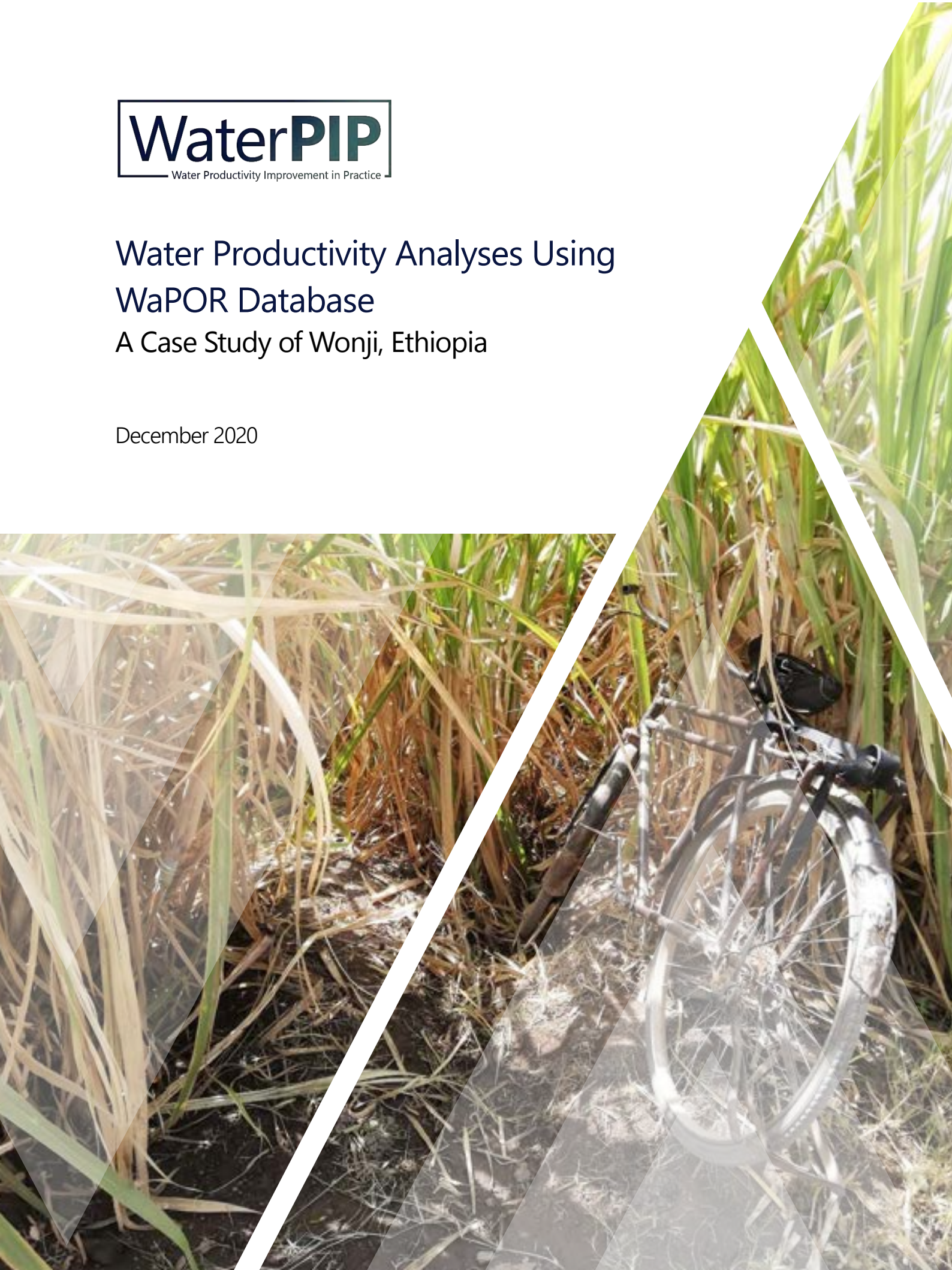
WaterPIP
Water Productivity Improvement in Practice

Water Productivity Analyses Using WaPOR Database

A Case Study of Wonji, Ethiopia

December 2020



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Prepared by MetaMeta

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Acronyms

A	adequacy
AOT	above ground over total biomass
AwBA	Awash Basin Authority
BDA	Basin Development Agency
CV	coefficients of variation
EEPCO	Ethiopian Electric Power Corporation
EOS	end of season
ESC	Ethiopian Sugar Corporation
fAPAR	fraction of absorbed Photosynthetically Active Radiation
HVA	Handlers Vereeniging Amsterdam
LCC	land cover classification
L1, L2 and L3	WaPOR data with a spatial resolution of 250m (L1), 100m (L2) and 30m (L3)
LUE	light use efficiency
NOAA	National Oceanic and Atmospheric Administration
NPP	net primary production
RS	remote sensing
SOS	start of season
USD	United States Dollar
WaPOR	FAO portal to monitor Water Productivity through Open access of remotely sensed derived data

List of symbols

B	above-ground biomass
ET_a	actual evapotranspiration
ET_{ref}	reference evapotranspiration
f_c	crop factor
H_i	harvest index

m_c	moisture content in fresh biomass
P	precipitation
T_a	transpiration
WP_b	biomass water productivity based on actual evapotranspiration
$WP_{b(T)}$	biomass water productivity based on transpiration
$WP_{b(T/ETref)}$	biomass water productivity based on normalized transpiration
ΔET_a	change in water consumption

1 Introduction

1.1 Sugar cane production in Ethiopia

Sugarcane has been cultivated in Ethiopia since the 16th century; always within the premises of smallholder farmers at a very modest scale. Commercial production only started up in Ethiopia in the 1950s when the Dutch HVA ((Handlers Vereeniging Amsterdam) company entered the sector as a foreign share holder by establishing a sugarcane irrigation scheme in Wonji. The factory itself was a reconstruction of one of the factories of HVA in Indonesia, which was removed after their independence. Soon afterwards, in 1962, another sugar factory was built (Shoa Sugar Factory) which later merged with the first becoming the Wonji-Shoa Sugar Factory. In 1965 another sugar factory was established, becoming a share company between HVA and the Ethiopian government in Metehara. Following the fall of the emperor's regime, both sugar factories were administered under the ownership of the government in 1974 during which the Ethiopian Sugar Corporation (ESC) was also established by the Ministry of Industry.

For a long period both factories and estates, which covered approximately 15,000 hectares, were the only domestic producers of sugar (Table 1-1). Initially domestic demand was low which allowed for export in exchange for valuable foreign currency. The export of sugarcane however decreased considerably in Ethiopia with a turning point around 2006 when import started to exceed export. As imports overran exports, the government decided to step in 2010. To meet the growing demand and step up its efforts, as set out in the first Growth and Transformation Plan, a revamped sugar corporation was therefore established. Highly ambitious goals were set for the sugar development projects to the effect of increasing the sugarcane area six-fold and sugar production more than three-fold. The number of factories also increased (see Figure 1-1). The ambitions of the government are still far from being achieved. With the lack of technical and in particular financial resources, the developments are stalling and the existing schemes and factories are bearing the brunt.

Table 1-1: Comparison of sugar development in 1991 and 2019 (ESC, 2019).

Development	1991	2019
Number of sugar factories	2 (Wonji-Shoa and Metehara)	8 (Wonji-Shoa, Metehara, Finchaa, Kessem, Tendaho, Arjo-Dediessa, Omo-Kuraz Two and Omo-Kuraz Three)
Number of sugar factories under construction	1 (Finchaa)	5 (Omo-Kuraz One, Omo-Kuraz Five, Tana Beles One, Tana Beles Two and Welkayit)
Annual Sugar Production	149,658 tons	400,000 tons (2017/2018) (USDA Foreign Agricultural Service, 2019)
Land covered with sugarcane	15,501 ha	102,741 ha
Land covered with sugarcane outgrowers	1,020 ha	17,247 ha
Average sugar yield per ha	9.06 t/ha	3.33 t/ha

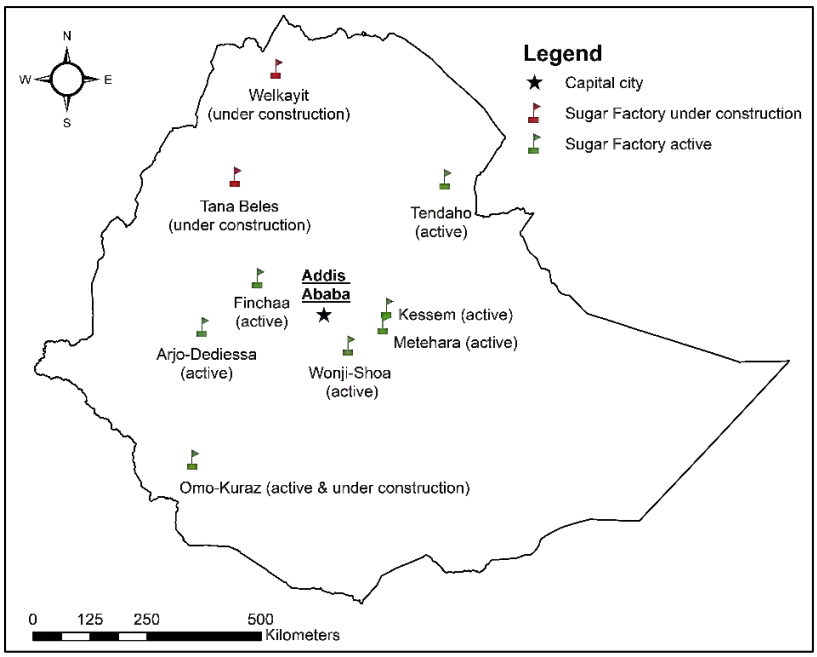


Figure 1-1: Overview of Sugar Factories in Ethiopia

Ethiopia's potential for further developing its sugar cane sector is enormous with near-optimal soils and climates. However, of the irrigable land in Ethiopia suitable for sugar cane development, currently only a mere 2.5% has actually been developed. Considering this, the official announcement for the privatisation of sugar (cane) production in June of 2018, could actually lead to an influx of investors who would want to capture this remaining potential.

However eager the government is to provide for domestic demand and to become an exporting nation again, it is also aware that the developments must go hand in hand with appropriate water resources planning and management. In the Awash basin, the Basin Development Agency has been established to oversee current water usage and future development. Sugar estates such as Wonji have been trialling new methods of irrigation, and several Dutch supported projects are being implemented to support '*Optimising water use*' and '*Water Pricing for Inclusive and Sustainable Growth*'. All these efforts have however not yet been able to capture at scale what the current land productivity and water consumption is in sugar cane areas, nor what alternate methods of irrigation could imply for water allocation.

This study therefore aims to set a standard (or protocol) for the assessment of irrigated sugarcane by means of determining the performance of land and water productivity of the oldest estate, Wonji-Shoa. The standards are meant to facilitate the study of other irrigated (sugarcane) areas in Ethiopia; the outcomes are meant to support irrigation (re)development and improved land practices in the study site. Finally, the overall aim is to contribute to a sustainable future of sugar cane production in Ethiopia.

1.2 Study Area

Four of the current operating sugar factories in Ethiopia (see Figure 1-1) are dependent on the Awash river for their irrigation water in the dry season. From upstream to downstream these are: Wonji-Shoa, Metehara, Kessem and Tendaho. This study focuses on the Wonji-Shoa Sugar Factory and associated sugar cane areas. Wonji is located in the Oromia Region about eighty kilometres south-east of Addis Ababa and close to the city of Adama, between 39.21° - 39.40° longitude and 8.33° - 8.62° latitude. The main cultivated crop within the area irrigated by the 'Wonji schemes' is sugarcane, however there are also outgrowers that produce vegetables crops. In this study, only sugarcane irrigation schemes are analysed including outgrowers with sugarcane. An overview of the Wonji Sugar Estate is given in Figure 1-2.

The first regular sugarcane production of Wonji was in 1954 using surface irrigation (Girma & Awulachew, 2007). This oldest part of the irrigation scheme, Wonji main, was established by the Dutch company HVA and is still in use to date. Wonji estate started a comprehensive expansion from 2009 onwards, in which new outgrowers schemes were established for the production of sugarcane using different irrigation methods than those at Wonji main. The newly established sub-schemes are Dodota (with centre pivots and sprinkler irrigation), Welenchiti (with hydroflume irrigation), Wake Tio (with sprinkler irrigation) and Ulaga (with sprinkler irrigation). Table 1-2 below summarise the area, year of establishment and irrigation type per sub-scheme, while section 1.3 details the different irrigation methods and provides a map. The development of these new areas was severely hampered due to financial constraints of the governing ESC; at the time (2010), the ESC had its hands full and wallets empty with the ambitious national development projects set in the Growth and Transformation Plan (2010-2015). Budgets were reallocated for the new developments which drew funds away from the expansion and rehabilitation of the existing schemes within Wonji. As direct result of this funding reallocation running costs such as those for fertilisers and herbicides could not be covered in Wonji-Shoa plantation.

There are three main reservoirs in the Awash river that store water for irrigation during the dry season. Lake Koka (visible in Figure 1-2) stores water for the irrigation schemes of Wonji and Metehara. The reservoir Kessem, further downstream, stores water for the irrigation scheme of Kessem and the reservoir Tendaho stores water for the irrigation scheme of Tendaho.

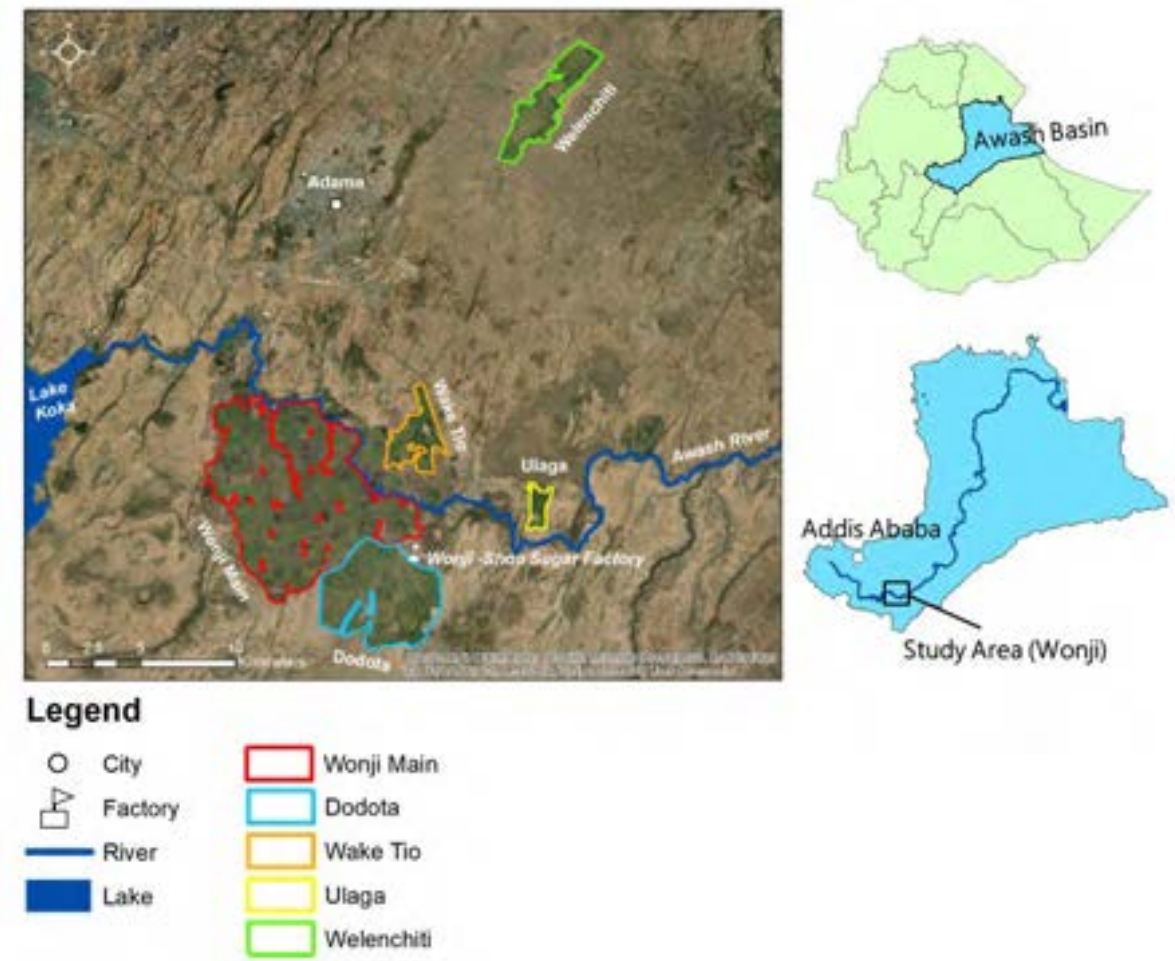


Figure 1-2: Location and overview of Wonji Irrigation Schemes

Table 1-2: Characteristics of Wonji Irrigation Schemes

Sub-Schemes	Establishment	Area size	Main crop	Irrigation type
Wonji Main	1954	6,800 ha	Sugarcane	Surface (furrow)
Dodota	2012-2013	2,600 ha	Sugarcane	Center pivots and sprinkler
Wake Tio	2008-2009	750 ha	Sugarcane	Sprinkler
Welenchiti	2014-2015	1,050 ha	Sugarcane	Surface (hydroflume)
Ulaga	2013	250 ha	Sugarcane	Sprinkler

1.2.1 Climate

The climate at Wonji Estate can be classified, according to Köppen climate classification as tropical savanna climate, with a distinct rainy season in summer and a dry winter. For its allocation planning, the Awash Basin Development Authority also considers the rainy season to take place from July – October. Determined using CHIRPS derived data from the WaPOR[1] portal, Figure 1-3 shows the average monthly precipitation in Wonji of 2009 to 2019. It shows that July, August and September have the highest monthly precipitation and amounting to 673 mm/month. Average annual temperatures in Wonji gathered from National Oceanic and Atmospheric Administration (NOAA) show relatively stable minimum and maximum temperature in this region, provided in Figure 1-4.

Figure 1-3: Average Precipitation in Wonji 2009-2019 (from WaPOR using CHIRPS, 2019)

Figure 1-4: Average monthly minimum and maximum Temperature in Adama, Ethiopia (Source: NOAA)

1.2.2 Soils

The predominant soil types in the area of Wonji-Shoa sugarcane plantation are described as Fluvisols, Andosols and Leptosols according to FAO soil classification (FAO, 1998). They comprise of a complex of grey cracking clays in the topographic depressions and semi-arid brown soils. On the basis of texture they

[1] https://wapor.apps.fao.org/home/WAPOR_2/1

are categorized into 'light' (coarse textured) soils and 'heavy' soils (clayey black types) (Ruffeis et al., 2008). Spatial distribution, provided by the Africa Soil Atlas (Jones et al. 2013) confirms the predominant soil in Wonji main, Dodota and Wake Tio to be Silandic Andosols (clayey black types), and in Ulaga and Welenchiti, Eutric Leptosols and Haplic Phaeozems, respectively. Haplic Phaeozems would indicate a higher level of organic matter (mollic horizon) and presence of coarser material. The Andosols, common in volcanic rift areas in Ethiopia are fertile soils, that have good water storage capacity (FAO, 2001). The strong phosphate fixation of particularly Silandic Andosols (Gonzalez-Rodriguez & Fernandez-Marcos, 2018) is also a problem. Ameliorative measures to reduce this issue (caused by active Aluminium decreasing the soil pH and immobilizing phosphates) include application of lime, silica, organic material and `phosphate' fertilizer (FAO, 2001). Hence, whereas the soils may seem suitable for crop production, the agronomic and water management practices can strongly affect their productivity. In an interview in June 2020 the irrigation manager of Wonji mentions that Wonji main sub-irrigation scheme (the State owned part of Wonji plantation) has soils with low fertility, requiring a higher and differentiated application of fertiliser, whereas the soils in Welenchiti are considered fertile (Girma, 2020).

1.3 Wonji Estate

1.3.1 Irrigation application methods at Wonji

The analysed sugarcane schemes in Wonji have four different irrigation methods. Surface (furrow), Centre Pivot, Sprinkler and Surface (hydroflume). Every scheme has a single, specific, irrigation method except for Dodota, where both sprinkler irrigation and centre pivot irrigation are applied. Figure 1-5 shows the irrigation type per scheme.

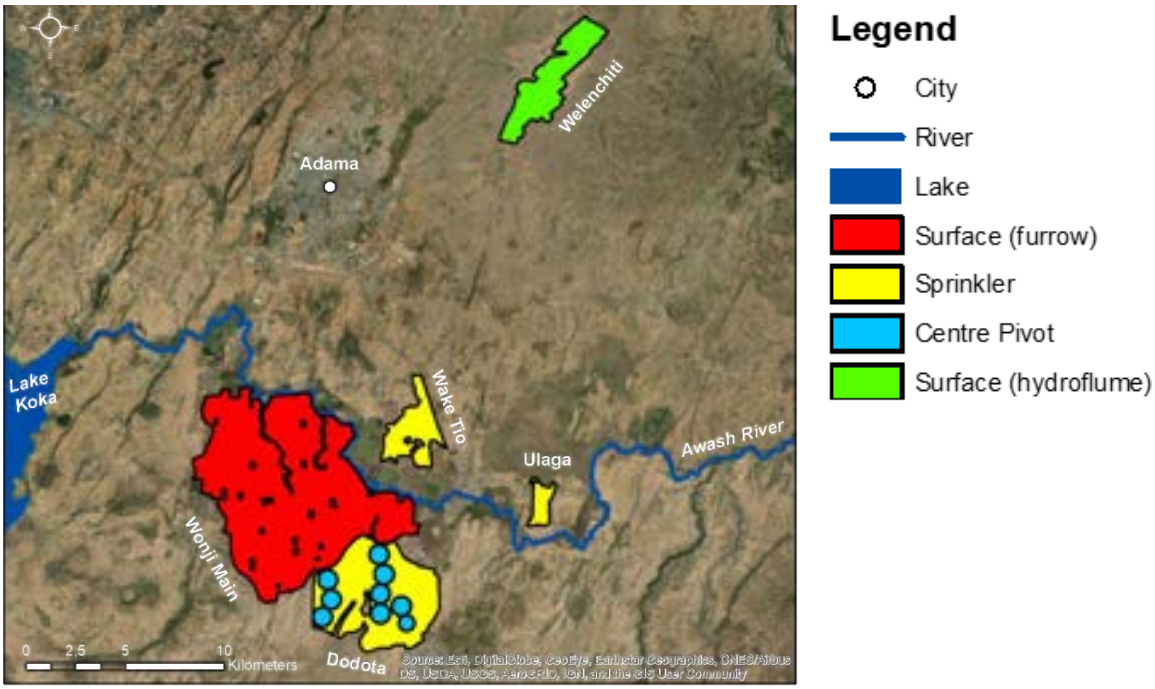


Figure 1-5: Irrigation methods in Wonji.

As perceived by the Wonji estate, the application of water in the Wonji main sub-scheme is found to be more difficult (or more difficult to manage) when compared with the application methods in Dodota (center pivot) and Welenchiti (hydroflume) (Girma, 2020). The 'furrow irrigation method' is referred to as resembling field 'flood like type irrigation application'.

The different irrigation methods (i.e. the different sub-schemes) come with varying costs. The costs for outgrower farmers (i.e. field to factory) for producing sugarcane is, on average, 60 Ethiopian birr per quintal

of sugarcane, or 18.50 USD/ton. The costs for producing sugar from factory run fields include transportation, system irrigation and labour. Labour can be divided into permanent workers, seasonal workers and day labourers. Permanent employees are guards, operational managers, pump managers, mechanics and irrigation workers. Seasonal workers are hired for irrigation, harvesting, planting and factory purposes. The amount of labour input per hectare per year and the costs of the production of sugarcane are shown in Table 1-3.

Table 1-3: Amount of labour and costs in Wonji (Wonji-Shoa Sugar Factory, 2020)

Scheme	Number of workers per year per hectare				Costs of sugarcane ($/ton) [2]
	Permanent	Seasonal	Day labours	Total	
Wonji Main	0.4	0.6	0.4	1.4	
Dodota	0.1	0.0	0.8	0.9	17.38
Wake Tio	0.0	0.0	0.2	0.2	19.59
Welenchiti	0.0	0.0	2.0	2.0	20.54
Ulaga	0.0	0.0	0.3	0.3	16.43

The costs of production in Wonji Main sub-scheme is not shown as the costs of overhead and running the factory could not be differentiated from the field to factory costs. According to the Wonji estate the differences in production costs can mainly be attributed to the methods of irrigation (Girma, 2020). The maintenance of draglines, i.e. replacing of hoses and sprinkler heads, is time consuming and also comes at a high (foreign currency) price; whereas the maintenance of the centre pivot systems is limited and currently only means re-inflating the tyres now and then. In operation however, both methods are dependent on the availability of electricity that is provided by the government (through the Ethiopian Electric Power Cooperation (EEPCO)); shortages and blackouts are frequent and hence the quantity and timing of irrigation is affected. Furrow irrigated areas in comparison, still have the highest operation costs in terms of labour.

1.3.2 Water Management

The Wonji-Shoa Sugarcane Plantation is located at the upstream end of many other irrigation schemes in the Awash Basin. It abstracts water from the Awash River, which is regulated from the releases from Lake Koka. The Awash Basin Authority (AwBA; recently renamed as Basin Development Agency, BDA) is responsible for the sustainable and equitable distribution of the water that is released from Lake Koka (and reservoirs further downstream). However, as users and usage of Awash River increase, the downstream parts of Awash River struggle to secure sufficient water, especially in periods of drought. These downstream users are therefore the first to experience water shortage as compared to the upstream water users. As such the BDA, with support of the Addis Ababa University, developed an allocation plan for all the irrigation schemes in the Awash Basin in 2015. The allocation plan is meant to improve the transparency on the utilization of the natural resources, as it is shared publicly. It also helps commercial irrigators to manage the water for their estates. The methods to establish daily water requirements by AwBA and the comparison between allocation, consumptive water use and actual abstraction have been studied in depth (Bastiaanssen, 2019). Allocation amounts are calculated using ET_{ref}, crop coefficients, effective precipitation and irrigation efficiencies (for furrow irrigation schemes set at 50%).

The daily water requirements as derived from the allocation plan for all Wonji sub-schemes are shown in Table 1-4, noting that allocation data for Ulaga sub-scheme could not be found. The dry season is

[2] this study assumes an ETB/USD conversion rate of 31.6489 ETB/USD (01/01/2020)

considered to last from November to June and the rainy season from July to October. During the rainy season the daily water requirements are zero according to the allocation plan.

Table 1-4: Daily water requirements (m^3/s) from allocation plan for Wonji (AwBA, 2017a).

Schemes	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wonji Main	4.63	4.75	4.49	4.24	3.76	3.66	0.0	0.0	0.0	0.0	5.3	4.8
Dodota	1.43	1.47	1.39	1.31	1.16	1.13	0.0	0.0	0.0	0.0	1.8	1.6
Welenchiti	0.82	0.83	0.79	0.69	0.80	0.57	0.0	0.0	0.0	0.0	0.9	0.8
Wake Tio	0.40	0.41	0.39	0.36	0.32	0.31	0.0	0.0	0.0	0.0	0.5	0.4

The above figures are the essentially the maximum permissible pumping rates assumed to apply 24/7 for a particular month. Throughout the irrigation season water may be pumped at the specified rates then applied to the whole production area. As example the 4.63 m^3/s pumping rate in January for Wonji main sub-scheme, implies a total irrigation depth of 91 mm that month for any given part in the scheme (considering 50% irrigation efficiency)

Measured abstraction data collected by the Awash Basin Authority at the Wonji-Shoa Sugar Factory for the calendar year 2017 is presented in Table 1-5. Comparing allocation with abstraction shows that for all months except October, abstraction is below allocation. This also tallies with interviews held with staff; in principle, there are no problems with water availability in the Awash River, however water shortages for irrigation purposes are encountered nonetheless, primarily due to shortages in electricity supply and black outs in the months of May and June (pumps used to abstract water require electricity to function).

Despite the fact that there is no official allocation of water during the month of October, according to the daily abstraction data, the scheme does start abstracting already in October as the month is rather dry (Figure 1-3). Similar observations were made in the Metehara irrigation scheme.

Table 1-5: Daily water abstraction (m^3/s) of Wonji (AwBA, 2017b).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wonji Main	2.82	2.55	2.89	2.43	2.04	2.39	0.0	0.0	0.0	2.68	3.47	3.11
Dodota	0.65	0.51	0.62	0.69	0.66	0.56	0.0	0.0	0.0	0.65	0.98	0.97
Welenchiti	2.39	2.05	1.74	1.62	1.32	1.64	0.0	0.0	0.0	0.73	1.91	2.00
Wake Tio	0.12	0.11	0.15	0.15	0.19	0.23	0.0	0.0	0.0	0.10	0.22	0.23

The above suggests that adaptation of the allocation plan, both in timing and in allocation amounts should be looked into. This to address the unallocated abstraction taking place in October and the discrepancies in allocation and abstraction rates in other months. For some sub-schemes less than half of what is allocated is abstracted, whilst for example in Welenchiti, the most recently developed scheme, the abstraction rate is higher as compared to the allocation.

1.4 Sugarcane Production and Challenges

1.4.1 Sugar cane production

Of the five irrigation schemes, Wonji-Shoa Sugar Factory only owns the largest and oldest scheme: Wonji Main. The sugar cane in the schemes of Dodota, Welenchiti, Wake Tio and Ulaga are grown by outgrowers supplying to the Wonji-Shoa Sugar Factory. With regards to production and methods, the Wonji-Shoa Sugar Factory determines the methods for all areas, which only differ depending on the soil type that is being cropped on.

The 'heaviest' soils (Vertisols) are planted and consequently ratooned three times according to the following cropping schedule: 24 month (plant); 12 months (ratoon); 24 months (ratoon); and 12 months (ratoon). Following this third and last ratoon of 12 months, the crop is uprooted and the land is left fallow for 4 months and then prepared again for new plants. In total, the planting season is 6 years with a harvest on average every 18 months. This planting season differs for other soil categories found on the estate with plants being cropped either 8 or 10 years with 'lighter' soils having longer seasons.

Within the estate 10 different varieties of sugarcane are cropped, however, regardless of variety or soil type, fertiliser application rates are the same throughout the estate: for planting cane, 200 kg/ha of Urea; and for ratooning 500 kg/ha of Urea.

The average sugarcane production per cropping season, based on data collected by Wonji-Shoa Sugar Factory, for all the schemes, is shown in Table 1-6, data pertains to the 2017-2018 season.

Table 1-6: Sugarcane production in Wonji per season (Wonji-Shoa Sugar Factory, 2020)

Scheme	Sugarcane production		Area size (ha)	Sugarcane production (ton)
	quantal/ha	ton/ha		
Wonji Main	1,000	100	6,700	670,000
Dodota	1,200	120	2,600	312,000
Wake Tio	1,200	120	700	84,000
Welenchiti	1,400	140	1,000	140,000
Ulaga	1,300	130	200	26,000
TOTAL	1,100	110	11,200	1,232,000

According to their data, Welenchiti has the highest land productivity in ton/ha, however it was noted by the factory that the Welenchiti area has a cropping season that lasts on average more than 25 months. Wonji Main still has the largest total production volume, however according to their data, it also has the lowest land productivity at 100 ton/ha - this is also lower than the weighted average of all the schemes (110 ton/ha).

1.4.2 Challenges in sugarcane production at Wonji estate

Wonji estate has (almost) reached its development goals, i.e. implemented all the planned expansion projects. Despite the mismatch of plans for rehabilitation and development, and the lack of financial resources, the Woni-Shoa Sugar Factory is still keen on increasing its production though intensifying production on existing lands. Wonji main is underperforming when compared with historical production levels, as well as with the other areas with differing irrigation methods. The estate is well aware of the limitations of the distribution systems, and the potential to increase efficiencies in conveyance and application, however it has not looked in detail (temporally and spatially) into the agronomical factors that affect land and water productivity. The only major reason identified for the differences in land productivity, as mentioned by Wonji estate are the difference in soils and the methods of irrigation application, as the fertilisers application rate is equal for areas and sub-schemes. Productivity is considered higher in the areas that have centre pivot systems, however this claim mostly relates to perceived water application efficiency (Wonji Estate) and the ease of irrigation management as opposed to the laborious furrow systems and the failing and costly sprinkler systems. In his extensive research into several large irrigation schemes in Ethiopia, including the Wonji-Shoa scheme, Dejen also concludes that huge seepage losses occur from the main system (Wonji main) and storage ponds, and considerable amounts drain into escapes and salty tail waters (Dejen, 2014). In almost 50% of the command area in Wonji main, the groundwater levels are within

1 m depth below ground surface and the salinity of shallow groundwater is high (as high as 2 dS/m), which is posing a serious risk of soil salinization in significant portions of the scheme area (Dejen, 2014).

Water resources distribution in the Awash Basin have officially been fixed in allocation plans, these however are vulnerable to: impact of drought, i.e. a smaller buffer of water in Lake Koka to share; and growing demand for water further downstream, particularly for agricultural expansions. With this in mind, all water users should effectively consider that new allocation plans will only provide for less water. In Wonji, particularly the newly developed areas face challenges in capturing enough water. All in all, this calls for improving the irrigation water management, as already extensively studied by Dejen (2014), and substantially increasing the land and water productivity at Wonji. This should however go hand in hand with the appropriate stimuli by the government to conserve water, i.e. by means of increasing the costs of abstraction licenses (Girma, 2020).

To improve the performance of agricultural water use we need to understand the quantity and spatio-temporal patterns of water productivity in a given area. In most cases, water productivity is assessed using observed average crop yield and water use over a farm, and climatic data observed at a point. However, such data does not adequately represent the spatial variation across the irrigation system (Bastiaanssen et al., 2000).

Remote sensing (RS) based assessments of water productivity and irrigation performance offers a viable alternative to traditional field methods to measure crop growth and evapotranspiration (Bastiaanssen et al., 1996; Karimi et al., 2011). The RS based assessments can be used as a cost-efficient method to conduct large scale analysis to identify areas with higher or lower water productivity and to compare water delivery practices in irrigation schemes and over several cropping seasons. The results can help assess the potential for improvement by identifying the conditions that are needed to achieve high water productivity. One of the main factors behind the variation of water productivity is thought to be water management practices. These practices in Wonji, to a large extent, depend on soil and drainage management, as well as the irrigation application methods. Therefore, an analysis of productivity of an estate such as Wonji should be segmented according to (at minimum) the irrigation method, to gain a better picture of what factors influence water productivity and subsequently identify possible solutions for improvements.

2 Objective

The main objective of this study is to provide insight into water and land productivity in the Wonji sugarcane estate with use of remotely sensed data derived from FAO Water Productivity through Open access Remotely sensed derived data (WaPOR)[3]. The study focuses on analysing the spatial variation of water and land productivity, and irrigation performance indicators at Wonji sugarcane estate differentiated by irrigation application method. Furthermore, the productivity gap and implications of its closure on production and water use are explored, considering water allocation in Awash River Basin.

[3] https://wapor.apps.fao.org/home/WAPOR_2/3

3 Methodology and Data

The methodology applied in this study follows the approach developed as part of the WaterPIP project and detailed by Chukalla et al. (2020a). The study also utilises the standardized protocol developed by the WaterPIP project (Chukalla et al., 2020b). In this chapter, the approach is presented by first giving a general overview of the data and performance assessment framework used. After this, the methodology is explained in more detail.

Two data sources were used in this study: remote sensed data and local information. The remotely sensed data is obtained from FAO Water Productivity through Open access Remotely sensed derived data, WaPOR (see https://wapor.apps.fao.org). These datasets are spatially and temporally explicit and available from 2009 to present[4]. The local information, such as crop parameters and crop season, were obtained from literature. The data were resampled and aggregated, and the analyses were done at 30 metre and 100 metre spatial resolution, at a seasonal time step defined as one year.

Figure 3-1 shows the schematic procedure used to calculate indicators of water and land use and irrigation performance in the Wonji sugarcane estate (Chukalla et al., 2020a). First, the system boundary was created using Google Earth and input of local experts from Wonji estate, in combination with the land cover classification (LCC) data from WaPOR for the irrigated area of Welenchiti. For the system area, datasets were collected from the WaPOR portal on actual evapotranspiration and interception (ET_a), transpiration (T), reference evapotranspiration (ET_{ref}), and net primary production (NPP). The data was pre-processed to the desired spatial resolution and no-data pixels were filtered. Second, the datasets were accumulated to obtain seasonal data, and the above-ground biomass (hereafter referred to as biomass, B) is calculated with use of the NPP data and local, crop specific data. Third, a WaPOR data consistency check was performed, an essential part when using the WaPOR data. The data was checked by analysing how the data reflects the known relationships between biomass and ET_a, biomass and transpiration, and biomass and $\sum T/ET_{ref}$ (de Wit, 1958; Steduto et al., 2007). This was done for the whole project area, and for different areas based on the irrigation method. Fourth, the indicators were analysed. Finally, the implication of closing productivity gaps on production and water consumption were explored.

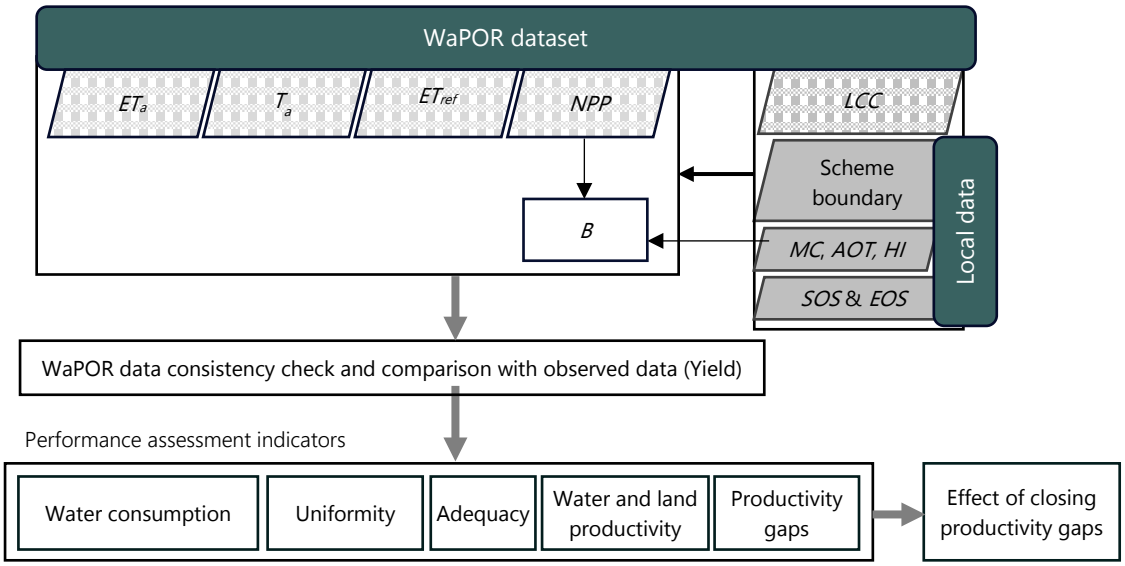


Figure 3-1: Flowchart of the used methodology for calculating the indicators for irrigated sugarcane at Wonji (Chukalla et al., 2020a).

[4] https://wapor.apps.fao.org/home/1

3.1 Determining the different irrigation areas

Wonji Sugar Estate has been expanding in recent years, with different irrigation methods begin applied in different areas. This means that the scheme boundary used for this study has changed over time. Table 3-1 shows for each of the irrigation areas that are part of Wonji Sugar Estate in which years they were cultivated and taken into account in the scheme boundary (indicated with green). The starting year per scheme is determined from information obtained during a field visit to Wonji Sugar Estate, in combination with visual observation from Google Earth. When this was not detailed enough, the land cover classification maps on the WaPOR portal were used to get more information, as well as the transpiration trends for the different irrigated areas (Appendix A.1). For the new irrigation areas, only years where the full area was cultivated were taken into account. The area of Wake Tio had a large uncultivated period in 2017, therefore Wake Tio is excluded from the analysis for the year 2017. For the area of Welenchiti, the annually provided land cover classification maps on WaPOR was used to filter out non-irrigated pixels. The area size is based on the number of pixels used in the analysis.

Table 3-1: Characteristics of Wonji Irrigation Schemes

Irrigation Scheme	Area size (ha)	Irrigation Method	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Wonji Main	6,712	Surface (furrow)											
Dodota	643	Centre Pivot											
	1,918	Sprinkler											
Wake Tio	691	Sprinkler											
Ulaga	201	Sprinkler											
Welenchiti	833	Surface (hydroflume)											

3.2 WaPOR Datasets

The FAO portal to monitor Water Productivity through Open access of remotely sensed derived data (WaPOR), provides free, open access, spatial data to monitor land and water productivity with layers covering Africa and the Near East in near real-time for the period between 2009 to present day. It is a comprehensive dataset that combines data on water use, net primary production, land cover, phenology, and climate (precipitation and reference evapotranspiration). WaPOR datasets are available at continental scale (Level 1 at 250 m), country scale (Level 2 at 100 m) and for at least eight areas at project level (Level 3 at 30 m). The methodology used for compiling the WaPOR database is provided in FAO (2020b).

In this study, WaPOR data at a spatial resolution of 30 m and 100 m are used. The majority of the project area is located within the 30 m resolution area of the Awash basin (Figure 3-2). Only the Welenchiti area is not available at 30 m resolution, therefore the 100 m resolution (L2) data is used for Welenchiti. An overview of the WaPOR data used in this study is provided in Table 3-2. The level 3 data is used for the period 2009-2019, and the level 2 data for the period 2015-2019, since Welenchiti is only included in the scheme boundary from 2015 onward. The WaPOR ET_a and NPP is based on images from PROBA-V for L2 (from 2014 onwards), and Landsat for L3. These satellites differ in spatial resolution and return intervals, which is 100 m and 2 days for PROBA-V, and 30 m and 16 days for Landsat. The data for L3 and L2 will be analysed separately. The precipitation (L1, 5 km resolution) and reference evapotranspiration (L1, 20 km resolution) datasets were downscaled to 100m and 30m resolution.

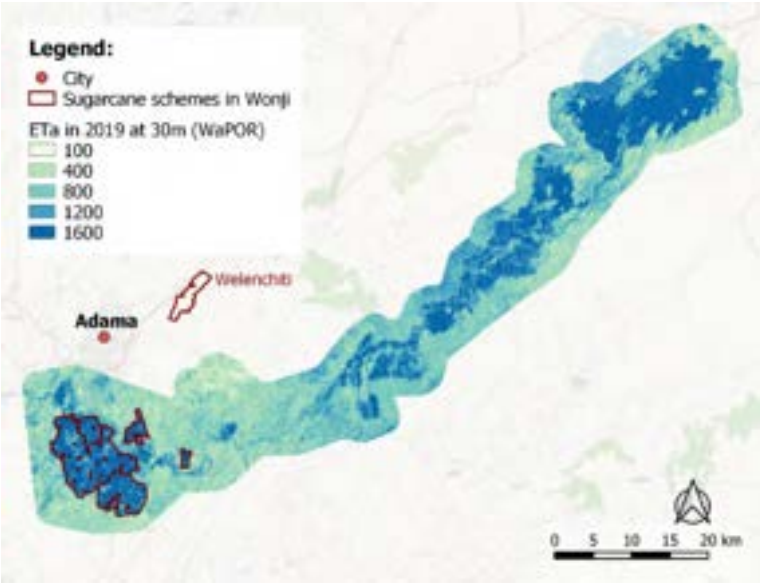


Figure 3-2: Location of Wonji sugarcane estate, and the available 30 m WaPOR data for the Awash basin.

Table 3-2: WaPOR layers used in the analyses

Remote sensing products	Abbreviation	Spatial resolution	Temporary resolution (coverage)
Actual evapotranspiration	ET_a	30 m and 100 m	Decadal (2009-2019)
Transpiration	T	30 m and 100 m	
Net primary production	NPP	30 m and 100 m	
Precipitation	P	5 km	
Reference evapotranspiration	ET_{ref}	20 km	
Land Cover Classification	LCC	100 m	Annual (2015-2019)

In this study, the decadal WaPOR data are aggregated to seasonal values, based on the start and end of a growing season. An example for estimating the seasonal values is given in Equation 1 (Chukalla et al., 2020a):

$$ET_{a,s} = \sum_{SOS}^{EOS} ET_a$$

Equation 1

Where ET_a is the actual evapotranspiration and interception (mm/dekade), SOS and EOS are respectively the start of the cropping season and end of the cropping season, and $ET_{a,s}$ is the seasonal evapotranspiration and interception in mm/season. The WaPOR evapotranspiration layer is calculated as the sum of the soil evaporation, canopy transpiration and interception. Interception, defined as the rainfall intercepted by the plants canopy, is first calculated. Energy used for interception is not available for transpiration and soil evaporation. The evaporation and transpiration are calculated based on the ETLook model described in Bastiaanssen et al. (2012) (FAO, 2020).

The sugarcane plantation operates on ratooning system and harvesting is done throughout the year to keep the sugar factory in operation. Thus, the start of season and end of season per farm unit varies. In absence of detailed information of start and end of season for each plot, we considered for the analysis an average annual biomass production for the period from January 1st to December 31st. By using this

hypothetical annual season, the inter annual utilization of both land and water resources can be compared, i.e., production per unit of land and per unit of water consumed.

In Wonji, the cropping season covers a period larger than one year, varying from 12-24 months. After a cropping period of 6-10 years, the soil is left fallow for 4 months. This varying duration of the growing season, as well as the varying start of growing season per plot and a time of fallow land, will be reflected in the annual data. To even out the difference in cropping season, the data will be analysed per 6-year average (2014-2019) for L3 and per 5-year average (2015-2019) for L2 data for Welenchiti. Part of the results will be analysed per year to analyse and compare inter-seasonal variations.

3.3 Calculating biomass production

The biomass production (*B*) is calculated from the seasonal NPP data provided by WaPOR using Equation 2 (Chukalla et al., 2020a). Where AOT is the above ground over total biomass production ratio, f_c is the light use efficiency correction factor to correct the calculated NPP for C4 crops, and m_c is the moisture content of the fresh biomass at the moment of harvest.

$$B = AOT * f_c * \frac{NPP * 22.222}{(1 - m_c)}$$

Equation 2

These values of these parameters are crop specific. Literature was consulted to estimate the crop parameters, the used values are presented in Table 3-3. The WaPOR estimated NPP uses a generic light use efficiency (LUE of 2.7), which is applicable for C3 crops. As sugarcane is a C4 crop, it has a different LUE, and therefore f_c was set at 1.8 (Villalobos & Fereres, 2016). After this, the seasonal NPP (gC/m^2/season) is converted to dry biomass production (kg dry biomass production/ha/season) by multiplying the seasonal NPP with 22.222 (FAO, 2020).

The m_c of 59 percent was measured by Yilma (2017) for sugarcane at Wonji. This value was obtained from field observations by dividing the difference between fresh and dry weight of sugarcane stalk by the total fresh weight of stalk. The AOT was set at 80 percent following the root shoot ratios measured for pot-grown sugarcane (Smith et al., 2005).

Table 3-3: Crop parameters used in the analysis

Local data	Abbreviation	Value	Source
Moisture content of fresh crop biomass	m_c	59 %	Yilma (2017)
Ratio of light use efficiency of C4 and C3 crops	f_c	1.8	Villalobos & Fereres (2016)
The ratio of above ground over total biomass	AOT	0.8	Smith et al., (2005); Villalobos & Fereres (2016)

The main source of variation in Biomass production is the WaPOR NPP data. As described by Chukalla et al. (2020b), the NPP is corrected for stresses induced by water, nutrient, pests and diseases, while additional variation may be due to spatial and temporal gap filling.

3.4 Review of Consistency of WaPOR Data for Crop Response to Water

Biomass production is known to have a linear relationship with transpiration (de Wit, 1958; Steduto & Albrizio, 2005). With some concerns about the transpiration and soil evaporation layers of WaPOR (FAO and IHE Delft, 2019), we compared the biomass and water consumption (ET_a). A linear relation would indicate consistency between the two independently generated datasets, while the slope of the line accounts for the effect crop variety and soil fertility (Steduto et al., 2007).

Figure 3-3 show the biomass plotted against three seasonal water consumption variables: transpiration, actual evapotranspiration and normalized transpiration ($\sum T/ET_{ref}$) for the Wonji Sugar Estate area with level 3 data in 2019, Figure 3-3 show the same figures for Welenchiti (level 2 data) with the annual average values for the period 2015-2019. Figures for the other years are provided in Appendix A.2. The normalized transpiration is calculated by summing the product of decadal time interval and the ratio of decadal transpiration over decadal reference evapotranspiration over the crop season, following the methods described in Steduto et al. (2007).

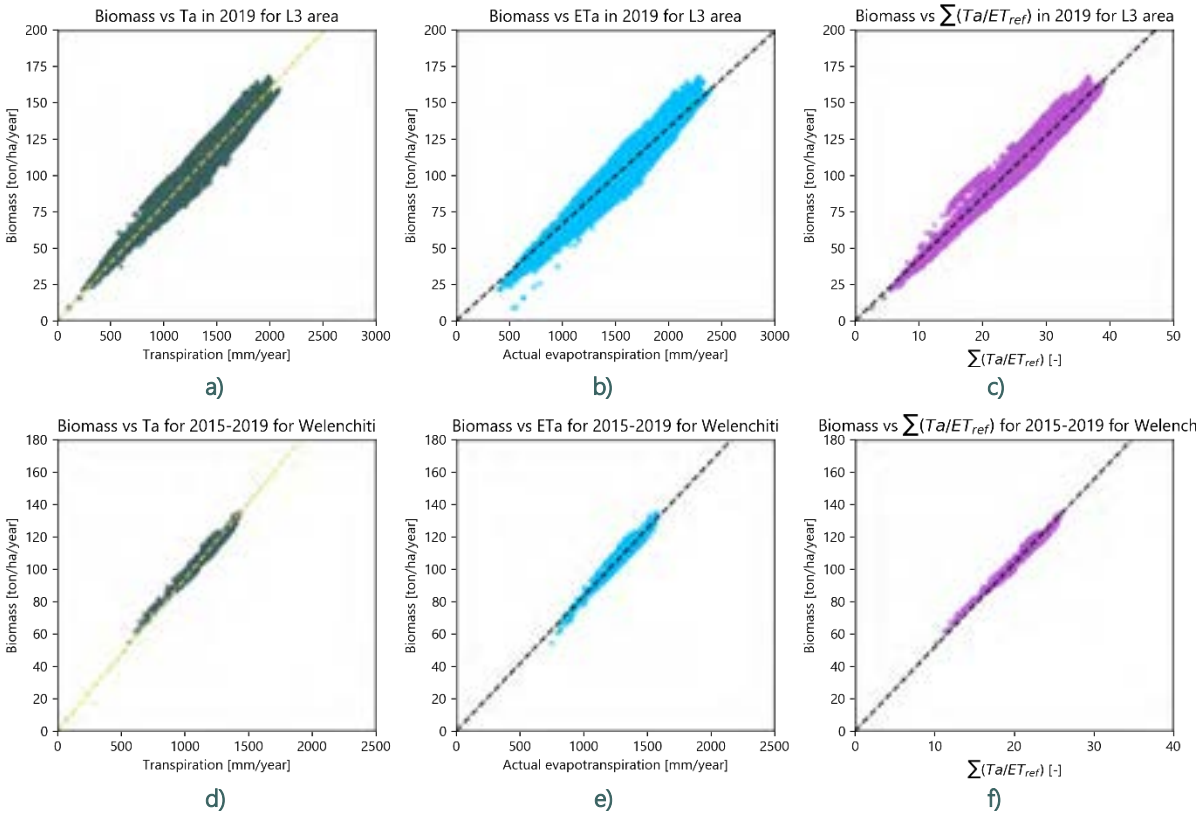


Figure 3-3: The relationship between biomass and transpiration (a and d), between biomass and actual evapotranspiration (b and e), and biomass and normalized transpiration (c and f) for the Wonji sugarcane estate in the areas that are cover by L3 data and Welenchiti, which is covered by L2 data.

Table 3-4 and Table 3-5 show the slope, intercept and R^2 for the linear regression lines per year for respectively the L3 data and the L2 data. The biomass production is directly related to the transpiration and the normalized transpiration, therefore the linear regression line is forced through the origin. The relationship between the biomass and the ET_a does not necessarily pass through the origin, the intercept can be attributed to non-beneficial evaporation, such as interception or soil evaporation. In this study, the linear regression line is also forced through the origin for the relationship between the biomass and ET_a.

Table 3-4 shows a stronger correlation for B vs T, compared to B vs ET_a, the slope is steeper and the R^2 values are higher for B vs T, which is as expected. The slope for the linear regression line of B vs normalized transpiration is quite stable, with an average value of 4.28.

From Table 3-5 follows that for the L2 data at Welenchiti. In all years the slope is steeper for B vs T, which is as expected. And the R^2 values for B vs T are higher than those for B vs ET_a for most years, with exception of 2018 and 2019. The R^2 values are for most years the highest for the linear regression lines of biomass vs normalized transpiration, only in 2016 the R^2 is higher for B vs T. However, the values do vary over the years.

Figure 3-3(a-c) and Table 3-4 show a consistent and good correlation between the biomass and the different water consumption variables for the level 3 dataset in the period 2009-2019. A similar observation is done from Table 3-5 and Figure 3-3(d-f) for the L2 data at Welenchiti. Therefore, in this analysis the WaPOR data will be used for the complete period of interest for the different layers: for the area with L3 data the period 2009-2019, and for the L2 area (Welenchiti) the period 2015-2019.

Table 3-4: Linear regression parameters for the relationship between biomass and transpiration (T), biomass and actual evapotranspiration (ET_a), and biomass and normalized transpiration $\sum(T/ET_{ref})$ for the L3 area of the sugarcane production in Wonji for the period 2009-2019.

Line	Regression parameters	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
	slope	0.081	0.090	0.080	0.082	0.089	0.083	0.074	0.082	0.075	0.082	0.080
B vs T	intercept	0	0	0		0	0	0	0	0	0	0
	R^2	0.976	0.981	0.970	0.966	0.974	0.975	0.956	0.966	0.942	0.945	0.944
	slope	0.065	0.075	0.066	0.065	0.071	0.071	0.062	0.068	0.062	0.070	0.066
B vs ET_a	intercept	0	0	0	0	0	0	0	0	0	0	0
	R^2	0.937	0.943	0.938	0.898	0.913	0.954	0.935	0.926	0.900	0.922	0.928
	slope	4.224	4.254	4.275	4.320	4.351	4.326	4.221	4.306	4.217	4.330	4.236
B vs $\sum(T/ET_{ref})$	intercept	0	0	0	0	0	0	0	0	0	0	0
	R^2	0.961	0.939	0.936	0.927	0.924	0.960	0.950	0.962	0.952	0.956	0.961

Table 3-5: Linear regression parameters for the relationship between biomass and transpiration (T), biomass and actual evapotranspiration (ET_a), and biomass and normalized transpiration $\sum(T/ET_{ref})$ for the L2 area, Welenchiti, in the sugarcane production in Wonji for the period 2015-2019.

Line	Regression parameters	2015	2016	2017	2018	2019	2015-2019
	slope	0.087	0.103	0.091	0.096	0.094	0.094
B vs T	intercept	0	0	0	0	0	0
	R^2	0.952	0.962	0.937	0.961	0.818	0.956
	slope	0.079	0.091	0.080	0.084	0.084	0.083
B vs ET_a	intercept	0	0	0	0	0	0
	R^2	0.944	0.957	0.926	0.962	0.881	0.949
	slope	5.101	5.381	5.287	5.146	4.983	5.180
B vs $\sum(T/ET_{ref})$	intercept	0	0	0	0	0	0
	R^2	0.961	0.958	0.950	0.967	0.908	0.972
ET_{ref} (mm/year)		2,213	1,976	2,221	2,007	2,075	2,098

3.5 Performance Assessment Indicators

Productivity and irrigation performance indicators provide a way to measure the effectiveness of resources use and to evaluate irrigation system. We applied the same indicators as detailed in Chukalla et al. (2020a). These consisted of i) water consumption, ii) equity (measured by the uniformity of water consumption), iii) adequacy (measured by relative evapotranspiration), iv) land and water productivity, and v) productivity gaps. The definitions and methods applied for each indicator described below are derived from Chukalla et al. (2020a).

3.5.1 Water Consumption

Water consumption refers to the amount of water that is depleted from the root zone through the process of transpiration by a crop and direct evaporation from the soil. In this study the seasonal evapotranspiration and the season transpiration (beneficial consumption) are the key indicators for water consumption.

3.5.2 Uniformity

Uniformity measures the evenness of the water supply in an irrigation scheme. In the absence of plot-level water distribution records, the uniformity of water consumption can be used as a proxy to estimate equity. It is calculated as the coefficients of variation (CV) of seasonal ET_a in the area of interest (Bastiaanssen et al., 1996). A CV of 0 to 10 % is defined as good uniformity, CV of 10 to 25 % as fair uniformity and CV > 25 % as poor uniformity (Bastiaanssen et al., 1996; Molden & Gates, 1990).

3.5.3 Adequacy

Adequacy (A) is the measure of the degree of agreement between available water and crop water requirements in an irrigation system (Bastiaanssen & Bos, 1999; Clemmens & Molden, 2007). Adequacy can be estimated from relative evapotranspiration, which is defined as the ratio of ET_a over potential evapotranspiration (Karimi et al., 2019; Kharrou et al., 2013). The relative evapotranspiration can be used to indicate crop water stress. When de ratio ET_a over potential evapotranspiration approaches 1, this indicates that sufficient water is available. In this study, the ET_{ref} is considered instead of potential evapotranspiration (Equation 3).

$$A = \frac{ET_{a,s}}{ET_{ref}}$$

Equation 3

Where $ET_{a,s}$ and ET_{ref} are the seasonal actual and refence evapotranspiration in mm/season.

3.5.4 Productivity

Although there are various definitions of productivity, in this study we focus on biophysical production per unit of land or water resources, also known as land and water productivity.

Land productivity is defined as the biomass production or yield in ton/ha/season. Crop yield can be estimated by multiplying the biomass production by the harvest index (H_i) (Equation 4). For the harvest index, a value of 0.69 is used (Yilma, 2017; Chukalla et al., 2020a).

$$Yield = B * H_i$$

Equation 4

The estimated yield will be compared with the yield data presented in Table 1-6. The yield data is provided in ton/ha/season and average annual yield data will be determined based on the average season length. For this, an average season of 18 months is used for all areas, except Welenchiti. For Welenchiti, an average season duration of 25 months is used.

The biomass water productivity (WP_b) is defined as the ratio of above-ground biomass (B) over the seasonal actual evapotranspiration (ET_a) (Equation 5):

$$WP_b = \frac{B}{ET_a}$$

Equation 5

To obtain WP_b in kg/m^3/season B in kg/ha/season has to be converted to kg/m^2/season and ET_a in mm/season has to be converted to m/season, this can be done by multiplying B with a factor 10^{-4} and ET_a with a factor 10^{-3}. It is important to note that this measure of water productivity includes consumed green water (from rainfall) and blue water (from irrigation).

For each of the irrigation areas, the mean WP_b is calculated. To see which areas have consistently a higher WP_b, or a lower WP_b than the mean water productivity in the area, the difference between the pixel WP_b and the mean WP_b are determined per season (Equation 6).

$$\Delta WP_b = WP_{b,i} - WP_{b,mean}$$

Equation 6

Where $WP_{b,i}$ is the water productivity at pixel i, $WP_{b,mean}$ is the mean WP_b of that area, and ΔWP_b the difference between these two values. By selecting the pixels that have a negative ΔWP_b for each season, a spatial overview of the areas with a consistently lower WP_b was created. The same has been done for the pixels that have a positive ΔWP_b for each season, to select the consistently better performing areas with regard to water productivity.

3.6 Productivity Gaps

Land and water productivity gaps give an indication of the performance of a field in comparison with the surrounding area using a productivity target. The methodology described in this section is based on Chukalla et al. (2020a).

Productivity Target

Productivity targets refer to target biomass and target water productivity, which are attainable within the biomass and productivity distributions of a crop across areas in a similar agro-climatic zone. Biomass (B) and water productivity (WP_b) targets, or attainable productivities, are identified applying upper percentiles to the distribution of biomass and productivity values. In this study, we estimate attainable B and WP_b of sugarcane at Wonji for L3 areas in a particular year at the 95th percentile of the respective productivity distributions (see Chukalla et al., 2020a for justification for selecting the 95th percentile). For the L2 area the attainable B and WP_b of sugarcane was estimated at the 90th percentile of the productivity distributions.

Target Field and Bright Spots

Target plots are defined as plots that have B and WP_b equal to the target values and the corresponding ET_a is also defined as the target ET_a (indicated by the vertical and horizontal dashed grey lines in Figure 3-4). Bright spots are fields that have B and WP_b greater than or equal to the target values. The bright spots in Wonji sugarcane state are identified by tracking the pixels that have both B and WP_b equal or greater than the targets for the five seasons.

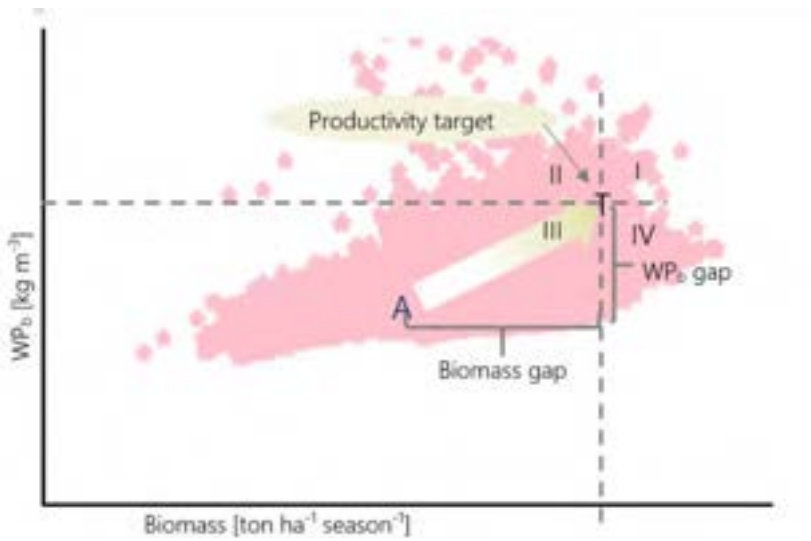


Figure 3-4: Schematic representation of productivity target, and disentangled WP_b, gaps and biomass gaps for a production at a plot compared to target productivities. The arrow indicates the path to be followed in closing the productivity gaps at plot A, it links productivities at a plot A to the target productivities at plot T. The grey vertical and horizontal dashed lines represent the 95 percentile of Biomass and WP_b, respectively, divided the plots in four quadrants (Chukalla et al., 2020a).

Productivity Gap

The productivity gap of a crop at a plot (e.g., at pixel A in Figure 3-4) is calculated by subtracting the productivity value at pixel A from the productivity at the target pixel (pixel T in Figure 3-4). The productivity gap of pixel A can be divided into a water productivity gap and a land productivity gap.

Pixels fall into four quadrants as seen in Figure 3-4 that fulfil the following conditions: I) $B > B$ target and $WP_b > WP_b$ target, II) $B < B$ target and $WP_b > WP_b$ target, III) B < B target and $WP_b < WP_b$ target, and IV) $B > B$ target and $WP_b < WP_b$ target (Chukalla et al., 2020a). All pixels in the first quadrant have higher B and WP_b than the target productivity, they are bright spots from which good practices can be learnt. The pixels that fall in the remaining three quadrants are potential sites in closing WP_b and B gaps.

The total production gap (in tons) is defined as the sum of the production gaps over the irrigated area (Equation 7). Areas falling in the II and III quadrants have $B < B$ target and thus there is a productivity gap. The production gap where B or WP_b exceed or equal to their respective target values are excluded in the summation.

$$B\ gaps = \sum_{i}^{n} (B_i - B_t), \quad B_i < B_t$$
$$= 0 \quad B_i \geq B_t$$

Equation 7

Where B_i and B_t are biomass of a pixel i and the target biomass in ton/ha/season. The WP_b gaps are calculated in similar fashion.

Change in Water Consumption Associated with Closing the B Gap

Closing the B and WP_b gaps for fields located in the four quadrants depicted in Figure 3-4 have different impact on the change in water consumption (Chukalla et al., 2020a). Closing productivity gaps at a pixel implies improving the actual B and WP_b to the target levels. Pixels in quadrant II have sufficiently high WP_b, closing the biomass gaps at these pixels may be possible by additional water consumption. Pixels in

quadrant III need to close both the water productivity and biomass gaps, requiring sometimes more and sometimes less ET_a. Pixels in quadrant IV need to close the WP_b gap, which can only be achieved by reducing ET_a.

Closing B gaps is associated with change in ET_a (ΔET_a), which is calculated as follow:

$$\Delta ET_a = \sum_{i}^{n} (ET_{a,i} - ET_{a,t})$$

Equation 8

where $ET_{a,i}$ and $ET_{a,t}$ are actual evapotranspiration of a pixel i and target pixel t in mm/season. A positive ΔET_a implies ET_a reduction and a negative ΔET_a implies ET_a increase.

4 Results

In this section, the results for areas with a 30m spatial resolution (L3) are provided together with the data for Welenchiti with a spatial resolution of 100m (L2), however the values will be analysed separately for each level. The maps show the average annual values for the period 2014-2019 for the L3 data, and the period 2015-2019 for the L2 data. The results for the separate years can be found in Appendix A.3–15. When observing the spatial data, it should be noted that the growing season of one year is a hypothetical season.

4.1 Review of Consistency of WaPOR Data for Crop Response to Water per Irrigation Method

The WaPOR consistency review (section 3.4) showed a clear and consistent initial result for the WaPOR data in the L3 area in Wonji for the whole period of 2009-2019. In this section, a similar check is done for the different areas disaggregated according to irrigation method and area. Again, the biomass water productivity based on the transpiration, evapotranspiration and normalized transpiration is analysed to see if there are discrepancies between the areas that question the usability of the data for comparison in this study. Detailed analysis and comparison of the different areas based on these results will be provided in section 4.5.2.

The different irrigation methods should have a different ratio transpiration to surface evaporation. Biomass production is linked to the beneficial transpiration rate of plants (de Wit, 1958; Steduto et al., 2007), but not to the evaporation losses. This difference per irrigation method will be reflected in the water productivity based on ET_a (Equation 5).

If the crops have non-limiting nutrient conditions, the difference between the irrigation application methods is expected to become smaller when the evaporation component is eliminated and only the transpiration is taken into account to determine the water productivity ($WP_{b(T)}$) (Perry et al., 2009). The slope for the regression line biomass versus transpiration approaches then the average $WP_{b(T)}$ in kg biomass per kg water. The water productivity is also influenced by the atmospheric demand of the area or season. These differences can be accounted for by normalizing the transpiration for climate (Hellegers et al., 2009; Steduto et al., 2007). The slope of the linear regression line, $WP_{b(T/ETref)}$, is expected to be more stable over the years, and comparable for the different irrigation methods. The results of the normalized transpiration will be influenced by the large spatial resolution of the ET_{ref} data component of 25 km.

Figure 4-1 shows the scatterplots of biomass versus the three different water consumption variations for the year 2019, the regression line parameters (slope and R^2) for the other years can be found in Appendix A.3. The linear regression lines for all the areas combined in one graph. The slopes (estimated water productivity) for the different scatter plots per year are provided in Figure 4-2. The ET_{ref} values per irrigation area are provided in Table 4-1, maps with the spatial distribution are provided in Appendix A.4.

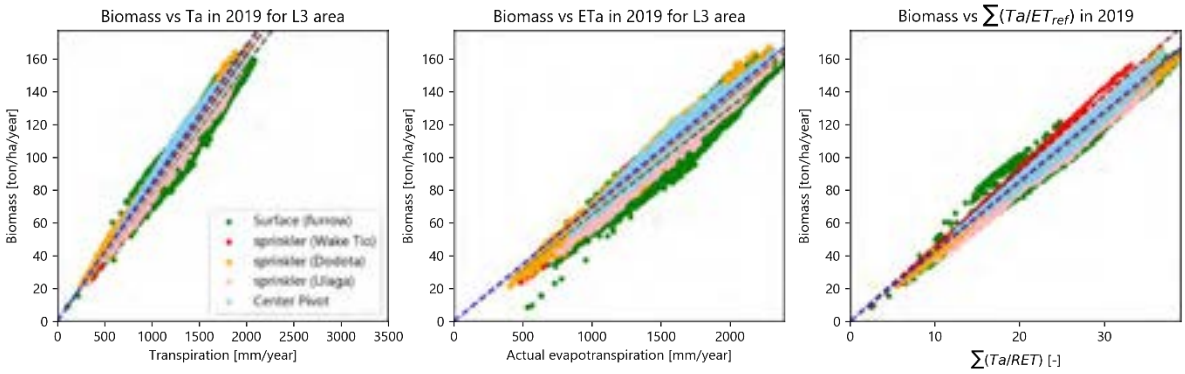


Figure 4-1: Scatterplots for biomass versus three different water consumptions in the year 2019, indicated for each irrigation area and method.

Table 4-1: Annual ET_{ref} [mm/year] per irrigation area for the period 2009-2019.

Irrigation Scheme	Irrigation Method	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2014-2019*
Wonji Main	Surface (furrow)	1,923	1,755	2,022	2,017	1,841	1,982	2,190	1,969	2,186	2,005	2,068	2,067
Dodota	Centre Pivot						1,890	2,080	1,900	2,068	1,899	1,951	1,965
	Sprinkler						1,885	2,070	1,893	2,059	1,884	1,936	1,954
Wake Tio	Sprinkler	2,018	1,856	2,133	2,122	1,945	2,075	2,291	2,040		2,075	2,133	2,123
Ulaga	Sprinkler						1,986	2,185	1,969	2,184	1,979	2,034	2,056
Welenchiti (L2 – 100m)	Surface (hydroflume)							2,213	1,976	2,221	2,007	2,075	2,098

**For Welenchiti the annual average ET_{ref} of 2015-2019 is provided.*

In Figure 4-2a and b the different irrigated areas show no unexpected variations, and the statistical correlation (R^2) increased, or is equal, for the relation B versus T, compared to B versus ET_a. However, in Figure 4-2c it is very clear the irrigated area of Wake Tio does not behave according to what we expect when normalizing the data for climate, which is that the differences between the different areas and the different years will become smaller. The ET_{ref} in Wake Tio is larger than that of the other areas (Table 4-1). The high ET_{ref} is reflected in the normalized transpiration, and therefore in the $WP_{b(T/ETref)}$. Because of these high values for Wake Tio, it is unclear how reliable the WaPOR data values are for Wake Tio when comparing to the other areas. Therefore, the data of Wake Tio is not included in the sprinkler data when comparing the different irrigation methods in the rest of the water productivity analysis. Instead the data will be shown separately for the results with regards to the water consumption and the productivity. The data of Wake Tio is excluded from further analysis on the productivity gaps and the effects of closing these gaps on the water consumption.

With the exclusion of the area Wake Tio from the analysis, Wonji Main is the only area that has been fully developed before 2014. Therefore, the different irrigation methods will be compared for the annual average values over the period 2014-2019.

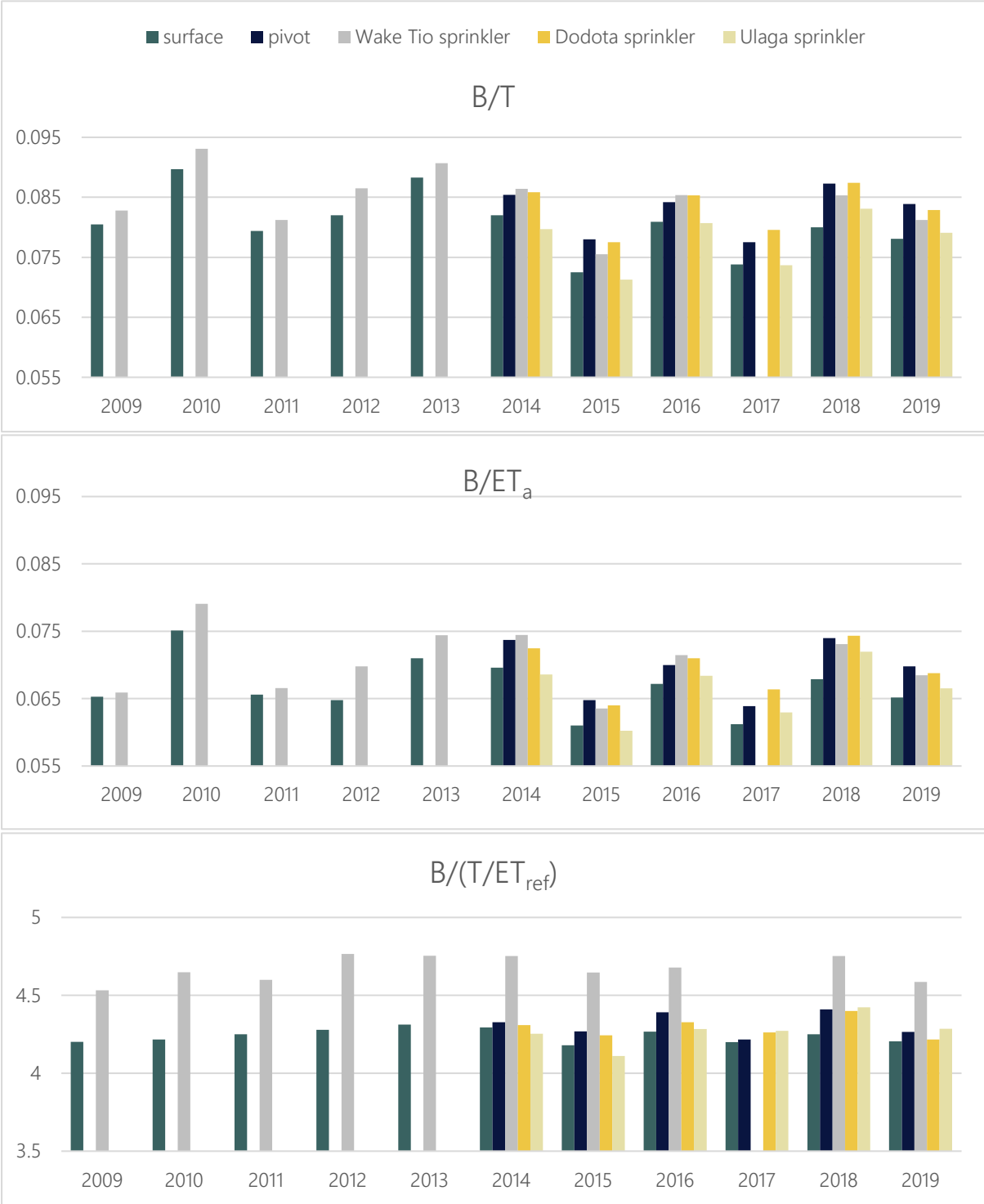


Figure 4-2: Comparison of the different slopes of the linear relation between biomass [ton/ha] and different water consumptions [mm/year] per year for the different irrigation areas and methods.

Figure 4-3 show the relationship between annual average biomass and the water consumption variations for the different irrigation methods for the period 2014-2019, where the sprinkler irrigated areas consist of the Dodota sprinkler area and Ulaga. The values of the slope and R^2 of the linear regression lines are provided in Table 4-2. The statistical correlation increases from B vs ET_a to B vs T and is highest for B vs $\sum(T/ET_{ref})$ for all irrigation methods, with exception of the surface irrigation, where B vs $\sum(T/ET_{ref})$ has the lowest statistical correlation. The graphs and linear regression parameters for the annual data is provided in Appendix A.5.

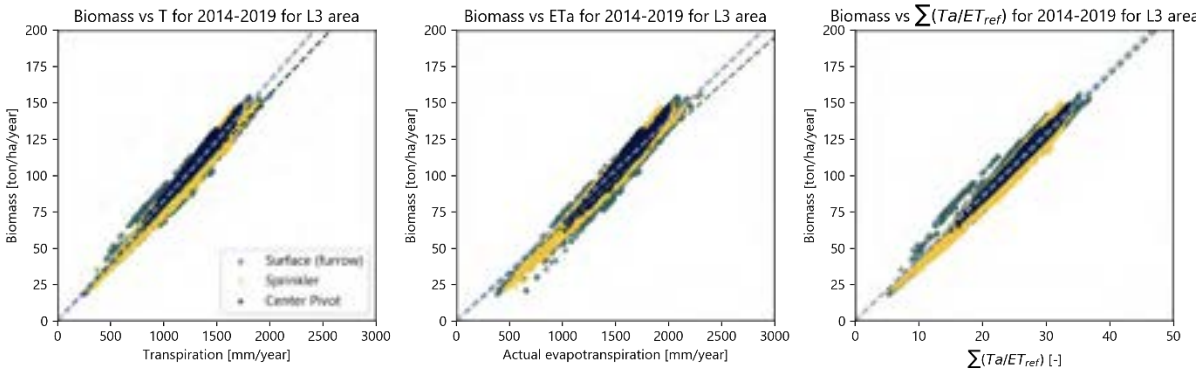


Figure 4-3: The relationship between the annual average biomass and transpiration (a), actual evapotranspiration (b), and normalized transpiration (c) for the period 2014-2019 differentiated between different irrigation methods for the L3 data.

Table 4-2: Linear regression parameters for the relationship between biomass and transpiration (T), biomass and actual evapotranspiration (ET_a) and biomass and normalized transpiration $\sum(T/ET_{ref})$ per irrigation method for the average annual values over the period 2014-2019.

Line	Regression parameters	Surface (furrow) n = 74,576	Centre Pivot n = 7,140	Sprinkler n = 23,547
B vs T	slope	0.0777	0.0827	0.0824
	R^2	0.958	0.965	0.971
B vs ET_a	slope	0.0653	0.0694	0.0689
	R^2	0.915	0.948	0.954
B vs $\sum(T/ET_{ref})$	slope	4.224	4.300	4.288
	R^2	0.928	0.978	0.971

4.2 Water Consumption

Figure 4-4 shows the average annual ET_a and T over the period 2014-2019 for the different irrigation methods and Wake Tio, as well as the average annual ET_a and T for Welenchiti, and the 6-year average annual precipitation over the total area of 645 mm/year. The spatial distribution of 6-year average annual ET_a and T for the L3 area in Wonji sugarcane estate are shown in Figure 4-5a and b. Figure 4-6 shows the spatial distribution of the annual average ET_a (a) and T (b) for Welenchiti for the period 2015-2019. The maps for the individual years are shown in Appendix A.6.

The average annual ET_a in the L3 area is 1,578±190 mm/year. It varies slightly over the different irrigation areas. The land irrigated by centre pivots has the highest average ET_a (1,622±167 mm/year) compared to the land irrigated by sprinkler irrigation (1,584±252 mm/year), furrow irrigation (1,581±155 mm/year) and Wake Tio (1,492±258 mm/year). The transpiration for the whole area has a mean value of 1,320±178

mm/year. The transpiration is also highest for centre pivots (1,356±160 mm/year), followed by furrow irrigation (1,322±148 mm/year) and sprinkler irrigation (1,322±235 mm/year). The transpiration for Wake Tio is 1,260±238 mm/year.

For the data at L2, one of the input datasets is the land surface temperature of MODIS, at a 1km resolution. The difference in spatial resolution might influence the determined evaporation and transpiration for areas where the land surface temperature pixel is not fully covering (irrigated) cropland, as described in detail in the WaPOR Methodology (FAO, 2020). Appendix 7A.7 shows the location of the different LST pixels with respect to the area of Welenchiti.

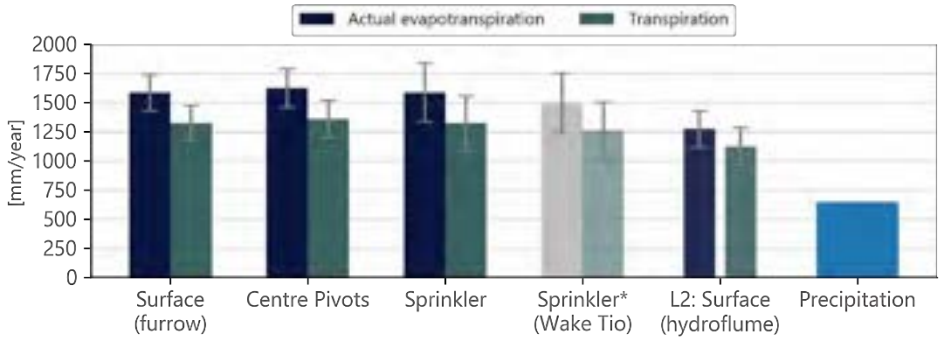
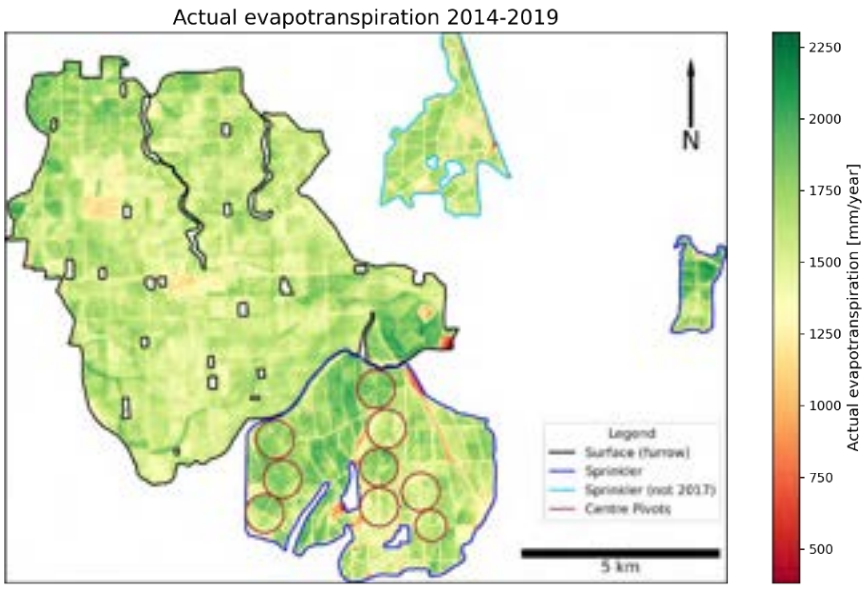
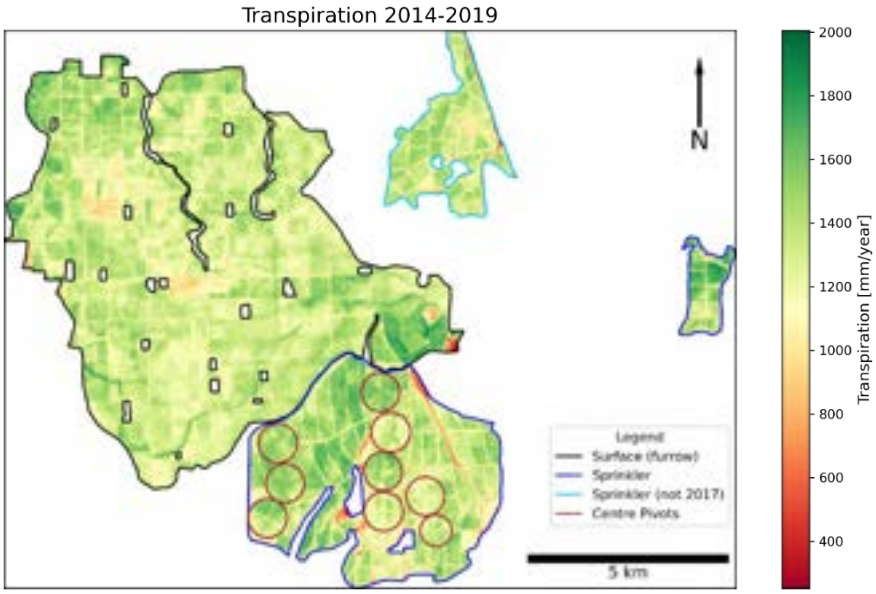


Figure 4-4: Average annual actual evapotranspiration (ET_a) and transpiration (T), categorized by irrigation method, and data level (30m and 100m for L2), and the average annual precipitation in the area for the period 2014-2019. The error bar indicates the standard deviation across the pixels per irrigation method.



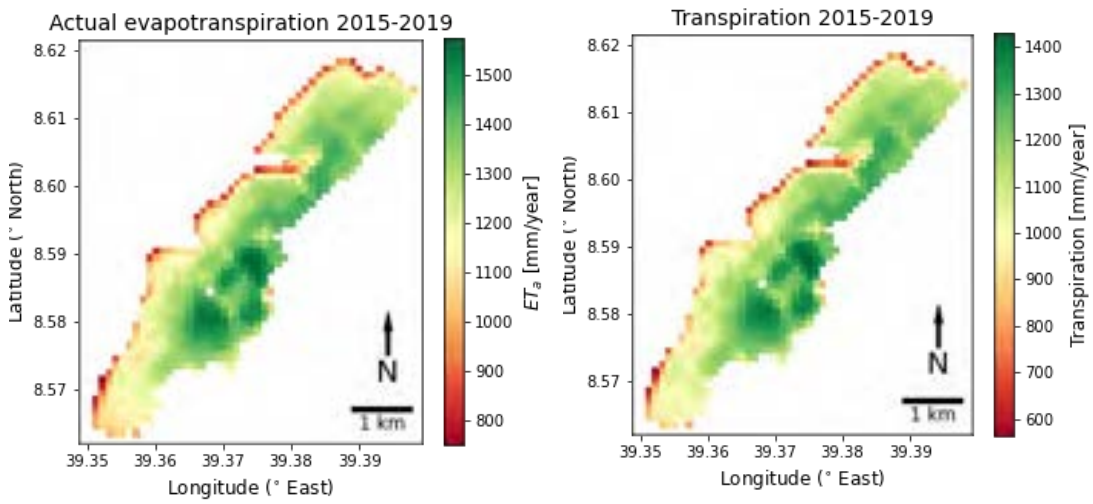
(a)



(b)

Figure 4-5: Spatial distribution of the average annual ET_a (a), and T (b) over the period 2014-2019 for Wonji Sugarcane estate area available at 30 m resolution (L3).

The average annual ET_a for Welenchiti is 1,272±157 mm/year. The average annual ET_a for Welenchiti ranges between 563 and 1,429 mm/year, and for T between 560 and 1,430 mm/year, with a mean value of 1,124±160 mm/year.



(a) (b)

Figure 4-6: Spatial distribution of the average annual ET_a (a), and T (b) over the period 2015-2019 for Welenchiti area in Wonji Sugarcane estate (L2).

4.3 Uniformity

The evenness of the water supply in an irrigation scheme (uniformity) can be assessed with the coefficient of variation (CV) of ET_a. Figure 4-7 shows the CV of ET_a for the different irrigation methods for the average annual ET_a for the period 2014-2019 (Figure 4-5 and Figure 4-6). The uniformity of the ET_a in the total L3 area (Wake Tio included) is 12%. For the areas under surface irrigation (furrow), centre pivot irrigation and

sprinkler irrigation the CV of ET_a are respectively 9.8%, 10.3% and 15.9%. Wake Tio has, with 17.3%, the lowest performance on uniformity, but still well within the range of fair uniformity. The uniformity for the L2 area is 12.4%. Overall, the Wonji has a fair uniformity, with good uniformity in the surface (furrow) irrigated area of Wonji Main.

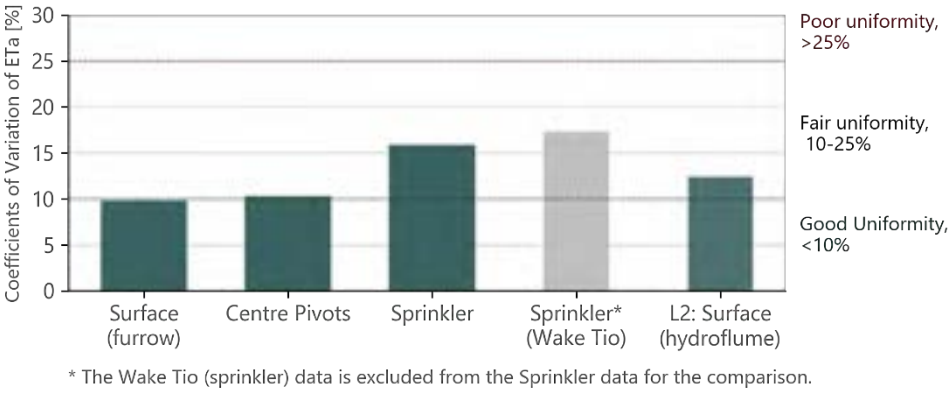


Figure 4-7: Coefficient of variation of the annual average ET_a at Wonji sugarcane estate categorized by irrigation method and spatial resolution.

4.4 Adequacy

The adequacy is a measure to what extent the irrigated water delivered meets the required water consumption by the crops. In this study, this was simplified to the ratio of ET_a over ET_{ref} (Equation 3). From this simplified methodology, the results show the highest adequacy for the areas with centre pivot irrigation (adequacy of 0.83±0.08), followed by the sprinkler irrigated area (0.81±0.13), and lowest of the L3 area for the furrow irrigated area (0.77±0.08). Wake Tio has the lowest score on adequacy (0.70±0.12), since the ET_{ref} for Wake Tio is much higher than for to the rest of the L3 areas (Table 4-1).

Welenchiti has an adequacy of 0.61±0.08). The spatial distribution of the adequacy (2014-2019) for the L3 area and the L2 area are provided in Figure 4-9 and Figure 4-10, and seasonal maps are provided in Appendix A.8.

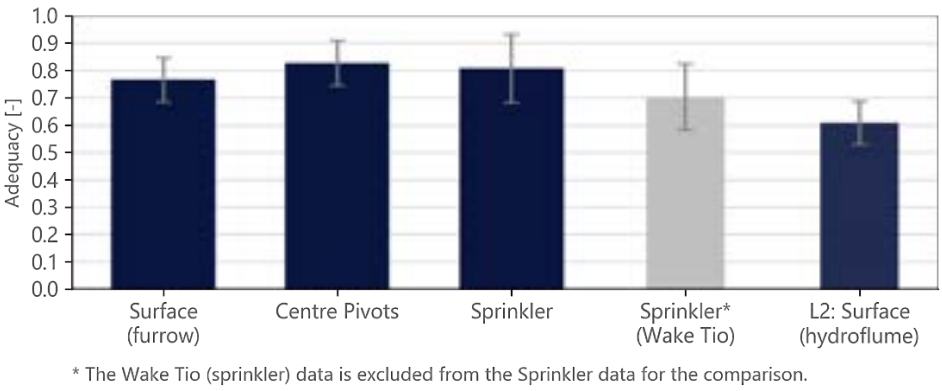


Figure 4-8: Adequacy of the average annual water consumption at Wonji sugarcane estate categorized by irrigation method and spatial resolution.

The simplification of using ET_{ref} instead of the required evapotranspiration (ET_{req}) does not take into account the variation in ET_{req} between different irrigation methods, irrigation frequency and soil type (Allen et al. 1998, eq. 59, Table 20, Figure 29 and Figure 30). Compared to furrow irrigation, centre pivots and sprinklers have a higher intrinsic evaporation rate, which is influenced by the atmospheric demand.

As highlighted by Chukalla et al. (2020a), to perform a meaningful adequacy assessment, one thus needs to be able to assess the differential ET_{req} per irrigation method requiring additional information from the field. Caution in interpreting the results is needed as the higher ET_a / ET_{ref} ratio for centre pivots largely determined by the fact that these require more water (and ET_a) than other irrigation methods (see also Chukalla et al., 2020a).

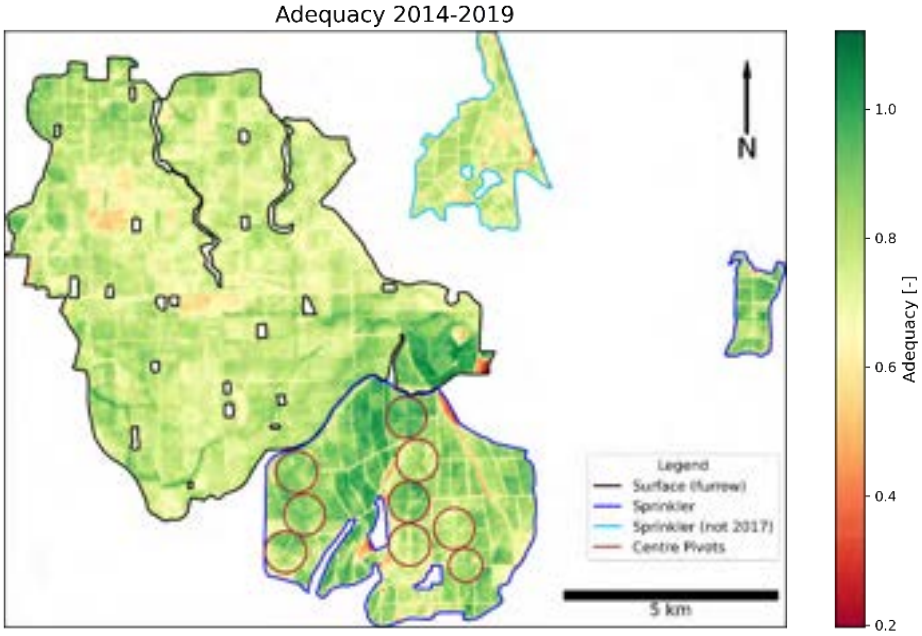


Figure 4-9: Spatial distribution of the adequacy at Wonji sugarcane estate at L3.

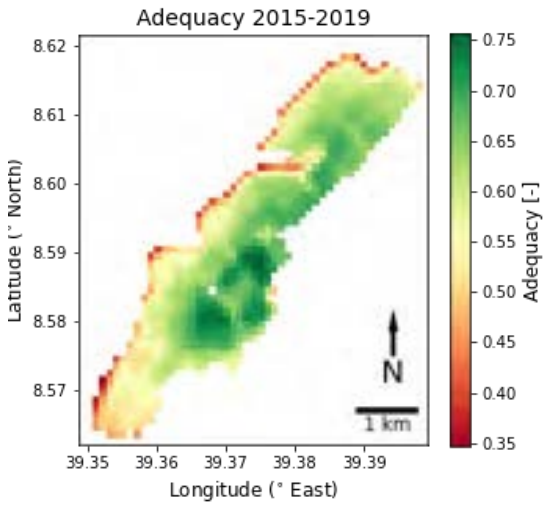


Figure 4-10: Spatial distribution of the adequacy at Welenchiti, part of Wonji sugarcane estate, at L2.

In addition to assessing the adequacy, inter-seasonal variations in the ratio ET_a / ET_{ref} give an indication of the adjustment of the irrigation application to the climatic conditions. The data presented in Table 4-3,

shows the lowest inter-seasonal variation in ET_a/ ET_{ref} for the areas that are irrigated by sprinkler irrigation (CV=3.31%), suggesting a better adjustment of the irrigation application to the climatic conditions. The data also suggest that there could be further room for improvement in adjusting the irrigation application to the climatic conditions for centre pivot irrigation, and the furrow irrigation.

Table 4-3: Seasonal water consumption [mm/year], reference evapotranspiration [mm/year] and ratio between those for the different irrigation methods in the L3 area and the L2 area of Welenchiti of Wonji.

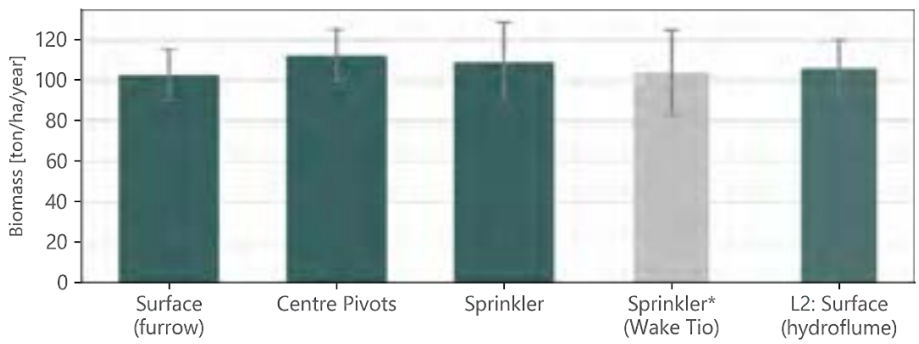
	Surface (furrow)			Centre Pivot			Sprinkler			L2 : Surface (hydroflume)		
Season	ET_{ref}	ET_a	$\frac{ET_a}{ET_{ref}}$	ET_{ref}	ET_a	$\frac{ET_a}{ET_{ref}}$	ET_{ref}	ET_a	$\frac{ET_a}{ET_{ref}}$	ET_{ref}	ET_a	$\frac{ET_a}{ET_{ref}}$
2014	1,982	1,461	0.74	1,890	1,746	0.92	1,894	1,450	0.77			
2015	2,190	1,710	0.78	2,080	1,708	0.82	2081	1,683	0.81	2,213	1,299	0.59
2016	1,969	1,591	0.81	1,900	1,641	0.86	1,900	1,570	0.83	1,976	1,193	0.60
2017	2,186	1,632	0.75	2,068	1,531	0.74	2,071	1,631	0.79	2,221	1,294	0.58
2018	2,005	1,467	0.73	1,899	1,506	0.79	1,893	1,587	0.84	2,007	1,242	0.62
2019	2,068	1,625	0.79	1,951	1,602	0.82	1,945	1,584	0.81	2,075	1,343	0.65
CV	*4.83%*	*6.24%*	*4.01%*	*4.46%*	*5.86%*	*7.55%*	*4.52%*	*4.91%*	*3.31%*	*5.44%*	*5.20%*	*4.33%*

4.5 Productivity

4.5.1 Land productivity and biomass water productivity

The average annual biomass production per irrigation method for the period 2014-2019 is shown in Figure 4-11. A variation in land productivity per irrigation method is observed, the highest biomass production is estimated for the centre pivot irrigated area (112±13 ton/ha/year), followed by sprinkler (109±20 ton/ha/year), and furrow (103±13 ton/ha/year). The average biomass production over the areas with the three irrigation methods combined is 105±15 ton/ha/year. The biomass production of Wake Tio is 104±21 ton/ha/year.

In Welenchiti, the estimated biomass production is 106±14 ton/ha/year. The spatial distribution of the average biomass production in the period 2014-2019 is shown in Figure 4-12 for the L3 area and in Figure 4-13 for Welenchiti (annual maps are provided in Appendix A.9).



* The Wake Tio (sprinkler) data is excluded from the Sprinkler data for the comparison.

Figure 4-11: Average annual biomass production [ton/ha/year] for the period 2014-2019, categorized by irrigation method, and data level (30 m and 100 m for L2). The error bar indicates the standard deviation across the standard deviation across the pixels per irrigation method.

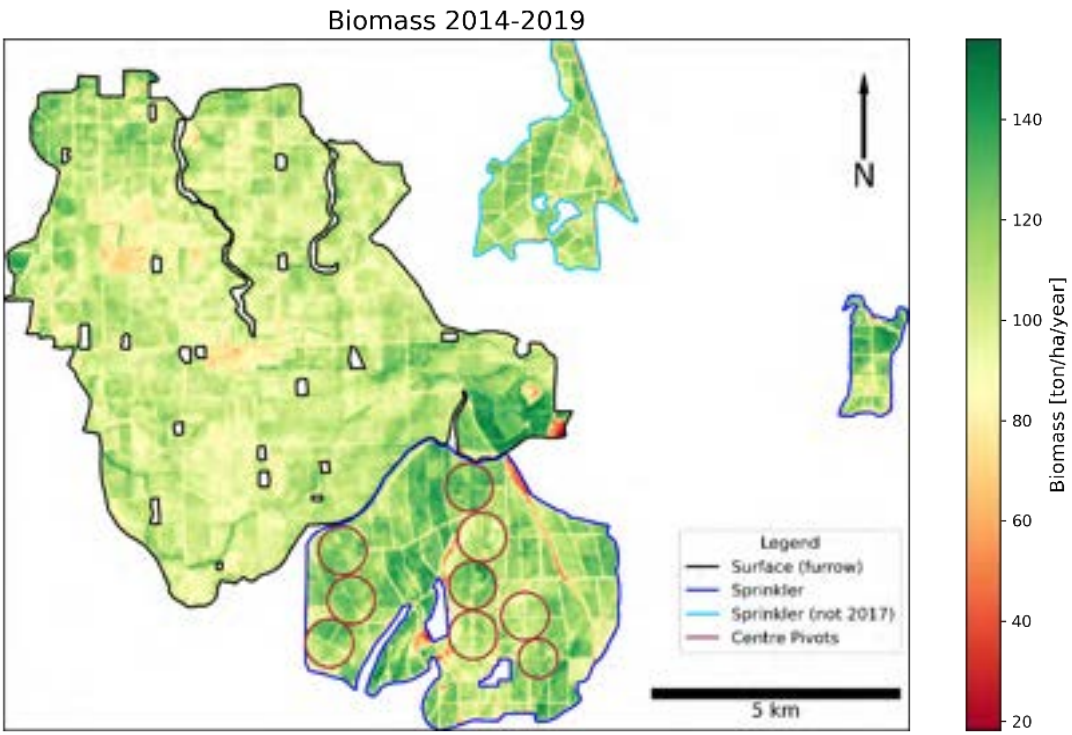


Figure 4-12: Spatial distribution of the average annual biomass production [ton/ha/year] over the period 2014-2019 for Wonji Sugarcane estate area available at 30 m resolution (L3).

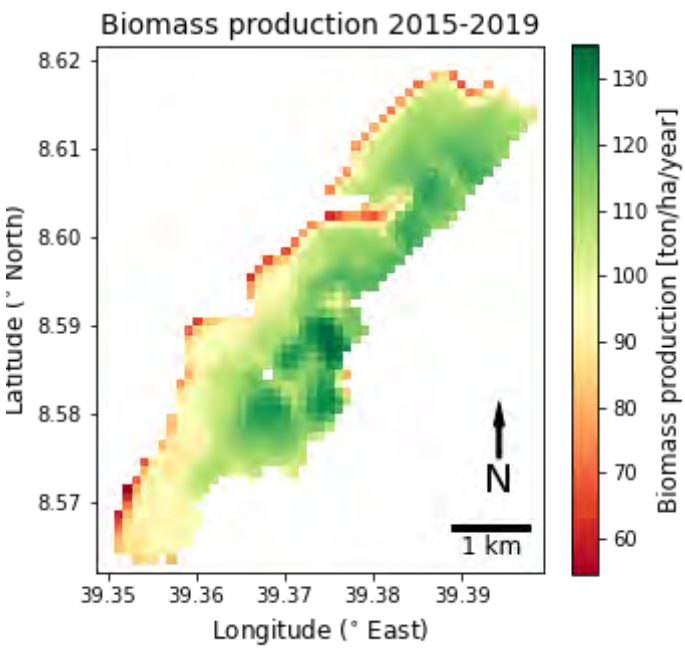


Figure 4-13: Spatial distribution of the average annual biomass production [ton/ha/year] over the period 2015-2019 at Welenchiti, part of Wonji sugarcane estate, at L2.

In Table 4-4 the results of the WaPOR analysis are compared with the sugarcane production data of Wonji as presented in Table 1-6 (Wonji-Shoa Sugar Factory, 2020). From the seasonal data, first the annual

production was calculated with use of the average growing season. This can then be compared with the yield estimated with WaPOR biomass and a literature based harvest index. Both the field data and the estimated yield indicate that Wonji Main has the lowest production, and Ulaga the highest production of the areas within the L3 boundaries. The differences between the observed yield and the estimated yield from WaPOR biomass could be explained by the use of the calculated inter-seasonal average biomass for the comparison, as well as by the estimates made, such as the exact season length per irrigation scheme and the harvest index set at one value for all areas.

Table 4-4: Comparison of the yield estimated with WaPOR per irrigation area and the sugarcane production in Wonji per season.

Irrigation Scheme	Irrigation Method	Duration of season [months]	Sugarcane production per season [ton/ha]	Annual sugarcane production [ton/ha/year]	Biomass WaPOR [ton/ha/year]	Yield WaPOR [ton/ha/year]	Difference WaPOR – field [%]
Wonji Main	Surface (furrow)	18	100	66.7	102.6	70.79	6%
Dodota*	Centre Pivot and sprinkler	18	120	80.0	109.6	75.59	-6%
Wake Tio	Sprinkler	18	120	80.0	103.8	71.62	-11%
Ulaga	Sprinkler	18	130	86.7	110.6	76.31	-13%
Welenchiti (L2 – 100 m)	Surface (hydroflume)	25	140	67.2	105.9	73.07	8%

Note. Data for sugarcane production per season form Wonji-Shoa Sugar Factory (2020).

**The WaPOR data is analysed for Dodota without separating between the two different irrigation methods.*

Figure 4-14 shows the average annual biomass water productivity (WP_b). The highest WP_b is observed for the areas irrigated by centre pivots with an average annual value of 6.9±0.2 kg/m^3, and for Wake Tio (WP_b=6.9±0.3 kg/m^3). This is followed by the areas irrigated with sprinklers (6.8±0.2 kg/m^3) and the area irrigated with furrow irrigation has the lowest WP_b of 6.5±0.2 kg/m^3. The average WP_b over the three irrigation methods is 6.6±0.3 kg/m^3. Figure 4-15 shows the spatial distribution of the WP_b.

For Welenchiti, the WP_b has the high value of 8.3±0.3 kg/m^3. The spatial distribution of the WP_b (Figure 4-16) in Welenchiti shows a clear spatial variation, with in the north of the area values in the range 8.4 – 8.9 kg/m^3. The seasonal spatial variation is provided in Appendix A.10.

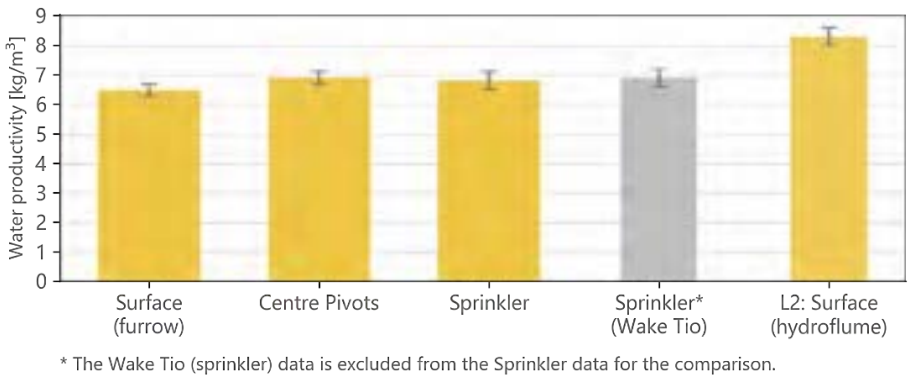


Figure 4-14: Average annual biomass water productivity [kg/m^3] for the period 2014-2019, categorized by irrigation method, and data level (30 m and 100 m for L2). The error bar indicates the standard deviation across the pixels per irrigation method.

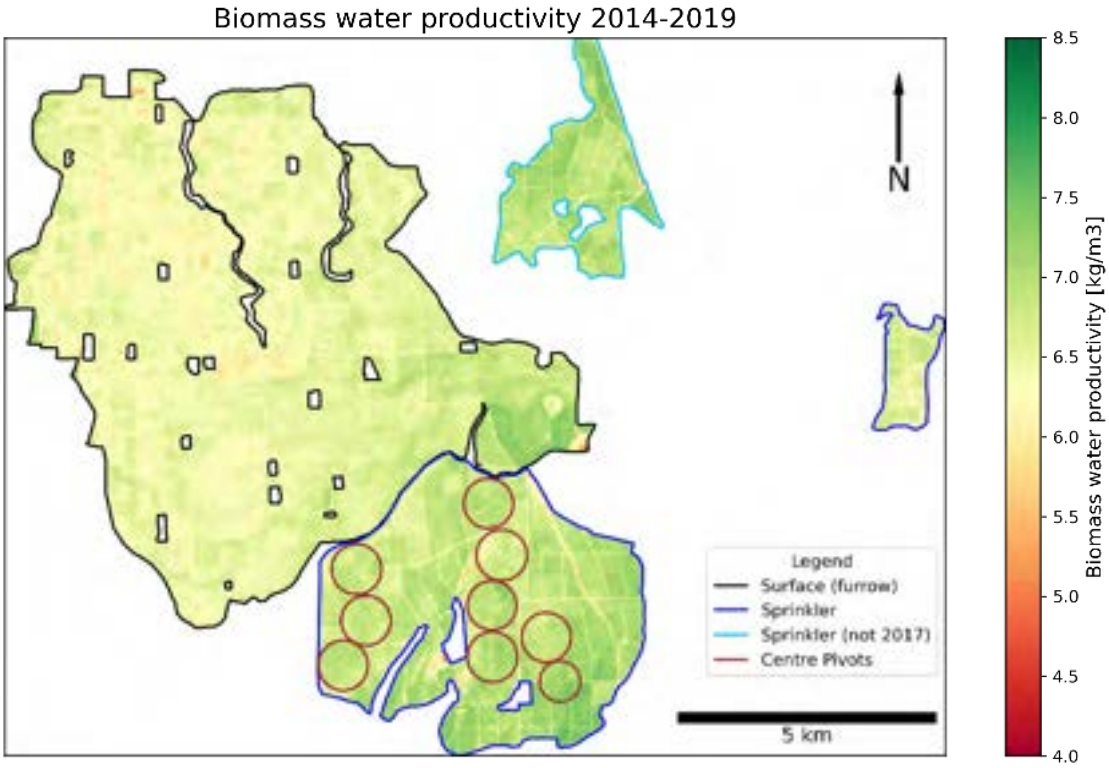


Figure 4-15: Spatial distribution of the average annual biomass water productivity [kg/m^3] over the period 2014-2019 for Wonji Sugarcane estate area available at 30 m resolution (L3).

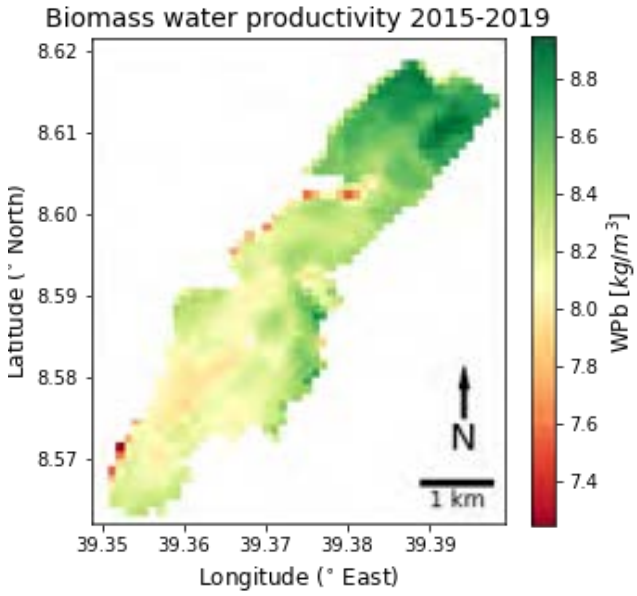


Figure 4-16: Spatial distribution of the average annual biomass water productivity [kg/m^3] over the period 2015-2019 at Welenchiti, part of Wonji sugarcane estate, at L2.

4.5.2 Agronomic diagnostic of water productivity for different irrigation methods in Wonji

In this section, the results of the irrigation methods are further analysed, based on the results of the different indicators and the relationships between the biomass and the different water consumptions, as presented in Section 4.1.

The irrigation methods have different characteristics, resulting in different evaporation rates. By using overhead sprinkler irrigation (which includes centre pivots), the entire soil surface is wetted (wetted fraction f_w=1.0 (Allen et al. 1998, Table 20), contributing to the soil evaporation. In addition, the water consumption over overhead sprinklers is affected by interception from the canopy and wind dispersal. With furrow irrigation, no interception of irrigation water from the canopy will take place, and only part of the soil surface is wetted (f_w = 0.6-0.8), leading to a lower soil evaporation when the canopy is not fully developed. Therefore, the evaporation of furrow irrigation is expected to be lower compared to sprinkler and centre pivot irrigation, and with that the WP_b higher. It is expected that the results for centre pivot irrigation and overhead sprinkler irrigation are more similar, as they have similar characteristics.

The results for the WP_b differentiated per irrigation method and season, provided in Table 4-5, do not completely confirm this agronomic expectation. For all years, furrow irrigation has the lowest WP_b, in contrast to the expectations. The results for centre pivot and sprinkler irrigation are close together, as expected, with centre pivot having a slightly higher WP_b in 3 of the 6 years, and sprinkler irrigation has the highest WP_b in 2016 and 2017. The WP_b shows a strong statistical correlation for all years and the different irrigation methods.

The WP_b values have a fairly small inter-seasonal variation, as is shown by the coefficient of variation in Table 4-5. Furrow irrigation shows the lowest inter-seasonal variation, and centre pivots the highest. The evaporation rate of centre pivots and sprinkler are most susceptible to changes in ET_{ref}. Figure 4-17 shows that the WP_b decreases when the climatic evaporative demand (ET_{ref}) increased. No clear difference in the influence of climatic evaporative demand on the WP_b on separate the irrigation methods can be observed based on these results.

Table 4-5: Linear regression parameters for the relationship between biomass (ton/ha/year) and actual evapotranspiration (ET_a in mm/year) per irrigation method.

Season	Surface (furrow) (n = 74,576)			Centre Pivot (n = 7,140)			Sprinkler (n = 23,547)		
	ET_{ref}	slope	R^2	ET_{ref}	slope	R^2	ET_{ref}	slope	R^2
2014	1,982	0.070	0.956	1,890	0.074	0.984	1,894	0.072	0.968
2015	2,190	0.061	0.944	2,080	0.065	0.943	2,081	0.064	0.940
2016	1,969	0.067	0.934	1,900	0.070	0.947	1,900	0.071	0.946
2017	2,186	0.061	0.912	2,068	0.064	0.975	2,071	0.066	0.927
2018	2,005	0.068	0.930	1,899	0.074	0.958	1,893	0.074	0.960
2019	2,068	0.065	0.926	1,951	0.070	0.973	1,945	0.069	0.965
CV [%]		5.48			6.17			5.66	

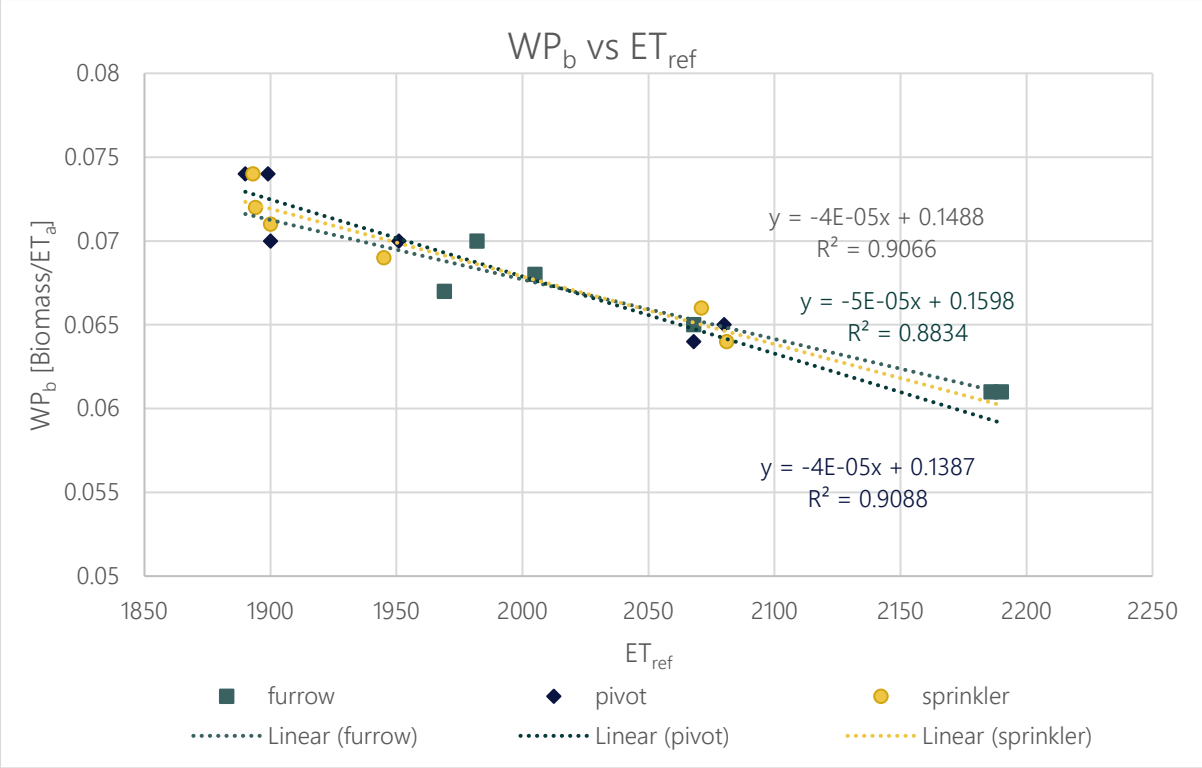


Figure 4-17: Annual WP_b per irrigation method over ET_{ref}

As Chukalla et al. (2020a) indicated, the shape and width of the data clouds (as presented in Appendix 5) can be influenced by differences in evaporation per pixel, as a result of differences in: I) irrigation frequencies; II) timing, frequency and quality of WaPOR image capture[5]; III) a combination of both; and, IV) differences in agronomic performance of the crop that lead to lower crop transpiration and productivity. To get a better understanding of the results presented above, the non-beneficial evaporation component can be eliminated from the WP analysis, which would thus result in a more robust $WP_{b(T)}$ ratio (de Wit, 1958; Steduto et al., 2007).

Where the latter would be the case under non-limiting nutrient conditions, or similar nutrient conditions across the different areas (Perry et al., 2009). When there would be limiting nutrient conditions in one of the areas, the $WP_{b(T)}$ is expected to be lower for that area. However, even then the difference in evaporation rate between the irrigation methods should be reflected when comparing $WP_{b(T)}$ with the WP_b results of the same season. For irrigation methods with a high evaporation rate (centre pivot and sprinkler), the difference between WP_b and $WP_{b(T)}$ would be larger compared to furrow irrigation, which has a lower evaporation rate.

The 6-year average results of $WP_{b(T)}$, Table 4-2, shows for all irrigation methods an increase in the water productivity for $WP_{b(T)} = B/T$ and a smaller spread of the data cloud (higher R^2), both are observed for all individual seasons. The results of the seasonal data for $WP_{b(T)}$ and $WP_{b(T/ETref)}$ are provided in Appendix A.5. These seasonal results show a smaller inter-seasonal variation in $WP_{b(T)}$ (CV values between 4.79% for sprinkler to 5.01% for furrow) as compared to WP_b. These observations are according to the expectations (I)-(III) as described above.

[5] As defined by the Richie method (Allen et al., 1998) evaporation is a highly temporal phenomena; typically, high just after irrigation and quickly reducing to low rates (depending on soil type and climatic conditions) in a matter of 3-6 days. The timing and number of images on which the WaPOR analysis is based may thus influence this outcome.

Besides it is expected that there is a smaller difference between the water productivity of the different irrigation methods when considering only transpiration (T) instead of the actual evapotranspiration (ET_a). However, this cannot be observed when comparing the different irrigation (Table 4-2, Table 4-6 and Appendix A.5). The values for $WP_{b(T)}$ for furrow irrigation do not approach the same value as much as the sprinkler and centre pivot do, nor does the difference between the irrigation methods convincingly increase compared to WP_b. These observations are not expected with the different intrinsic evaporation rates for the irrigation methods. A possible reason for this could be that the partitioning of ET_a into E and T by WaPOR does not work adequately enough to distinguish the difference in evaporation rate between the irrigation methods. There could be an over attribution of T for sprinkler based systems, as has previously been indicated in studies conducted with L2 data of WaPOR (Chukalla et al., 2020a; WUR, 2020). This over attribution might be caused by the methodology of ETlook to estimate transpiration based on the energy balance at canopy level. Through this, the interception from sprinkler irrigation might be considered as transpiration, instead of evaporation. An over attribution of T will lead to a lower calculated $WP_{b(T)}$ for sprinkler based systems, compared to the actual $WP_{b(T)}$, leading to a larger difference between the $WP_{b(T)}$ for furrow and the sprinkler based methods. However, also the difference in atmospheric evaporative demand between the areas may play a role in the variations in $WP_{b(T)}$.

When the data is normalized for climatic conditions ($WP_{b(T/ETref)}$), the inter-seasonal variability per irrigation method becomes lower, with CV values ranging of 1.06% for furrow, 1.56% for sprinkler, and 1.78% for centre pivot (Table 4-2 and Table 4-7). Furrow irrigation has the lowest $WP_{b(T/ETref)}$ also for the individual years. The estimated 6-year average $WP_{b(T/ETref)}$ for sprinkler and centre pivot are very close, respectively 4.30 ton/ha/year and 4.29 ton/ha/year. Figure 4-18 shows for each irrigation method the relationship between $WP_{b(T)}$ and ET_{ref}, and the relationship between $WP_{b(T/ETref)}$ and ET_{ref}.

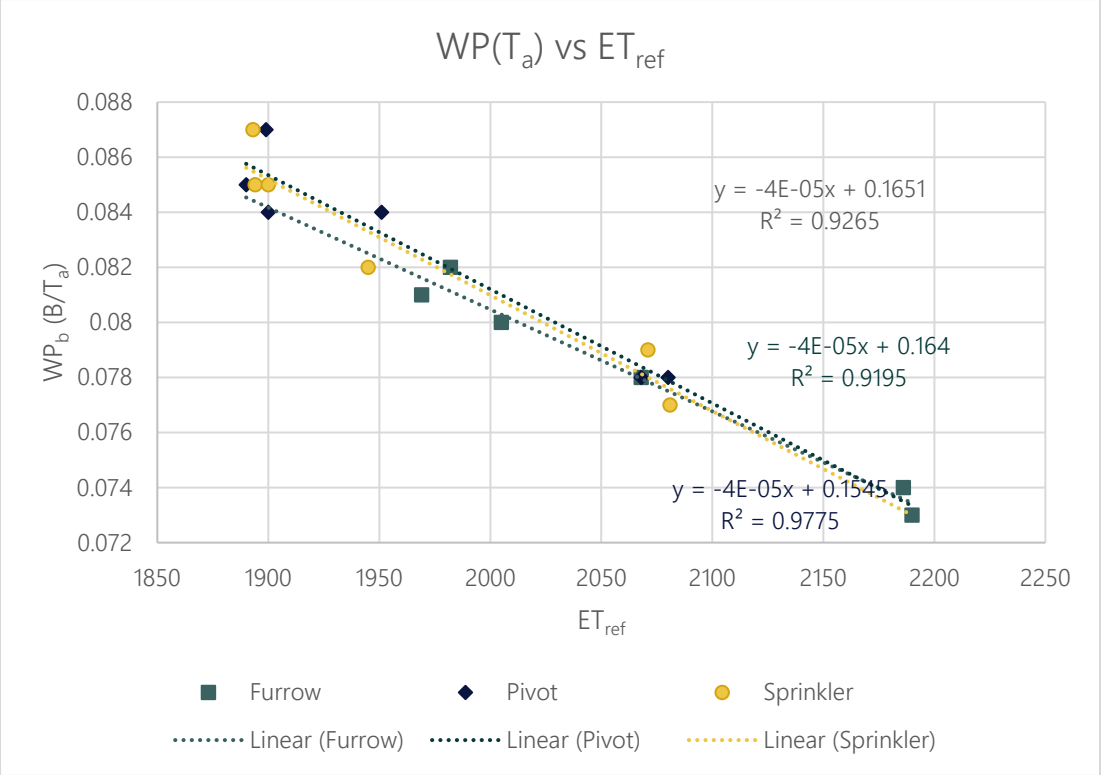
The results show for furrow irrigation the lowest water productivity for each type of water consumption. From the results for $WP_{b(T)}$ and $WP_{b(T/ETref)}$, it follows that these differences are not induced by the irrigation application method, or climatic conditions. Therefore, this low WP_b is likely the result of hydrated soils and limiting nutrient conditions. This is in agreement with observations from the field, as Wonji main is by far the oldest scheme within the entire estate (see Table 1-2), and the continuous irrigation practice and monotonous fertiliser application has reduced the water holding capacity (prolonged ponding in the furrows) as well as depleted the available phosphorus in the soil.

Table 4-6: Linear regression parameters for the relationship between biomass (ton/ha/year) and Transpiration (*T* in mm/year) per irrigation method.

Season	Surface (furrow) (n = 74,576)			Centre Pivot (n = 7,140)			Sprinkler (n = 23,547)		
	ET_{ref}	slope	R^2	ET_{ref}	slope	R^2	ET_{ref}	slope	R^2
2014	1,982	0.082	0.981	1,890	0.085	0.987	1,894	0.085	0.979
2015	2,190	0.073	0.973	2,080	0.078	0.987	2,081	0.077	0.969
2016	1,969	0.081	0.980	1,900	0.084	0.969	1,900	0.085	0.979
2017	2,186	0.074	0.960	2,068	0.078	0.987	2,071	0.079	0.957
2018	2,005	0.080	0.957	1,899	0.087	0.979	1,893	0.087	0.975
2019	2,068	0.078	0.949	1,951	0.084	0.977	1,945	0.082	0.977
CV [%]		5.01			4.87			4.79	

Table 4-7: Linear regression parameters for the relationship between biomass (ton/ha/year) and normalized transpiration $\sum(T/ET_{ref})$ per irrigation method.

Season	Surface (furrow) (n = 74,576)			Centre Pivot (n = 7,140)			Sprinkler (n = 23,547)		
	ET_{ref}	slope	R^2	ET_{ref}	slope	R^2	ET_{ref}	slope	R^2
2014	1,982	4.295	0.957	1,890	4.328	0.995	1,894	4.304	0.987
2015	2,190	4.179	0.953	2,080	4.268	0.986	2,081	4.231	0.969
2016	1,969	4.267	0.965	1,900	4.392	0.967	1,900	4.324	0.988
2017	2,186	4.200	0.940	2,068	4.216	0.989	2,071	4.263	0.964
2018	2,005	4.251	0.958	1,899	4.410	0.983	1,893	4.401	0.972
2019	2,068	4.205	0.967	1,951	4.266	0.982	1,945	4.223	0.975
CV [%]		1.06			1.78			1.56	



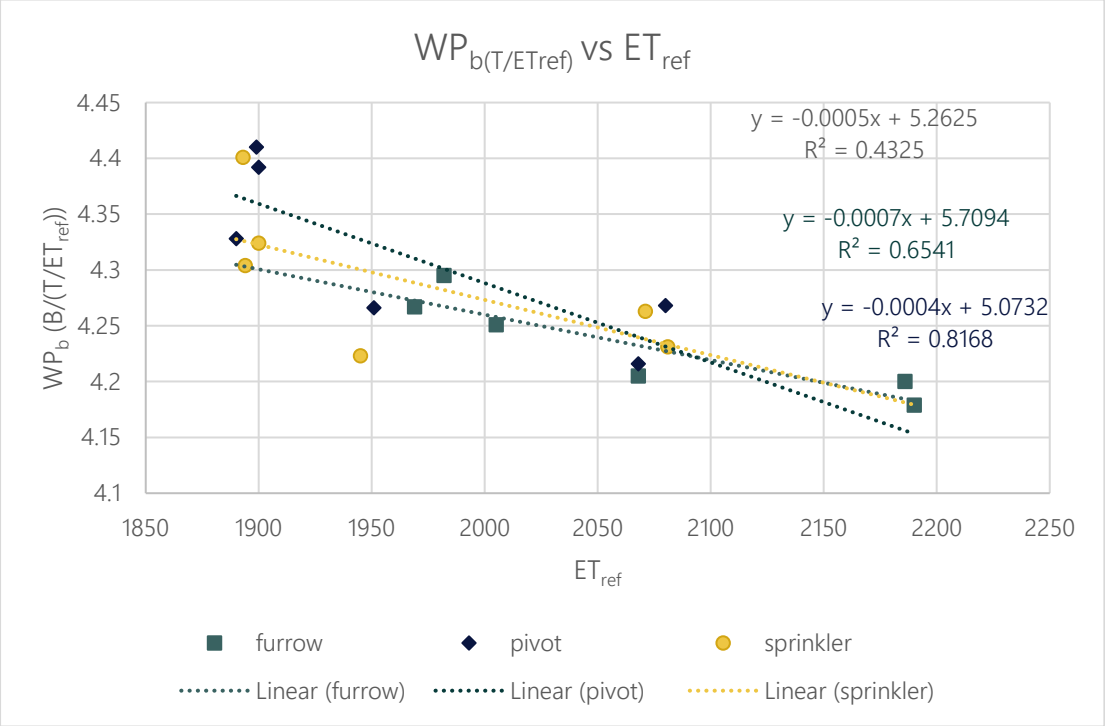


Figure 4-18: Annual *WPb* for transpiration (top) and normalized transpiration (bottom) per irrigation method over *ETref*.

4.5.3 Inter-seasonal patterns in water productivity

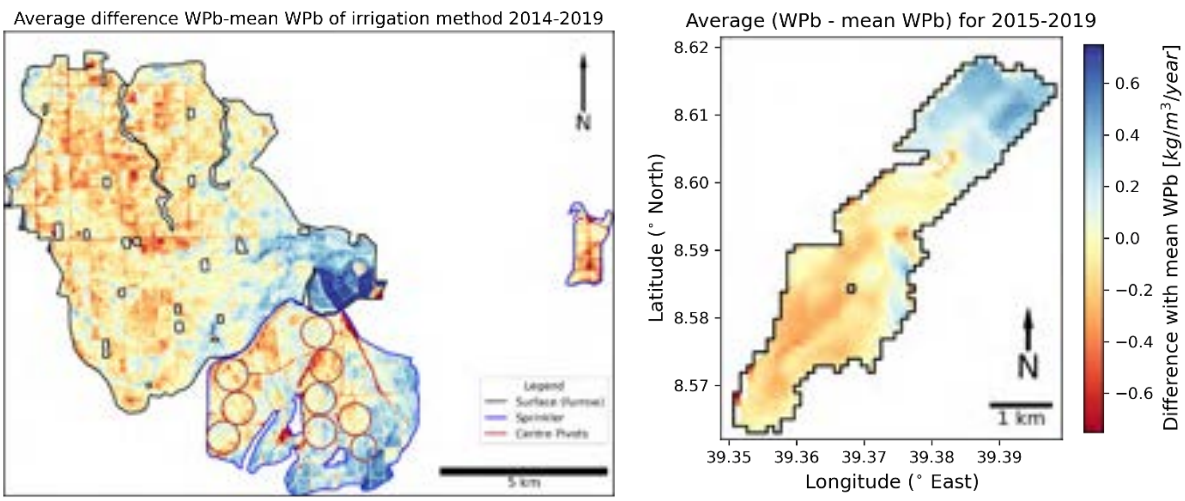
The nutrient status of crops is influenced primarily by two aspects: i) the fertilizer/manure application and management of the farm; ii) the soil type/condition – i.e. clayey soils and high organic matter content tend to have a higher nutrient holding capacity with a timelier release for plant uptake. Soil type, and condition,

is a physical geographical bounded characteristic one can expect to be spatially distinguishable. Fertilizer management is determined by agronomic practices of the farmer or farm labourer. In Wonji, the fertilizer application is the same of all soils, and depends on whether the plot has the first planting of cane or ratoon crops.

If the nutrient status of the crops has a discernible effect on the water productivity WP_b of sugarcane in Wonji, differential slopes of WP_b within the datasets should be visible that are both statistically significant and spatially discernible. The shape of the data clouds for sprinkler irrigation in 2014 and 2019 (Appendix A.5), for instance, appear to show a marked swallowtail pattern that might be indicative of a differential high and low WP_b slope that might be explained by nutrient management.

A first step analysis is conducted by calculating the differences ΔWP_b, based on the mean WP_b for the corresponding irrigation area for that season, so the furrow irrigated areas, the centre pivot areas, and the sprinkler irrigated areas have each a different mean WP_b (see section 4.5.1). Where a positive ΔWP_b indicates optimum productivity, and a negative ΔWP_b a potentially nutrient delimited low WP_b within each seasonal dataset or cloud. In order to be reasonably attributable to the effect of nutrient management, the inter-seasonal high/low productivity should become spatially discernible (i.e. spatially bounded) as soil characteristics are geographically bounded and fertility management is unlikely to change significantly season by season per plot.

Since a hypothetical season of 1 year is used in this study, the spatial pattern of ΔWP_b in individual seasons (years) do not necessarily provide information on nutrient conditions. A seasonal negative ΔWP_b can be caused by soil characteristics, limiting nutrient conditions, by crops that are in the earlier stages of their developed, or the field could have been fallow for part of the year. To limit the impact of the hypothetical seasonality, the average annual ΔWP_b over the total analysed period is calculated for the L3 area and the area of Welenchiti, as presented in Figure 4-19a and b. The maps for the individual years are provided in Appendix A.11.



(a) (b)

Figure 4-19: Period average difference between the annual WP_b of the pixel and the annual WP_b mean of the irrigation area for L3 areas, period 2014-2019 (a) and L2 area, period 2015-2019 (b).

To further rule out the impact of the hypothetical seasonality, the pixels that have a negative ΔWP_b for each of the individual years are selected (Figure 4-20 a and b), and those that have a positive ΔWP_b for all years (Figure 4-20 c and d). The spatial distribution of the results (Figure 4-20a) shows that the areas in the eastern part of Wonji Main, above Dodota, has consistently a higher WP_b than the rest of Wonji Main, on

average more than 0.7 kg/m^3/year higher. It should be noted that this area falls for a large part within a different ET_{ref} pixel than the rest of the area, which has a lower climatic evaporative demand (Appendix A.4). This means that the high WP_b might be influenced by climatic conditions as well. For the sprinkler irrigated area, the areas in the south of Dodota have consistently a higher WP_b. In the north western part of Wonji Main, multiple areas with a lower WP_b (negative ΔWP_b) are observed (Figure 4-20c). The areas a smaller compared to the areas observed in Figure 4-20a, and clearly include noise caused by roads or other infrastructure. However, outside of these noises the consistently low WP_b is observed in the same region, but more seem to be more on a field level, compared to the observed areas with a positive WP_b in Figure 4-20a. For the sprinkler irrigation, a constant negative WP_b is observed in Ulaga.

In Welenchiti, large parts of the northern part have in each year a higher WP_b compared to the area average WP_b (Figure 4-20b). In the south of the area, large areas are observed that have a negative ΔWP_b for each year. Since these areas are large and distinct, it might be linked to soil characteristics.

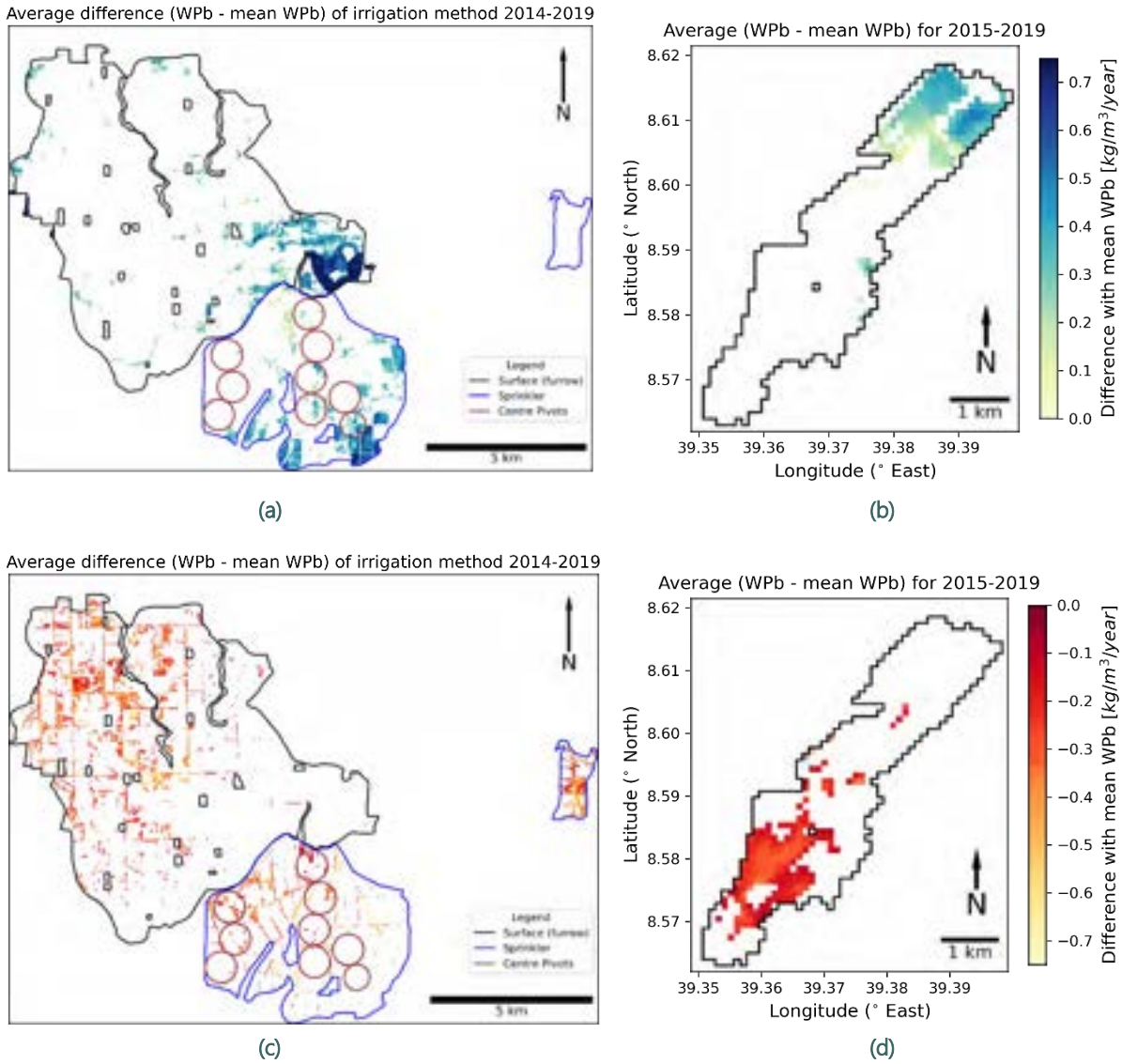


Figure 4-20: Spatial distribution of the pixels that have for each year in the analysed period a higher WP_b (a, b), or a lower WP_b (c, d) than the annual mean WP_b of their irrigated area.

4.6 Productivity Gaps

4.6.1 Land and Water Productivity Targets

Figure 4-21 shows the distribution of the biomass productivity (a) and the biomass water productivity (b) of the annual average values across the L3 area in Wonji over the period 2014-2019. The area of Wake Tio is not taken into account.

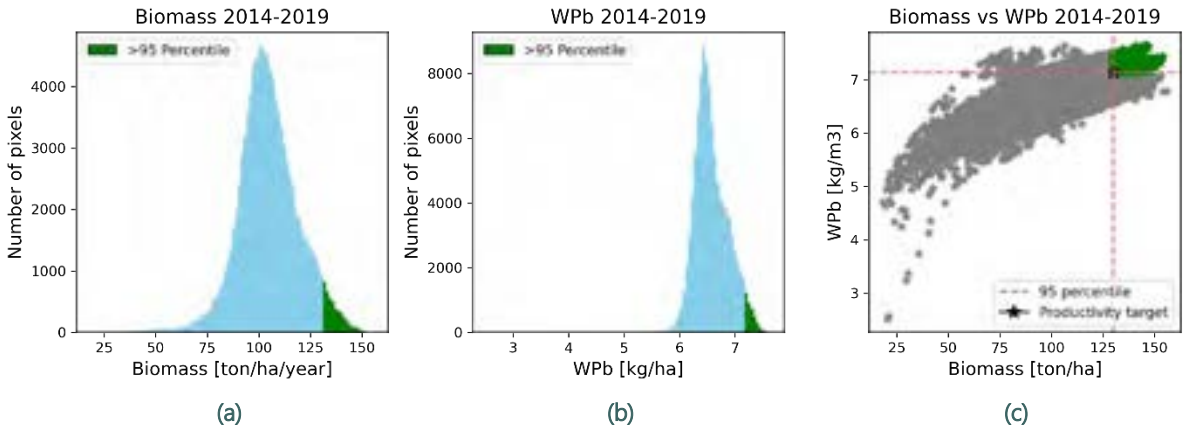


Figure 4-21: Distribution of the average annual biomass production (a) and biomass water productivity for the Wonji Main, Dodota and Ulaga (L3) areas in Wonji of the period 2014-2019. The land productivity (biomass) target and biomass water productivity target (WP_b) at 95 percentile is indicated in green in (a) and (b), and by the red dashed lines in (c).

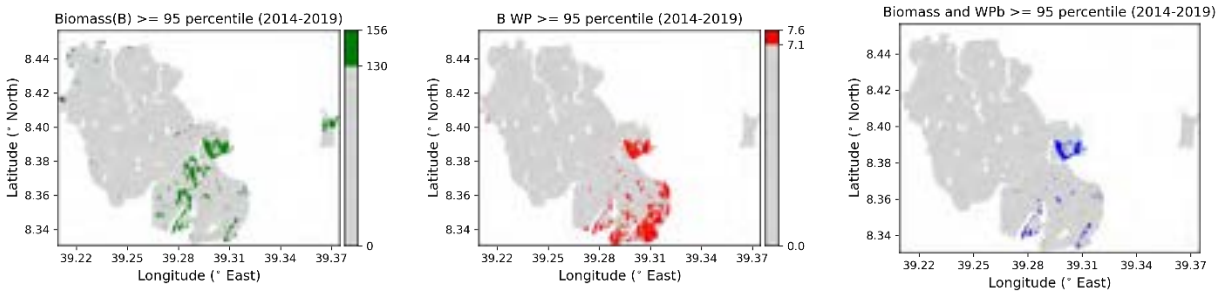
The attainable biomass (land productivity) and WP_b is estimated at the 95-percentille of their respective distribution. In Figure 4-21a-b the biomass and WP_b values that meet or exceed the attainable productivity (productivity target) are indicated in green. In Figure 4-21c, the values of the productivity targets are indicated with the red dashed lines, their interception is marked with the black star. The pixels that meet both the land productivity target and the biomass water productivity target are in the upper right corner of Figure 4-21c, marked in green. Table 4-8 provides the productivity targets and the corresponding ET_a, for the annual average Biomass and WP_b over the period 2014-2019. Figures with the distribution of the biomass and WP_b across Wonji, and the corresponding productivity targets for the individual years are provided in Appendix A.12.

Table 4-8: Biomass, WP_b and ET_a of the target pixel for 2014-2019 for L3 area in Wonji.

Period	Biomass target [ton/ha/year]	WP_b target [kg/m^3]	ET_a at target pixel [mm/year]
2014-2019	130	7.1	1,831

The spatial distribution of the areas that meet the productivity target for only biomass, only WP_b, and those that meet both of the targets, so called bright spots, are shown in respectively Figure 4-22 a, b and c. The results are based on the average annual biomass and WP_b for the period 2014-2019. Figures with the bright spots for the individual years in that period are also provided in Appendix A.12. The identification of the bright spots is important for the identification of best practices, and for drawing lessons to suite the conditions of each pixel.

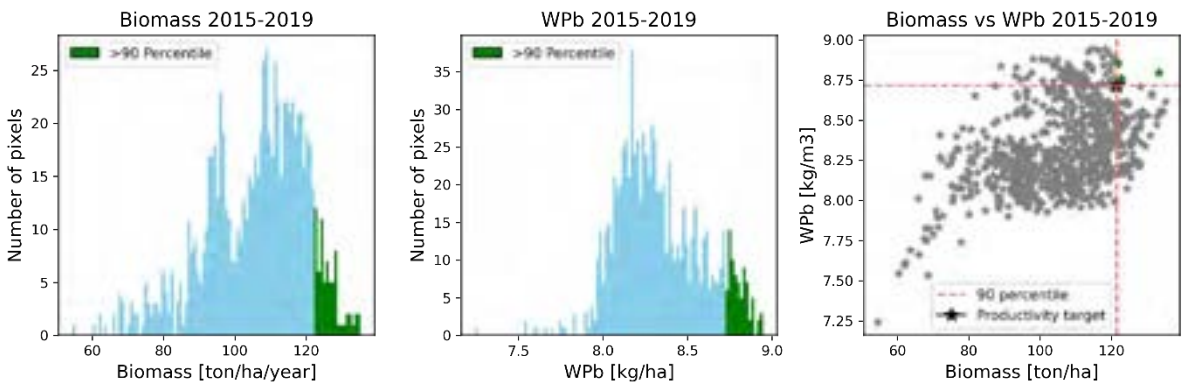
The majority of the areas that meet the land productivity target and the WP_b are located in the most eastern part of Wonji Main (surface irrigation) and Dodota, in both sprinkler irrigated areas and centre pivot irrigated areas. Most of the bright spots (Figure 4-22c) are located in the most eastern part of Wonji Main. Other bright spots are found in the sprinkler irrigated areas in Dodota.



(a) (b) (c)

Figure 4-22: Locations within the L3 area in Wonji where the land productivity target is met or exceeded (a), locations where the biomass water productivity target is met or exceeded (b), and the locations where both targets area met (c) for the 6 year average values (2014-2019).

Figure 4-23 shows the distribution of the pixel values for the average annual Biomass (a) and WP_b (b) over the period 2015-2019 for Welenchiti. For this L2 data, the top 90 percent is used as a target, since there were hardly any pixels in the 5 observed years that met the requirement of being in the best 5% for biomass production and yield. The biomass and WP_b values above the target value are indicated in green in Figure 4-23a and b, and in Figure 4-23c the target values are indicated with the red dashed lines, and the point of interception is indicated with the black star. The productivity targets for the average annual biomass and WP_b over the period 2014-2019, together with the corresponding ET_a, are provided Table 4-9. The annual distribution of the biomass and the WP_b, together with the estimated productivity targets for each year are provided in Appendix A.13.



(a) (b) (c)

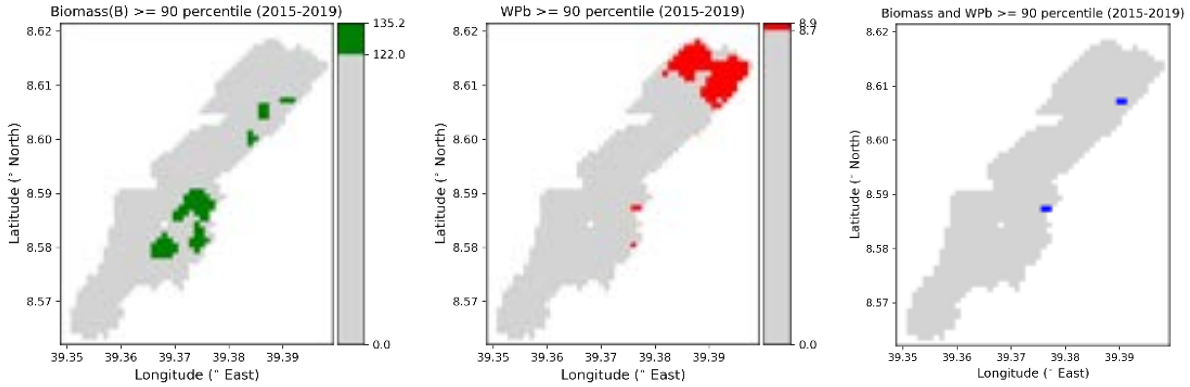
Figure 4-23: Distribution of the average annual biomass production (a) and biomass water productivity the L2 area, Welenchiti, in Wonji of the period 2015-2019. The land productivity (biomass) target and biomass water productivity target (WP_b) at 90 percentile is indicated in green in (a) and (b), and by the red dashed lines in (c). The pixels that meet both productivity targets are indicated with green stars in (c).

Table 4-9: Biomass, WP_b and ET_a of the target pixel for 2015-2019 for L2 area in Wonji.

Period	Biomass target [ton/ha/year]	WP_b target [kg/m^3]	ET_a at target pixel [mm/year]
2015-2019	122	8.7	1,402

Figure 4-24 shows the areas where the land productivity target is met (a), the areas where the water productivity target is met (b), and the areas that meet both productivity targets (c) for the average annual data over the period 2015-2019. Figures with the bright spots for the individual years in that period are also

provided in Appendix A.13. The location of the areas that meet the land productivity target and those that meet the WP_b target vary. A clear majority of the high WP_b is observed in the Northern part of the scheme, whereas the high land productivities is more distributed and located in the east side of the middle part of the scheme. As a result, there are only few pixels identified as bright spots (Figure 4-24 c). The areas that meet the individual targets are clustered, and are also in the individual years observed in the same area.



(a) (b) (c)

Figure 4-24: Locations within the L2 area (Welenchiti) in Wonji where the land productivity target is met or exceeded (a), locations where the biomass water productivity target is met or exceeded (b), and the locations where both targets area met (c) for the 6 year average values (2014-2019).

4.6.2 Production Gaps

For the areas of Wonji Main, Dodota and Ulaga combined, the gap in the 6-year average biomass production (2014-2019) 27±13 ton/ha/year. This corresponds to an average annual production gap for those areas combined of 243,008 tons/year. The WP_b gap for the 6-year average WP_b is 0.6±0.3 kg/m^3. In Welenchiti, the 5-year average biomass gap is 18±12 ton/ha/year. This would mean an increase of 13,570 ton/year. For the 5-year average WP_b in Welenchiti, the WP_b gap is 0.4±0.2 kg/m^3. The annual maps providing the spatial distribution of each year's productivity gaps are provided in Appendices A.14 and A.15.

Figure 4-25 shows the productivity gaps per irrigation method in the L3 area, as average value of the pixels that do not meet the productivity targets for the average annual productivities of the period (2014-2019). The total productivity gaps are 185,520 ton/year for the surface irrigation in Wonji Main, 11,683 ton/year for the centre pivot irrigation in Dodota, and 70,014 ton/year for the sprinkler irrigated areas in Dodota and Ulaga combined.

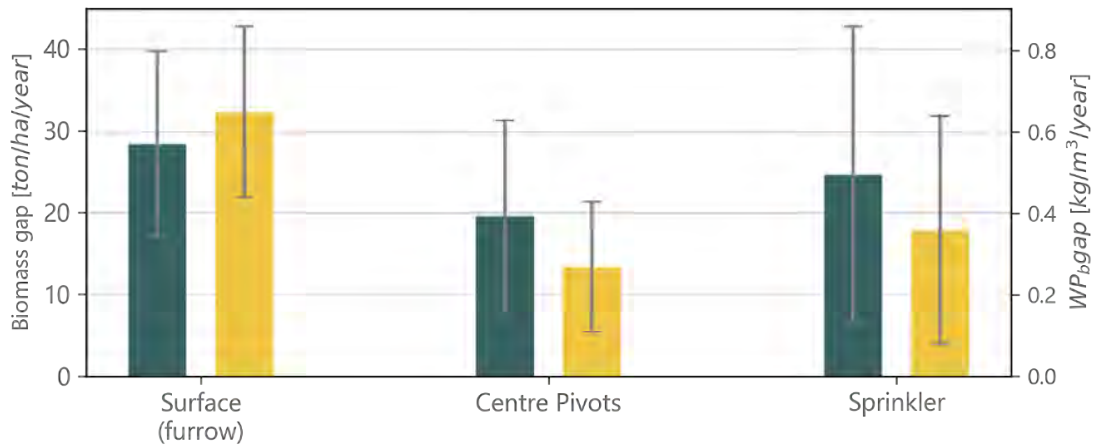


Figure 4-25: Average productivity gaps per irrigation method (L3 area) for the pixels that do not meet the average productivity targets for the period 2014-2019. The error bar indicates the standard deviation across the pixels per irrigation method.

4.6.3 Effect of Closing the Biomass Gap on water consumption

Closing the land productivity gap and the water productivity gap would in most situations require a change in water consumption. An increase in land productivity at the same WP_b requires an increase in ET_a, whereas an increase in only WP_b while keeping the same biomass productivity would need a reduction of ET_a. This is made visible in Figure 4-26, where the biomass production of a pixel is plotted against the WP_b, and coloured according to the ET_a value. All areas (pixels) that do not meet both the land productivity target and the water productivity target can be placed into one of 3 groups identified. The ET_a of the red, yellow and most of the light green pixels needs to increase. The dark green pixels require a reduction of ET_a while maintaining the same biomass production.

The change in water consumption that accompanies meeting the productivity targets is provided in Table 4-10 for the L3 areas Wonji Main, Dodota and Ulaga combined, and for Welenchiti (L2). For the L3 areas, the average annual ET_a increase over the period 2014-2019 is 279±161 mm/year over 8,318 ha, making a total increase of 23.2 Mm^3/year. The reduction in ET_a would be 37±29 mm/year over only 295 ha, leading to a total possible reduction of 0.1 Mm^3/year. To meet the annual average productivity targets for the area Wonji Main, Dodota and Ulaga, the total change in ET_a would be an increase of 23.1 Mm^3/year.

When closing the biomass gap and WP_b gaps in Welenchiti, the average annual increase in ET_a is 1.06 Mm^3/year (189±141 mm/year over 559 ha). The possible reduction of ET_a would be 32±21 mm/year over 106 ha (0.03 Mm^3/year). To meet the annual average productivity targets over the period 2015-2019 for Welenchiti, the total change in ET_a is estimated to be in increase in ET_a of 1.03 Mm^3/year.

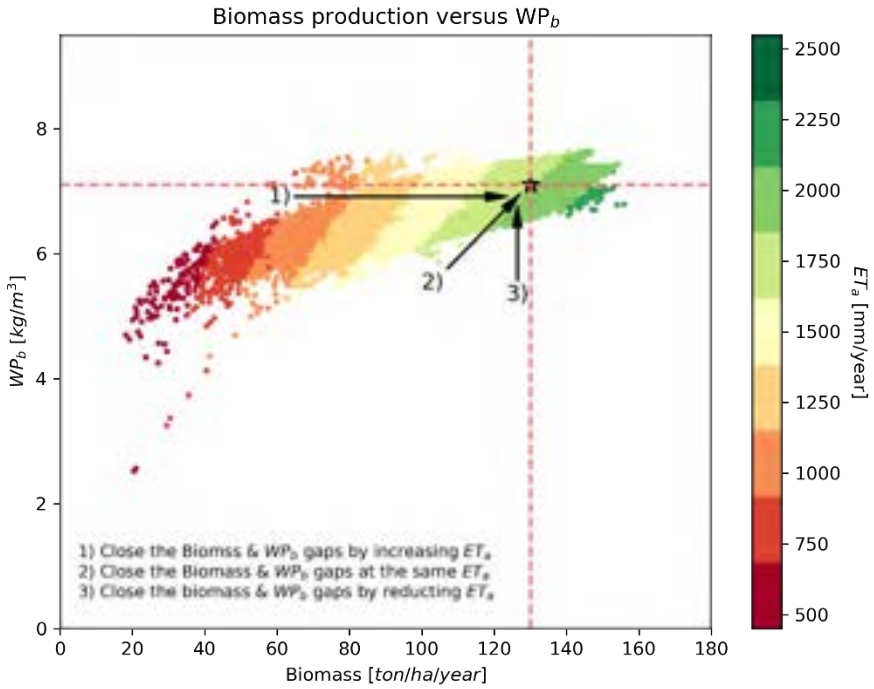


Figure 4-26: The 6-year (2014-2019) average biomass production, WP_b and ET_a for the irrigation areas of Wonji Main, Dodota and Ulaga combined (L3), with the productivity targets indicated by the red-dashed lines.

Table 4-10: Increase and reduction of the ET_a associated with meeting the productivity targets in Wonji, based on an average season from January 1st- December 31st in het given period.

		ET_a increase				ET_a decrease			
Spatial resolution	Period	Area [ha]	Mean [mm/year]	Std [mm/year]	Total [Mm^3/year]	Area [ha]	Mean [mm/year]	Std [mm/year]	Total [Mm^3/year]
30 m - L3	2014-2019	8318	279	161	23.2	295	37	29	0.11
100 m - L2	2015-2019	559	189	141	1.06	106	32	21	0.03

5 Discussion

5.1 Comparative irrigation method analyses

Figure 5-1 shows the summary of the performance indicators for the different irrigation methods and for Welenchiti, having normalised the five indicators in the figures using their maximum (100 %) or target values. It should be noted that the target value of Welenchiti is solely based on the data of that area, whereas the target values for furrow irrigation, sprinkler and centre pivot follow from the top 95% in land productivity and water productivity of their combined area. The figure shows that there is not one irrigation method that stands out the best in all indicators.

Areas irrigated by centre pivots and sprinklers share a distinct similar pattern for all indicators with the exception of irrigation uniformity. Whereas areas irrigated by means of furrows and hydroflumes show distinct difference in performance in uniformity and adequacy respectively. Also, furrow irrigation appears to score low in WP_b the low scores are also reflected in the most important indicators related to production and irrigation water management: land productivity and adequacy. Our analysis shows that centre pivots has higher WP_b adequacy and land productivity, but a marginally lower uniformity of water consumption; than furrow irrigation method. The disaggregated analysis per irrigation method showed results that are consistent with the established theory (Perry et al., 2009; Steduto et al., 2007): the relationship between biomass and water consumption increased when only transpiration was taken into account, instead of evapotranspiration. For all irrigation methods $WP_{b(T)}$ was higher than WP_b and the statistical correlation increased.

Considering the established theory with regards to inter-irrigation method variation (Allen et al., 1998; Perry et al., 2009; Steduto et al., 2007) furrow irrigation 'should' consistently return the highest WP_b, which 'would' be indicative of its lower evaporation fraction, given that the nutrient conditions and climatic conditions are equal for the compared areas. The results from the study reveals the opposite for Wonji estate. For all of the years studied the linear regression parameters for the relationship between biomass and transpiration (T), biomass and actual evapotranspiration (ET_a), and biomass and normalized transpiration $\sum(T/ET_{ref})$, show that for furrow irrigated areas (i.e. Wonji main sub-scheme) the regression is lower as compared to centre pivot or sprinkler irrigation. It is argued that this shows that variations in agronomic management practices/ growing conditions can be statistically discerned within the (disaggregated) dataset. It supports the perception that soil fertility is the limiting factor for the furrow irrigated areas, besides also the findings that identified salinised groundwater at shallow levels.

Our findings show that furrow and centre pivot show similar uniformity, closely followed by hydroflume irrigated areas whilst areas irrigated with sprinklers distinctly show lower uniformity. These performance results are remarkable as other research suggests that the uniformity in areas irrigated by centre pivots and sprinkler is higher than the uniformity of laborious systems such as furrow and hydroflume (Karimi et al., 2019). On the one hand do these results tally with what is perceived by Wonji Estate, i.e. that the operation and maintenance of sprinkler irrigation systems are challenged by electricity outages and frequent failure (damage) of draglines and the difficulty to replace. On the other hand, the highest uniformity performance in furrow irrigated areas challenges the local and science based perception that sprinklers and centre pivot systems have higher uniformity.

The adequacy performance of the hydroflume irrigated area in Welenchiti (L2 data), is remarkable considering that the area also returns the highest WP_b, with above average land productivity and below average water consumption performance. As ET_{ref} in Welenchiti does not vary much from the others, the

low adequacy can predominantly be attributed to a lower ET_a in Welenchiti. This lower ET_a can be a result of the different spatial resolution, in a recent study by Blatchford et al. (2020) the results of the different WaPOR resolutions were compared for the area of Wonji Main, among others. From this study, it followed that the variation between the ET_a at the different levels was less than 6%, with the ET_a of level 3 data higher than that of level 2 data. Besides the possible influence of the WaPOR data resolution, arguments for these adequacy scores may relate to (distinctly) different soil type found, agronomic practices and or also the sugarcane variety grown. These variables have not been discussed with Wonji yet, however, again these results lead to suggest that studies such as these can discern variations in growing conditions and agronomic practices.

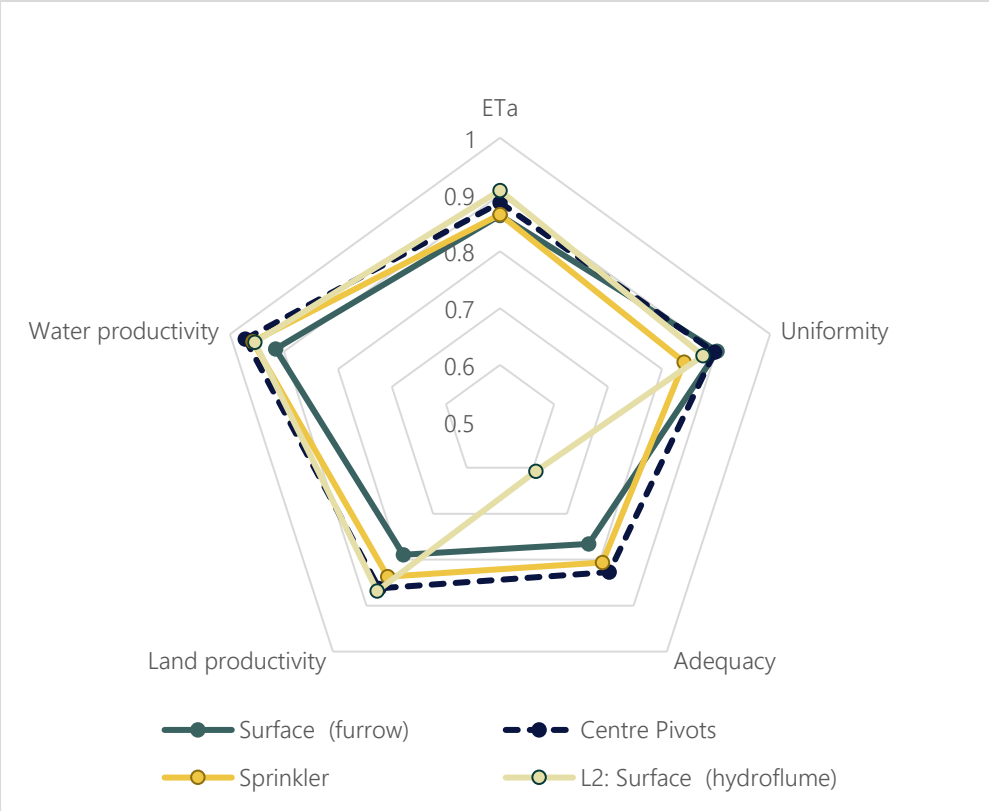


Figure 5-1: Comparison of the different irrigation methods in Wonji across five normalized indicators, including the L2 area of Welenchiti

Similar to the Xinavane case study (Chukalla et al., 2020a), the disaggregated dataset reveals a marked inter-seasonal variation of WP_b. This could be explained by the variation of the climatic conditions – in specific the variation in evaporative demand of the climate (ET_{ref}), which increases the evaporative demand, thereby lowering the WP_b.

This also means that high WP_b targets (e.g. set at WP_b = 7.1) for high ET_a ranges (that are mostly associated with higher ET_{ref} climatic conditions) cannot be realistically assumed to be attainable targets for irrigation systems with a higher intrinsic evaporation fraction, such as centre pivtos or sprinkler (Chukalla et al., 2020a).

Finally, when considering the land productivity performance and the inter-irrigation variances of $WP_{b(T)}$, it can be argued that there is room for improving WP_b values in the furrow irrigated areas without actually increasing overall water consumption (ET_a). The variances show that alleviating the nutrient stress in the furrow irrigated may improve the consumptive fraction (T_a), and thereby achieving similar $WP_{b(T)}$ values as

the other irrigation methods, without increasing overall water consumption (ET_a). As 'the theory' also supports that furrow irrigated (sugarcane) should have higher water productivity scores than that irrigated by sprinklers or center pivots. Achieving higher WP_b rates in the furrow irrigated areas will however require major changes within the Wonji main sub-scheme (agronomic and irrigation system improvements) that may be off-set by the benefits of automated farm management offered by centre pivot operations.

Being able to use remote sensing information to conducting spatial analyses of performance indicators is an advantage especially in areas where both water and land resources are scarce. The analyses show the potential use of WaPOR dataset in providing spatial performance assessment and evaluate the effectiveness of the land and water resource uses. By comparing the productivity across space in a given agro-climatic zone, WaPOR can help to set targets and evaluate the implication of closing productivity gaps on water consumption and production. Such information cannot be generated with the data collected traditionally (point data) and would come at significant cost.

5.2 Limitations of the WaPOR database

The findings presented in this report are solely based on information from the WaPOR database, which need to be used with some caution.

In this study, WaPOR datasets from Level 2 and Level 3 are used. The WaPOR L2 data after 2014 is derived from PROBA-V, which has a spatial resolution of 100 m and a 2-day revisit. The WaPOR L3 is derived from Landsat at a 30 m spatial resolution, and a 16-day revisit, providing less frequent NDVI input for L3 data. Limited satellite data availability due to high cloud cover will therefore more quickly lead to large data gaps for L3, making the gap filling results less accurate and more smoothened (FAO, 2020). Blatchford et al. (2020) found that the dekad-to-dekad changes were not captured as well in the L3 data, as compared to L2 and L1.

The project areas used in this study are determined in agreement with local experts. Pixels that did not contain agricultural land were removed from the area of interest, based on visual inspection and the WaPOR LCC for Welenchiti. However, farm roads and canals within the farm boundary and irrigated classes could be sources of noises in the data.

Statistical noise (representing over- or under-estimated data outputs) may emanate from various sources that are inherent to the WaPOR method and process (source: Chukalla et al., 2020a):

i. land cover noise of non-agricultural (non-sugarcane) land use within a pixel (coarse pixels are more prone to this noise than fine pixels, and boundary pixels are more prone to this noise for which the boundary pixels are discarded in a corrected analysis);
ii. the number and quality (e.g. cloud cover) of RS images on which the analysis and numerical interpolation is based (the poorer the quality and the fewer the images, the higher the variation in WP_b one can expect);
iii. the time of day on which the images are taken (determinant for which part of the daily ET curve is monitored and the time of day the water stress is more eminent);
iv. the angle of image capture and its correction function; etc.

All these factors and elements are potential sources of (small) deviations in the numerical output of WaPOR that may lead to over- and under-estimation of the WP_b output. In large and long-term datasets, such as for Wonji-Shoa sugar estate, one should thus expect that some degree of the variation in data output is part of the normal statistical noise. However, Table 4-5 shows a strong statistical correlation for the disaggregated analysis (per irrigation method and growing season) of WP_b (with R^2 values ranging between 0,91 and 0.98). This suggests that a clear irrigation method-based WP_b that can be explained with agronomic principles governing evaporation. Nevertheless, the intra-method and intra-season data do

show some variance in pixel-based WP_b values. Chukalla et al. (2020a) recommend to assess whether RS image quality (both in terms of numbers/frequency as in cloud coverage) is an issue, one should conduct a quality check by linking the WaPOR quality layer to each seasonal irrigation method WP_b analysis.

5.3 Other Limitations

The differences in the timing and duration of crop development stages per fields as the sugarcane is harvested throughout the dry season to keep the factory operational can be additional sources of noises. As the crop-growth cycles for sugarcane may extend to 18 months or more (essentially surpassing the arbitrary chosen 12-month season), the crop stages may affect the WP_b after harvest up to the full canopy development stage of the next ratoon crop, fields will have a relatively high E:T ratio as a larger surface area of the soil is exposed to the sun and evaporation. This is effect is also noticeable in the WP_b graphs presented in Appendices A.2, where low ET_a and low Biomass values tend to drop below the statistical WP_b line (as they have a relative higher evaporation compared to high production points that represent a full canopy cover). Other variations may stem from differential exposure to pests and diseases, wind and/or soil and rooting conditions (Chukalla et al., 2020a).

6 Conclusions

This study sets the contours for the assessment of irrigated sugarcane in Ethiopia using WaPOR data and a standard protocol as developed by and described in Chukalla et al (2020a). It assesses spatial variability of water and land productivity and irrigation performance average of five cropping seasons (2015 to 2019) at Wonji, host to Ethiopia's oldest sugarcane estate. We applied a comprehensive number of indicators that include water consumption, uniformity, adequacy, land and water productivity, and productivity gaps. In addition, the potential implication of closing the gaps were explored.

The seasonal monitoring of sugarcane production for Wonji sugar estate through the application of WaPOR for the season 2015 to 2019 show a remarkable good result for the assessment of WP_b.. The statistical correlation for the linear WP_b trend analysis of seasonal Biomass (B) over seasonal ET_a, once disaggregated for different irrigation methods (furrow, centre pivots, sprinklers and hydroflume) is very strong. This confirms that the established agronomic principles governing photosynthesis and crop water consumption is represented in the WaPOR data. Combining theory and RS-derived data, this study discerns inter-irrigation crop performance variances that can only be attributed to plant stress, findings that are confirmed by field observations and previous studies. These are strong and positive outcomes, that bodes well for the applicability of the WaPOR method on large and uniform scales of agricultural production as provided by the Wonji estate (also seen by Chukalla et al., 2020a). The following additional and supporting observations were made:

- To offset the variances in sugarcane cropping in terms of space (rotations of planting/ratooning, harvesting and fallows) and time (differences in length of cropping season and fallow periods) this study on sugarcane land and water productivity and irrigation scheme performance considers an average 12 month cropping season, using data for the period 2014 – 2019. Inter-annual analyses are performed, these are particularly used to visualise trends and (minor) differences.
- The average annual water consumption (ET_a) for the whole Wonji estate is 1,578±190 mm/year, excluding Welenchiti (hydroflume irrigated) which average equals 1,272±157 mm/year; Water consumption is highest for areas irrigated by center pivots (1,622±167 mm/year) compared to the land irrigated by sprinkler irrigation (1,584±252 mm/year), furrow irrigation (1,581±155 mm/year) and Wake Tio (1,492±258 mm/year)
- Overall uniformity of irrigation within the Wonji estate is fair, sprinkler and hydroflume irrigated areas perform less, which tally with field level accounts of challenges in operation (electricity outages) and maintenance (high costs). The furrow irrigated areas perform best in terms of uniformity, which considering the large amount of labour input and distribution challenges is remarkable and worth to consider for Wonji estate when comparing irrigation scheme performance and trade-offs.
- The centre pivot irrigated areas show highest levels of adequacy (0.83), whereas adequacy in the areas irrigated using hydroflumes is distinctly lower than the rest (0.61), this in particular due to the comparatively lower amounts of water consumed (larger comparative difference between Et_a and ET_{ref}),
- Land productivity averages 105 ton/ha/year in the Wonji estate, when deducing yields – by means of using one and the same harvest index – the yield estimates using WaPOR data vary from -13% to +6% when comparing with annual sugarcane production data from Wonji. The lowest land productivity is found in Wonji main sub-scheme, which tallies with field level data as well as with the perception that the scheme is least productive
- The analysis of water productivity performance for the areas irrigated by center pivots, sprinklers and furrows show an average WP_b of 6.6±0.3 kg/m^3, which can be considered fairly good. The hydroflume irrigated areas (Welenchiti) calculated separately score highest with 8.3±0.3 kg/m^3,

and furrow irrigated score the lowest with WP_b of 6.5±0.2 kg/m^3. Centre pivot and sprinkler score respectively 6.9±0.2 kg/m^3 and 6.8±0.2 kg/m^3.

- As water productivity results in this study are contrary to the theory in which center pivot irrigation has lower WP values than furrow an additional check of the data has been performed, ie. the response of WP_b to climatic evaporative demand (ET_{ref}); and the elimination of the non-productive evaporation component (smaller inter-irrigation method variation) by establishing the $WP_{b(T)}$.
    - The statistical variation analysis shows that water productivity varies with the climatic conditions, as such WP_b declines for a higher ET_{ref} (conform research). This decline is stronger for irrigation methods with a higher non-productive evaporation rate (center pivot and sprinkler), as the non-productive evaporation rate increases with higher ET_{ref}.
    - $WP_{b(T)}$ performance for each of the irrigation systems also show a smaller spread in the 'data-cloud'; a stronger statistical correlation and a smaller inter-seasonal variation; however, it does not show a smaller inter-irrigation method variation between furrow irrigated areas and those irrigated by center pivots or sprinklers. Hence, the differences between the irrigation methods might be attributed to plant stress due to other limiting conditions such as nutrient conditions.
    - Previous research and field perception suggest that, these 'limiting conditions' to producing sugarcane and achieving higher WP in the furrow irrigated areas, can be the result of excess water or wet soils (high and slightly saline groundwater tables). Besides this continued wetting the monotonous fertiliser application regime (Urea) also needs adaptation as the soils may be leaching the applied urea or urea may be lost to surface runoff.
- Inter-seasonal patterns in water productivity discern that the areas in the eastern part of Wonji Main, above Dodota, have consistently higher WP_b than the rest of Wonji Main, on average more than 0.7 kg/m^3/year higher. Also the areas in the south of Dodota have consistently a higher WP_b. In Welenchiti, large parts in the north-east have a higher WP_b each year compared to the area average. In the south-west of Welenchiti, large areas are observed that have a negative which might be linked to soil characteristics.
- Intensification at Wonji by closing the biomass gap can increase production up to 243,008 tons/year, separately for Welenchiti an increase of 13,570 tons/year. This however would come at an increase in water consumption (ET_a) of 23.09 Mm^3/year and 1.03 Mm^3/year respectively.
- The total the productivity gap in Wonji Main estimated at 185,520 ton/year making up for the largest portion of the gap, this study argues that there is distinct room improving WP_b values in the furrow irrigated areas without actually increasing overall water consumption (ET_a). The exact extent of this 'room for improvement' needs to be further determined.

The study shows the potential use of RS-derived data to identify bright spots with the highest land and water productivity besides also discerning spatial variability in performance that can be attributed to plant stress. Although we are unable to determine the underlying causes for the variability with RS-derived data, the attribution of plant stress within this study are confirmed by field observations and previous studies by others. These identify that: farm management, inputs, as well as stresses resulting from factors such as water logging and salinity; are (part of) the root causes of the land productivity variation.

This goes to show that accurate interpretation of the results, diagnoses of the productivity gaps and formulation of practical solutions can only be made unless the WaPOR analyses and results are complemented with observed data of field conditions that can help to understand the production setting of the fields and explore the constraints.

Subsequent studies (also suggested by Chukalla et al., 2020a), could additionally consider socio-economic performance indicators, such as social water productivity (e.g., employment per water use or land use) and

economic water productivity (economic return per water or land use), which could help to implement comprehensive performance assessment of irrigation schemes.

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