soil-water depletion level at which crops start experiencing stomatal closure stress, which reduces transpiration and thus crop growth. TAW quantifies the range of soil-water depletion levels at which plants can take up any water (Steduto et al., 2012). TAW is the difference between FC and permanent wilting point (PWP), the point at which roots can no longer extract any water from the soil due to it being too strongly attached to the soil (Raes et al., 2018).

The AquaCrop model was set up with the model framework Aqua21 of (Hogeboom et al., submitted), which calculates crop water use and yields at a 5 x 5 arcminute grid. The model is forced by monthly CRU climate data (CRU, 2013) which was downscaled to daily data using ERA reanalysis products (Dee et al., 2011) through the procedure by Van Beek et al. (2011). Soil hydraulic parameters for 253 soil classes for two soil layers were obtained from De Lannoy et al. (2014) and shallow groundwater tables up to 2 meters of depth were taken from Fan et al. (2013). Crop-specific harvested areas for around the year 2000 were taken from MIRCA2000 (Portmann et al., 2010).

Since we are only interested in the implementation of irrigation strategies, and not in changing irrigation techniques, and the majority of irrigation in SSA is surface irrigation (FAO, 2017) of which furrow irrigation is the most efficient, we implemented our irrigation strategies as furrow irrigation.

Due to the vast size of SSA, modelling the influence all these strategies on crop yields for the whole of SSA would be infeasible. Therefore, a selection of representative locations was made. These were selected based on a unique combination between the important factors of soil characteristics and climate (Raes et al., 2009). For soil, FC and PWP, combined as TAW, have a large influence on yields whereas Ksat does not (Cosmo Silvestro et al., 2017; Geerts et al., 2009; Lievens, 2013). Consequently we categorized soil into groups of roughly equal TAW (steps of 20 mm). Climate was grouped by different agroecological zones which define the climatic conditions for rainfed agriculture. These were obtained from (IFPRI, 2014). Taking unique combinations of these two factors resulted in 70-100 locations per crop which are shown in SI figure 2.

2.2 Characteristics of robust supplemental irrigation strategies

Robust SI strategies are those SI strategies that have a high MWP in many different locations and years and are therefore applicable to many different situations.

To create irrigation strategies we translated the qualitative description of SI, “ the addition of **small amounts** of irrigation water during **critical crop growth stages** to improve, stabilize and secure harvests **when rainfall fails to provide** sufficient moisture”, into quantifiable irrigation strategies.

We characterize a potential SI strategy by two factors: (1) a timing threshold on when to irrigate the crop, based on when soil-water depletion is above a certain percentage of RAW; (2) how much irrigation will be given in an irrigation event, expressed in terms of an absolute volume (mm). Both were defined separately for each of the three major crop stages (the vegetative, flowering and yield formation stage).

By using information about crop responses to stresses and sensitive crop stage as supplied by Steduto et al. (2012) and Okogbenin et al. (2013) and stress parameters from AquaCrop crop files, a couple of hundred potential SI strategies per crop were created. The crop files for maize, sorghum and wheat were taken from the default AquaCrop library and cassava was generated by AquaCrop as a C3 root/tuber crop.

The potential SI strategies, a rainfed scenario and a fully irrigated scenario, implemented as refilling soil-water to FC once a soil-water depletion of 30% of RAW was reached, were used as input to the AquaCrop model for each representative location and year between 1986 and 2015. The output of which was a value of ET and Y for each location, year, crop and irrigation strategy.

We then found the relation between ET and Y for each combination of location, year and crop by finding a best fitting (3rd degree) polynomial through the ET-Y pairs of all irrigation strategies. From this relation we selected all SI strategies for each combination of location, year and crop, as defined by our definition of having a MWP of at least 95% of the maximum MWP.

We then visualized, in a crop specific histogram, the amount of times a strategy was within the 95% MWP range . Strategies that were in this range in a large percentage of the years and locations are seen as a robust SI strategy. To confirm this robustness is present for all situations we categorised each combination of crop, year and location into one of 20 unique combinations of soil and climate characteristics. The soil characteristics were grouped in sand, loam, clay (Brouwer et al., 1985) and peat (De Lannoy et al., 2014) based on their respective TAW. The climate characteristics were grouped as hyper-arid, arid, semi-arid, dry sub-humid and humid based on their respective yearly aridity index (Middleton & Thomas, 1992). For each crop we then visualised, in a soil-climate specific histogram, the amount of times a strategy was within in the 95% MWP range for each of the 20 categories and checked whether or not the same pattern emerged as with the crop specific histogram.

2.3 The potential of supplemental irrigation in sub-Saharan Africa

Simulated yields, interannual variability in yields and associated water use were compared between SI and a rainfed scenario for all four crops for the whole of SSA over the years 1986-2015 to find the potential of SI for currently rainfed agriculture in SSA.

For each crop we picked three strategies, that were in the 95% MWP range a large amount of times, and are thus seen as robust SI strategies. These strategies were picked from the previously created crop specific histograms after checking that the soil-climate specific histograms show the same occurrence pattern for these strategies.

These three strategies and a rainfed reference scenario were then used as separate inputs to the Aqua21 AquaCrop model and were used to model simulated yields and associated water use for the whole of SSA over the period 1986-2015. This was done for all four crops.

The distinction between green water use, blue water use from irrigation and blue water use from capillary rise has been made using the method of Hoekstra (2019). To determine whether or not SI is a viable option, when considering the availability of blue water, we compared the increased yearly blue water demand with the remaining water availability of Mekonnen & Hoekstra (2016).

For each location the simulated yield and water use information of the SI strategy with the highest yield, and with equal yields the lowest ET of irrigation water, was picked as data for comparison with the rainfed scenario. To calculate total production and total water use in SSA, the harvested areas were scaled to the level of 2015 by comparing the MIRCA 2000 data to the average harvest areas between 2011 and 2015 (FAO, 2019b), these harvested areas are shown in SI figure 3.

3 Results

3.1 Characteristics of robust supplemental irrigation strategies

We found no combinations of timing threshold and irrigation amount per event as robust SI strategy. However, when we grouped strategies by timing threshold, we found that some strategies are within 95% MWP range in a large part of the locations (occurrence of 60-75% depending on the crop) as shown in SI figure 4. These strategies are also robust in different combinations of soil and climate , as shown in SI figures 5-8, with the strategies in the 95% MWP range in a very large amount of the (hyper-)arid regions with a small decrease towards more humid regions. The same tendency is found for soils; with sandy and loamy soils having these strategies in the 95% range in a very large amount of locations, clayey soils a bit less and peat soils being inconclusive due to their low occurrence in SSA.

Three of these timing strategies were picked for analysis of whole SSA. A summary of the timing of irrigation per crop stage, given in TAW instead of RAW for easy comparison between crops, for these strategies is shown in Table 1. This table also contains the average maximum MWP that was used in determining the SI strategies for each crop. The complete strategies are shown in SI table 1.

For maize the stomatal closure stress is kept low in the vegetative and flowering stage while it can become significantly higher in the yield formation stage. Sorghum allows medium stress in the vegetative stage, limited stress during the flowering stage and medium stress once again during the yield formation stage. For cassava medium stress is allowed in all crop stages. For wheat low to medium stress is allowed in the vegetative and flowering stage while the stress in the yield formation stage seems irrelevant since low to full stresses are allowed with different strategies.

Table 1: Supplemental irrigation strategy timing value ranges (soil-water depletion as a percentage of TAW) per crop and crop stage and average marginal water productivity (tonne/m^3) for the steepest part of the ET-Y curve; complete strategies shown in SI table 1

Crop	Timing of irrigation (depletion in % TAW) in vegetative crop stage	Timing of irrigation (depletion in %TAW) in flowering crop stage	Timing of irrigation (depletion in %TAW) in yield formation crop stage	Peak marginal water productivity (tonne/m^3)
Maize	83 – 90%	83%	90 – 97%	0.0000164 – 0.514 (0.0138)
Sorghum	92 – 97%	81 – 92%	92 – 97%	0.000149 – 0.340 (0.0159)
Cassava	75 – 90%	75 – 90%	90%	0.0000397 – 0.220 (0.0079)
Wheat	81 – 85%	81 – 85%	85 – 100%	0.000116 – 0.146 (0.0053)

By using the same methodology, of visualizing strategies in a histogram if they are within the 95% MWP range, on irrigation amounts for the picked irrigation timing strategies, we found no irrigation amount that has a high occurrence in the whole of SSA. However, when we looked at the histograms for different combinations of soil and climate we found a bell curve with a clear peak for most combinations. The values of these peaks are shown in SI figures 10-13 and were used as irrigation amounts per event for the whole of SSA. Irrigation amounts for peat ware taken from clay, since data of peat was not available for most combinations of soil and climate. The general trend is that soils with a lower water holding capacity have lower amounts of irrigation per event and locations with arid climates have higher amounts of irrigation per event.

3.2 The potential of supplemental irrigation in sub-Saharan Africa

We used the three picked strategies per crop as input to the AquaCrop model and for each grid cell the strategy with highest yield, or with equal yields the strategy with the lowest ET of irrigation water, was picked to serve as our point of comparison against the rainfed situation. The picked strategies are shown in SI figure 25. By taking the weighted average yield, based on harvested areas, we get the yields as shown in Figure 2. The weighted average yield for currently rainfed locations increases by 22, 54, 30 and 33% for respectively maize, sorghum, cassava and wheat under SI. If we limit application of SI to those locations with enough available water, as visualised in SI figure 26, the increases are limited to 15, 25, 28 and 19% for maize, sorghum, cassava and wheat.

The weighted average of interannual coefficient of variation in yield makes a very significant drop of 73, 70, 74 and 72% for respectively maize, sorghum, cassava and wheat under not water availability limited conditions as shown in Figure 3. If we implement our water availability limitation the coefficient of interannual variation in yield decreases with 70, 43, 32 and 36% for cassava, maize, sorghum and wheat.

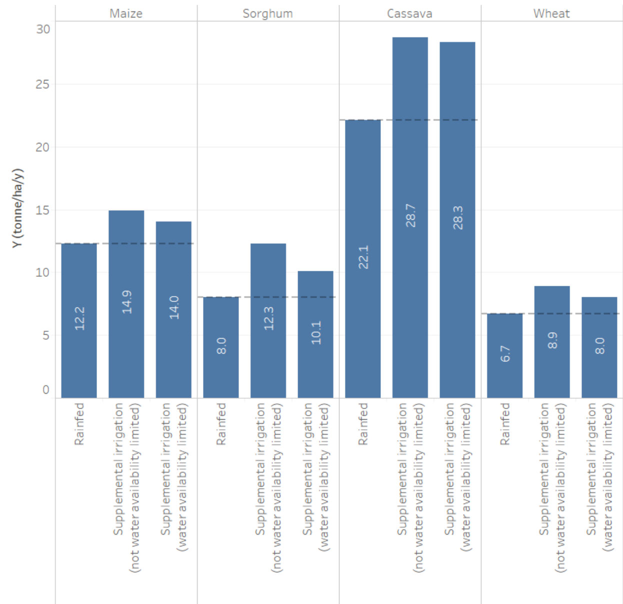

Figure 2: Harvested area weighted average of simulated yield (tonne/ha) for currently rainfed, non-limited supplemental irrigation and water availability limited supplemental irrigation. For maize, sorghum, cassava and wheat in sub-Saharan Africa over the years 1986-2015.

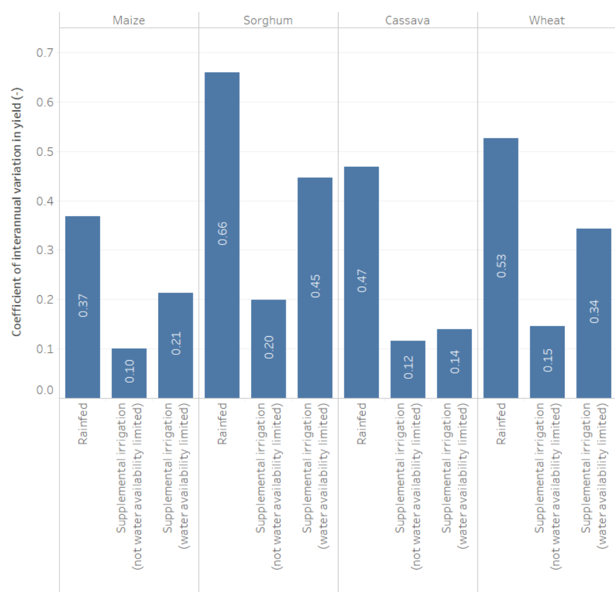

Figure 3: Harvested area weighted average of the coefficient of interannual variation in yield for currently rainfed, non-limited supplemental irrigation on currently rainfed fields and water availability limited supplemental irrigation on currently rainfed fields. For maize, sorghum, cassava and wheat in sub-Saharan Africa over the years 1986-2015.

There are large spatial differences in yields and variability in yield for rainfed agriculture and for SI as shown in figures 5-8.

Maize

There are high rainfed yields in almost all locations except for the Sahel, the Horn of Africa, Southern Africa and parts of the Democratic Republic of the Congo (DRC), Central African Republic (CAR), Angola and inland Tanzania. These are also the locations were variability in yield is high. Implementation of SI boosts yields and drops variability in those locations with the largest changes in the Horn of Africa, while many other locations don't benefit from SI.

Sorghum

There are relatively high rainfed yields in southern West Africa, northern Central Africa, East Africa, in central Ethiopia and on Madagascar. Interannual variability in these yields follows almost the same pattern and is high in the Sahel, the Horn of Africa, Southern Africa and in the southern DRC while it is relatively high in Eastern Africa as well. Implementation of SI considerably raises the average yields in the Sahel, Horn of Africa and Southern Africa with lower increases in Eastern Africa, the southern DRC and on the western part of Madagascar. We can see the same pattern in decrease of interannual variability with parts of the Sahel, Horn of Africa and Southern Africa still showing considerable differences between years.

Cassava

Rainfed yields are high in Central Africa, southern West Africa and on eastern Madagascar with some spots of higher yields in Mali, Niger, Chad and Angola. Interannual variability in yield is high in all other locations with the exception of some spots in South Sudan, Somalia and Tanzania. Implementation of SI sees large increases in yield in the Sahel, parts of South Sudan, Angola and Zambia and smaller increases in all places except for those locations with high rainfed yields. Interannual variability in yield decreases in all locations except those with low rainfed variability. Some spots with high variability remain in Chad, CAR, the Horn of Africa, southern East Africa and on western Madagascar.

Wheat

Rainfed yields are high in southern and central Nigeria, Cameroon, on Madagascar and in parts of the DRC, Ethiopia, Mozambique and Tanzania. Variability is low in those locations except for Tanzania, Mozambique and western Madagascar. With implementation of SI we see a substantial increase in yield in Mauritania, Sudan, the Horn of Africa, Angola and Mozambique and smaller changes in other locations. Variability decreases substantially in the locations with yield increase with the largest remaining variability the Horn of Africa and Southern Africa.

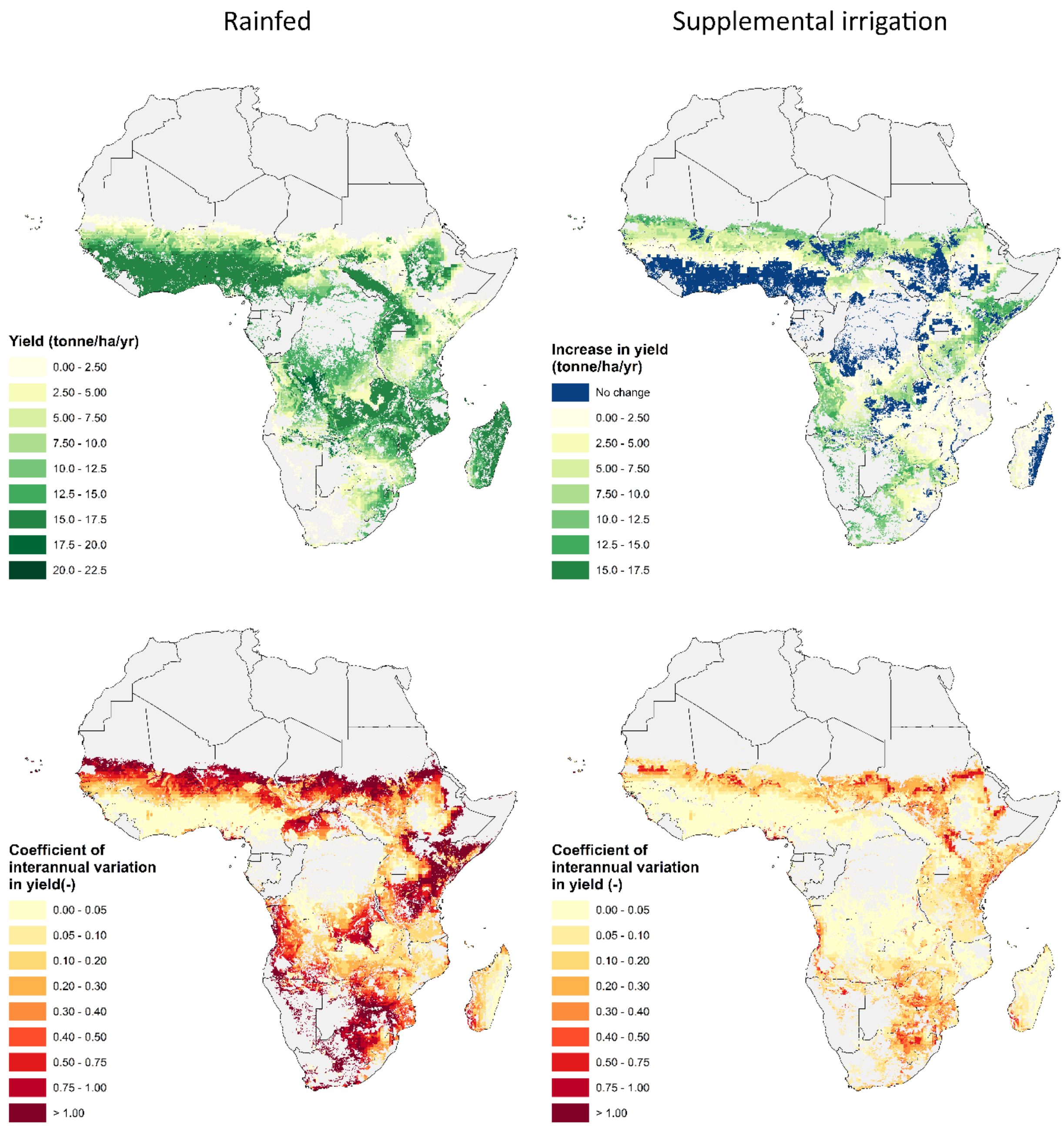

Figure 4: Average yield (tonne/ha) and coefficient of interannual variation in yield (-) for currently rainfed maize (left) and increase in average yield (tonne/ha) and coefficient of interannual variation in yield (-) for not water availability limited supplemental irrigation on currently rainfed maize (right). Map of sub-Saharan Africa between the years 1986-2015 at a 5x5 arcminute resolution.

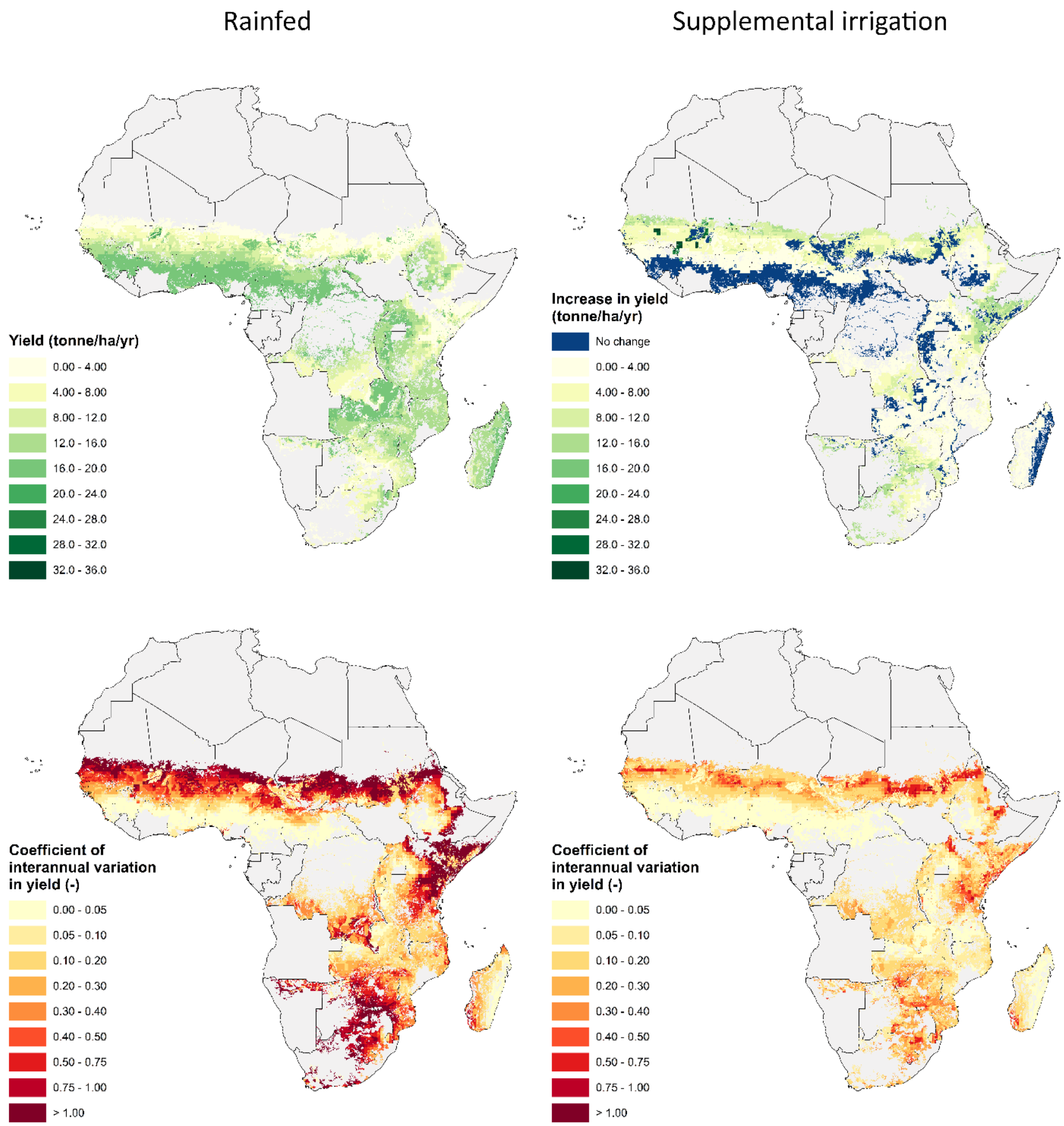

Figure 5: Average yield (tonne/ha) and coefficient of interannual variation in yield (-) for currently rainfed sorghum (left) and increase in average yield (tonne/ha) and coefficient of interannual variation in yield (-) for not water availability limited supplemental irrigation on currently rainfed sorghum (right). Map of sub-Saharan Africa between the years 1986-2015 at a 5x5 arcminute resolution.

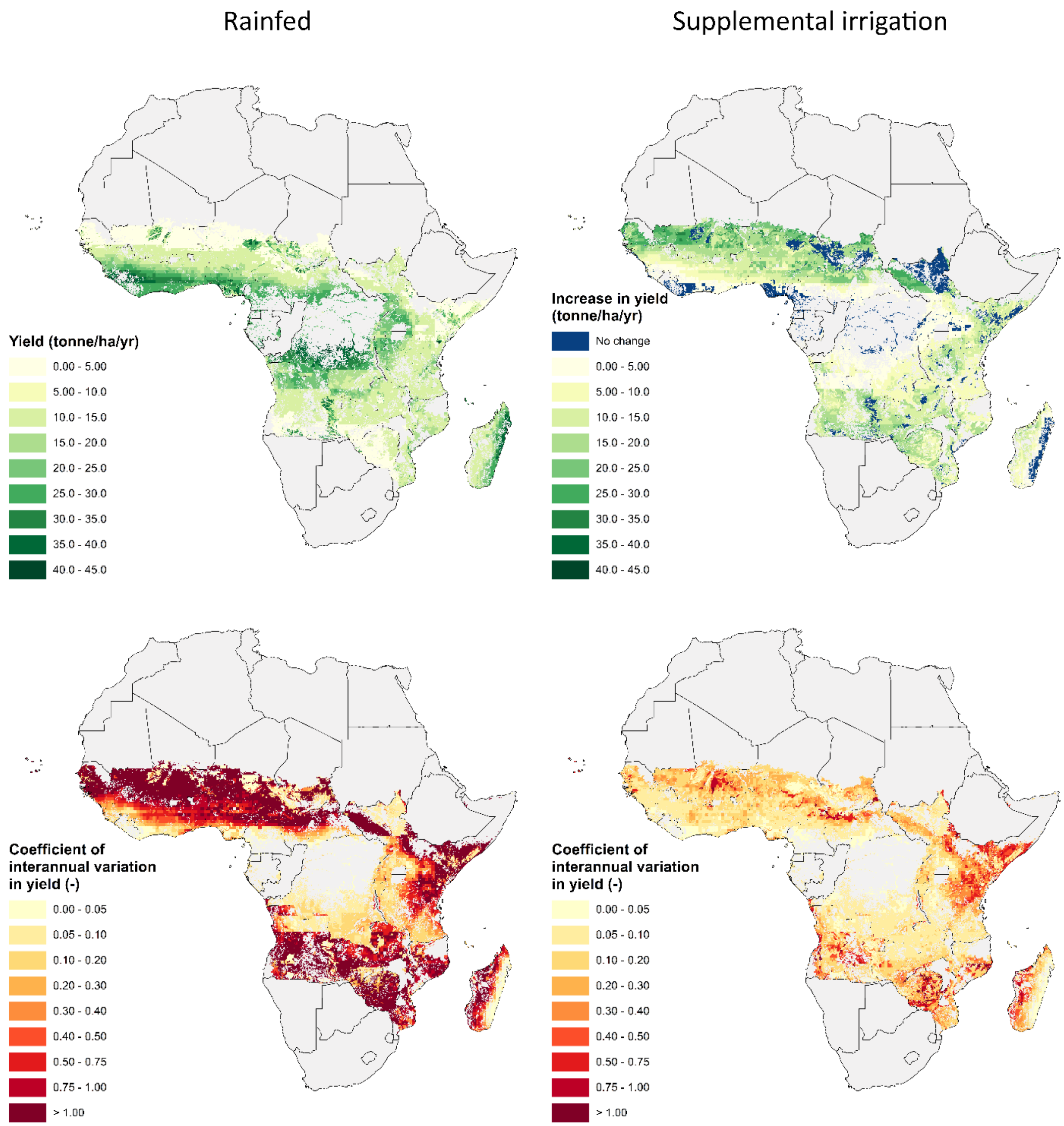

Figure 6: Average yield (tonne/ha) and coefficient of interannual variation in yield (-) for currently rainfed cassava (left) and increase in average yield (tonne/ha) and coefficient of interannual variation in yield (-) for not water availability limited supplemental irrigation on currently rainfed cassava (right). Map of sub-Saharan Africa between the years 1986-2015 at a 5x5 arcminute resolution.

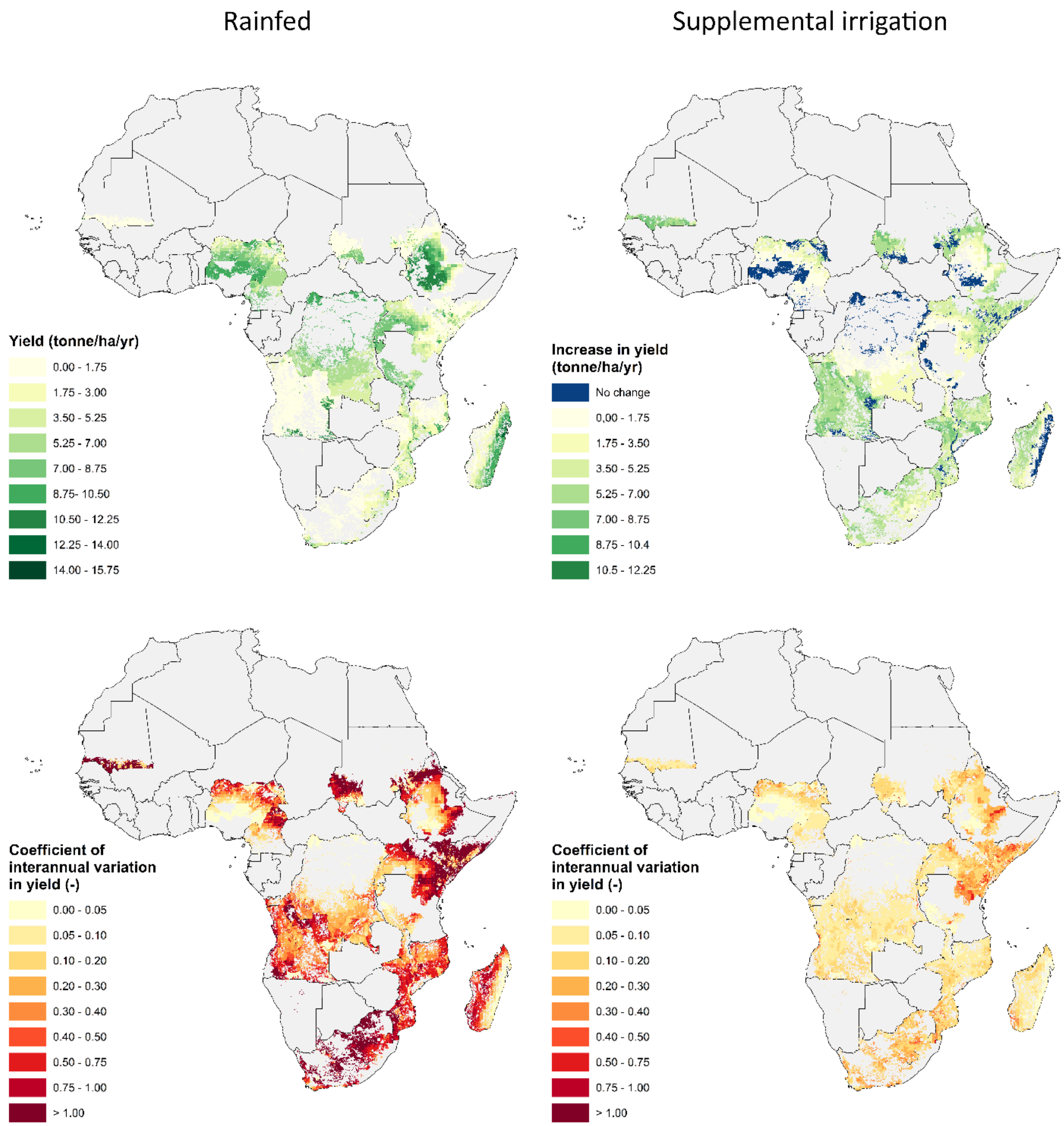

Figure 7: Average yield (tonne/ha) and coefficient of interannual variation in yield (-) for currently rainfed wheat (left) and increase in average yield (tonne/ha) and coefficient of interannual variation in yield (-) for not water availability limited supplemental irrigation on currently rainfed wheat (right). Map of sub-Saharan Africa between the years 1986-2015 at a 5x5 arcminute resolution.

To implement SI, and achieve the increase in yield and yield stability, we need quite substantial amounts of water. Table 2-4 show the required amount of irrigation water and the amount of this water that is lost through ET averaged over hectares and summed for the whole of SSA for each crop. It also shows the harvested rainfed area and the total amount of production for the whole of SSA for maize, sorghum, cassava and wheat (production figures per country and crop are shown in SI table 2). This is shown for not water availability limited and water availability limited SI with information about currently rainfed cropland as a reference.

There are large differences, in the amount of added irrigation water and the amount of ET of irrigation water, between the different crops . The ET of irrigation water is 326, 834, 699 and 967 m^3/ha/yr for respectively maize, sorghum, cassava and wheat for not water availability limited SI. This is limited to 171, 308, 634 and 521 m^3/ha/yr if we constrain the implementation of SI to those locations with enough available water. The spatial distribution of ET of irrigation water per crop throughout SSA is shown in SI figure 27.

Table 2: Yearly average added irrigation water (in m3/ha/yr and m3/yr), evapotranspiration of irrigation water (in m3/ha/yr and m3/yr), cropland surface area (ha) and simulated production (tonne/yr). For curently rainfed maize, non water availability limited supplemental irrigation on currently rainfed maize and water availability limited supplemental irrigation on currently rainfed maize over the years 1986-2015.

Maize	Rainfed	Supplemental irrigation (not water availability limited)	Supplemental irrigation (water availability limited)
Added irrigation water (m^3/ha/yr)	0	496	288
Evapotranspiration of irrigation water (m^3/ha/yr)	0	326	171
Cropland (10^6 ha)	34.6	34.6	34.6
Added irrigation water SSA (10^9 m^3/yr)	0	17.2	10
Evapotranspiration of irrigation water SSA (10^9 m^3/yr)	0	11.3	5.9
Production SSA (10^6 tonne/yr)	424	517	486

Table 3: Yearly average added irrigation water (in m3/ha/yr and m3/yr), evapotranspiration of irrigation water (in m3/ha/yr and m3/yr), cropland surface area (ha) and simulated production (tonne/yr). For curently rainfed sorghum, non water availability limited supplemental irrigation on currently rainfed sorghum and water availability limited supplemental irrigation on currently rainfed sorghum over the years 1986-2015.

Sorghum	Rainfed	Supplemental irrigation (not water availability limited)	Supplemental irrigation (water availability limited)
Added irrigation water (m^3/ha/yr)	0	900	341
Evapotranspiration of irrigation water (m^3/ha/yr)	0	834	308
Cropland (10^6 ha)	26.0	26.0	26.0
Added irrigation water SSA (10^9 m^3/yr)	0	23.4	8.8
Evapotranspiration of irrigation water SSA (10^9 m^3/yr)	0	21.6	8.0
Production SSA (10^6 tonne/yr)	209	319	262

Table 4: Yearly average added irrigation water (in m3/ha/yr and m3/yr), evapotranspiration of irrigation water (in m3/ha/yr and m3/yr), cropland surface area (ha) and simulated production (tonne/yr). For curently rainfed cassava, non water availability limited supplemental irrigation on currently rainfed cassava and water availability limited supplemental irrigation on currently rainfed cassava over the years 1986-2015.

Cassava	Rainfed	Supplemental irrigation (not water availability limited)	Supplemental irrigation (water availability limited)
Added irrigation water (m^3/ha/yr)	0	861	791
Evapotranspiration of irrigation water (m^3/ha/yr)	0	699	634
Cropland (10^6 ha)	17.9	17.9	17.9
Added irrigation water SSA (10^9 m^3/yr)	0	15.5	14.2
Evapotranspiration of irrigation water SSA (10^9 m^3/yr)	0	12.5	11.4
Production SSA (10^6 tonne/yr)	397	514	508

Table 5: Yearly average added irrigation water (in m3/ha/yr and m3/yr), evapotranspiration of irrigation water (in m3/ha/yr and m3/yr), cropland surface area (ha) and simulated production (tonne/yr). For curently rainfed wheat, non water availability limited supplemental irrigation on currently rainfed wheat and water availability limited supplemental irrigation on currently rainfed wheat over the years 1986-2015.

Wheat	Rainfed	Supplemental irrigation (not water availability limited)	Supplemental irrigation (water availability limited)
Added irrigation water (m^3/ha/yr)	0	1299	722
Evapotranspiration of irrigation water (m^3/ha/yr)	0	967	521
Cropland (10^6 ha)	2.4	2.4	2.4
Added irrigation water SSA (10^9 m^3/yr)	0	3.1	1.7
Evapotranspiration of irrigation water SSA (10^9 m^3/yr)	0	2.3	1.2
Production SSA (10^6 tonne/yr)	16	21	19

Figure 9 shows the amount of ET of irrigation water for all four crops combined and spread out over each grid cell. This is a combination of SI figure 3 and 27 and shows the influence of irrigating all croplands of our four crops. We can see that the largest amounts of water are required in the Sahel and south and east Africa, with particularly large hotspots in Niger, Sudan and South Africa.

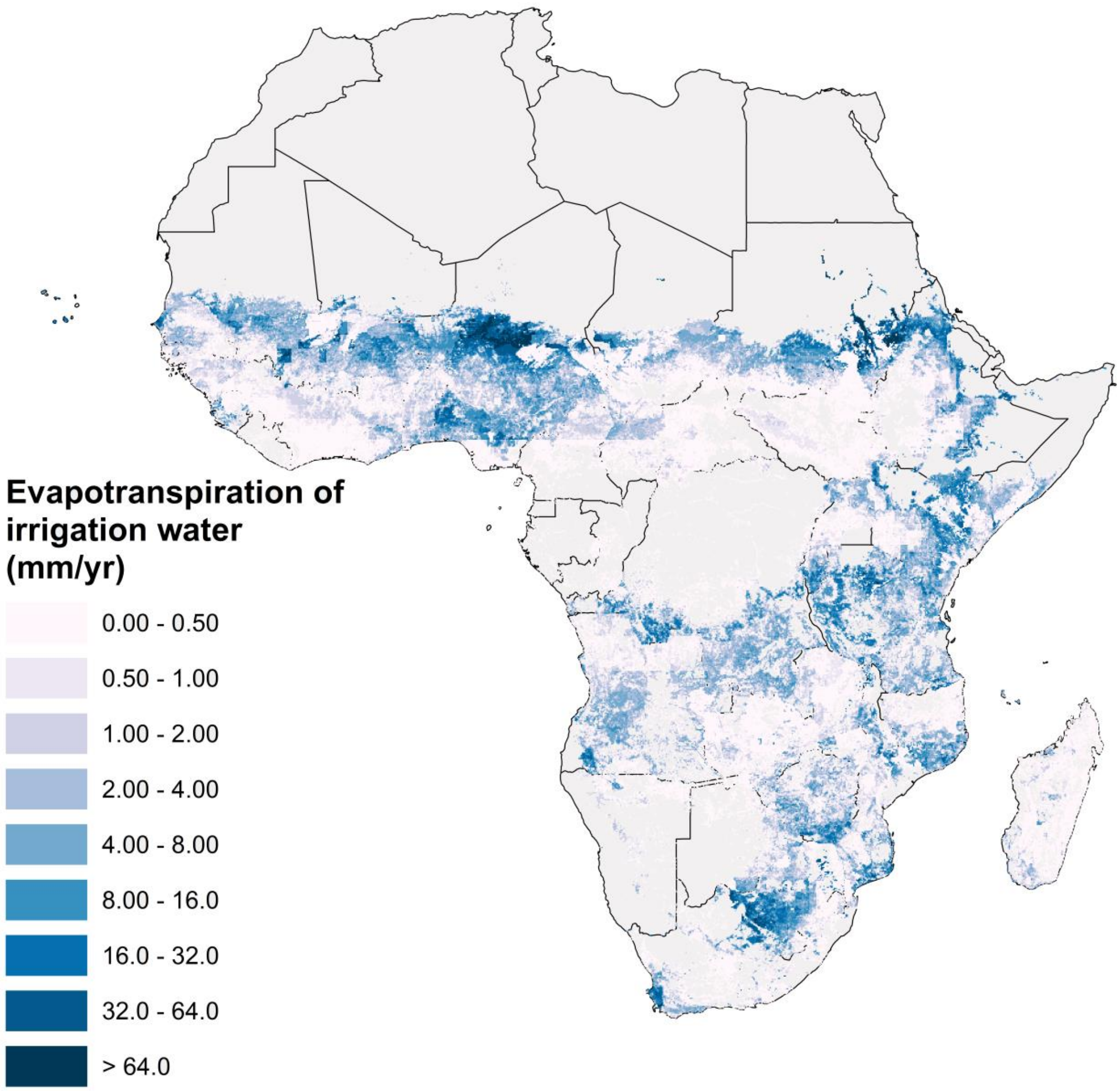

Figure 8: Average yearly evapotranspiration of irrigation water (mm/yr) spread over the grid cell when currently rainfed fields of maize, sorghum, cassava and wheat get supplemental irrigation over the years 1986-2015 (at 5x5 arcminute resolution) . Calculated by summing the total evapotranspiration of irrigation water of a grid cell of all crops and dividing by the surface area of the specific 5x5 arcminutes grid cell.

4 Discussion

4.1 Comparison with previous studies

We found an average increase in maize yield under SI is 22% while the coefficient of interannual variation drops by 73%, this requires an average irrigation of 50 mm per season. This is comparable to Muluneh et al. (2017) which shows for an increase of 20% in yield at a cost of 94-111 mm irrigation in a dry sub-humid location in Ethiopia. Barron & Okwach (2005) show an increase of yield of 50% and a reduction in the coefficient of variation of 11% at a cost of 20 to 240 mm of irrigation per season for a semi-arid region in Kenya, while Manivasagam & Nagarajan (2015) a yield increase of 138% at a cost of 93-126 mm for a semi-arid to dry sub-humid location in India. We found that sorghum yields increase by 54% under SI, while the coefficient of variation decrease by 70% at an average irrigation amount of 90 mm per season. Fox & Rockström (2003) show an increase in sorghum yield of 56%, a decrease of the coefficient of interannual variation of 13.5% at a cost of 60-90 mm irrigation for a semi-arid location in Burkina Faso. We found an increase of 30% in cassava yield with an associated water use of 86 mm of irrigation, while Odubanjo et al. (2011) show an increase in yield for cassava of 118% at a cost of 136 mm irrigation for a dry sub-humid location in Nigeria. We found that average wheat yields have increased 33% under SI with an associated water use of 130 mm of irrigation. Nangia et al. (2018) show an increase in wheat yield of 140%, 26% and 55% for respectively Syria, Morocco and Iran, while Oweis et al. (1999) show an increase in yield of 46% at a use of 100 mm irrigation for a semi-arid location in Syria.

The irrigation amounts required for SI are within a factor two between our study and previous studies. We do see that increase in yield vary wildly between prior studies and between prior studies and our results, this can be attributed to the many different climates and therefore different amounts of available water in SSA. This makes direct comparison between our overall results and results of previous studies difficult.

4.2 Limitations in method and data

This study has used AquaCrop to model the relationship between water and crop yields. This model ignores many other important factors in the development of the crop such as fertility, pests and differences between cultivars meaning that actual yields for both rainfed and SI on currently rainfed crops will likely be lower than those mentioned in this study.

Different types of input data into the AquaCrop model have different resolutions and quality introducing uncertainty into the output of the model.

Changes in harvested area between 2000 and 2015 have been accounted for by scaling on country level based data between 2011 and 2015 (FAO, 2019b). This disregards intranational differences in development of cropland and differences between the MIRCA2000 dataset and the FAO data of around 2000 creating the possibility of over- or under-scaling and therefore introducing uncertainty into our model output.

Potential SI strategies were picked based on incremental increases in water stresses leaving out changes smaller than our step size. Potentially leaving out better strategies. These strategies would be very similar to strategies that were tested and the possible influence on yields and variability in yields would therefore be marginal.

Irrigation amounts per event were kept equal over the whole growing period to reduce the amount of simulations that were required, which has undoubtedly resulted in over-irrigation on moments with low requirements and under-irrigation in moments with higher water requirements. By differentiating the irrigation amount given per irrigation event between i.e. crop stages, growing days or root depth the performance of SI can increase even further.

We have looked at implementation of SI in all climates even though our methodology and SI in general might not be suitable for very arid and very humid regions. However, these areas are either not taken into account in water availability limited SI or are not irrigated at all.

There are multiple strategies that have high representation in the 95% MWP range and are therefore a robust SI strategy, we only continued our analysis of the effect of SI on yields with three strategies therefore creating the possibility that larger increases in yield and yield stability have been left out.

Irrigation amounts per event for timing strategies were picked from the peak of a bell curve. This leaves out the values around this peak, creating the possibility that some locations were not irrigated with the optimal amount. However, total irrigation amounts are relatively equal between different soils in the same climate even though they are irrigated with different values per event. It is therefore unlikely that different irrigation amounts per event would result in vastly different results.

One of the underlying reasons to why SI might be interesting to SSA is the negative effect climate change will likely have on SSA agriculture. This study has however used climate data from 1986 to 2015 and might thus not properly show the influence SI could have on future agriculture. Further study into the influence of SI on agriculture under future climate is therefore required.

5 Conclusion

This study has tried to get better insights into SI, its characteristics and the effect it has on yields. From our analysis into what characteristics a robust SI strategy has, we found that the timing of when to irrigate is equal over different soils and climates while the amount to irrigate per event is not.

The timing for SI of maize allows some water stress in the vegetative crop stage while during flowering all stresses should be avoided, in the yield formation stage medium water stresses are allowed as is the case for sorghum and wheat. For sorghum the vegetative stage is less sensitive and quite high stresses are tolerable, the flowering stage is more sensitive but not as sensitive as maize. Wheat tolerates some water stresses in the vegetative and flowering crop stage. Cassava tolerates medium water stress in all crop stages and only very severe stresses should be avoided.

The amount to irrigate per event is low in humid locations with sandy, low water holding capacity, soils and increases with increasing aridity and increasing soil-water holding capacity of soils.

Implementation of SI for SSA increase weighted average yields by 30, 22, 53 and 33% for respectively cassava, maize, sorghum and wheat while decreasing respective variability, measured in the coefficient of variation, by 74, 73, 70 and 72%. When we limited the implementation of SI to those locations with sufficient available water yields increased 28, 15, 26 and 20% for cassava, maize, sorghum and wheat respectively while decreasing respective variability by 70, 43, 32 and 36%. To achieve this an average ET of irrigation water of 70, 33, 83 and 97 mm was required in the non-limited situation for respectively cassava, maize, sorghum and wheat while this would cost a respective 63, 17, 31 and 52 mm for water availability limited SI.

SI increase total yearly production for the 4 crops with 324.81 M tonne (31%) at a cost of 47.74 Gm3 of evapotranspired irrigation water, while water limited SI increase total yearly production by 229.35 M tonne (22%) at a cost of 26.52 Gm3 of evapotranspired irrigation water.

The increase of production and yield stability significantly increases food security for SSA and has an even greater potential then only its direct influence. With more certainty in annual yields, and therefore in income, farmers can more easily invest in other ways to improve yield such as equipment or fertilizer, making the potential to food and economic security even greater.

To successfully implement SI in SSA, policy is required that diffuses knowledge about when and how much to irrigate certain crops and on how to set up a SI system. Development of i.e. a simple visual aid could assist in determining the crop growth stage and soil-water content and subsequently the amount and timing of irrigation.

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Supplemental information

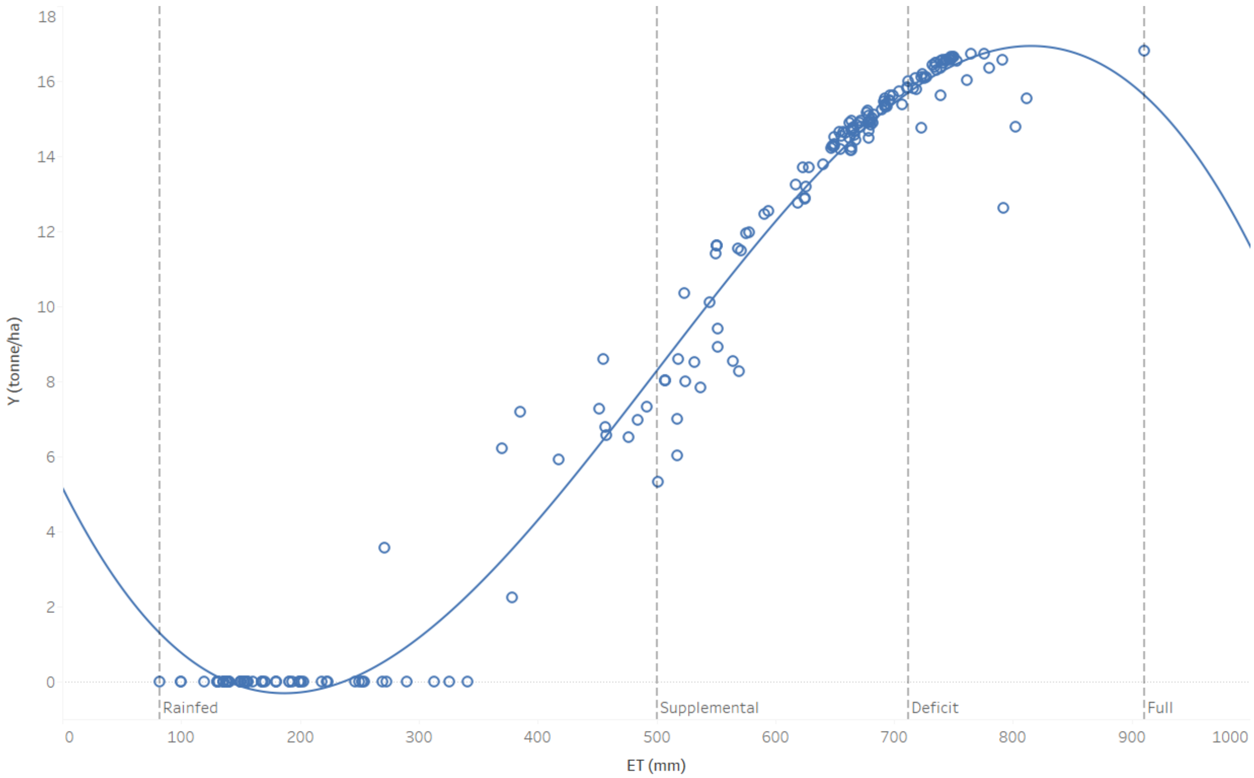

Figure 1: Evapotranspiration-yield s-curve diagram with the different types of irrigation visualised, with supplemental irrigation having the highest MWP $(\frac{\Delta Y}{\Delta ET})$ *, deficit irrigation having the highest WP* $(\frac{Y}{ET})$ *and full irrigation having the highest yield (tonne/ha); based on modelled data for maize in southern Mauritania in the year 2002, location shown in SI figure 2*

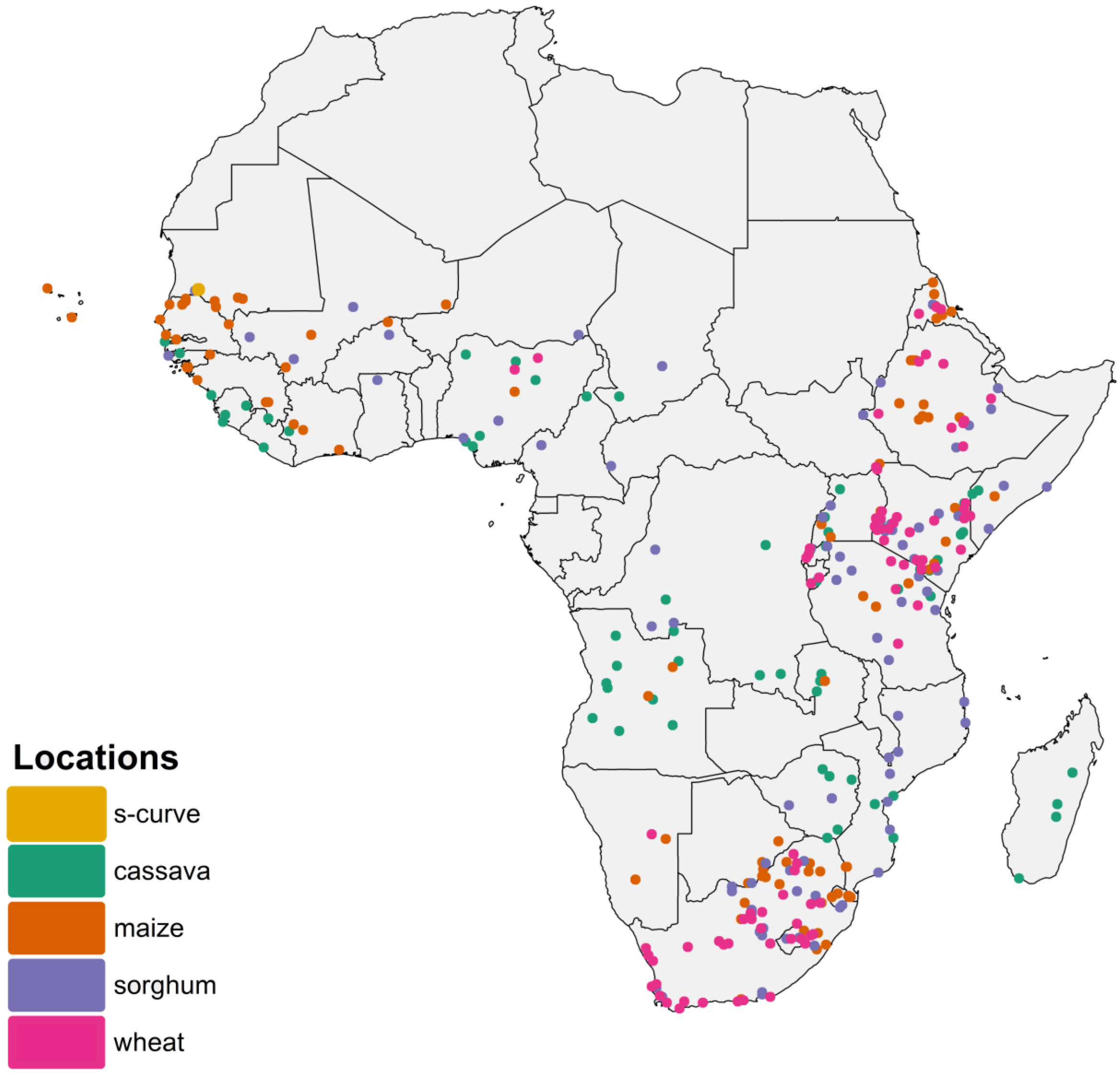

Figure 2: Location of modelled ET-Y diagram s-curve data and representative locations for creation of supplemental irrigation strategies

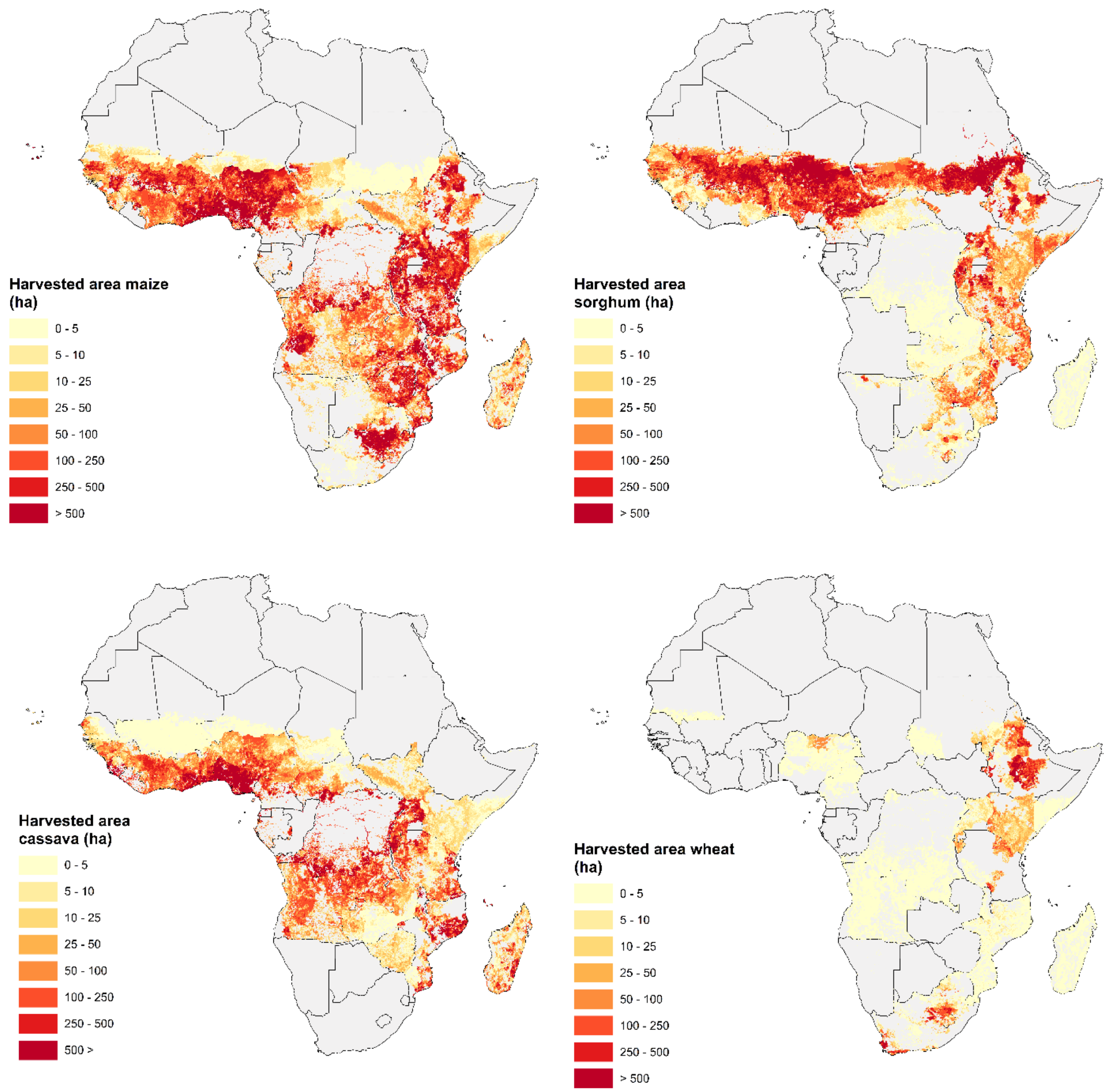

Figure 3: Harvest area (ha) per grid cell (at 5x5 arcmin resolution) of currently rainfed croplands for maize, sorghum, cassava and wheat

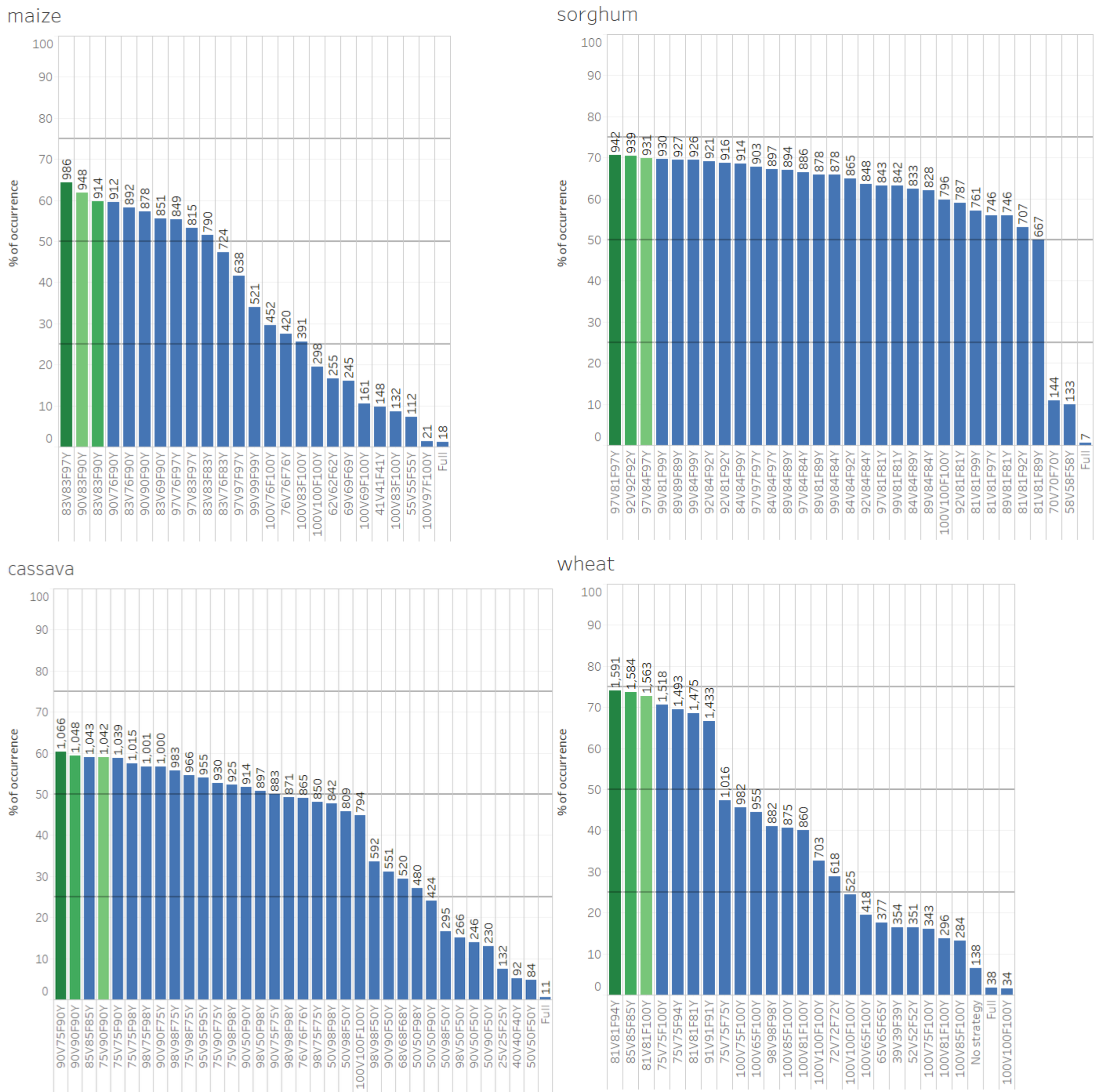

Figure 4: Histogram of occurrence of supplemental irrigation strategies for maize, sorghum, cassava and wheat with used supplemental irrigation strategies in green

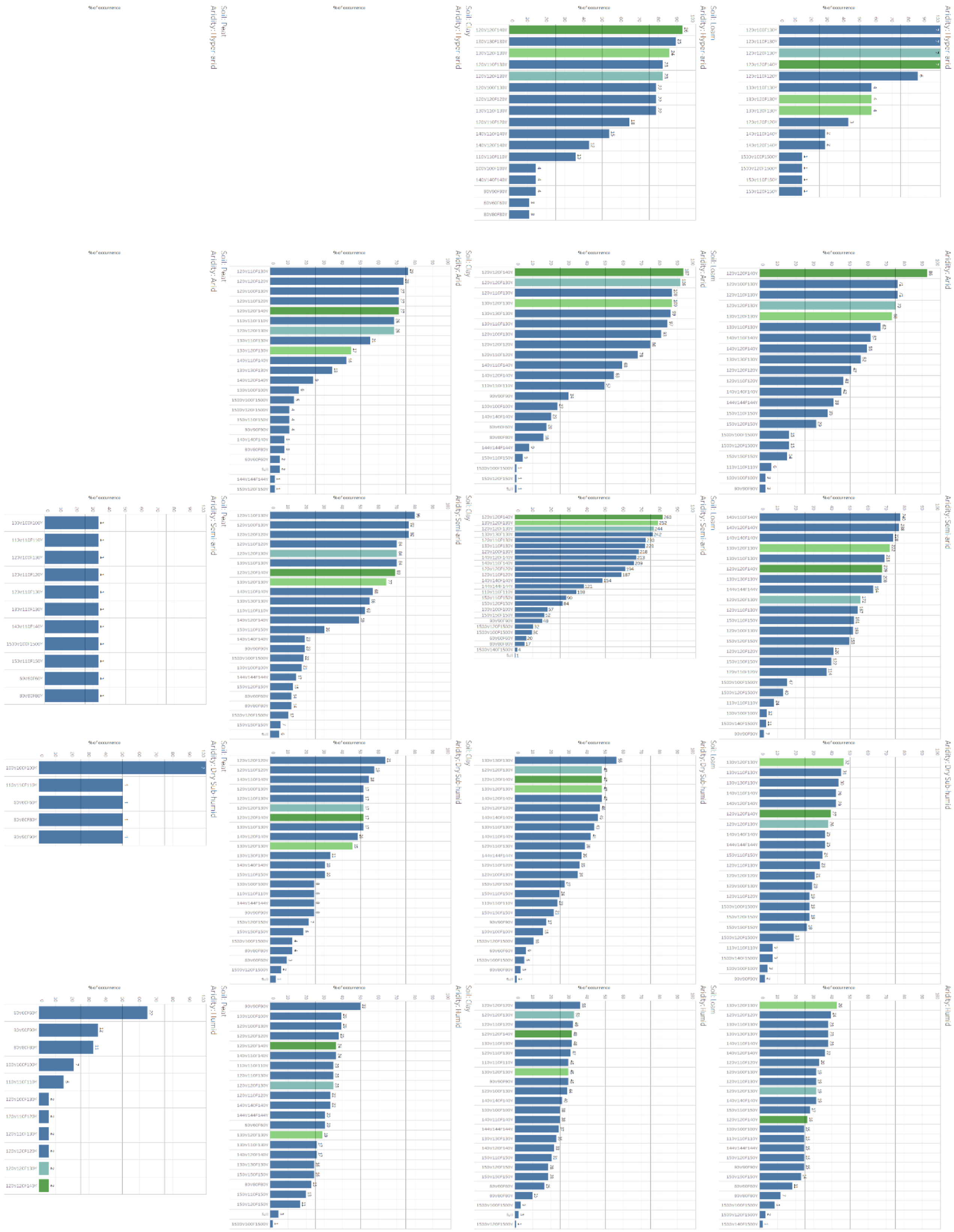

Figure 5: Histograms of supplemental strategies per soil-climate combination for maize given in RAW (translatable into TAW by multiplying by 0.69)

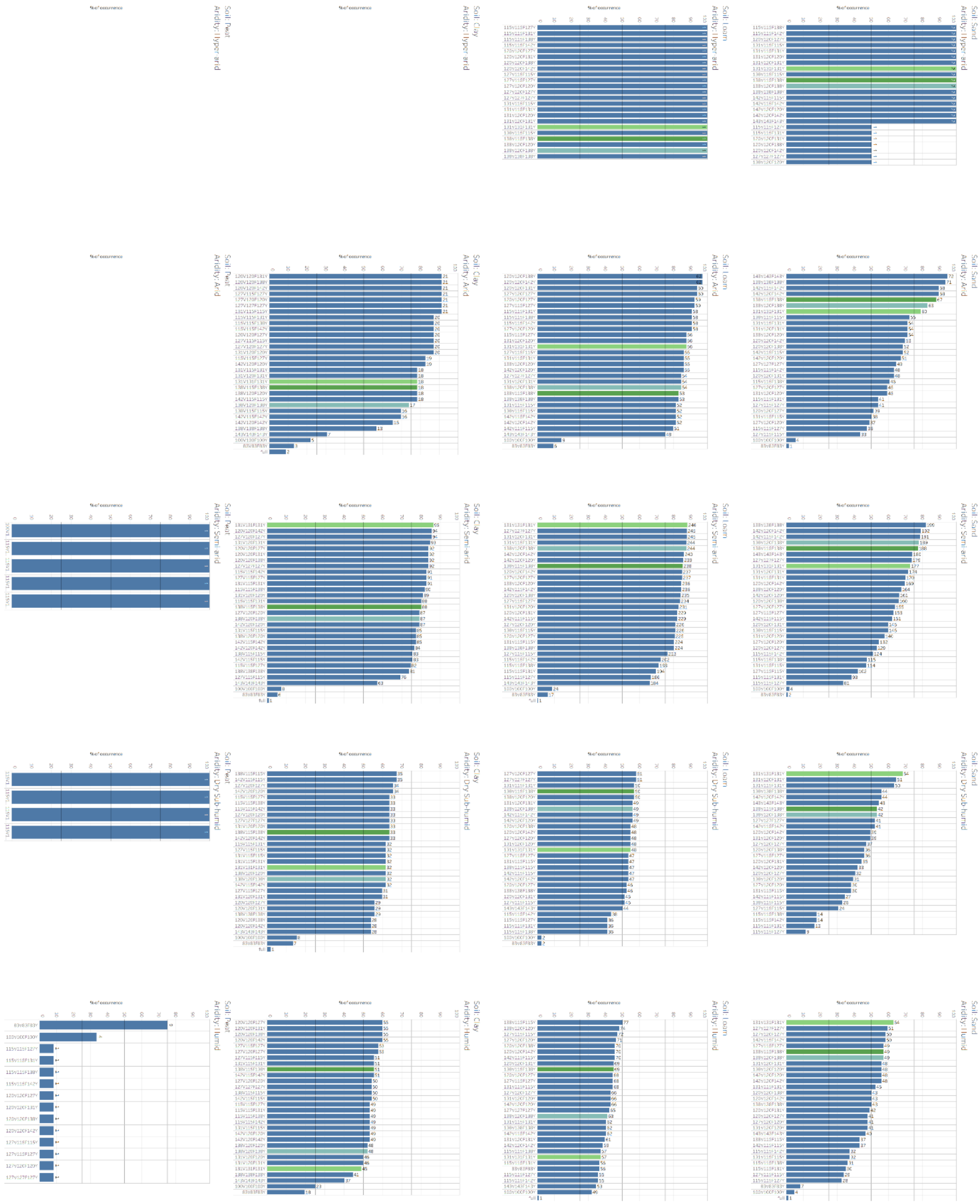

Figure 6: Histograms of supplemental strategies per soil-climate combination for sorghum given in RAW (translatable into TAW by multiplying by 0.70)

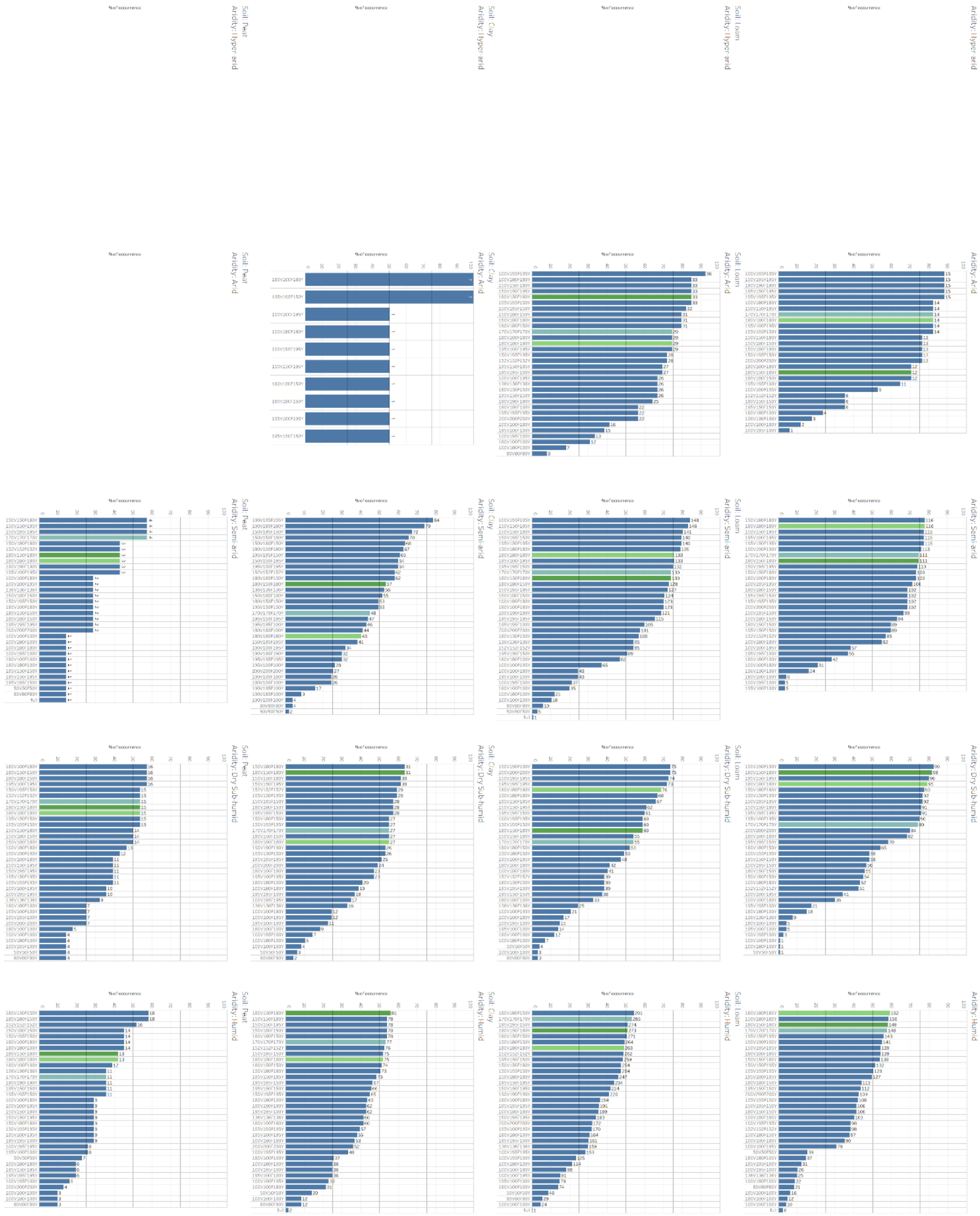

Figure 7: Histograms of supplemental strategies per soil-climate combination for cassava given in RAW (translatable into TAW by multiplying by 0.55)

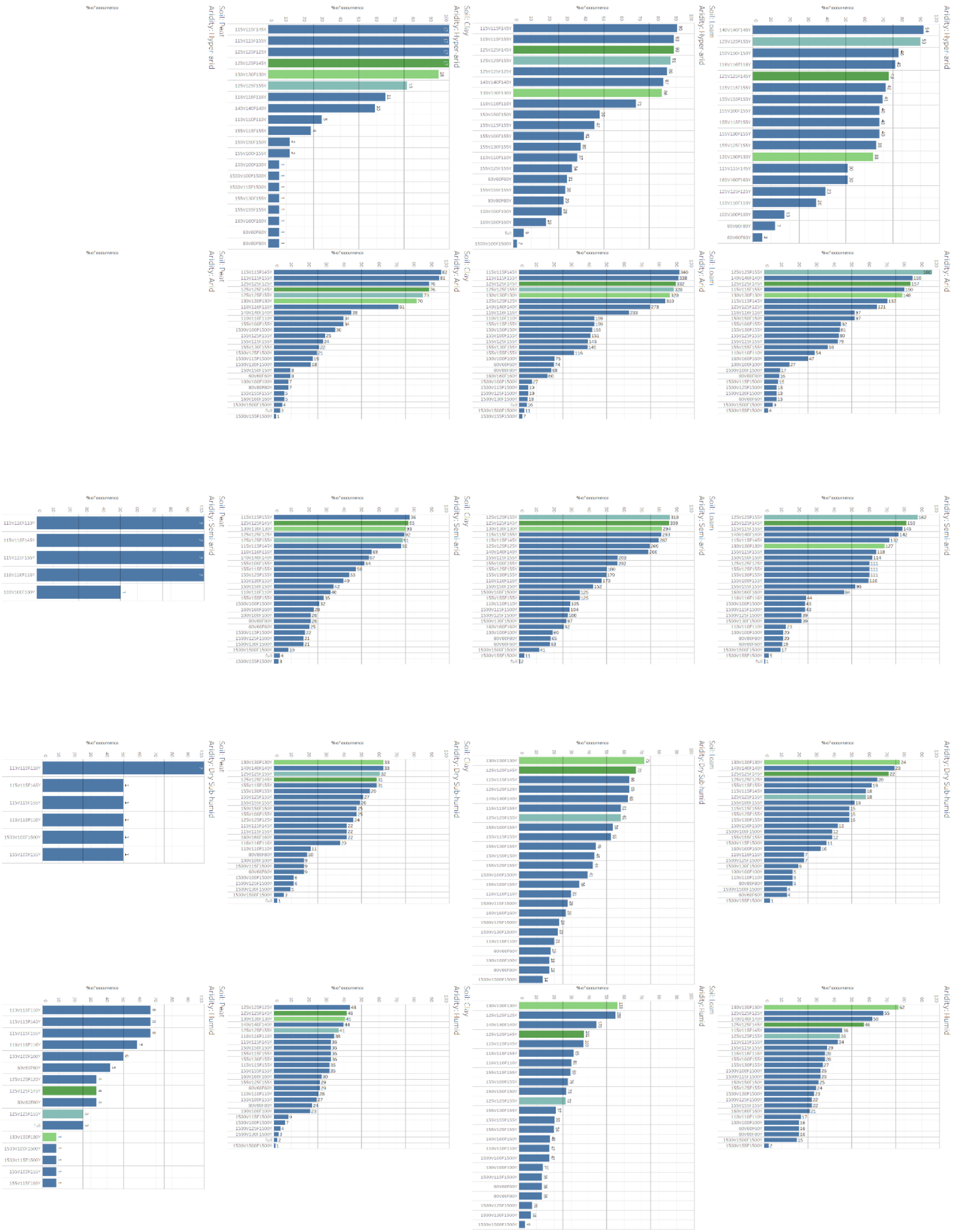

Figure 8: Histograms of supplemental strategies per soil-climate combination for wheat given in RAW (translatable into TAW by multiplying by 0.65)

Table 1: Selected supplemental irrigation timing strategies as a percentage of total available soil water depletion

Crop	Vegetative crop stage timing (% TAW)	Flowering crop stage timing (% TAW)	Yield formation crop stage timing (% TAW)	Timing strategies (%TAW per crop stage)
Maize	83	83	97	83V83F97Y
	90	83	90	90V83F90Y
	83	83	90	83V83F90Y
Sorghum	97	81	97	97V81F97Y
	92	92	92	92V92F92Y
	97	84	97	97V84F97Y
Cassava	90	75	90	90V75F90Y
	90	90	90	90V90F90Y
	75	90	90	75V90F90Y
Wheat	81	81	94	81V81F94Y
	85	85	85	85V85F85Y
	81	81	100	81V81F100Y

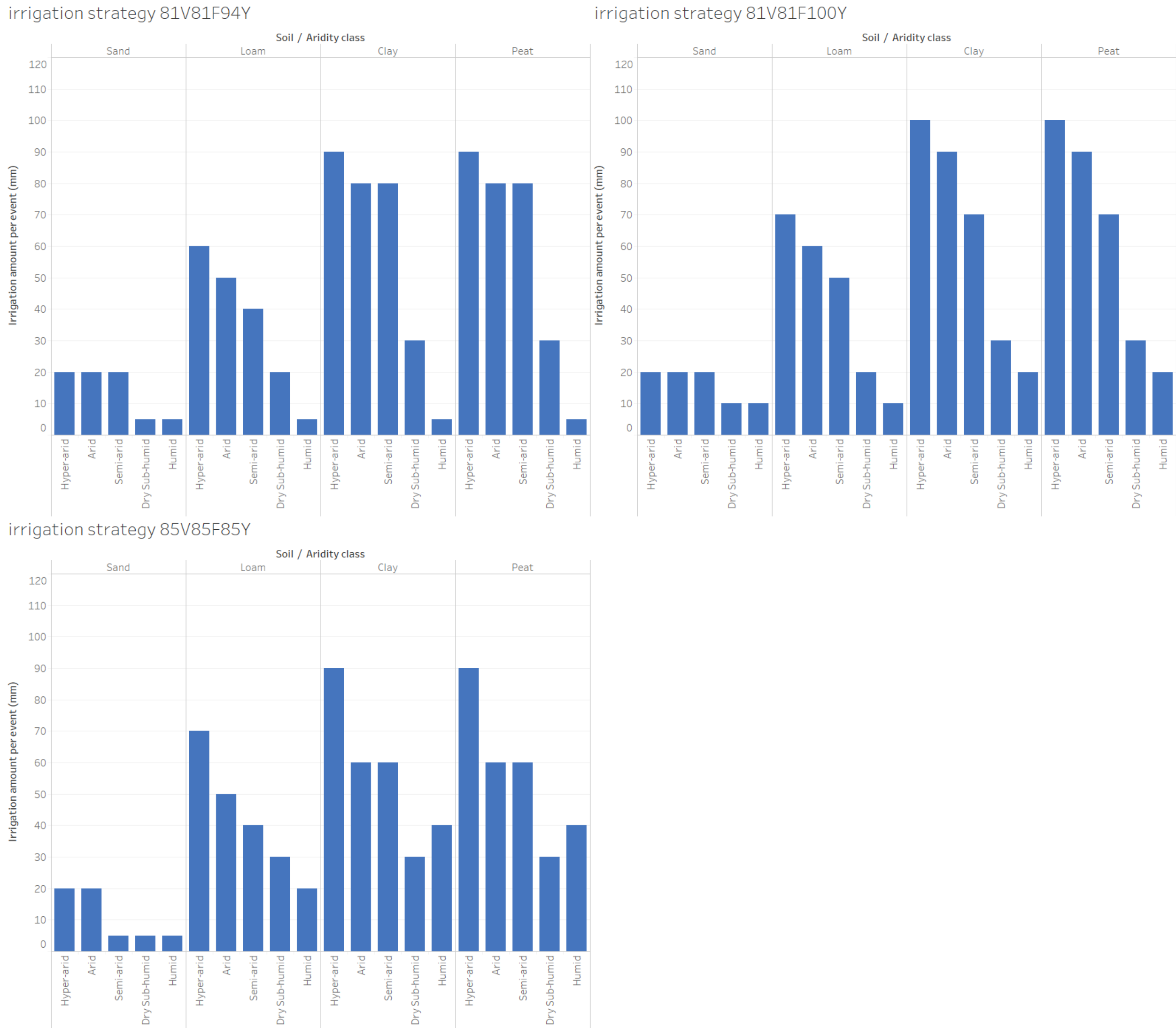

Figure 9: Irrigation amount per event (mm) for the three selected strategies of maize; based on values of SI figure 13-15

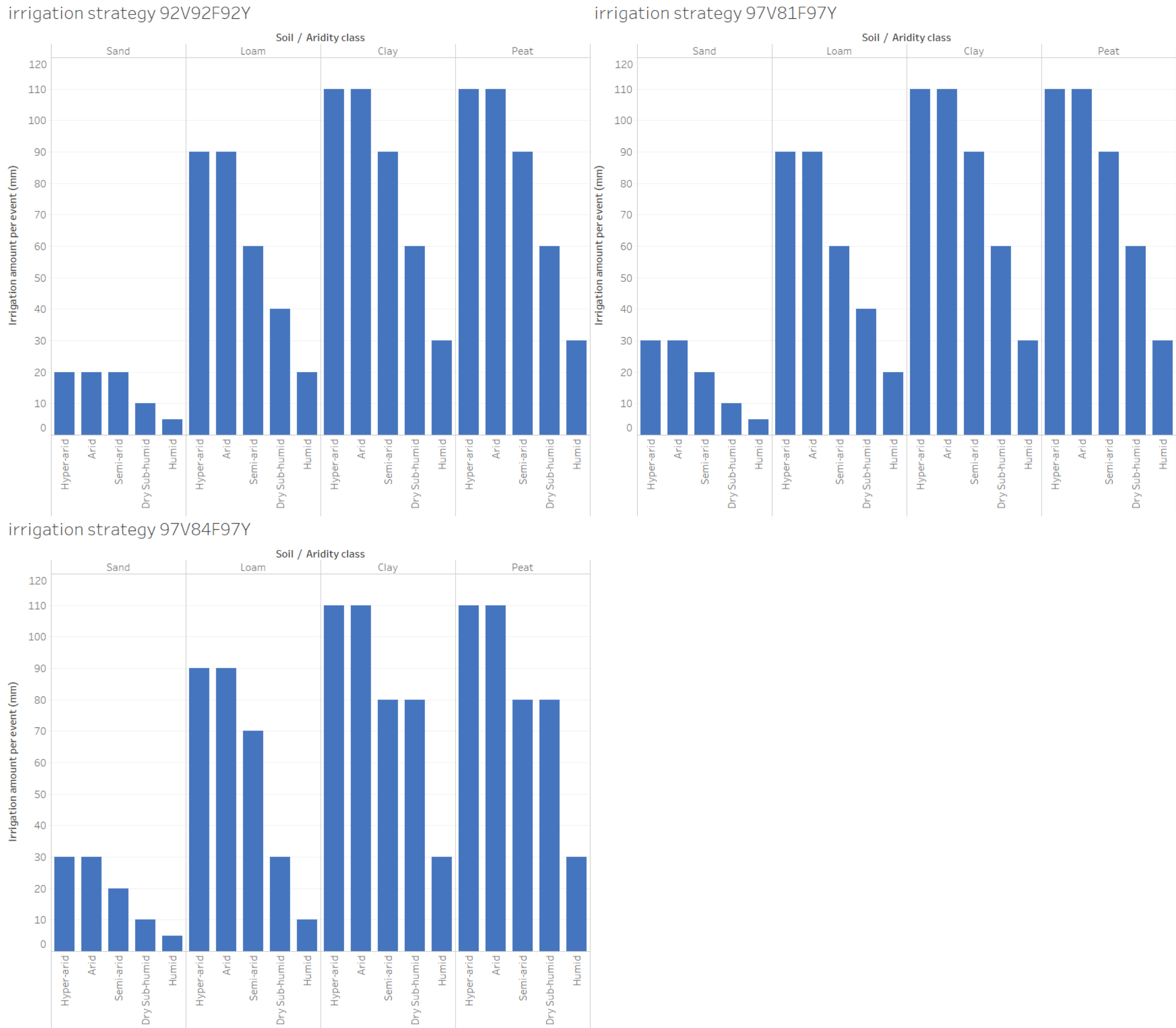

Figure 9: Irrigation amount per event (mm) for the three selected strategies of sorghum; based on values of SI figure 16-18

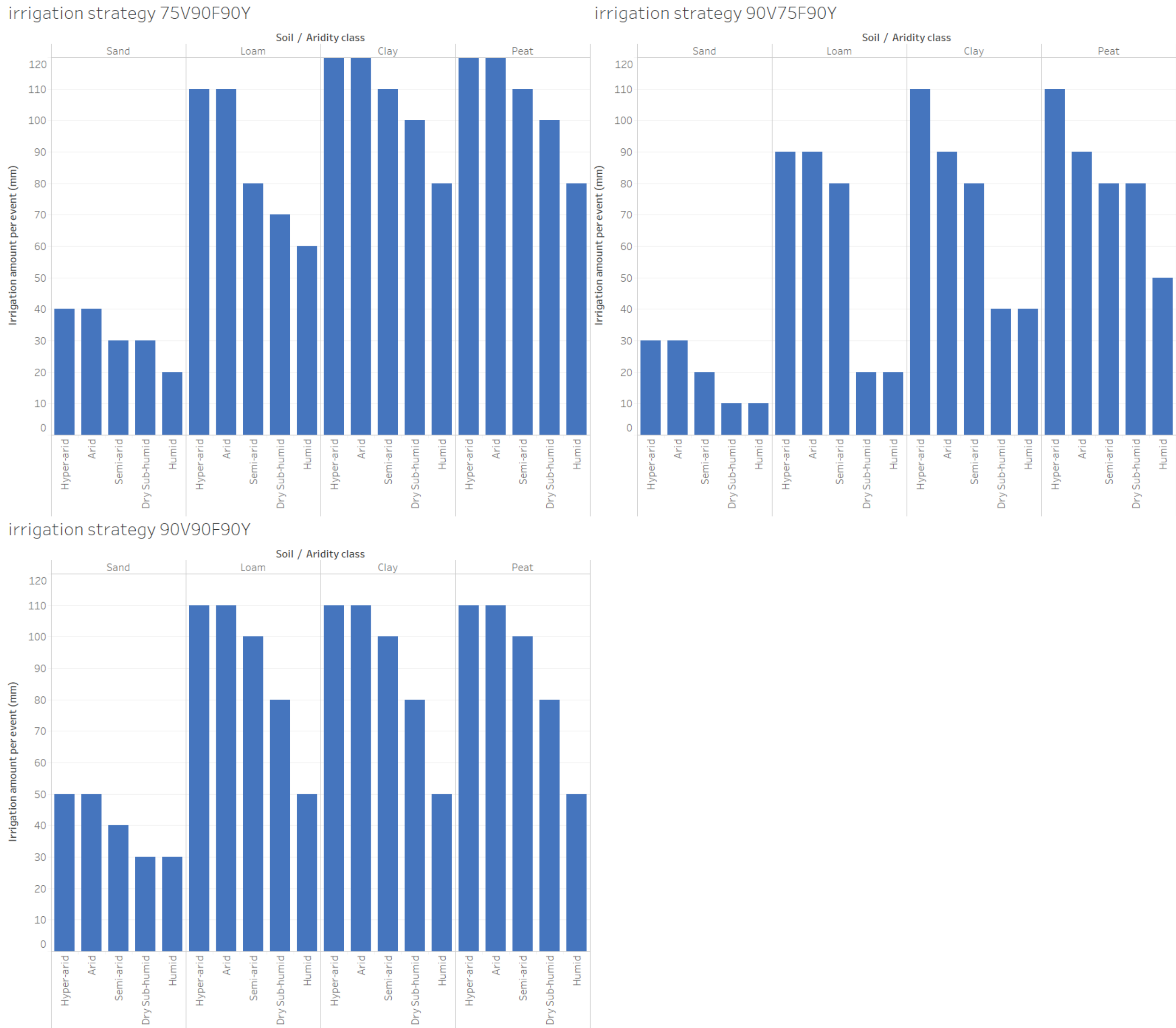

Figure 10: Irrigation amount per event (mm) for the three selected strategies of cassava; based on values of SI figures 19-21

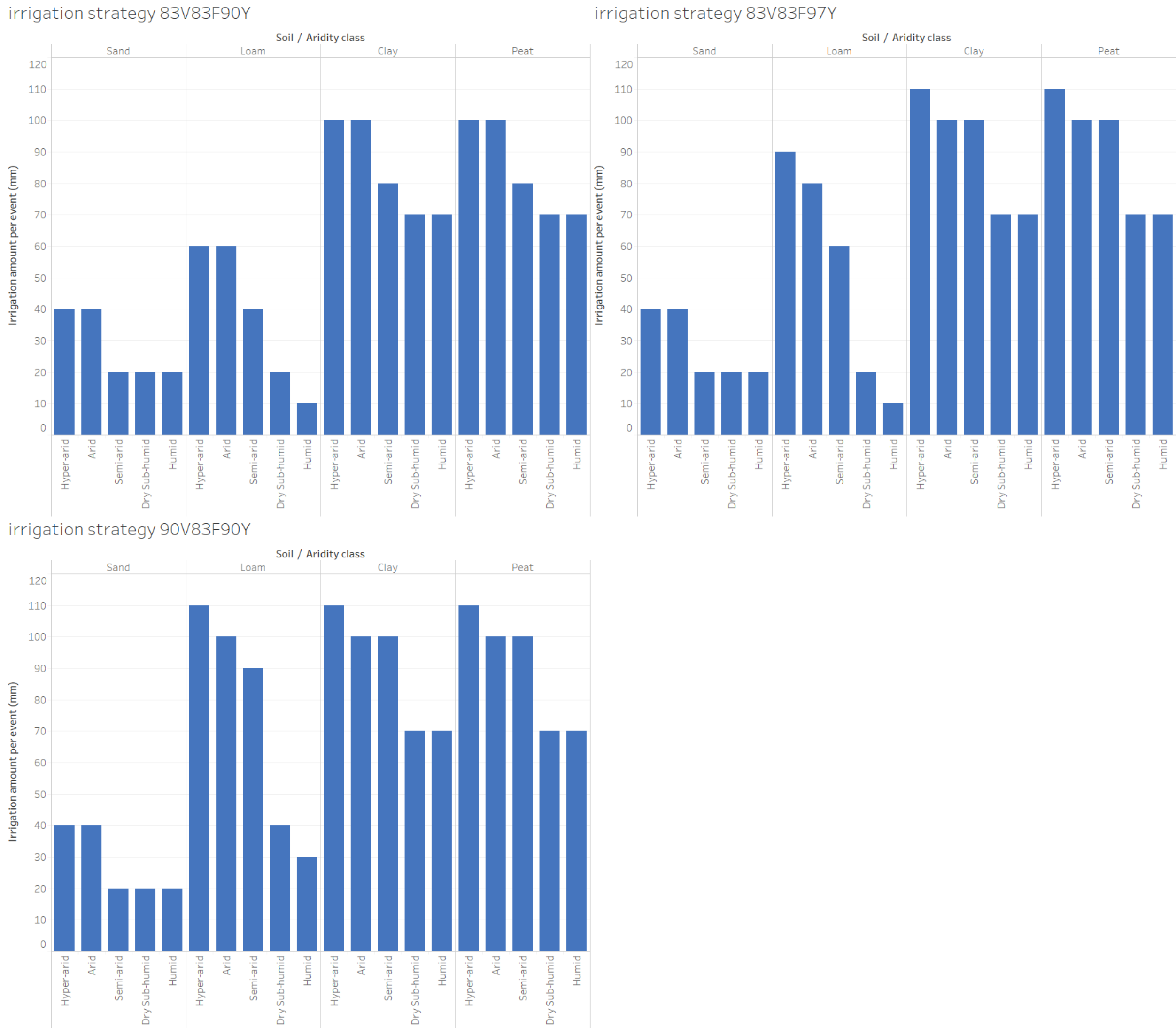

Figure 12: Irrigation amount per event (mm) for the three selected strategies of wheat; based on values of SI figure 22-24

Figure 13: Histogram of irrigation amounts per soil-climate combination for the supplemental irrigation strategy 83V83F90Y for maize

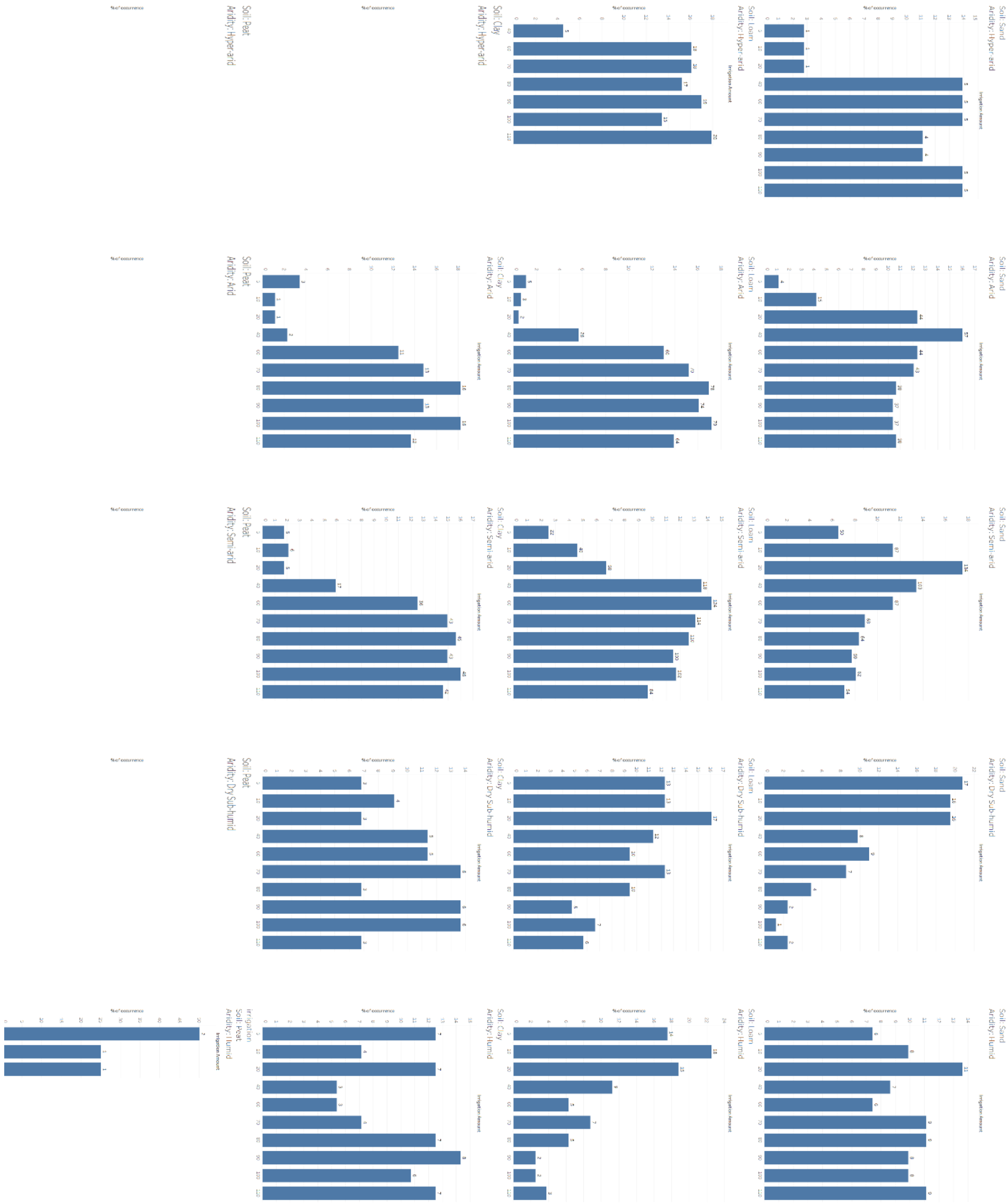

Figure 14: Histogram of irrigation amounts per soil-climate combination for the supplemental irrigation strategy 83V83F97Y for maize

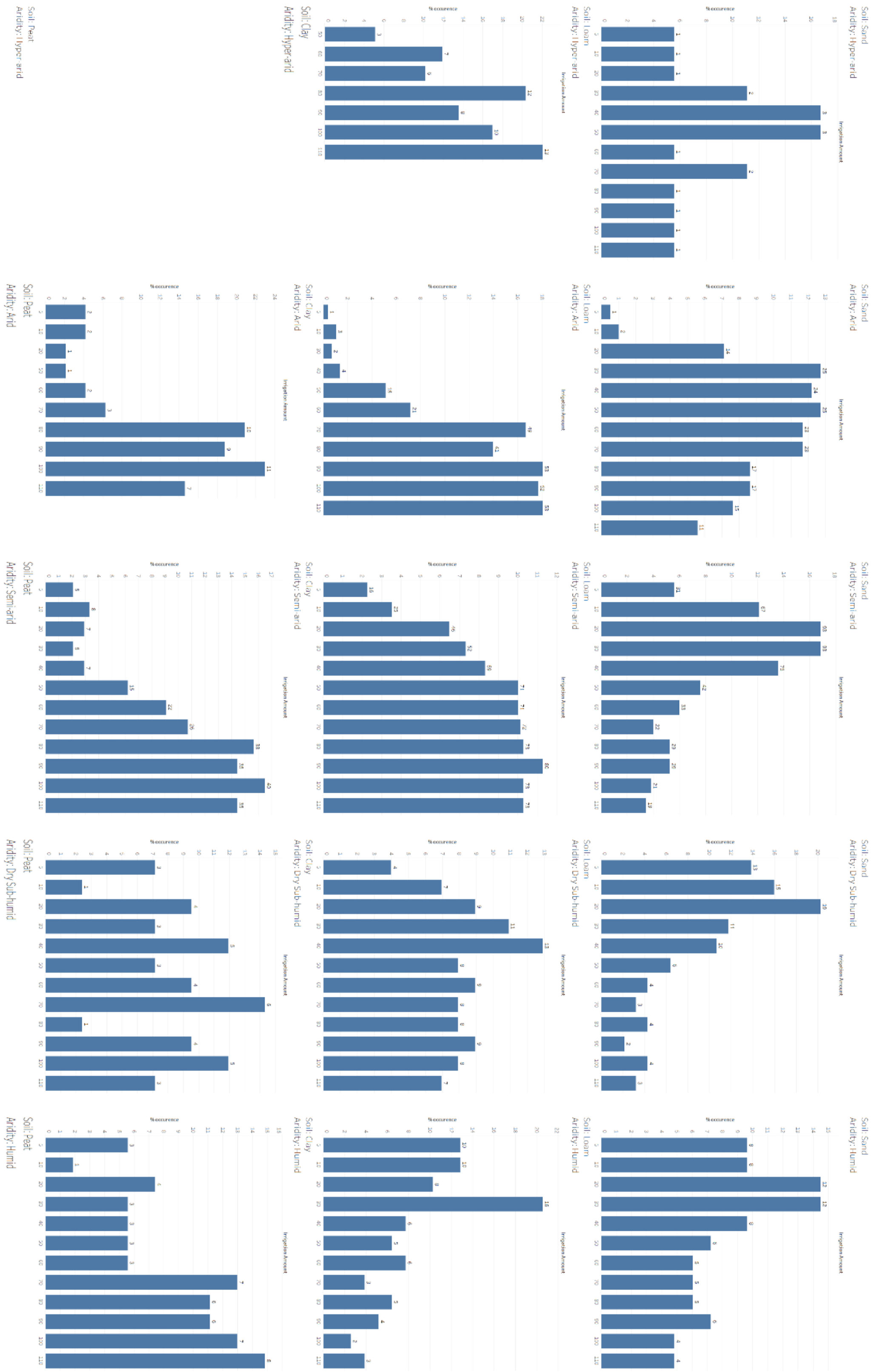

Figure 15: Histogram of irrigation amounts per soil-climate combination for the supplemental irrigation strategy 90V83F90Y for maize

Figure 16: Histogram of irrigation amounts per soil-climate combination for the supplemental irrigation strategy 92V92F92Y for sorghum

Figure 17: Histogram of irrigation amounts per soil-climate combination for the supplemental irrigation strategy 97V81F97Y for sorghum

Figure 18: Histogram of irrigation amounts per soil-climate combination for the supplemental irrigation strategy 97V84F97Y for sorghum

Figure 19: Histogram of irrigation amounts per soil-climate combination for the supplemental irrigation strategy 75V90F90Y for cassava

Figure 11: Histogram of irrigation amounts per soil-climate combination for the supplemental irrigation strategy 90V75F90Y for cassava

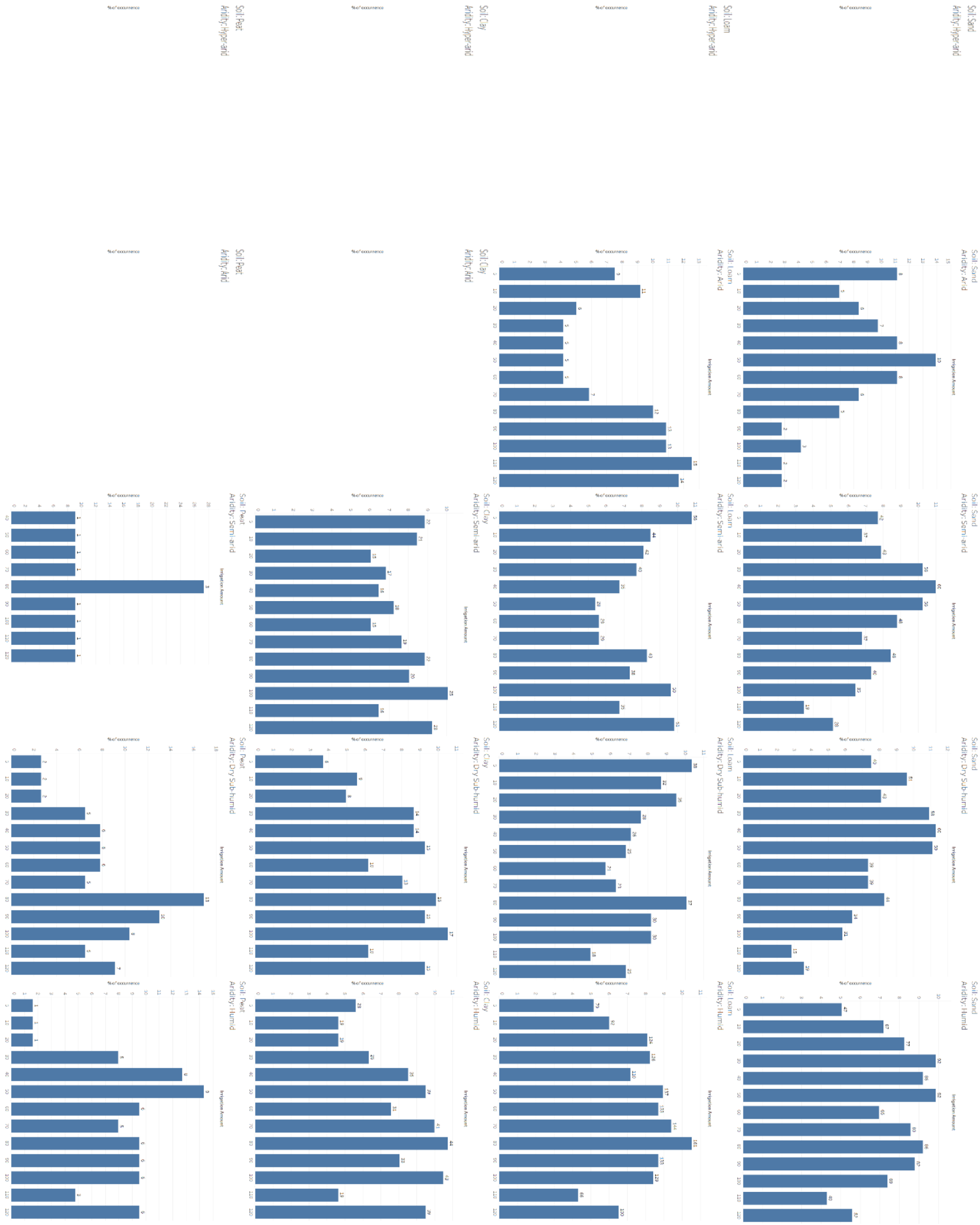

Figure 12: Histogram of irrigation amounts per soil-climate combination for the supplemental irrigation strategy 90V90F90Y for cassava

Figure 22: Histogram of irrigation amounts per soil-climate combination for the supplemental irrigation strategy 81V81F94Y for wheat

Figure 23: Histogram of irrigation amounts per soil-climate combination for the supplemental irrigation strategy 81V81F100Y for wheat

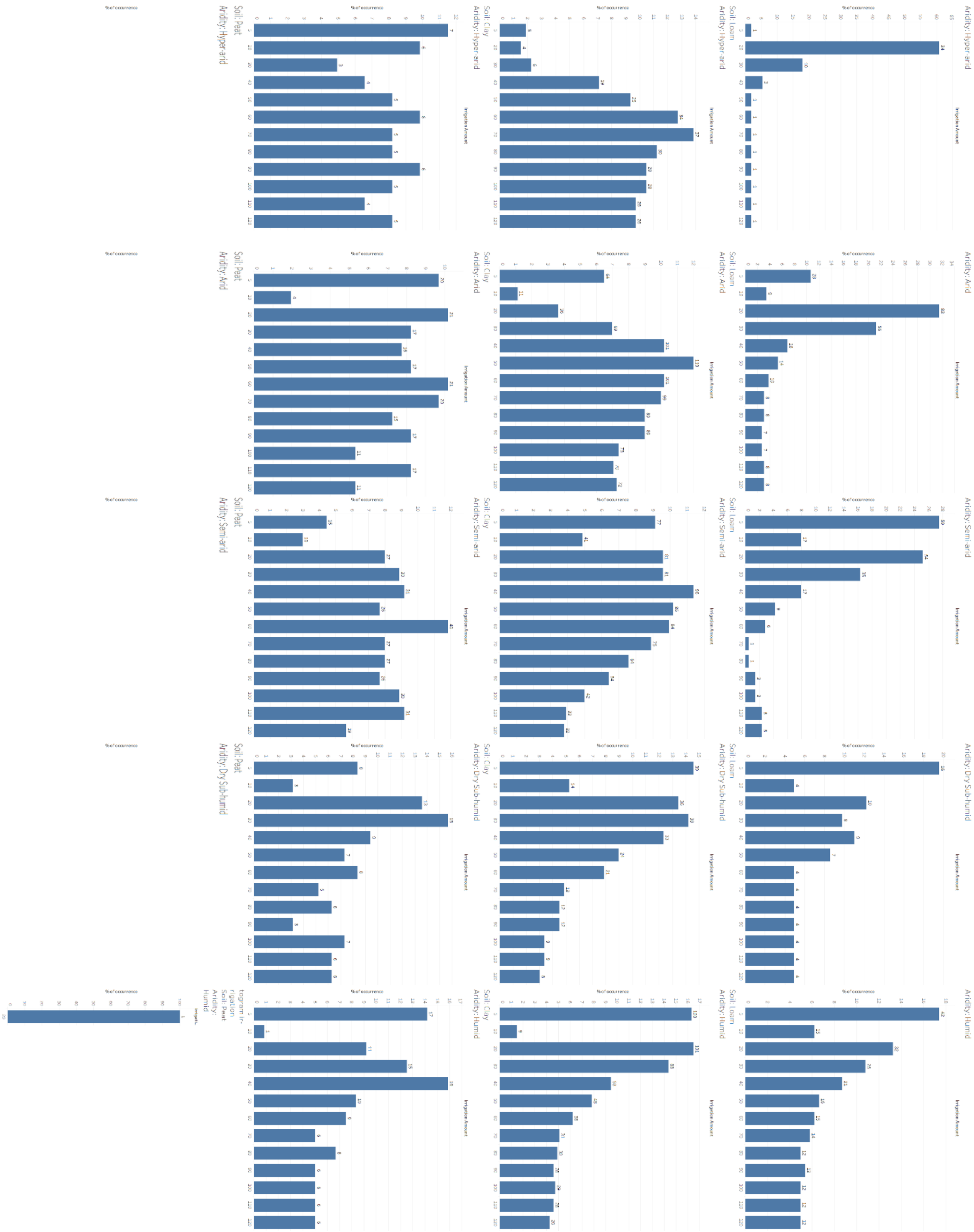

Figure 24: Histogram of irrigation amounts per soil-climate combination for the supplemental irrigation strategy 85V85F85Y for wheat

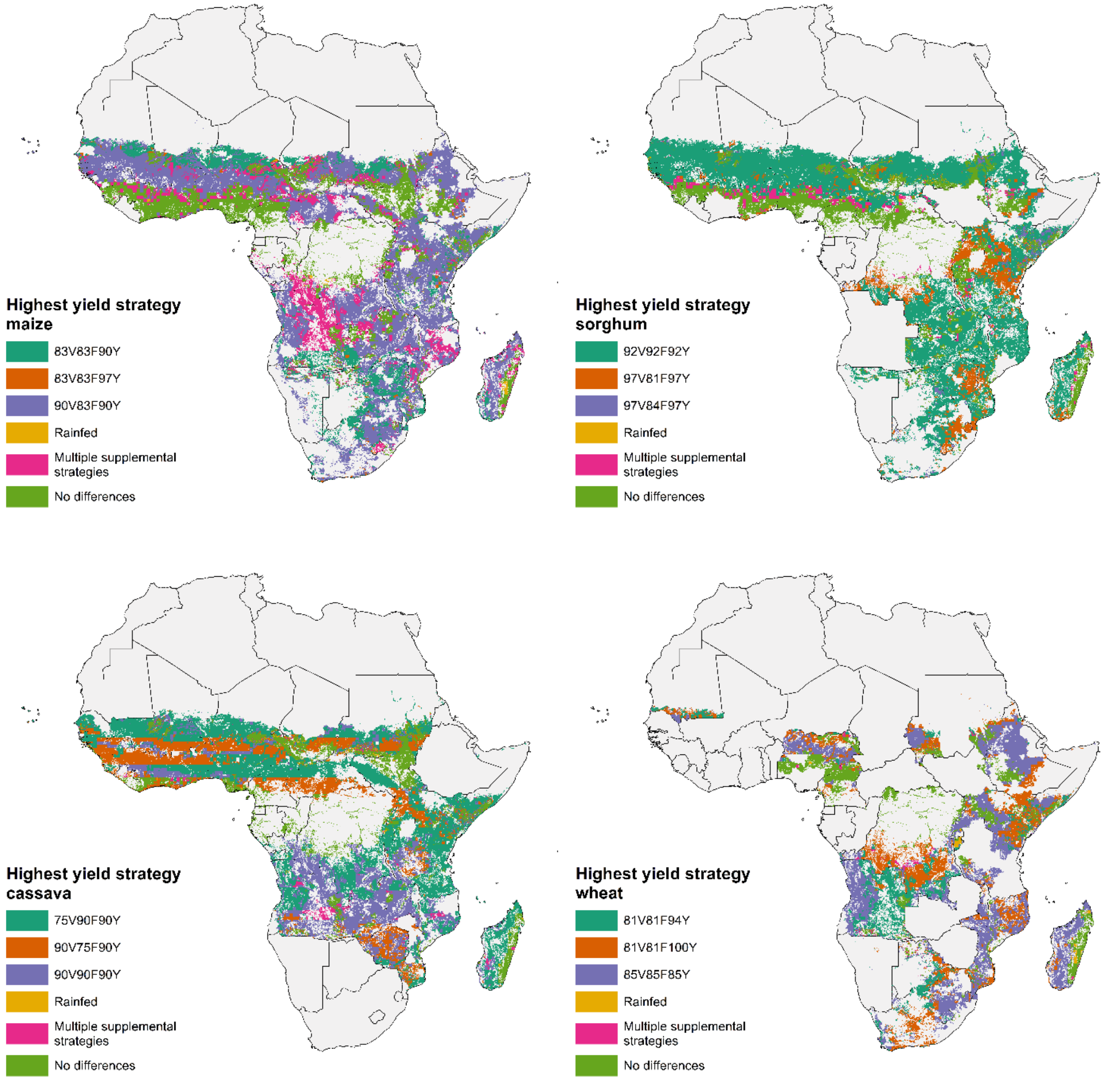

Figure 25: Strategy with highest average simulated yield, with equal yields the strategy with the lowest evapotranspiration of irrigation water was picked, per crop for the years 1986-2015 (at 5x5 arcminute resolution)

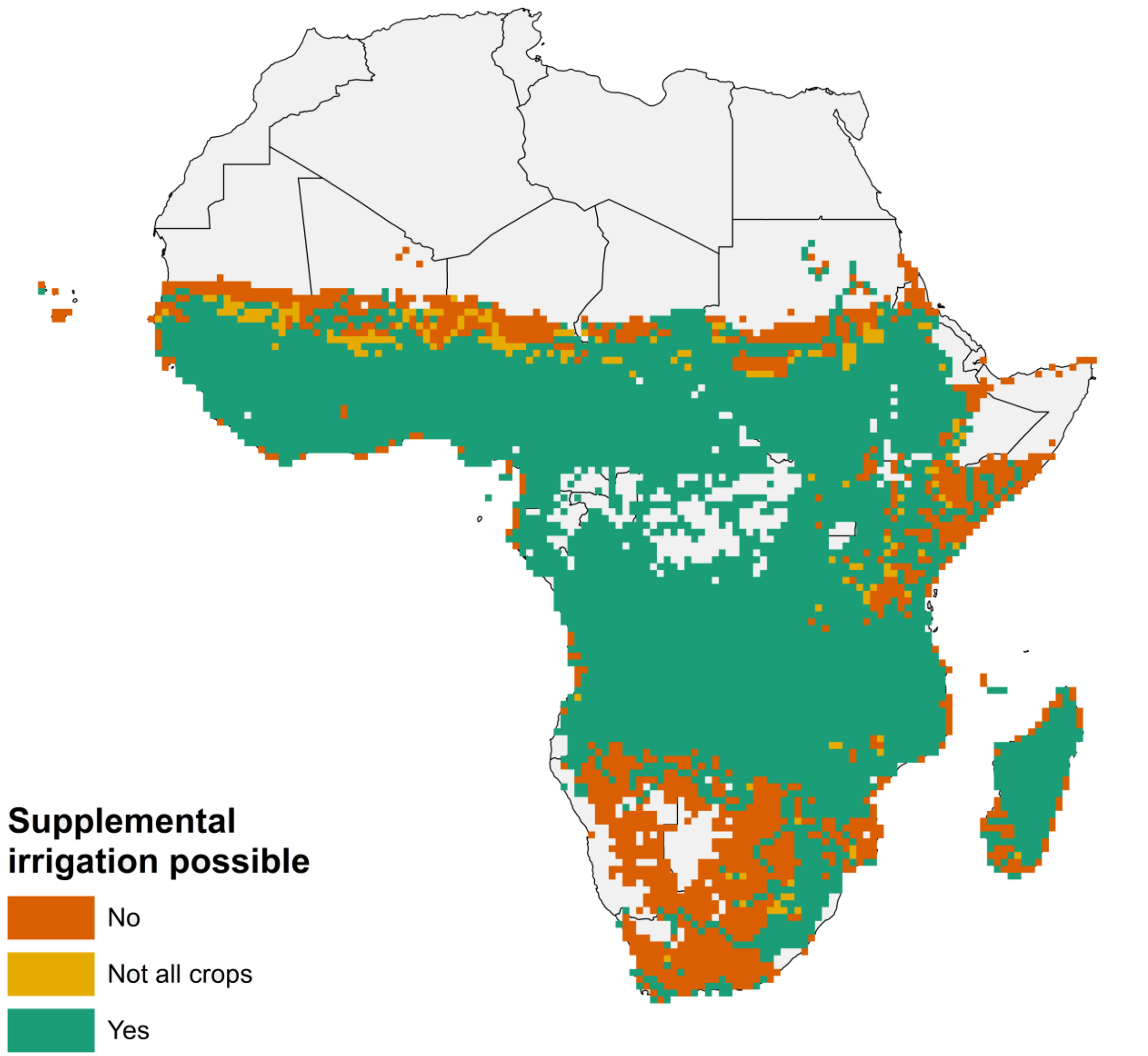

Figure 26: Locations were supplemental irrigation can be applied without being limited by water availability (at 5x5 arcminute resolution)

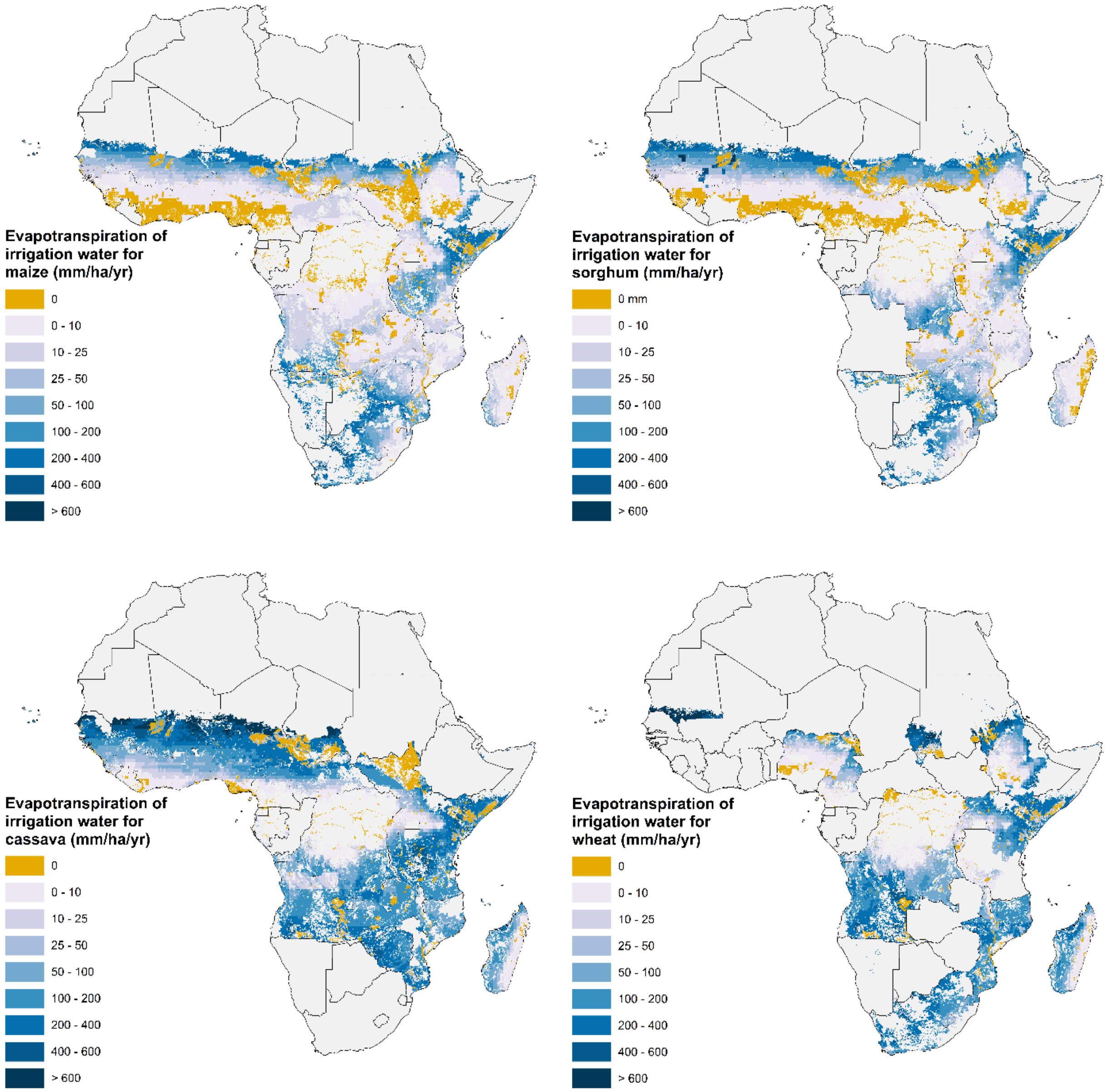

Figure 27: Distribution of average yearly evapotranspiration of irrigation water when currently rainfed areas get supplemental irrigation (mm/ha/yr) for sub-Saharan Africa between the years 1986-2015 (at 5x5 arcminute resolution)

Table 2: Average production figures per country. Split between rainfed production, supplemental irrigation production and supplemental irrigation production limited by water availability constraints

Country	Crop	Rainfed production (million tonne)	Supplemental irrigation production (million tonne)	Water scarcity limited supplemental irrigation production (million tonne)
Angola	Maize	12.3	26.2	25.9
	Sorghum	1.78	2.01	2.01
	Cassava	14.2	23.5	23.3
	Wheat	0	0	0
Benin	Maize	15.6	15.8	15.8
	Sorghum	1.53	1.66	1.66
	Cassava	5.22	7.84	7.83
	Wheat	0	0	0
Botswana	Maize	0.31	0.86	0.36
	Sorghum	0.14	0.54	0.18
	Cassava	0.00	0.00	0.00
	Wheat	0.00	0.00	0.00
Burkina Faso	Maize	9.19	12.6	11.7
	Sorghum	13.3	20.6	17.9
	Cassava	0	0	0
	Wheat	0.00	0.00	0.00
Burundi	Maize	1.81	1.82	1.82
	Sorghum	0.81	0.81	0.81
	Cassava	6.36	7.40	7.40
	Wheat	0	0	0
Cabo Verde	Maize	0	0.33	0
	Sorghum	0.00	0.00	0.00
	Cassava	0	0	0
	Wheat	0.00	0.00	0.00
Cameroon	Maize	15.1	15.8	15.8
	Sorghum	11.8	12.4	12.4
	Cassava	7.48	8.85	8.85
	Wheat	0	0	0
Central African Republic	Maize	1.05	1.34	1.34
	Sorghum	0.55	0.58	0.58
	Cassava	4.63	6.71	6.71
	Wheat	0.00	0.00	0.00
Chad	Maize	1.63	2.97	2.20
	Sorghum	9.06	13.3	12.2
	Cassava	0.23	0.66	0.61
	Wheat	0	0	0
Comoros	Maize	0	0	0
	Sorghum	0.00	0.00	0.00
	Cassava	0.33	0.37	0.35
	Wheat	0.00	0.00	0.00
Congo	Maize	0.00	0.00	0.00
	Sorghum	0.00	0.00	0.00
	Cassava	0.00	0.00	0.00
	Wheat	0.00	0.00	0.00
Côte d'Ivoire	Maize	6.21	6.23	6.23
	Sorghum	1.20	1.23	1.23
	Cassava	13.0	16.0	16.0
	Wheat	0.00	0.00	0.00
Democratic Republic of the Congo	Maize	29.8	32.5	32.5
	Sorghum	0	0	0
	Cassava	97.2	110	109
	Wheat	0	0	0

Country	Crop	Rainfed production (million tonne)	Supplemental irrigation production (million tonne)	Water scarcity limited supplemental irrigation production (million tonne)
Djibouti	Maize	0	0	0
	Sorghum	0.00	0.00	0.00
	Cassava	0.00	0.00	0.00
	Wheat	0.00	0.00	0.00
Equatorial Guinea	Maize	0.00	0.00	0.00
	Sorghum	0.00	0.00	0.00
	Cassava	0.64	0.64	0.64
	Wheat	0.00	0.00	0.00
Eritrea	Maize	0	0.20	0.10
	Sorghum	0.29	2.39	1.28
	Cassava	0.00	0.00	0.00
	Wheat	0	0.17	0
Ethiopia	Maize	21.6	26.5	25.1
	Sorghum	17.3	22.0	20.1
	Cassava	0.00	0.00	0.00
	Wheat	13.1	15.5	14.9
Gabon	Maize	0.36	0.37	0.37
	Sorghum	0.00	0.00	0.00
	Cassava	1.50	1.53	1.52
	Wheat	0.00	0.00	0.00
Gambia	Maize	0.32	0.52	0.51
	Sorghum	0.24	0.43	0.41
	Cassava	0	0	0
	Wheat	0.00	0.00	0.00
Ghana	Maize	16.9	17.1	17.1
	Sorghum	3.45	3.74	3.74
	Cassava	24.5	28.9	28.7
	Wheat	0.00	0.00	0.00
Guinea	Maize	8.69	8.90	8.90
	Sorghum	0.56	0.67	0.67
	Cassava	2.89	4.45	4.45
	Wheat	0.00	0.00	0.00
Guinea-Bissau	Maize	0.11	0.12	0.12
	Sorghum	0.27	0.33	0.32
	Cassava	0	0.12	0.12
	Wheat	0.00	0.00	0.00
Kenya	Maize	16.0	28.1	21.6
	Sorghum	1.65	3.02	2.28
	Cassava	0.61	1.08	0.85
	Wheat	0.49	0.96	0.74
Lesotho	Maize	0.97	1.26	1.25
	Sorghum	0.14	0.17	0.17
	Cassava	0.00	0.00	0.00
	Wheat	0	0	0
Liberia	Maize	0.00	0.00	0.00
	Sorghum	0.00	0.00	0.00
	Cassava	2.13	2.16	2.16
	Wheat	0.00	0.00	0.00
Madagascar	Maize	3.61	3.80	3.72
	Sorghum	0	0	0
	Cassava	9.12	10.4	10.2
	Wheat	0	0	0

Country	Crop	Rainfed production (million tonne)	Supplemental irrigation production (million tonne)	Water scarcity limited supplemental irrigation production (million tonne)
Malawi	Maize	23.8	25.7	25.5
	Sorghum	1.19	1.30	1.28
	Cassava	2.52	4.84	4.45
	Wheat	0	0	0
Mali	Maize	9.64	12.4	12.0
	Sorghum	10.5	22.3	18.9
	Cassava	0	0	0
	Wheat	0	0	0
Mauritania	Maize	0	0.23	0
	Sorghum	0.28	1.94	0.93
	Cassava	0.00	0.00	0.00
	Wheat	0	0	0
Mauritius	Maize	0.00	0.00	0.00
	Sorghum	0.00	0.00	0.00
	Cassava	0.00	0.00	0.00
	Wheat	0.00	0.00	0.00
Mozambique	Maize	23.1	25.5	24.7
	Sorghum	4.87	5.47	5.36
	Cassava	12.9	22.8	21.3
	Wheat	0	0.13	0.12
Namibia	Maize	0.18	0.45	0.24
	Sorghum	0.25	0.40	0.35
	Cassava	0.00	0.00	0.00
	Wheat	0	0	0
Niger	Maize	0	0.23	0.10
	Sorghum	14.5	39.6	17.1
	Cassava	0	0	0
	Wheat	0.00	0.00	0.00
Nigeria	Maize	89.4	97.0	95.0
	Sorghum	63.7	75.6	72.8
	Cassava	138	186	186
	Wheat	0.30	0.36	0.34
Rwanda	Maize	3.65	3.67	3.67
	Sorghum	1.79	1.79	1.79
	Cassava	1.58	1.75	1.75
	Wheat	0	0	0
Sao Tome and Principe	Maize	0	0	0
	Sorghum	0.00	0.00	0.00
	Cassava	0	0	0
	Wheat	0.00	0.00	0.00
Senegal	Maize	1.44	2.27	2.20
	Sorghum	1.03	1.91	1.80
	Cassava	0	0.72	0.23
	Wheat	0.00	0.00	0.00
Sierra Leone	Maize	0.46	0.46	0.46
	Sorghum	0.53	0.53	0.53
	Cassava	10.4	11.5	11.5
	Wheat	0.00	0.00	0.00
Somalia	Maize	0.13	0.43	0.19
	Sorghum	0.74	2.26	1.05
	Cassava	0	0.14	0
	Wheat	0	0	0

Country	Crop	Rainfed production (million tonne)	Supplemental irrigation production (million tonne)	Water scarcity limited supplemental irrigation production (million tonne)
South Africa	Maize	18.4	30.1	20.9
	Sorghum	0.40	0.74	0.52
	Cassava	0.00	0.00	0.00
	Wheat	0.94	2.55	1.48
South Sudan	Maize	1.94	2.13	2.09
	Sorghum	3.08	4.51	3.59
	Cassava	0.68	1.83	1.80
	Wheat	0.00	0.00	0.00
Sudan	Maize	0	0	0
	Sorghum	19.5	49.0	33.5
	Cassava	0.00	0.00	0.00
	Wheat	0	0.11	0
Swaziland	Maize	1.02	1.08	1.07
	Sorghum	0	0	0
	Cassava	0.00	0.00	0.00
	Wheat	0	0	0
Togo	Maize	11.0	11.0	11.0
	Sorghum	4.50	4.72	4.72
	Cassava	5.71	7.42	7.26
	Wheat	0.00	0.00	0.00
Uganda	Maize	15.7	17.0	16.7
	Sorghum	5.43	5.86	5.79
	Cassava	17.9	19.4	19.2
	Wheat	0	0.11	0.11
United Republic of Tanzania	Maize	33.5	49.7	45.2
	Sorghum	10.4	11.8	11.3
	Cassava	14.3	21.9	20.6
	Wheat	0.53	0.68	0.63
Zambia	Maize	15.1	16.1	16.1
	Sorghum	0.26	0.29	0.29
	Cassava	1.99	4.14	4.13
	Wheat	0	0	0
Zimbabwe	Maize	13.9	17.7	16.7
	Sorghum	1.59	2.93	2.38
	Cassava	0.19	0.84	0.65
	Wheat	0	0	0
Sub-Saharan Africa	Maize	424	517	486
	Sorghum	209	319	262
	Cassava	397	514	508
	Wheat	15.8	20.9	18.8