WaterPIP

Water Productivity Improvement in Practice

Water Productivity Analyses using the WaPOR Database

A Case Study in Xinavane, Mozambique

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Prepared by IHE Delft Institute for Water Education

Prepared by Abebe Chukalla, Marloes Mul, Gerardo van Halsema, Pieter van der Zaag, Trui Uyttendaele, and Poolad Karimi.

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Acronyms

A	adequacy
AOT	above ground over total biomass
B	above-ground biomass
CV	coefficients of variation
EOS	end of season
ET_a	actual evapotranspiration
$ET_{a,s}$	seasonal actual evapotranspiration
ET_{ref}	reference evapotranspiration
f_c	crop factor
ha	hectare
km	kilometre
LCC	land cover classification
MC	moisture content in fresh biomass
mm	millimetre
m^3	cubic metre
Mm^3	million cubic metres
m^3/s	cubic metres per second
NPP	net primary production
RS	remote sensing
SOS	start of season
T_a	actual transpiration
$T_{a,s}$	seasonal actual transpiration
USD	United States Dollar
WaPOR	FAO portal to monitor Water Productivity through Open access of remotely sensed derived data
WP_b	biomass water productivity

1 Introduction

1.1 Sugarcane Production in Mozambique

The agriculture sector is the major employer in Mozambique, absorbing around three quarters of the labour force and contributing 25 percent of the total gross domestic product in 2007 (WTO, 2008). Next to subsistence farming, the largest employers of the agricultural workforce are the sugar estates and commercial farms (WTO, 2008). Sugarcane is the most important source of sugar production in the world, with Africa producing only a little over 5 percent of global sugarcane production (FAOSTAT, 2019).

Before independence in 1975, Mozambique was a major producer of sugar. During the season of 1972-1973, the total production reached levels of 325,000 tons/year. The civil war from 1977 until 1992 paralyzed rural Mozambique and resulted in destroyed infrastructure, including the infrastructure of the sugar mills, and total production dropped to 13,000 tons/year in 1980. With peace came the need to rebuild the country and to create employment. The sugar industry was designated to achieve that goal. South African companies, including Tongaat-Hulett and Ilovo, were invited by the Government of Mozambique to invest in the sector.

The sugar production over the past 10 years in Mozambique is driven by investment in irrigation and offering price incentives and trade opportunities in the region (Food Outlook, 2019). These have pushed an expansion of sugarcane production by an average annual rate of 10 percent. The sugarcane industry is considered to have contributed to economic, social, environmental and developmental benefits within Mozambique (Kegode, 2015).

Since the early 2000s, Mozambique became a signatory of different preferential trade agreements, including the Cotonou Agreement[1], Sugar Protocol and Everything But Arms (EBA) Agreement that provide quota-free and duty-free access of Mozambican sugar at guaranteed prices (above the world market price) to the EU market. Liberalization of the sugar market among Southern African Development Community members, in addition to the increased demand and interest for bioethanol production, fuelled the continued expansion of sugarcane in the country. Sugar is the second-largest agricultural export item for Mozambique (WTO, 2008, 2017). In 2007, the sugar companies produced 243,000 tons/year of raw sugar and exported 94,000 tons/year to Europe, the United States and other countries, earning US$46 million. From 2014 to 2017, Mozambique earned US$73 million/year from the export of 185,000 tons/year of raw sugar (FAOSTAT, 2019).

The largest estates where sugarcane is produced are in Xinavane and Maragra in Maputo Province, and in Sena and Mafambisse in the central province of Sofala. The focus of this study is on the agricultural estate located in Xinavane.

1.2 Study Area

The Xinavane sugarcane estate is located in the downstream part of the transboundary Incomati Basin (Figure 1-1). Situated on the banks of the Incomati River, Xinavane is approximately 136 kilometers (km) northwest of Maputo. Its region is characterized by optimal conditions for sugarcane production in terms of water availability from the Incomati River, temperatures and soils. The estimated total net runoff in the Incomati basin is 3,587 million cubic meters per year (Mm^3/year), of which 82% is generated in South Africa,

[1] Partnership Agreement African Caribbean and Pacific and European Commission (https://www.europarl.europa.eu/intcoop/acp/03_01/pdf/cotonou_2006_en.pdf)

13% in Swaziland and 5% in Mozambique (Van der Zaag and Carmo Vaz, 2003). About 80% of all runoff in a hydrological year is generated from November to April. In the basin, water is used by forest plantations and for domestic and industrial use, while irrigation is the principal water user (48% of total water use). From the late 1960s, major dams have been commissioned that allowed increased water withdrawals and water access. The most important water infrastructure in the Incomati Basin in Mozambique is the Corumana Dam. It is a multipurpose reservoir constructed between 1983 and 1989. The dam is located on the Sabie River, a tributary of the Incomati River, immediately downstream of the border with South Africa and approximately 90 km northwest of Maputo. The dam was originally constructed to improve flood control, regulate downstream irrigation abstractions (including Xinavane) and hydropower production (de Boer and Droogers, 2016).

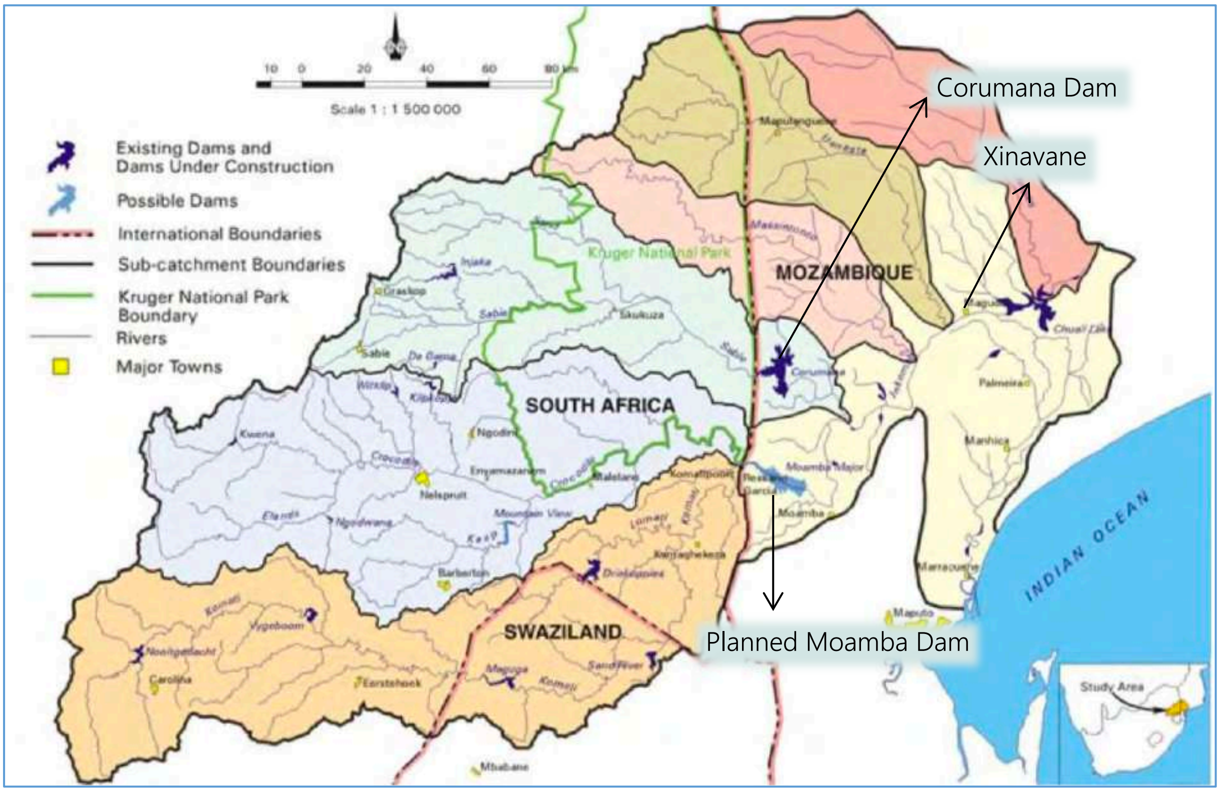


Figure 1-1: Overview of the Incomati Basin and location of Xinavane estate (source of map: JIBS (2001))

1.3 History of Xinavane Estate

British investors arrived at Xinavane in 1914 and undertook the initial development. Tongaat-Hulett, a South African sugar company, acquired 49% and 88% of Xinavane total shares in 1998 and 2008 respectively, while the remaining part is owned by the Government of Mozambique. During the rehabilitation phase (post 1998), most of the original canals, drains, and pumps were repaired and re-designed to the present flood/drainage and irrigation systems. Uncertainty about the continuation of the company as a majority shareholder arose in 2019 when serious financial difficulties came to light.

The command area of the Xinavane sugarcane estate expanded from 12,000 hectares (ha) in 2005 to 14,000 ha in 2009, 16,161 ha in 2015 and 18,000 ha in 2016 (de Boer and Droogers, 2016). Sugarcane is a water-intensive crop that needs irrigation almost all year round for optimal crop growth. The irrigation water demand for the Xinavane sugarcane estate is estimated at 10,000 m^3/ha/year (1,000 mm/year) (de Boer and Droogers, 2016).

Reoccurring droughts pose a threat towards the availability of sufficient irrigation water for the plantation. Existing drought mitigation measures for the Xinavane area include the construction of the new Moamba Major Dam (760 Mm^3, Figure 1-1) and the heightening of the Corumana Dam wall, which will result in its capacity being increased from 879 Mm^3 to 1,260 Mm^3 (Van der Zaag and Carmo Vaz, 2003; Tongaat Hullet, 2018). Though irrigation water requirements vary during the year, the outflow from the reservoir remains steady (Figure 1-2).

Meses	Cota	E D M	Agricultura				Outros Consumos
		Central Hidroeléctrica Volume	Xinavane	Maragra	Pequenos Agricultores	Total	
	(m)	(Mm^3)	(Mm^3)	(Mm^3)	(Mm^3)	(Mm^3)	(Mm^3)
Jan	105.01	36.06	5.95	4.05	0.17	10.17	25.89
Fev	104.61	32.62	5.95	4.05	0.17	10.17	22.45
Mar	104.01	35.44	5.95	4.05	0.17	10.17	25.27
Abr	103.69	16.95	5.95	4.05	0.17	10.17	8.53
Mai	103.62	18.42	5.95	4.05	0.17	10.17	9.41
Jun	103.12	17.59	5.95	4.05	0.17	10.17	9.67
Jul	102.65	17.52	5.95	4.05	0.17	10.17	10.13
Ago	102.12	17.56	5.95	4.05	0.17	10.17	9.60
Set	101.57	17.27	5.95	4.05	0.17	10.17	8.72
Out	101.10	17.08	5.95	4.05	0.17	10.17	7.98
Nov	100.82	16.42	5.95	4.05	0.17	10.17	6.25
Dez	101.81	9.24	5.95	4.05	0.17	10.17	-
Média	102.84	**21.01**	**5.95**	**4.05**	**0.17**	**10.17**	**11.99**
Total		**252.17**	**71.40**	**48.60**	**2.04**	**122.04**	**143.90**

Figure 1-2: Summary of the Corumana reservoir outflow in 2007. Source: ARA- Sul (de Boer and Droogers, 2016)

1.4 Sugarcane Production and Challenges

1.4.1 Sugarcane Production

There are three production sites in Xinavane: the Maholele Expansion Area (west of Magude), the Western Expansion Area (east of Magude and close to Xinavane) and the Eastern Expansion Area (further east of Xinavane) (Figure 1-3). The company itself owns 13,000 ha of land, and outgrower schemes have been developed since 1998 and have expanded the area for sugar production. Outgrower schemes have steadily increased over the past years. Appendix A provides an overview of the smallholder sugarcane activities in Xinavane for 2010. In 2010, a total of 2,091 ha and 1,539 outgrowers produced additional sugarcane for the Xinavane mill (Jelsma et al., 2010). This doubled to 5,000 ha and 3,392 outgrowers by 2016 (van Delden, 2016). The total area under sugarcane production in Xinavane in 2019 was 18,000 ha. Figure 1-3 illustrates the area of the plantation with pink areas demonstrating smallholder expansion areas.

In 2010, a total of 15 smallholder associations existed, most of which were established in the late 2000s. Each association has its own management which comprises of at least a president, a treasurer and a secretary. Associations are meant to safeguard the interests of smallholders and form an interface between the company and smallholders. The expansion program at Xinavane has been dynamic and a process of '*learning by doing'*. This implies that there is no detailed blueprint or past example which the company is learning from in dealing with the outgrowers. Problems are solved and dealt with on an *ad hoc* basis. The associations join their land in a block farm, and in this way create one large area of land for growing sugarcane. Farmers can only become a member of an association if they own land in the designated area. Since it is in the best interest of the company to have the highest yields possible, the Xinavane sugarcane estate provides technical assistance and extension services.

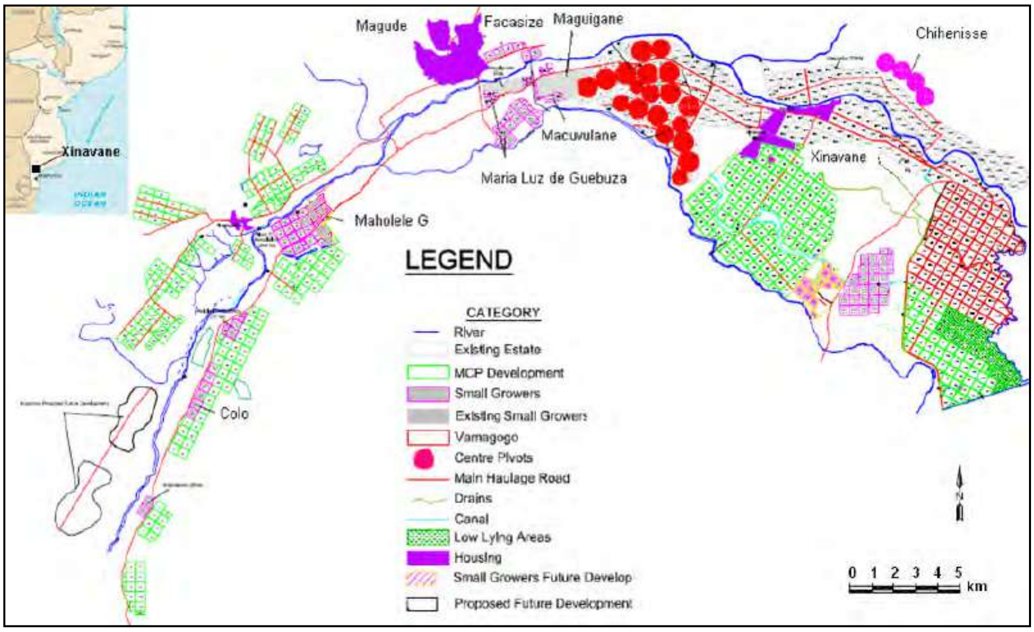


Figure 1-3: Map of Xinavane sugarcane estate (Jelsma et al., 2010)

1.4.2 Challenges in Sugarcane Production at Xinavane Estate

Sugarcane at Xinavane depends on irrigation, which is vulnerable to climate variability. For example, during the recent drought of 2016, reservoir levels in the Corumana Dam were very low and little water was available for irrigation in the Xinavane sugarcane estate, and only 60% of irrigation demand could be supplied (Xinavane Estate, November 2020). This resulted in a significant drop in sugarcane yields in 2016 compared to the previous years (Tongaat Hullet, 2018). Such events are expected to continue to occur. With increasing competition over water, the sugar estate is likely to experience water shortages more frequently. To partially address this, Mozambique put drought mitigation measures in place for the Xinavane area, including the construction of the new Moamba Major Dam (760 Mm^3, Figure 1-1) and the heightening of the Corumana Dam wall, which will result in its capacity being increased from 879 Mm^3 to 1,260 Mm^3 (Tongaat Hullet, 2018). These supply-oriented measures may help in creating a bigger buffer against droughts but their effectiveness will be limited if they are not coupled with interventions that aim at managing the water demand in the basin, which requires coordinated efforts by riparian countries.

On the other hand, the sugarcane industry aims to increase its production by expanding land. In addition, there is inefficient use of land and water resources that subsequently drive up production costs and increase opportunity costs. This calls for improving the irrigation water management and substantially increasing the land and water productivity at Xinavane.

To improve the performance of agricultural water use, we need to understand the quantity, distributions 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. Such data does not represent well 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 conditions that are needed to achieve high water productivity. One of the main factors behind the variation of water productivity is thought to be farm water management practices. These practices in Xinavane, to a large extent, depend on soil and drainage management, and the irrigation application methods. Therefore, an analysis of productivity of an estate such as Xinavane 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.

1.5 Irrigation Application Methods at Xinavane

The sugarcane scheme at Xinavane has three types of irrigation application methods: furrow, center pivots and sprinkler irrigation systems. These irrigation technologies require different inputs in terms of labour and maintenance (Table 1-1). For example, the drag hose sprinkler systems need to be moved every 12 hours while a pivot system only needs one central operator for the whole command area and runs fairly automatically. Also, the electricity costs associated with the pivots are lower than those of sprinkler systems (pivots use about ¼ of energy compared to sprinklers), mainly due to the lower pressure needed to irrigate (Jelsma et al., 2010). The overall operation cost of the three irrigation systems are comparable: centre pivot costs 131 USD/ha plus the cost of three labourers per day, furrow costs 130.4 USD/ha plus the cost of two labourers per day, and dragline sprinkler system costs 140 USD/ha plus the cost of two labourers per day. Table 1-1 provides an operational cost comparison between these systems. However, overall investment costs are not included.

Table 1-1: Costing of irrigation systems at Xinavane[2]

Cost	Centre Pivot	Dragline Sprinkler System	Furrow system
Labour	3 people/day/pivot*	2 people/day/16 hydrants	2 people/day/20 ha field
System maintenance	15 USD/ha	34 USD/ha[3]	14.6 USD/ha
Pump maintenance	44 USD/ha	44 USD/ha	44 USD/ha
Administration[4]	62 USD/ha	62 USD/ha	62 USD/ha

** one pivot is about 50 ha each*

Note: The original cost reported in South African Rand (R) is converted to USD using the average exchange rate in 2010 (Figure A-1 in the Appendix)

2 Objective

The main objective of this study is to provide insight into water and land productivity in the Xinavane sugarcane estate. The study focuses on analysing the spatial variation of water and land productivity, and irrigation performance indicators at Xinavane sugarcane estate differentiated by irrigation application method. Furthermore, the productivity gap and implications of its closure on production and water use are explored at the macroscale.

[2] Source: Collert Moyo, Irrigation Manager at Xinavane company, data collected by Jelsma et al. (2010)
[3] Due to thefts of hose pipes and tripod stands
[4] These include salaries, safety materials and equipment, stationary, vehicles, consumables etc.

3 Methodology and Data

This section starts with explaining the performance assessment framework, including the different productivity and other irrigation performance indicators used in this study. The final section describes and reviews the data and information used in the analyses.

Productivity and irrigation performance indicators provide a way to measure the effectiveness of resources use and to evaluate irrigation services. Figure 3-1 shows the performance assessment framework used in this study to calculate indicators of water and land use and irrigation performance in the Xinavane sugarcane estate. The procedure includes four steps. First, actual water consumption, actual transpiration, reference evapotranspiration and net primary production datasets are collected from the FAO Water Productivity through Open access Remotely sensed derived data (WaPOR; see https://wapor.apps.fao.org) and pre-processed to match the spatial resolution and remove non-crop pixels. Second, the seasonal water consumption (transpiration, actual evapotranspiration and reference evapotranspiration) and the seasonal net primary production and biomass are calculated. Third, the WaPOR data is evaluated for consistency. The consistency of the WaPOR data is checked following known relationships between biomass (B) vs ET_a, B vs T_a and B vs $\sum T_a/ET_{ref}$ (De Wit, 1958; Steduto et al., 2007). Fourth, the irrigation performance indicators are analysed. Finally, the implication of closing productivity gaps on production and water consumption are explored. The symbols in Figure 3-1 are described in the following text box.

ET_a stands for actual evapotranspiration, T_a for actual transpiration, ET_{ref} for reference evapotranspiration, *NPP* for net primary production, *LCC* for land cover classification, *MC* for moisture content in fresh biomass, *AOT* for the above ground over total biomass, *SOS* for start of season, *EOS* for end of season, and *B* for above-ground biomass.

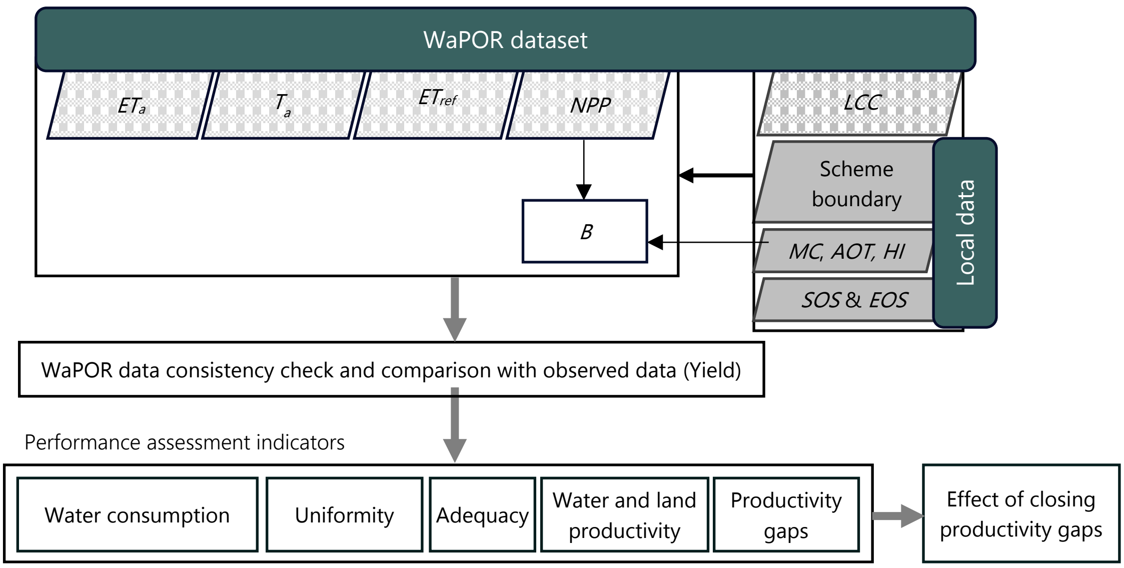


Figure 3-1: Flow chart for calculating indicators for irrigated sugarcane at Xinavane

3.1 Step 1. WaPOR Data

The FAO Water Productivity Open access Portal or FAO (2020a), is the first comprehensive dataset that combines water use (actual evaporation, transpiration and interception), production (net primary production), land use (land cover classification), phenology, climate (precipitation and reference evapotranspiration) and water productivity layers covering sub-Saharan Africa and the Middle East and North African regions in near real-time for the period between 2009 to present day. WaPOR datasets are available at continental scale (Level 1 at 250 m), country and river basin (Level 2 at 100 m) and project level (Level 3 at 30 m). The latest WaPOR portal (WaPOR v2.1), was improved from WaPOR v1.0 following the quality assessment by IHE Delft and ITC (Mul and Bastiaanssen, 2019). The methodology used for compiling the WaPOR database is provided in FAO (FAO, 2020b).

The WaPOR Level 2 (100m) is available for Mozambique and therefore also for our case study area[5]. The Level 2 data used in this study include actual evapotranspiration and interception and net primary production at a dekadal (10 day) timescale and annual land cover classification. In addition, dekadal precipitation at 5 km resolution, dekadal reference evapotranspiration at 25 km resolution. The precipitation and reference evapotranspiration datasets were downscaled to 100 m resolution. An overview of the WaPOR data used in this study is provided in Table 3-1.

Table 3-1: WaPOR layers used in the analyses

Remote sensing products	Description/ Spatial resolution	Temporary resolution (coverage)
Actual evapotranspiration (ET_a)	100 m	Dekadal (2009-2019)
Actual transpiration (T_a)	100 m	
Net primary production (NPP)	100 m	
Precipitation (P)	5 km	
Reference evapotranspiration (ET_{ref})	25 km	
Land cover classification (LCC)	100 m	Annual (2009-2019)

For the analyses the dekadal WaPOR data are aggregated to seasonal values.

3.2 Step 2. Calculating Seasonal Actual Water Consumption

Evapotranspiration is the sum of the soil evaporation, canopy transpiration and interception. Seasonal actual evapotranspiration is analysed from the dekadal WaPOR data by aggregating the seasonal values using Equation 1:

$$ET_{a,s} = \sum_{SOS}^{EOS} ET_a \qquad \text{Equation 1}$$

where ET_a is the actual evapotranspiration that includes evapotranspiration and interception, $ET_{a,s}$ is seasonal actual evapotranspiration in mm/season, SOS and EOS are starting and ending of the crop season.

[5] It is important to note that the WaPOR L2 data (100 m) is derived from the PROBA-V satellite which came into orbit in 2014. The data prior to 2014 is derived from resampled L1 (250m) data which is obtained from the MODIS satellite.

Because the sugarcane plantation operates on A ratooning[6] system and harvesting is done throughout the dry season, the start of season and end of season per farm unit varies. We therefore considered analysing the data using a hydrological year from October 1st to September 30th (Van der Zaag and Carmo Vaz, 2003). Further, the WaPOR yield is compared against the observed yields; these observed data are accessed only for the central and western part of the study area.

In WaPOR, the evaporation and transpiration are calculated based on the ETLook model described in Bastiaanssen et al. (2012). In the ETLook model, the Penman-Monteith (P-M) equation is solved adapting to remote sensing input data for evaporation and transpiration separately. The difference in the P-M equation applied to derive evaporation and transpiration is in the inputs to estimate the net available radiation, the aerodynamic and surface resistance: the P-M for evaporation uses soil heat flux, as well as the aerodynamic and surface resistance at the soil surface as influenced by soil moisture availability; and the P-M for transpiration uses the aerodynamic and surface resistance at the canopy as influenced by soil moisture availability. Interception is described as the rainfall intercepted by the plants canopy and evaporates directly from the leaves using energy that is not available for transpiration.

3.3 Step 2. Calculating Biomass Production

The biomass production is calculated from the seasonal net primary production (*NPP*) provided by WaPOR[7]. Four steps are applied in converting NPP to biomass. First, as sugarcane is a C4 crop and has light use efficiency (LUE) of 3.27 MJ/gr biomass, its seasonal NPP needs to be corrected as WaPOR estimates NPP using generic LUE of 2.7 MJ/gr biomass for rainfed and irrigated crops under non-stressed growing conditions. This is done by applying a light use efficiency correction factor (f_c), which is the ratio of light use efficiency of sugarcane over light use efficiency used to drive the NPP layer, set at 1.6 (Villalobos and Fereres, 2016). Secondly, the seasonal NPP of sugarcane is converted to the dry biomass production multiplying NPP by 22.222 to convert NPP in gC/m²/day to kg dry biomass/ha/day (FAO, 2020a). Thirdly, the total biomass is calculated by correcting the dry biomass production for moisture content in the crop (MC). Finally, the above-ground biomass (B) is estimated multiplying the total biomass by the above ground to total biomass production ratio (AOT) (Equation 2).

$$B = AOT * f_c * \frac{NPP*22.222}{(1-MC)}$$ Equation 2

In absence of field data, literature was consulted to estimate these crop parameters. Table 3-2 shows the values and the source of the parameters. The yield of sugarcane is calculated by multiplying the biomass by harvest index of 1, a default value reported in WaPOR portal (FAO, 2020a).

Table 3-2: Parameters used in the analyses

Parameter	Description	Value	Source
MC	Moisture content of fresh crop biomass	59%	Yilma et al. (2017); Mul and Bastiaanssen (2019)
f_c	Light use efficiency correction factor	1.6	Villalobos and Fereres (2016)

[6] Ratooning is the agricultural practice of harvesting a crop by cutting most of the above-ground portion but leaving the roots and the growing shoot intact so as to allow the plants to recover and produce a fresh crop in the next season
[7] https://wapor.apps.fao.org/home/WAPOR_2/1

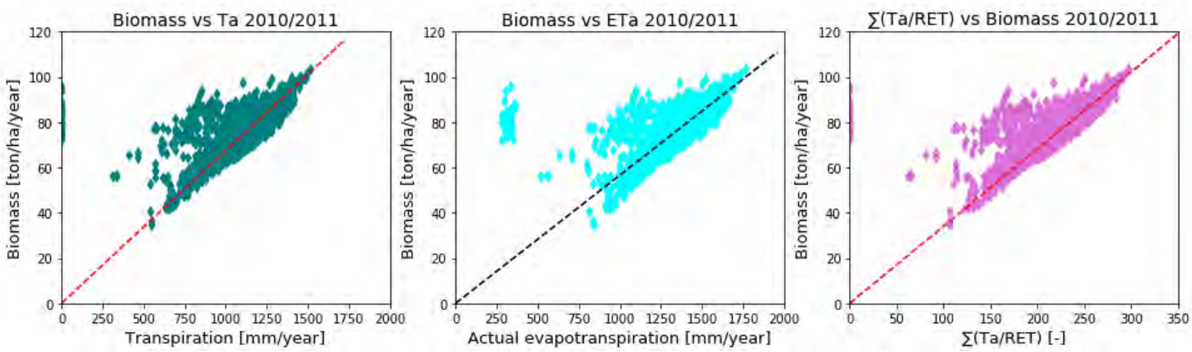
Table 3-2: Parameters used in the analyses

Parameter	Description	Value	Source
AOT	The ratio of above ground over total biomass (AOT)	0.8	Smith et al. (2005); Villalobos and Fereres (2016)
HI	Harvest index	1	FAO, 2020a

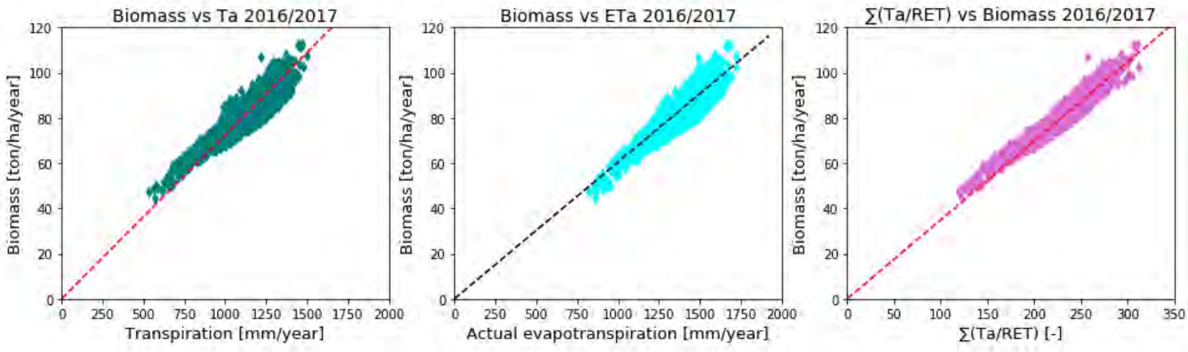
The main source of variation in Biomass production is the WaPOR NPP data. This is calculated by multiplying the maximum primary production (NPP_{max}) with several stress factors. NPP_{max} is climate limited by radiation, CO_2 concentration and temperature. The stress factors are combined in several parameters, the fraction of absorbed Photosynthetically Active Radiation (fAPAR), light use efficiency (*LUE*) of a crop land and soil moisture stress (Veroustraete et al., 2002; Myneni and Williams, 1994; FAO, 2018). Swinnen and Hoolst (2019) argue that the abiotic and biotic stresses (nutrient stresses, pests and diseases) are intrinsically manifested in fAPAR, which is derived from the normalized difference vegetation index (NDVI) (FAO, 2018; Myneni and Williams, 1994). NDVI has proven to be able to distinguish crop canopy under nutrient stressed conditions (Rouse et al, 1973) and predict crop yield under different concentration of leaf-tissue nutrients and soil quality (Swinnen and Hoolst, 2019). Thus, the variation in NPP across pixels is due to a combination of noises in the RS observation (distortion due to gap filling as a result of cloud cover), and stresses induced by water, nutrients, pests and diseases. In the Xinavane case study, additional variation is observed from the variation in crop season per farm unit.

3.4 Step 3. WaPOR Consistency Check

Biomass production is known to have a linear relationship with transpiration (De Wit (1958); Steduto and Albrizio (2005)). The slope of the linear line accounts for the effect of crop variety and soil fertility (Steduto et al., 2007). A linear relationship between biomass and water consumption would indicate consistency between the two independently generated datasets. Figure 3-2 shows the biomass plotted against three seasonal water consumption variables: transpiration, actual evapotranspiration and normalized transpiration ($\sum T_a/ET_{ref}$) for the Xinavane sugarcane estate for two years (2010-2011 and 2016-2017). Following the methods described in Steduto et al. (2007), the normalized transpiration is calculated by summing the product of dekadal time interval and the ratio of dekadal transpiration over dekadal reference evapotranspiration over the crop season.



a) b) c)



d) e) f)

Figure 3-2: The relationship between biomass and transpiration (a and d), between biomass and ET_a (b and e), and between biomass and normalized transpiration (c and f) in 2010/2011 and 2016/2017 for the Xinavane sugarcane estate.

Figure 3-2a-c for 2010-2011 show much larger scatter compared to Figure 3-2d-f for 2016-2017. This phenomenon can be seen for all years prior to 2014 (Table 3-3; Appendix B). This is related to when the data source for Level 2 was switched from MODIS (resampled) to PROBA-V. The data prior to 2014 was therefore excluded from the analyses.

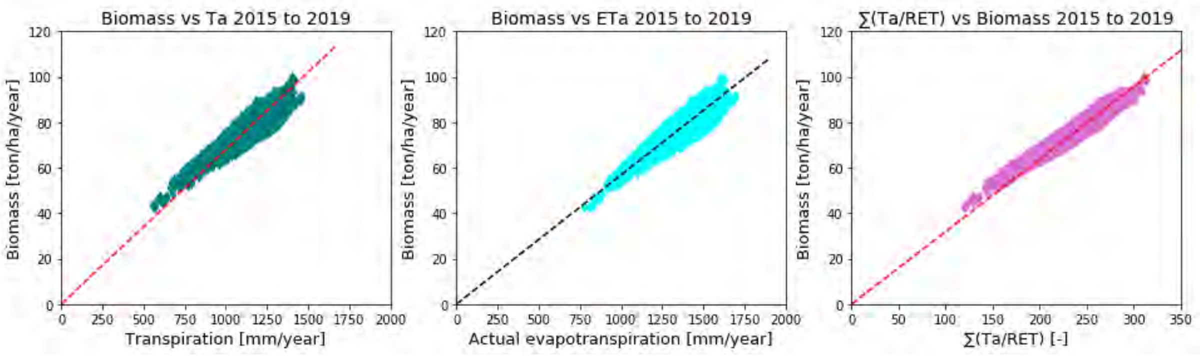
Table 3-3: Linear regression parameters of the relationship between biomass vs transpiration (T_a), biomass vs ET_a and $\sum(T_a/ET_{ref})$ vs biomass of sugarcane production at Xinavane from 2009/2010 to 2018/2019

Line	Regression parameters[8]	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2015/19
B vs T_a	a	0.07	0.067	0.074	0.078	0.073	0.069	0.065	0.073	0.071	0.065	0.068
	b	0	0	0	0	0	0	0	0	0	0	0
	r^2	0.067	0.091	0.367	0.275	0.698	0.86	0.606	0.772	0.808	0.782	0.723
B vs ET_a	a	0.059	0.057	0.063	0.066	0.062	0.058	0.054	0.06	0.06	0.054	0.057
	b	0	0	0	0	0	0	0	0	0	0	0
	r^2	0.366	0.372	0.565	0.497	0.764	0.937	0.735	0.833	0.865	0.843	0.818
B vs $\sum T/ET_{ref}$	a	0.324	0.341	0.365	0.37	0.366	0.352	0.342	0.349	0.361	0.353	0.319
	b	0	0	0	0	0	0	0	0	0	0	0
	r^2	0.19	0.156	0.408	0.326	0.761	0.937	0.849	0.916	0.924	0.903	0.902

Figure 3-2d-f shows a slightly increasing scatter as the seasonal T and ET_a values increase. One possible reason for the scatter could be the difference in the duration and percentage of the soil covered by canopy across the plots following the differences in the harvesting date. In addition, there are numerous management factors affecting the soil-water-plant relationships and thus affecting the relationship (Schmidhalter and Studer, 1998; Zwart and Bastiaanssen, 2004; Wichelns, 2014). For instance, soil fertility stresses could affect the biomasses vs transpiration of sugarcane as seen in other crops (Schmidhalter and Studer, 1998).

As the individual yearly plots show some additional noise due to the differences in the harvesting dates, the average annual water consumption and production values over the period 2014/2015-2018/2019 were generated and used to calculate the performance indicators (Figure 3-3).

[8] a is the slope of the regression line and b is the intercept

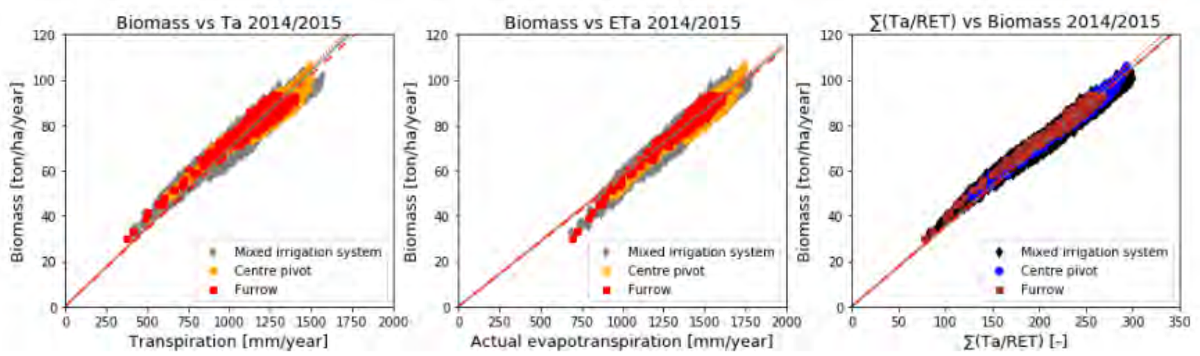


a) b) c)

Figure 3-3: The relationship between average annual biomass and transpiration (a), between average annual biomass and ET_a (b), and between average annual biomass and normalized transpiration (c) for the period 2014/2015-2018/2019 in Xinavane sugarcane estate.

Biomass versus Water Consumption (ET_a) per irrigation method

The WaPOR consistency check showed a clear and consistent relation for the period 2014/15 to 2018/19 between the actual (evapo)transpiration and crop production in terms of total above ground biomass. The analyses were further disaggregated according to irrigation type (Figure 3-4), which are expected to yield different Biomass production and Evapotranspiration rates resulting in different Water Productivity values, as well as in their beneficial transpiration ratio T_a/ET_a.



(a) (b) (c)

Figure 3-4: The relationship between biomass and transpiration (a), between biomass and ET_a (b), and between biomass and normalized transpiration (c) for the 2014/2015 season in Xinavane sugarcane estate differentiated by irrigation methods.

Centre pivots are characterised by overhead sprinklers that a) wet the entire surface area of the field (i.e. they have a wetted fraction f_w = 1.0 (re table 20 Allen et al. 1998)), and b) are affected by canopy interception and wind dispersal, the evaporation rate of this irrigation method will be the largest. Furrow irrigation, in contrast, only wets a part of surface area (f_w 0.6 – 0.8) that will feed evaporation from the wet soil as long as the canopy is not fully developed yet. The non-productivity evaporation for this method is therefore expected to be the lowest of the three. The mixed irrigation area that may consist of a mix of sprinkler, surface and sub-surface irrigation, is likely to show an intermitted value for evaporation, with most of the mixed area being under sprinkler irrigation.

Given the clear differential effect of evaporation per irrigation method and growing season on the WP_b (ET_a) as presented above, the next desired analytical step would be to eliminate the evaporation component from the WP analysis. The shape and width of the data clouds (as presented in Annex C) can be influenced by differences in evaporation per pixel (data point), as a result of differences in: i) irrigation frequencies; ii) timing, frequency and quality of WaPOR image capture[9]; iii) a combination of both; and, iv) differences in agronomic performance of the crop that lead to lower crop transpiration and productivity. Elimination of the non-productive evaporation component would thus result in a more robust WP_b (T_a) ratio (de Wit, 1958; Steduto et al., 2007), with: (i) a smaller spread of the data-cloud, (ii) a stronger statistical correlation, (iii) a smaller inter-seasonal variation of the WP_b ratio as the climatic and irrigation management effect on evaporation is eliminated, and iv) a smaller inter-irrigation method variation of WP_b values, as the differential evaporation rates associated with the different irrigation methods is eliminated.

As shown in Table 3-3, however, the statistical analysis of the WaPOR results show a degradation of the statistical correlation for WP_b = Biomass / T_a. This is agronomically not possible and thus indicates there is an issue with the manner in which WaPOR separates the evaporation from transpiration. This will have to be looked at and assessed in more detail. In the case of Xinavane, where sprinkler-based irrigation systems are prevalent, the intercepted fraction of irrigation water, especially on a canopy as sugarcane, can be quite large (as well as areal dispersal of irrigation water), which will lead WaPOR to record lower canopy temperatures that are attributed to higher ET_a values. As the data from Table 3-3 indicates, the subsequent separation of *E* from *T* is not working adequately (it decreases statistical correlation instead of increasing it). This may indicate a systemic over-attribution of *E* to *T* by WaPOR for sprinkler-based irrigation systems, which eliminates our analytical options to separate *E* from *T* and base our analysis on the more robust productive transpiration coefficient. In addition, transpiration is estimated using ETLook by assessing energy balance at canopy level, interception from sprinkler irrigation might already be considered as transpiration than evaporation.

3.5 Step 4. Performance Assessment Indicators

There are many performance assessment indicators available. In this study we focus on those which can be derived from remote sensing and in particular WaPOR data. The selected indicators in this study therefore are i) water consumption, ii) uniformity, iii) adequacy, iv) land and water productivity, and v) productivity gaps.

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 we use the seasonal evapotranspiration and the seasonal transpiration (beneficial consumption) as the key indicators.

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 coefficient of variation (CV) of seasonal ET_a in a plot (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 and Gates, 1990).

[9] 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.

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 and Bos, 1999; Clemmens and Molden, 2007). Adequacy can be estimated as the ratio of seasonal ET_a over seasonal *potential evapotranspiration* (Equation 3) (Kharrou et al., 2013; Karimi et al., 2019). In this study, the ET_{ref}, is considered instead of the potential evapotranspiration.

$$A = \frac{ET_a}{ET_{ref}} \quad \text{Equation 3}$$

Where ET_a and ET_{ref} are the actual and reference evapotranspiration in mm/day. Good performance is defined for the range of 0.8<A<=1, acceptable range 0.68<A<=0.8 and poor performance A <=0.68 (Karimi et al., 2019).

3.5.4 Productivity

Productivity is a measure of benefit generated per unit of resource used. The benefit could be biophysical, economic and/or social; the resource base could be consumed or supplied water or land covered by the crop (Zwart and Bastiaanssen, 2004; Mutiro et al., 2006; Hellegers et al., 2009; Karimi et al., 2011; Bastiaanssen and Steduto, 2017). In the absence of information on socioeconomic indicators, this study focussed 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 land productivity by the harvest index.

The water productivity of biomass water productivity (WP_b), referred as water productivity hereafter, is defined as the ratio of biomass over ET_a (Equation 4):

$$WP_b = \frac{B}{ET_a} \quad \text{Equation 4}$$

To obtain WP_b in kg/m^3 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. It is important to note that this measure of water productivity includes consumed green water (from rainfall) and blue water (from irrigation).

3.6 Step 5. Productivity Gaps

3.6.1 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. The targets help to measure productivity gaps and to project production that could improve the effectiveness of both land and water resources use. Even though WP_b is a conservative crop parameter under optimal conditions, meaning that it is very stable across climates and growing conditions (De Wit, 1958; Steduto et al., 2007), it is known to vary for different nutrient stress levels (Steduto and Albrizio, 2005).

Biomass (B) and water productivity (WP_b) targets, or attainable productivities, are identified applying upper percentiles to the distribution of biomass and productivity values of a crop in a particular season and agro-climatic zone. The upper percentile for estimating the attainable yield within regions of similar climate is defined at the 90th percentile by Licker et al. (2010) and at the 95th percentile by Foley et al. (2011). With respect to *crop water productivity*, Zwart and Bastiaanssen (2004) and Zwart et al. (2010) applied the 95th

percentile to the productivity distribution of global data to exclude extremes. In this study, we estimate attainable *B* and WP_b of sugarcane at Xinavane in a particular year at the 95th percentile of the respective productivity distributions, indicated by the vertical and horizontal dashed grey lines in Figure 3-5. The reason for selecting a value within the observed data set of a similar agro-climatic zone rather than a global target or climate limited potential is that it considers the current technology, management techniques and climatic conditions in the area (and for each season). The upper 5th percentile are assigned to accommodate very productive spots as a result of favourable soil and management conditions (Lobell et al., 2002) and whose productivity level cannot be realistically achieved across all areas. It can be argued that the upper 5th percentile also consists of outliers whose productivity is recorded due to noises.

3.6.2 Identifying Bright Spots

There are different definitions of bright spots. Blatchford et al. (2018) identified bright spots when both the yield and water productivity are the highest, whereas Karimi et al. (2019) defines a bright spot based on multiple indicators including equity, adequacy, reliability and productivity. In this study, bright spots are defined as areas where *B* and WP_b *is* greater than or equal to the target values.

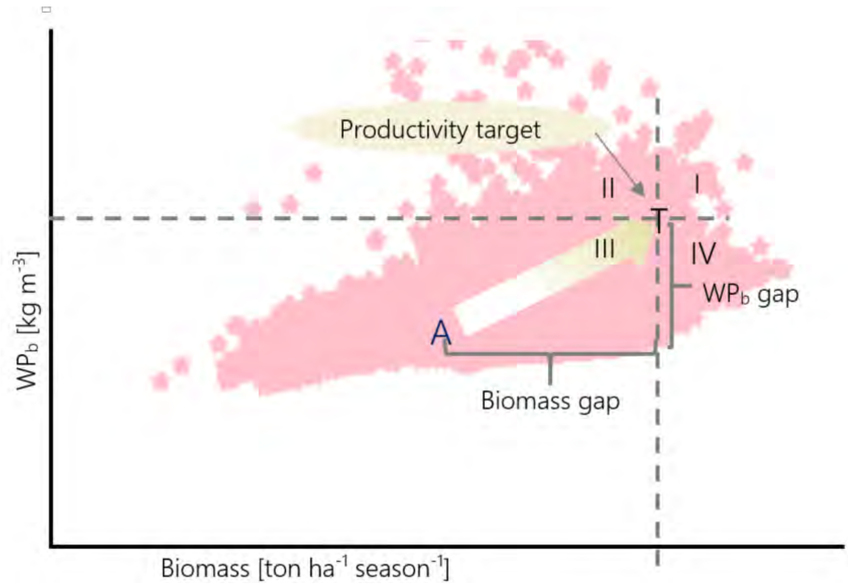


Figure 3-5: Schematic representation of productivity target, and disentangled WP_b gaps and biomass gaps for a crop plot compared to target productivities.

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 *B* and WP_b, respectively, dividing the plot in four quadrants.

3.6.3 Productivity and Production Gap

The productivity gap measures the productivity level of a particular field and gives insight on the performance of a field in comparison with the target value in the area. The productivity gap in an area (Figure 3-5) is calculated by subtracting the productivity value at pixel A from the productivity at the target pixel (pixel T in Figure 3-5). The productivity gaps of pixel A involves water productivity gap (vertical) and a land productivity (horizontal) gap.

With reference to the productivity targets and the two 95th percentile target lines in the WP_b vs *B* graph (Figure 3-5), crop plots (visualized as pixels) fall into four quadrants. All pixels in the first quadrant (I) have higher B and WP_b than the target productivity, they are ideally 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 land productivity gaps, areas falling in the II and III quadrants, over the irrigated area (Equation 5). Areas where B exceed or equal to their respective target values are excluded in the summation.

$$\begin{aligned} B\ gaps &= \textstyle\sum_i^n (B_i - B_t), \quad & B_i < B_t \\ &= 0 & B_i \geq B_t \end{aligned} \qquad \text{Equation 5}$$

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.

3.6.4 Change in Water Consumption

By closing B gaps in a field (represented by a pixel of 100m x 100m or 1 ha), we assumed the field to have the B, WP_b and ET_a equal to that of the target field. Closing the B and WP_b gaps, the four quadrants depicted in Figure 3-5 have different impact on the change in water consumption. Closing productivity gaps at a pixel implies improving the actual B and WP_b to the target levels. Since 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 by reducing ET_a.

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

$$\Delta ET_a = \sum_i^n (ET_{a,i} - ET_{a,t}) \qquad \text{Equation 6}$$

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.

3.7 Delineating Irrigation Application Methods

For the comparative analyses, the performance indicators were calculated for the different irrigation application methods. The scheme was separated into three categories of irrigation application methods: furrow, centre pivot, and mixed irrigation system (where the irrigation type was not confirmed) using information from the field and Google Earth (Figure 3-6). The mixed irrigation system is predominantly sprinkler irrigation (semi-solid set and drag-line). To exclude the non-cropped areas, the WaPOR land cover map (see next section for details) was used to limit the analyses only to the land use class 'irrigated cropland'. The total area considered for the analyses is 10,012 ha, with furrow irrigation covering 363 ha, centre pivot irrigation covers 935 ha, and the mixed irrigation system covers 8,714 ha.

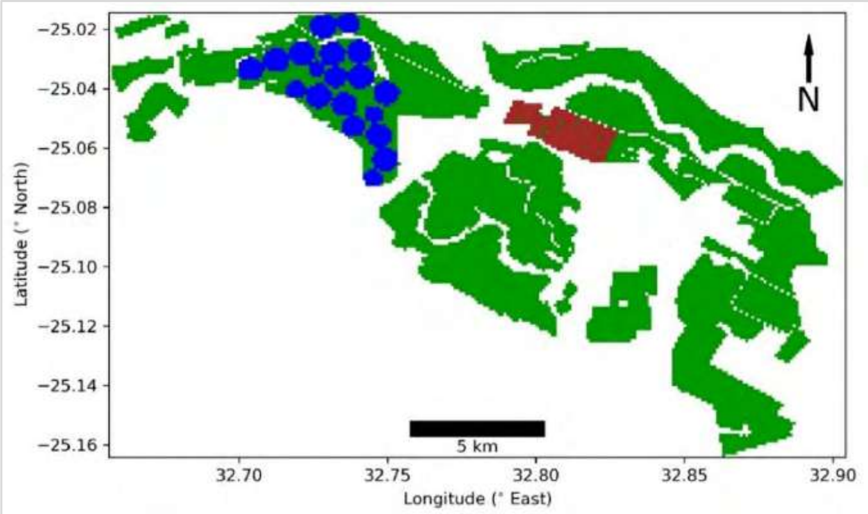


Figure 3-6: Sugarcane production at Xinavane command area using centre pivot (blue), furrow (brown) and mixed irrigation system (green)

4 Results

4.1 Water Consumption

Figure 4-1 shows the annual average ET_a for the period 2014/2015-2018/2019 for the different irrigation methods at Xinavane. The average water consumption at Xinavane sugarcane state is 1,358±128 mm/year and it varies between irrigation methods. The land irrigated by centre pivot has the highest annual average ET_a (1,505±82 mm/year) compared with the land irrigated by a mix of irrigation technologies (1,343±122 mm/year) and furrow (1,329±120 mm/year).

At Xinavane, precipitation and irrigation are the main sources of water used for crop growth. In areas where the groundwater is shallow, capillary water contributes for the sugarcane growth, and yet the water logging effect could also hamper crop growth due to aeration stresses. The long-term average observed precipitation at Chobela station is 687 mm/year (1.6 km from the Xinavane), which is comparable to the 10-year average precipitation of WaPOR data at Xinavane 685 mm/year (Figure 4-1). In all years of the investigation, the annual ET_a is greater than the precipitation, which signals the importance of irrigation at Xinavane.

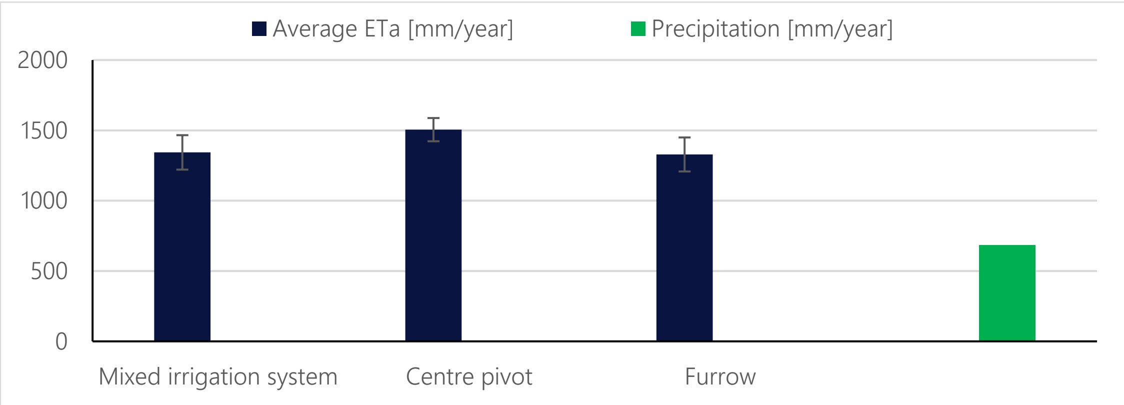
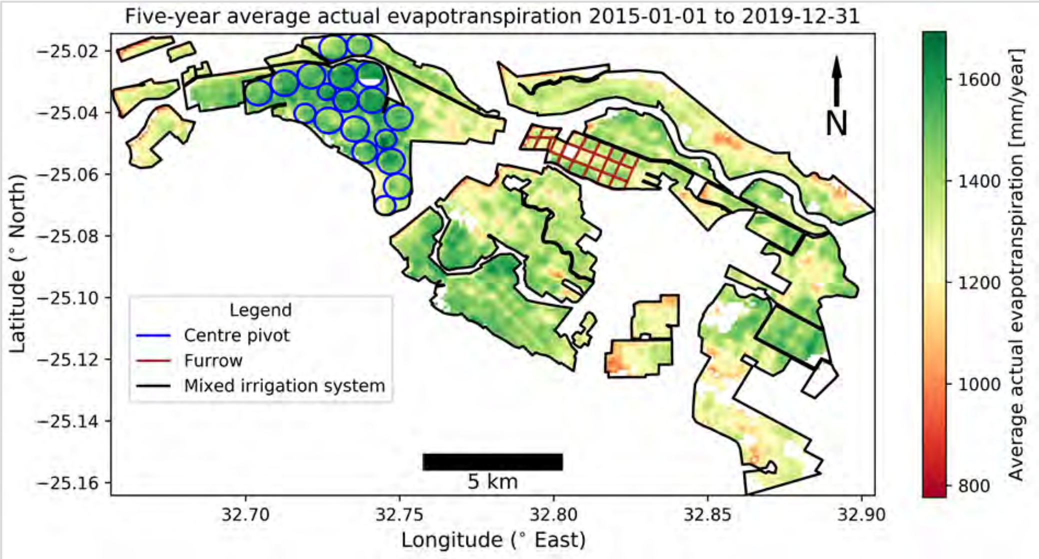
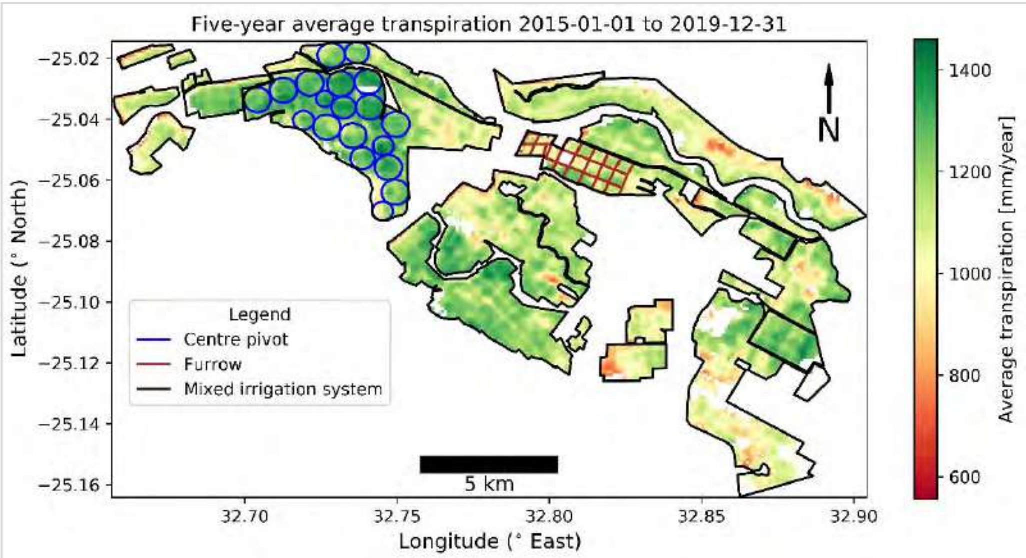


Figure 4-1: Annual average actual evapotranspiration (ET_a) categorized by irrigation methods, and annual average precipitation. The error bar in the annual ET_a indicates the standard deviation across the pixels irrigated by the different irrigation methods.

The five-year average spatial distribution of ET_a and T_a across the Xinavane sugarcane estate is shown in Figure 4-2 (annual maps from 2014-2019 are provided in Appendix D). Figure 4-2a shows the spatial variability of the average annual ET_a, which varies between 777 and 1,628 mm/year. The spatial distribution of the average annual transpiration is shown in Figure 4-2b. The transpiration varies between 560 and 1,413 mm/year with average 1,118±125 mm/year.



(a)



(b)

Figure 4-2: Spatial distribution of five-year average ET_a (a), and transpiration (T) (b) of sugarcane across Xinavane irrigation scheme categorized by irrigation methods.

4.2 Uniformity

4.2.1 Uniformity of water consumption

Figure 4-3 shows the coefficient of variation of ET_a, between pixels at the Xinavane sugarcane estate using the data from 2014/2015-2018/2019. The uniformity of water consumption at Xinavane is 9.4 %. The coefficient of variation of ET_a for the areas irrigated under centre pivot, furrow and mixed irrigation system are 9, 5.5 and 9 %, respectively. Thus, Xinavane sugarcane estate has good uniformity for all irrigation methods, with higher uniformity for the centre pivots.

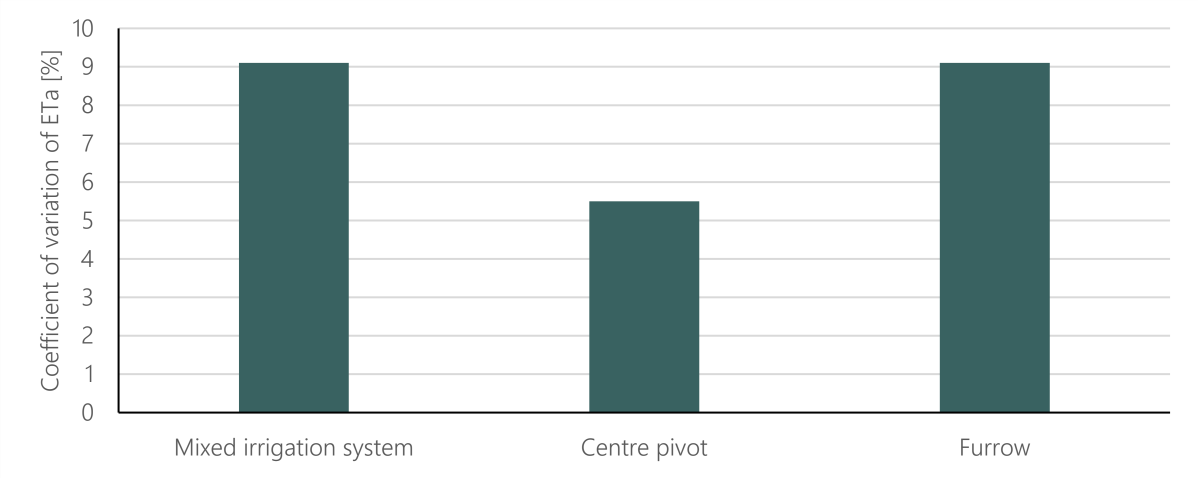


Figure 4-3: Coefficient of variation of ET_a at Xinavane irrigation scheme categorized by irrigation methods

4.3 Adequacy

Adequacy of irrigation water delivery at Xinavane sugarcane estate is shown in Figure 4-4. Adequacy varies between irrigation methods. For the period analysed (2014/2015 - 2018/2019), areas under furrow irrigation had the highest water deficit (adequacy of 0.69±0.06 [-]), and areas under centre pivot the lowest (adequacy of 0.78±0.04 [-]).

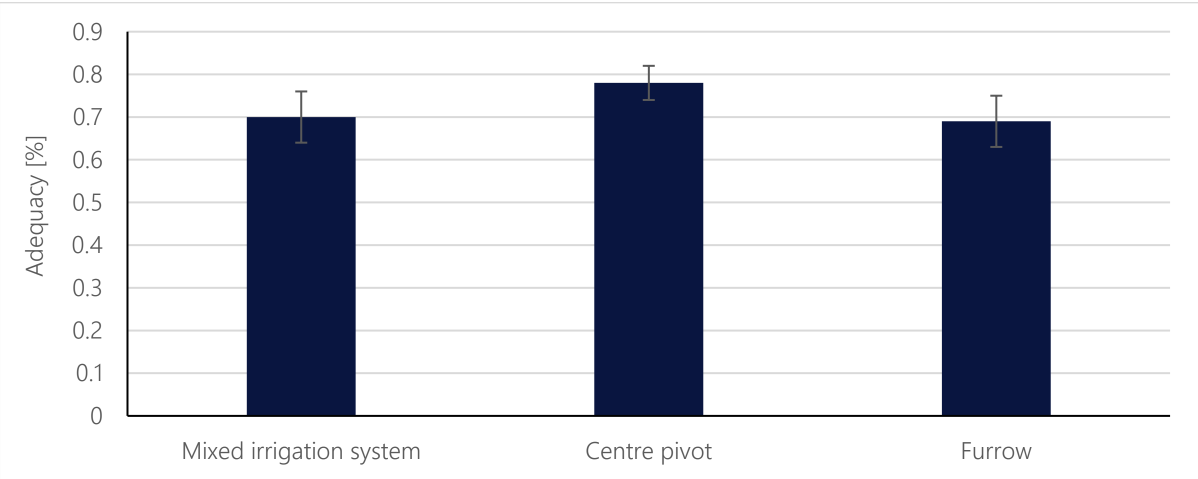


Figure 4-4: Adequacy [-] at Xinavane estate categorized by irrigation methods.

The spatial distribution of adequacy across the Xinavane irrigation scheme categorized into centre pivot, furrow and mixed irrigation system is shown in Figure 4-5 (annual maps from 2014-2019 are provided in Appendix E).

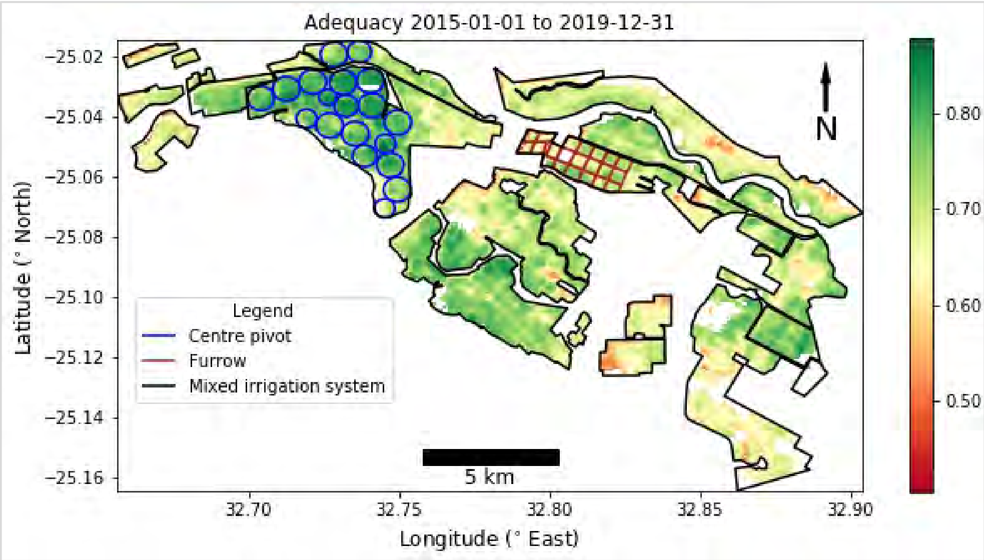


Figure 4-5: Spatial distribution of adequacy at Xinavane irrigation scheme.

Adequacy is defined as the ratio ET_a / $ET_{required}$ which was for this purpose simplified to the ratio ET_a / ET_{ref} as presented in equation 3. However, this is not agronomically correct, as the $ET_{required}$ will differ per irrigation method, frequency and soil type as per Allen et al., 1998 (re eq. 59, table 20, figure 29 and figure 30). To perform a meaningful adequacy assessment, one thus needs to be able to assess the differential $ET_{required}$ per irrigation method. But this requires a more detailed information base on soil type, irrigation frequency and application rates, crop growth stages as well as climatic conditions – all of which (except climate) are beyond the scope of WaPOR to determine on the basis of its RS images. Caution in interpretation is thus required, when asserting that the ET_a / ET_{ref} ratio of centre pivots is higher than that of other irrigation methods: this may, and should be the case, but is largely determined by the fact that centre pivots require more water (and ET_a) than other irrigation methods.

4.4 Productivity

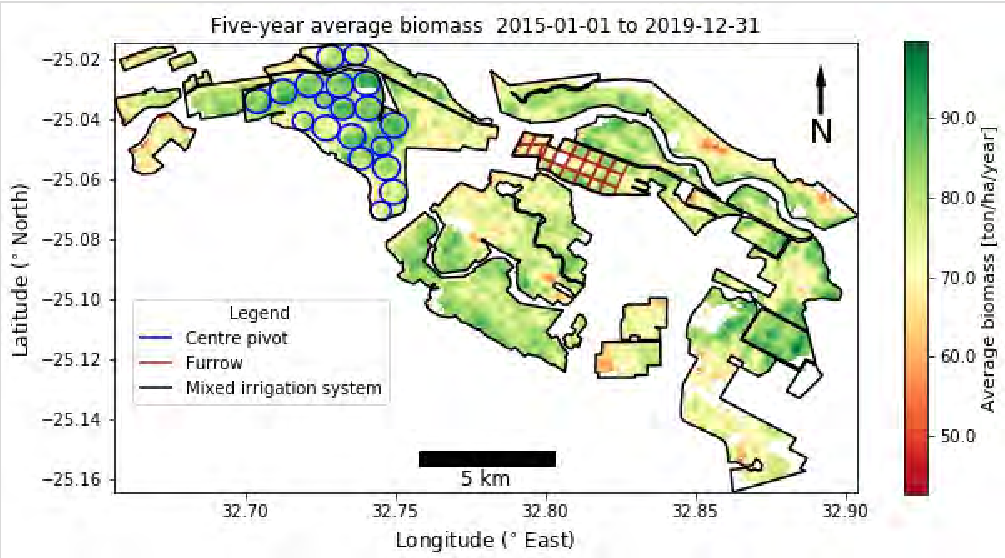
Table 4-1 presents the biomass and actual water consumption derived from WaPOR data based on the hydrological season over the study area, and the observed yield. The estimation of sugarcane yield production is quite close to the observed yield for the Xinavane sugarcane estate. The crop yield of plots equipped with centre pivots tend to be higher than those with mixed, and furrow irrigation. This can be mainly attribute to the higher ET_a for pivot and mixed. In essence, with these methods more water becomes effectively available for consumptive use by the plant. A lower irrigation efficiency for furrow irrigation may mean plant water uptake is less, as suggested by the data, which stunts overall yield production. The data presented in Table 4-1 also suggest that the irrigation applications of the Centre Pivots are better adjusted to the climatic conditions, showing the lowest inter-season variation in ET_a/ET_0. This suggests there is further room to improve irrigation scheduling for furrow and mixed irrigation systems, accounting more closely for inter-seasonal climatic variations.

Table 4-1: Average observed yield and WaPOR yield

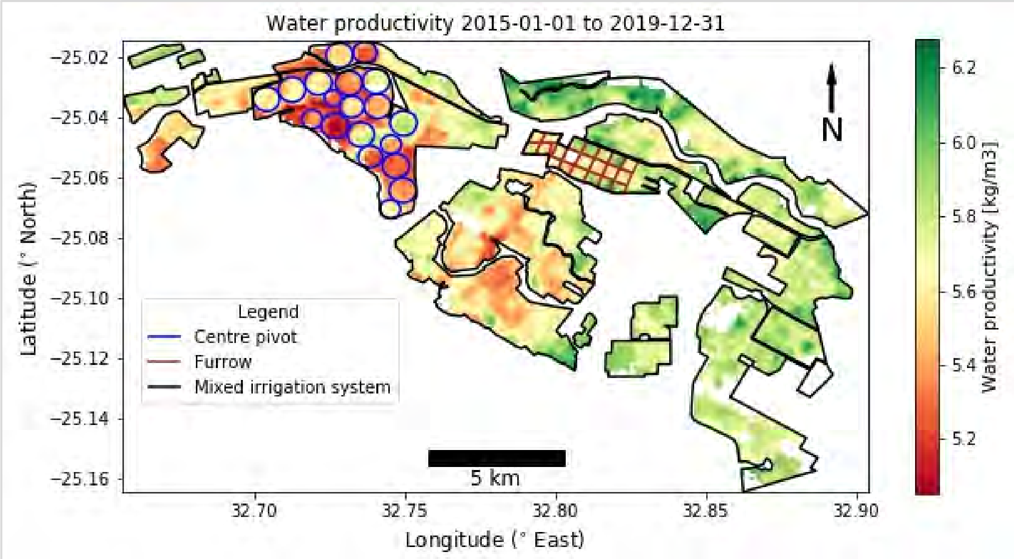
	Furrow				Mixed				Centre Pivot			
Season	Yield (t/ha)		ET_a (mm/ year)	ET_a / ET_0 (-)	Yield (t/ha)		ET_a (mm/ year)	ET_a/ET_0 (-)	Yield (t/ha)		ET_a (mm/ year)	ET_a/ET_0 (-)
	WaPOR	Observed			WaPOR	Observed			WaPOR	Observed		
14/15	80.5	83.1	1,382	0.72	78.6	87	1,366	0.71	78.6	94.8	1,481	0.77
15/16	75.3	82.9	1,377	0.66	71.0	73.2	1,293	0.62	78.1	98.4	1,537	0.74
16/17	80.4	80.0	1,329	0.71	82.8	86.9	1,364	0.73	87.2	90.5	1,489	0.80
17/18	79.5	77.6	1,298	0.67	83.8	92.0	1,384	0.71	91.1	99.9	1,563	0.80
18/19	73.8	71.1	1,335	0.65	74.6	91.0	1,366	0.66	79.2	85.2	1,526	0.74
CV	**4.0%**		**2.6%**	**4.9%**	**7.0%**		**2.6%**	**6.5%**	**7.2%**		**2.2%**	**4.0%**

Note: the WaPOR yield is calculated by multiplying the biomass by a harvest index equal to 1, the default harvest index of sugarcane in WaPOR portal (FAO, 2020a).

The spatial variation of land productivity and water productivity, indicators reflecting effectiveness of land and water resources use, are shown in Figure 4-6 (annual maps from 2014-2019 are provided in Appendix F). Land productivity varies between irrigation methods. The annual average biomass at Xinavane was 77±7 ton/ha/year. Irrigated areas under centre pivot have the highest average annual land productivity (82±5 ton/ha/year) followed by areas irrigated under mixed irrigation system (77±7 ton/ha/year), and furrow (76±7 ton/ha/year).



(a)



(b)

Figure 4-6: Spatial variation of biomass in ton/ha/year (a), and water productivity in kg/m³ (b) at Xinavane irrigation scheme categorized by irrigation methods (average 2014/2015-2018/2019).

Figure 4-7 shows water productivity (WP_b) of sugarcane at Xinavane derived from five seasons (2014/2015 to 2018/2019). The average WP_b at Xinavane is 5.7±0.2 kg/m^3 and it varies from 5 to 6 kg/m^3. Even though furrow irrigation has the lowest land productivity it scores highest in terms of water productivity, due to the relatively lower water application. On the other hand, centre pivots score high on the land productivity but lower on the water productivity due to the relatively high water-application

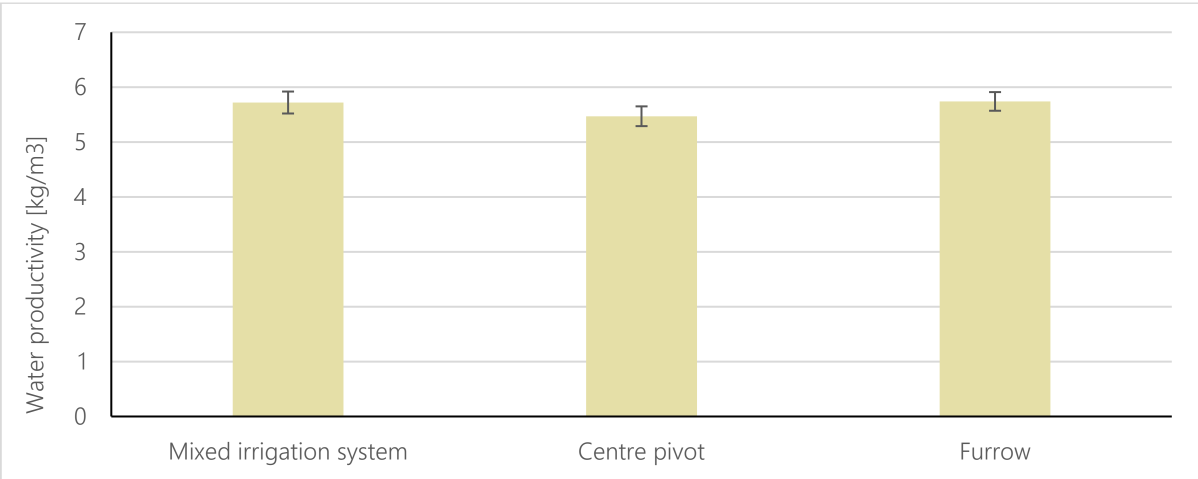


Figure 4-7: Water productivity of sugarcane production per year at Xinavane, annual average for a season from 2014/2015 to 2018/2019.

The WP_b analysis differentiated per irrigation method and season, clearly confirm the agronomic expectation. The WP_b for centre pivot is consistently lower, over all seasons, and the WP_b for furrow is highest (except for 2016/2017 season, where the mixed system shows a slightly higher WP_b), while the mixed method is closer to the value of furrow than that of the centre pivot system. The WP_b values vary over the seasons. As shown in Figure 4-8, the WP_b is lowest when the climate has the highest evaporative demand (high ET_0). The statistical correlations for all WP_b relations presented in Annex C are very good, indicating a strong fit for a differentiated analysis per irrigation method and per season.

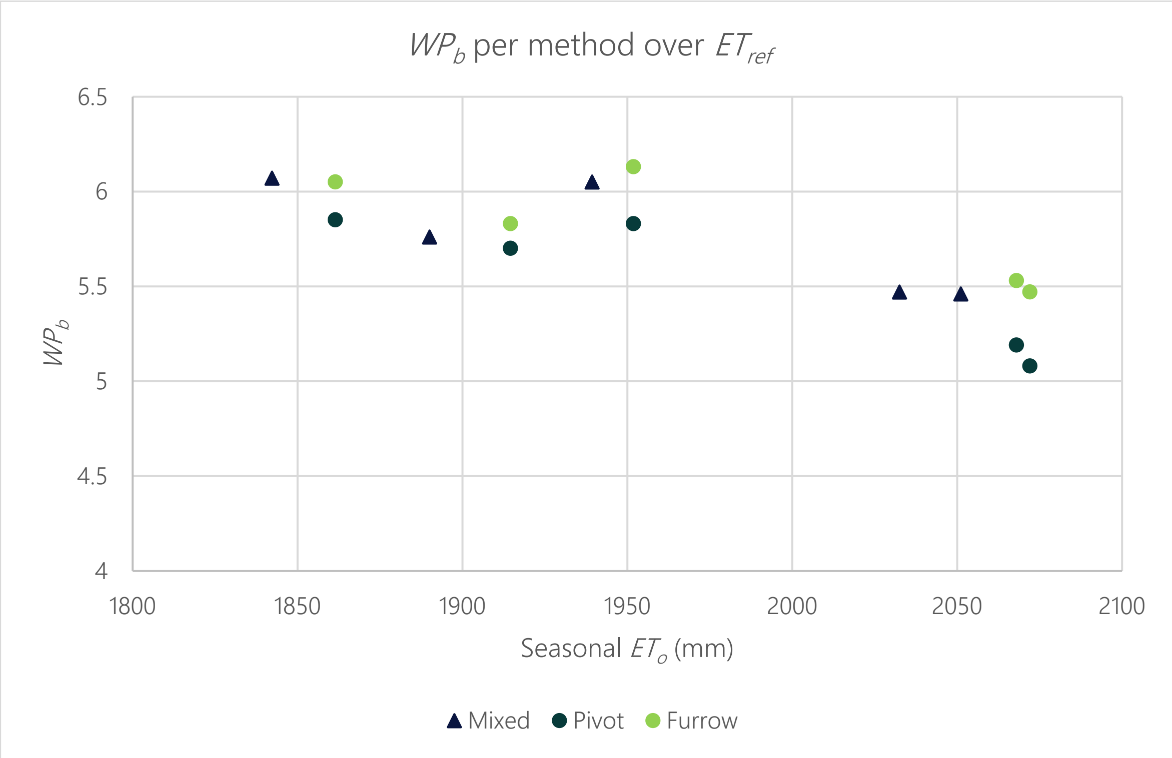
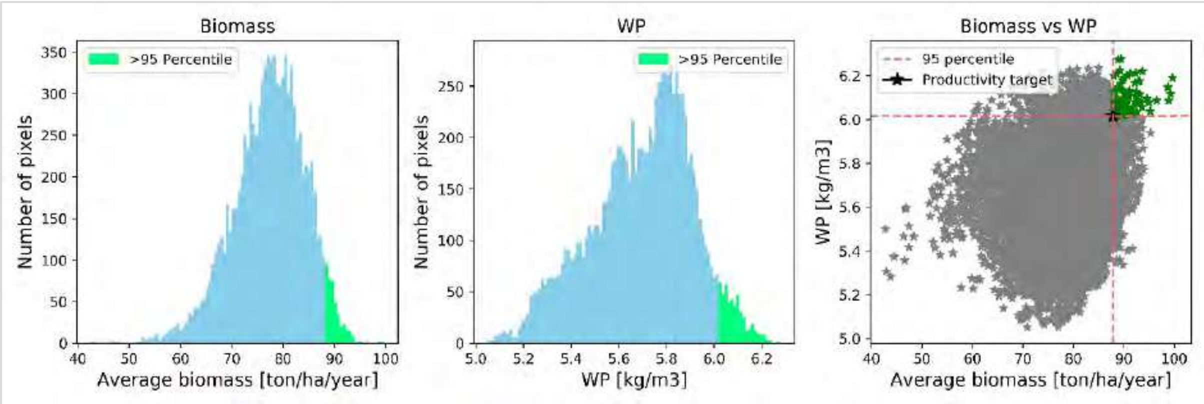


Figure 4-8: WP_b per irrigation method over seasonal ET_0

4.5 Productivity Gaps

4.5.1 Land and Water Productivity Targets

The land and water productivity distributions and the productivity targets based on the 95th percentile of sugarcane at Xinavane scheme for the average of five-years (2014/2015 to 2018/2019) are shown in Figure 4-9 (annual maps from 2014/2015-2018/2019 are provided in Appendix G). The land productivity and water productivity of sugarcane across Xinavane seem to follow a normal distribution and thus statistical parameters such as average, standard deviation and percentiles help describing the characteristics of the productivity distribution. Such normal distribution is seen in the work of Sawasawa (2003) and Zwart and Bastiaanssen (2007) for the yield and water productivity, respectively, but others have found that crop yields are non-normally distributed (e.g. Ramirez et al. (2003)).



(a) (b) (c)

Figure 4-9: Distribution of five-year average biomass (a) and WP_b (b) across pixels at Xinavane irrigation scheme. The attainable land productivity (biomass) and WP_b is shown by dashed orange line at 95 percentile of each distribution (c).

Biomass and WP_b beyond the 95th percentile of their respective distribution for average year are shown in Figure 4-9a and b. Only part of the light green spots in Figure 4-9a and b have both their biomass and WP_b greater than the productivity targets. The target WP_b and biomass of sugarcane production, the productivity values estimated at the 95th percentile of the distribution, are indicated by orange dashed lines and their intersection is marked with dark star on the biomass versus WP_b graph (Figure 4-9c).

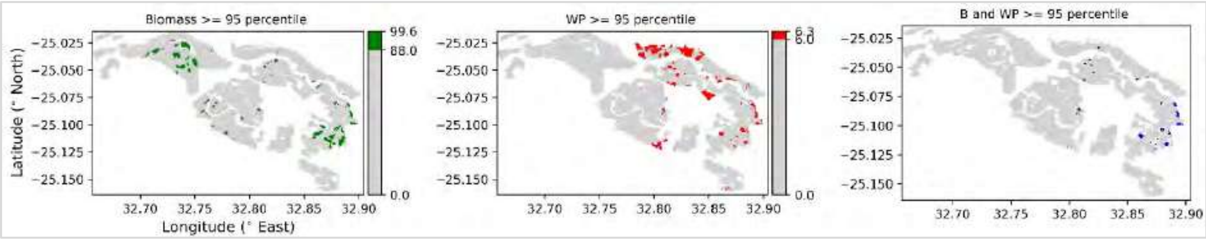
The target biomass and WP_b, indicators that are used to measure the productivity gaps and potential production increase, are presented in Table 4-2. The land and water productivity targets are calculated seasonally from the productivity distributions across pixels at Xinavane scheme. As such the productivity targets are considered attainable with the current technology and best management practices in the area, which is in the same agro-climatic zone.

Table 4-2: Biomass, WP_b and actual ET_a at the target pixel, 2014/2015-2018/2019

Year	Biomass target [ton/ha/year]	Biomass WP target [kg/m^3]	ET_a at the target pixel [mm/year]
2014/2015-2018/2019	88	6	1,460

The bright spots are the areas where both biomass and WP_b exceed the productivity targets. The bright spots averaged over five years (2014/2015 to 2018/2019) are shown in Figure 4-10a, b and c (annual maps from 2014/2015-2018/2019 are provided in Annex G). The spots where the biomass exceeds the target are shown in Figure 4-10a, spots where only their WP_b exceeds the target are shown in Figure 4-10b and the bright spots where both productivity targets fulfilled are shown in Figure 4-10c.

The bright spots are located within the area classified as mixed irrigation system. Examining these bright spots is important for identifying the best practises, and for drawing lessons to suit the conditions of each pixel. The potential implication of such actions is examined in the next sections.



(a) (b) (c)

Figure 4-10: Spots where biomass are beyond the target (a), spots where WP_b are beyond the target (b), and spots where both biomass and WP_b are beyond the target productivities (c) for average of five-year (2014/2015 to 2018/2019).

Figure 4-11 shows the results when differentiating the targets for the different irrigation methods, with the Biomass target for centre pivots being the highest (84.8 ton/ha/year) and furrow the lowest (79 ton/ha/year). Similarly, the WP target for centre pivot is the lowest at 5.5 kg/m^3, and for the other systems it is 5.6 kg/m^3 (Table 4-3).

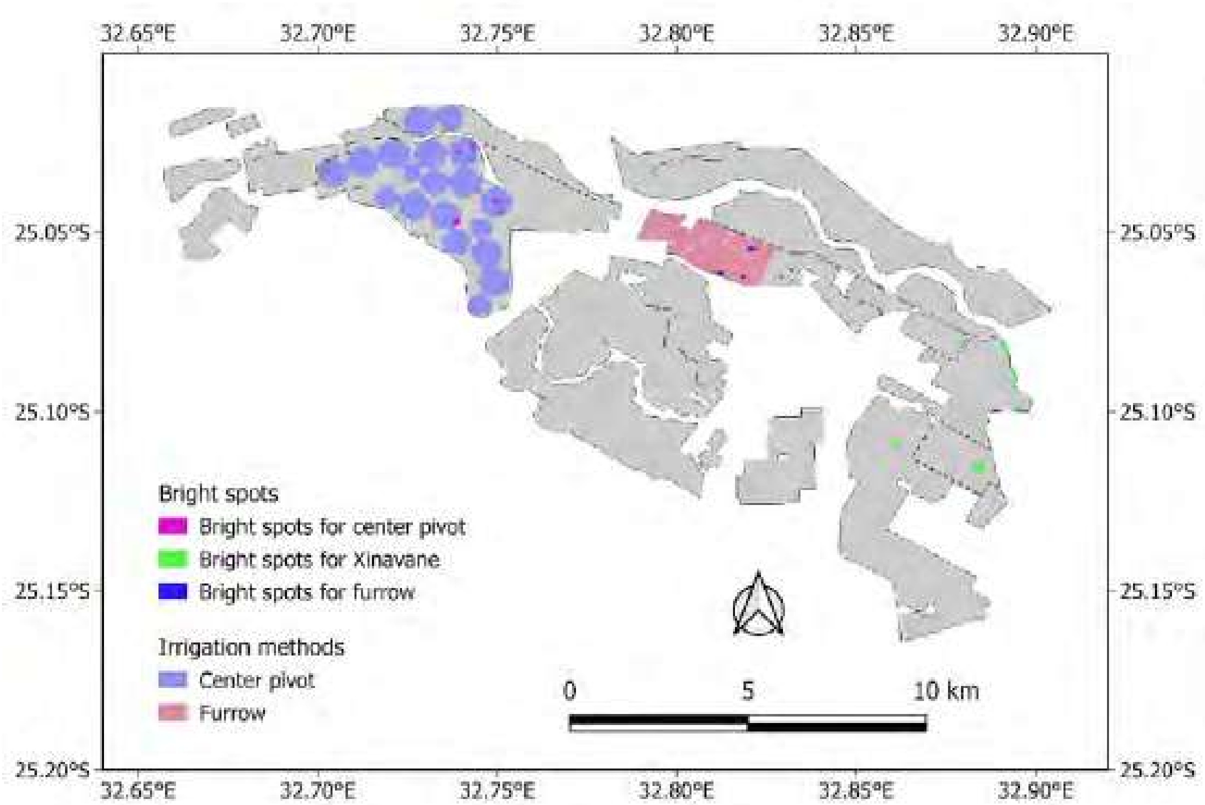


Figure 4-11: Bright spots where both biomass and WP_b are beyond the target productivities. Identified for average season based on average of five-year (2014/2015 to 2018/2019).

Table 4-3: Target biomass, WP_b, and ET_a and blue ET_a, five-year average (2014/2015-2018/2019), at Xinavane

Cluster of areas at Xinavane	Biomass target [ton/ha/year]	WP_b target [kg/m^3]	ET_a [mm/year]
Furrow	79	5.6	1,413
Centre pivot	84.8	5.5	1,542
Mixed irrigation system	82	5.6	1,463
Average	82	5.5	1,483

The WP_b across seasons indicates small variations within the margins of error. It is therefore more appropriate to use a different WP target for each year, which can be explained partly by climatic variation (Table 4-4).

Table 4-4: Biomass, WP_b and ET_a at the target pixel, 2014/2015-2018/2019

Year	Biomass target [ton/ha/year]	WP_b target [kg/m^3]	ET_a at the target pixel [mm/year]
2014/2015	83	5.4	1,538
2015/2016	76	5.5	1,385
2016/2017	85	5.7	1,490
2017/2018	87	5.7	1,529
2018/2019	77	5.2	1,474
Average	82	5.5	1,483
SD	5	0.2	61

4.5.2 Production Gaps

The average biomass gaps in the five-year (2014/2015 to 2018/2019) at Xinavane sugarcane estate is 11.2±6.5 ton/ha/year. The annual average production gaps for the entire estate is 105,860 tons/year. The annual maps of biomass gap at Xinavane are shown in Appendix I.

Figure 4-12 shows biomass and WP_b gaps at Xinavane categorized by irrigation method. It shows that the biomass gap is the lowest under centre pivot irrigation, whereas the WP_b gaps is the highest. WP_b gaps is the lowest under furrow irrigation. This implies that more water is consumed under pivot irrigation compared to furrow to produce the same biomass.

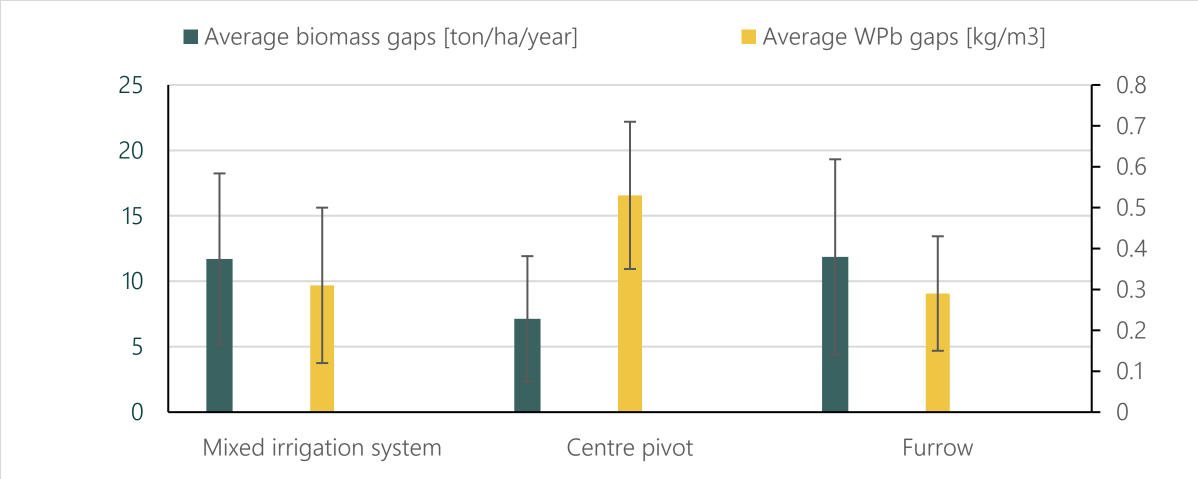


Figure 4-12: Biomass and WP_b gaps at Xinavane for different irrigation methods.

We speculate what the impact of closing the biomass gap would be, based on the assumptions made in this report. Closing the biomass gaps at Xinavane would raise the five-season average biomass production from 77±7 ton/ha/year over 9,453 ha to the target biomass 88±6 ton/ha/year. This could increase the biomass production by 105,860 tons/year, which is equivalent to expanding the cultivation by ~1,203 ha (based on the target productivity: 78 ton/ha and 5.5 kg/m^3) to ~1,375 ha (based on the current productivity: 77 ton/ha). Thus, such an increase in production from the existing irrigation scheme helps to limit agricultural land expansion which otherwise would compete with the land use by other crops or biodiversity.

4.5.3 Change in Water Consumption (ET_a)

Figure 4-13 shows the scatter plot of B and WP_b, the colors indicate the water consumption for each of the pixels. Bridging the B and WP_b gaps requires for the red, orange and light green pixels an increase of ET_a, whereas for the dark green pixels it requires a reduction in ET_a.

We speculate what the impact on water use would be in the biomass gap is closed, based on the assumptions made in this report. The required additional water consumption (and hence ET_a) as well as potential savings (hence reduced ET_a) associated with closing biomass gap at Xinavane is presented in Table 4-5. The average ET_a increases of the five-year period (2014/2015 to 2018/2019) is 150±104 mm/year across pixels of 7,617 ha. The potential ET_a reduction is 51±40 mm/year across pixels of 1,836 ha. So, there is a net additional water demand for closing the biomass gaps of (11.4-0.94) 10.5 Mm^3/year, which is less than the water consumption required to produce the 105,860 tons/year from land expansion (i.e. ~ 17.6 Mm^3/year on 1,203 ha based on the target productivity or ~ 18.5 Mm^3/year on 1,375 ha based on the current average productivity).

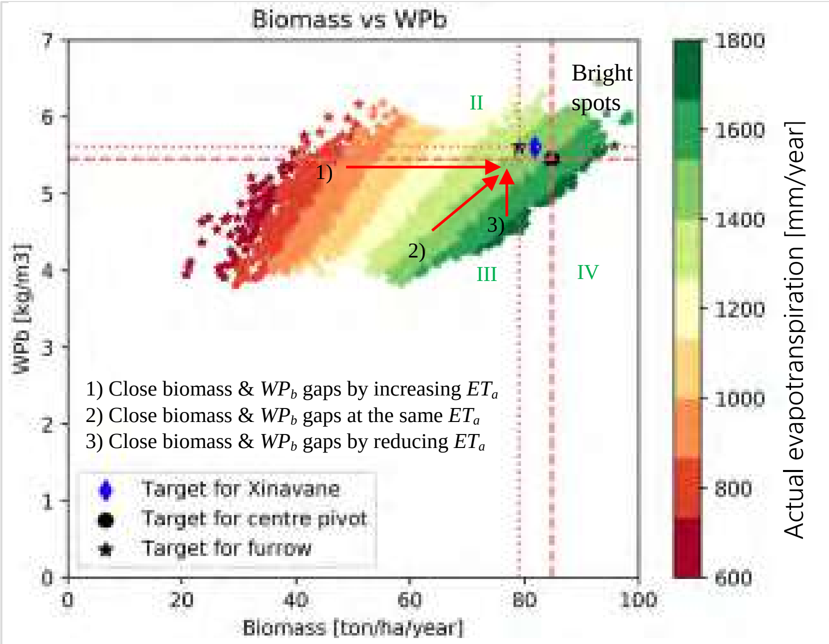


Figure 4-13: The effect of closing land and water productivity gaps on ET_a

Table 4-5: Potential ET_a increase and reduction associated with closing biomass gaps at Xinavane for a season between October 1st and September 30th from 2014/2015 to 2018/2019

	ET_a Increase				ET_a Reduction			
Year	Area [ha]	Mean [mm/year]	SD [mm/year]	[Mm³/year]	Area [ha]	Mean [mm/year]	SD [mm/year]	[Mm³/year]
2014/2015-2018/2019	7,617	+150	±104	+11.4	1,836	-51	±40	-0.94

5 Discussion

5.1 Comparative irrigation method analyses

Figure 5-1 summarizes the performance indicators for the different irrigation methods, with the five indicators in the figure being normalized using their maximum (100 %) or target values. The water consumption indicator could, however, be higher than 1 implying water is over consumed above the ET_a of the reference (target) spot. The figure shows that there is not one irrigation method that stands out as the best in all indicators.

Areas irrigated by centre pivots demonstrate distinct performance compared to area irrigated under furrow irrigation while the indicators for the areas irrigated under mixed irrigation systems overlap with that of the furrow. Furrow irrigation appears to have a higher WP_b than centre pivots but lower performance in the most important indicators related to production and irrigation water management: land productivity and adequacy. Our analysis shows that centre pivots have higher adequacy, land productivity and uniformity of water consumption than furrow irrigation method. The disaggregated analysis of WP_b reveals an ***inter-irrigation method variation*** that is consistent with established theory, indicative of the differential (non-productive) evaporation fraction associated with each irrigation method. Conform the theory (Allen et al., 1998), furrow irrigation consistently returns the highest WP_b, which is indicative of its lower evaporation fraction. Similarly, centre pivots return the lowest WP_b. The mixed irrigation systems return WP_b values in between those of furrow and centre pivots, with values closer to that of furrow than that of centre pivots. In addition, the outcome is in agreement with the conclusion by Karimi et al. (2019) who assessed performance of irrigated sugarcane in Swaziland by segmenting growers according to different management regimes including irrigation method. Centre pivots do, however, perform markedly worse regarding water productivity and water consumption indicators than furrow irrigation. Our finding that centre pivots have higher uniformity of water consumption than furrow irrigation confirms the findings in earlier studies (Griffiths and Lecler, 2001; Karimi et al., 2019).

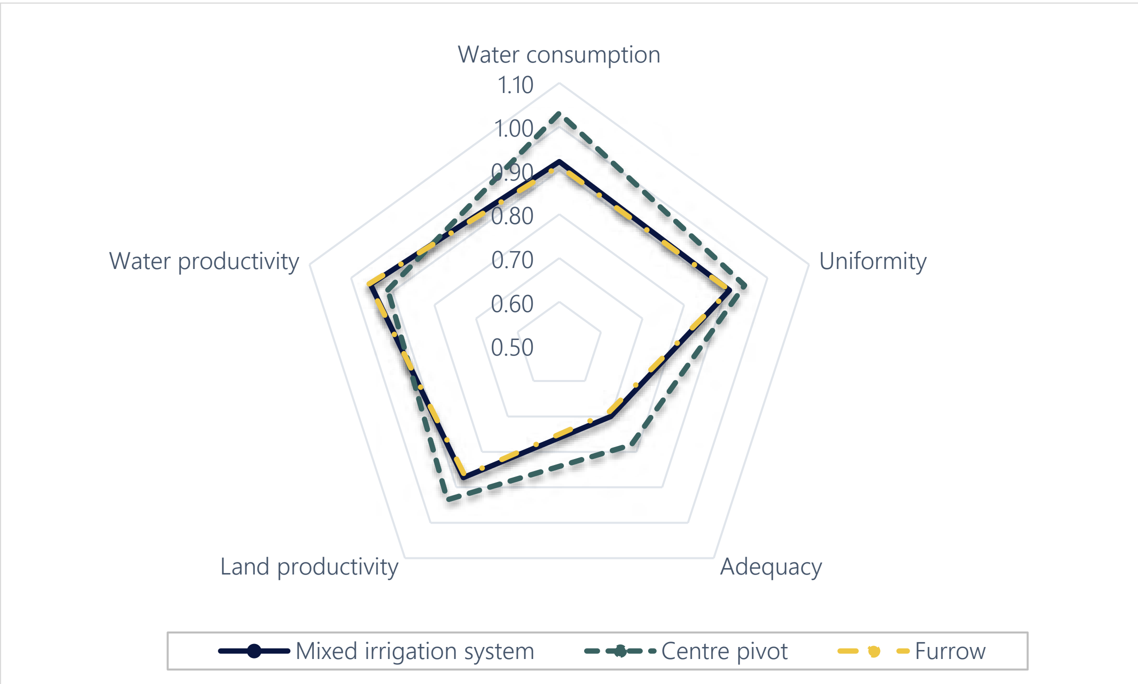


Figure 5-1: Comparison of irrigation method in Xinavane sugarcane estate across six indicators

The disaggregated datasets reveal also a marked ***inter-seasonal variation*** of WP_b that can be explained by the variation of the climatic conditions – in particular the variation in evaporative demand of the climate. This has a marked effect not only on crop transpiration, but also on (non-productive) evaporation. The higher the evaporative demand of the climate, the lower the WP_b. This effect is double edged, as a higher evaporative demand of the climate not only results in higher evaporation rates but may also require higher irrigation frequencies that further increase the evaporation fraction. Centre pivots show, as expected, the starkest decline in WP_b with higher evaporative demand of the climate. WP_b is thus affected by climatic conditions, and at high evaporative demand a lower WP_b is achieved due to a relative increase of the (non-productive) evaporation fraction. Irrigation methods with an intrinsic high evaporation fraction (re. sprinklers and centre pivots) are more susceptible to decrease in WP_b. This also means that high WP_b values (e.g. set at WP_b = 6.0) for high ET_a ranges (that are mostly associated with higher ET_{ref} climatic conditions) cannot be realistically assumed to be applicable for centre pivot irrigation systems due to their higher intrinsic evaporation fraction.

The other important finding of this study is that closing the biomass gaps can increase production. With the assumptions used in the analyses this could lead to up to 105,860 tons/year increase in production, which is equivalent to expanding the irrigated area with more than ~ 1,203 ha. This requires 17.6 Mm^3/year of water (based on the target productivity, or ~ 18.5 Mm^3/year on 1,375 ha based on the current average productivity). This is significantly higher compared to the increase in water consumption related to closing the gap (net increase of 10.5 Mm^3/year).

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. First, the annual LCC layer used to identify the irrigated areas within the boundary of the Xinavane estate is in fact not an annually changing LCC map. The LCC maps for Level 1 and Level 2 are based on the Copernicus Land cover map for 2015, with one adjustment: the class "cropland" is split into rainfed/irrigated and fallow classes on an annual basis using precipitation and actual evapotranspiration (source: personal communication, WaPOR database developers). Therefore, the analyses, summarized per irrigation technology, may include areas which in 2015 were classified as irrigated, but in fact were not irrigated in other years. In addition to methodological limitation to accurately capture different stress factor, also, farm roads and canals within the farm boundary and irrigated classes could be sources of noises in the data from 2014/2015-2018/2019.

In addition, the data source of the WaPOR data is not consistent throughout the 10 years. Before 2014, the data is derived from the MODIS satellite (250 m resolution), which is resampled to 100 m. In 2014, PROBA-V came into orbit, which provides the WaPOR L2 data for the period after 2014. The analyses in this report show a clear break 2009-2013 and 2014 onwards in the data (e.g., the noise in the biomass-transpiration and biomasses relationship are much even with patch of scatter pixels, such as high biomass at zero transpiration which cannot be explained agronomical). Thus, our analyses and interpretations are based on WaPOR data after March 2014.

Statistical noise (representing over- or under-valued data outputs) may emanate from various sources that are inherent to the WaPOR method and process. These may stem from:

i) the Land Surface Temperature (LST) layer which is used as an input to calculate water stress, which is not available from the Proba-V satellite, WaPOR therefore uses the MODIS LST layer at 1km resolution, which affects the accurate capturing of the spatial variability;

ii) 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);

iii) 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);

iv) 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);

v) the angle of image capture and its correction function.

All these factors and elements are potential sources of (small) deviations in the numerical output of WaPOR that may lead to over- and under-valuations of the WP_b output. In large and long-term datasets, such as for Xinavane sugar estate, one should thus expect some degree of variation in data output as being inherent to the method and can be regarded as normal *statistical noise*. As the data presented in Table 3-3 and Annex C show, however, the statistical correlation for irrigation method and growing season disaggregated analysis of WP_b is very strong (with R^2 values exceeding 0.99), indicating a clear irrigation method-based WP_b that can be explained with, and attributed to, agronomic principles governing evaporation (see above). Nevertheless, the intra-method and intra-season data clouds do show some variance in pixel-based WP_b values. 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 as presented in Table 3-3 and Annex C.

Our attempt to eliminate the inter-irrigation method variation caused by differential evaporation fractions was done by determining the WP_b (T_a). This would, in theory, eliminate the non-productive evaporation from the water productivity analysis, allowing us to concentrate on variations in the inter- and intra-seasonal values of WP_b (T_a) as being the effect of differences in agronomic management and growing conditions, rather than evaporation fraction of irrigation method applied. The results of this analysis (re. Table 3-3), however, did not make sense from an agronomic point of view as the statistical correlations for WP_b (T_a) were worse than those for WP_b in direct contradiction to established theory. We therefore had to discard this analysis option. There are clearly issues with the method in which WaPOR separates E_a from T_a, which renders it currently not applicable for agronomic analysis of water productivity. These need to be assessed and diagnosed more in-depth and detail and should be ***considered a priority*** for the further refinement and development of WaPOR to enhance its agronomic diagnostic and analytical capacity.

5.3 Other limitations

The timing and duration of crop development stages per field as the sugarcane is harvested throughout the dry season to keep the factory operational can be an additional source of noise. As the crop-growth cycles for sugarcane vary at Xinavane between 9 and 15 months (for 98% of the plots), this may affect the WP_b. In addition, the harvesting date (at the beginning of the dry season, or at the end) may influence the E:T ratio as a larger surface area of the soil is exposed to the sun and evaporation in the former case. This is effect is also noticeable in the WP_b graphs presented in Annex C, where low ET_a 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.

Crop specific parameters were determined using literature and field work in Ethiopia and one crop parameter across the area are applied while stress could vary per pixel. The study showed noises from the comparison (i) B vs T_a and (ii) B vs $\sum(T_a/ET_{ref})$. However, we are unable to determine how much of these noises are due to these assumptions and how much they can be attributed to underlying algorithms and quality of WaPOR input data and the conditions in the field. The effect of differences in the harvesting date, and cloud cover (gap filling) on the temporal variation of the results are avoided by analysis data on the average season.

Variations in agronomic management practices / growing condition (e.g. soil fertility management, crop varieties, pest management, soil type, etc.) could ***not*** be statistically discerned within the (disaggregated) dataset due to lack of sufficient field data.

WaPOR precipitation data is also compared to observation at the close by metrology station. A comparable result is found between the long-term observed annual precipitation at Chobela station in close proximity (~1.6 km) to Xinavane (687 mm/year) with the 10-year average annual precipitation from WaPOR (685 mm/year). Our estimate of annual average ET_a at Xinavane (1,358±128 mm/year) falls between 800 and 2,000 mm/year, a range reported as annual water consumption for sugarcane (Steduto et al., 2012).

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 a significant cost.

6 Conclusions

This study assesses the spatial variability of water and land productivity and irrigation performance average of five cropping seasons (2014/2015 to 2018/2019) at Xinavane sugarcane estate, which is disaggregated according to irrigation method. 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 Xinavane sugar estate through the application of WaPOR for the season 2014/2015-2018/2019 show a remarkable good result for the assessment of WP_b, based on the two principal variables, i.e. seasonal ET_a and seasonal Biomass production. 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, mixed and centre pivots) is very strong – confirming established agronomic principles governing photosynthesis and crop water consumption. This is a strong and positive outcome, that bodes well for the applicability of the WaPOR method on large and uniform scales of agricultural production as provided by the Xinavane sugar estate. Additional observations were made:

– The comprehensive analyses on the spatial variation of the indicators at Xinavane specify that there is not one irrigation method that stands out as the best in all indicators.

– Centre pivots achieve higher adequacy, land productivity and uniformity, but at the lower water productivity and seasonal water consumption, compared to furrow irrigation.

– Furrow irrigation has higher water productivity than centre pivots but scores lower on the indicators related to production and irrigation water management: land productivity and adequacy.

– Sugarcane productivity if fairly good and uniform across all irrigation methods and across all seasons with a WP_b ranging from 5.0 to 6.1 kg.m^{-3}.

– Productivity varies with the variation in the evaporative demand of the climate (ET_{ref}), whereby WP_b (ET_a) declines with higher ET_{ref} as the non-productive evaporation rate increases with ET_{ref}.

– In general land productivity (cane yield) in centre pivot irrigated areas is highest, followed by mixed and furrow; which is confirmed using both WaPOR yield and observed yield. This can be attributed to higher seasonal ET_a values in centre pivots, which suggest a better irrigation scheduling is taking place in the centre pivots compared to furrow and mixed irrigation. This is also attested by variation in ET_a/ET_{ref} ratio, which is lower for centre pivots than for the other irrigation methods (Table 4-2). There is thus scope to improve the land productivity and yield of furrow and mixed irrigation by ***improving irrigation scheduling*** by responding more accurately to the variations in the climatic conditions.

– The general lower seasonal ET_a, and hence biomass and yield production, of furrow irrigation compared to centre pivot and mixed, might be attributable to two factors: with a lower irrigation application efficiency, furrow irrigated sugarcane may receive a relative low consumptive water fraction (ET_a) that may constrain biomass production;

– Enhancing land productivity under optimal water productivity may be thus also be a matter of giving crops/plots the opportunity to mature; especially for furrow and trickle irrigation (non-sprinkler based) highest WP_b values can be achieved at full canopy cover when evaporation fractions are the lowest and the crop can accumulate biomass at its highest rate per unit of land and water.

– Intensification at Xinavane by closing biomass gaps can increase production up to 105,860 tons/year, which is equivalent to harvesting from additional irrigation land of more than ~ 1,203 ha.

– Increasing production though intensification could potentially save water compared to producing the same from land expansion. The additional water consumption (10.5 Mm^3) required to produce 105,860 tons/year by intensification is much smaller than water consumed to produce the same from land expansion (17.6 Mm^3/year required over 1,203 ha operating on the target productivity or ~ 18.5 Mm^3/year on 1,375 ha operating on the current productivity level).

The study shows the potential use of RS-derived data to identify bright spots with the highest land and water productivity. From remote sensing we are unable to determine the underlying causes for the variability, which can be caused by farm management, inputs, as well as stresses resulting from factors such as water logging and salinity. Investigating the root causes of the land productivity variation and whether proper management of salinity and drainage could bridge the productivity gaps requires further study.

These conclusions are based on the assumptions explained in the document. The accurate interpretation of the results, diagnosis of the productivity gaps and formulation of practical solutions cannot be made unless the WaPOR analyses and results are complemented with observed data of field conditions (e.g., the level of water and nutrient inputs, water logging, and salinity levels etc.) that can help to understand the production setting of the fields and explore the constraints. Though the limitations put a disclaimer on our findings, the procedures in this study can provide a useful reference for similar future studies.

Subsequent studies 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 conduct comprehensive performance assessment of irrigation schemes.

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8 Appendices

Appendix A Additional background information about Xinavane estate

Table A-1: Overview of Xinavane smallholder associations and some characteristics (Jelma et al., 2010)

Phase	Year	Association	Sugarcane area (ha)	No. of Small-holders	Area per small-holder	Irrigation system
I	1998	Maguigane	90	66	1.4	Dragline
II	2005	Macuvulane	185	180	1.03	Dragline
	2008	Chihenisse	200	40	5.0	Pivot
III	2008	Macuvulane 2	73	89	0.8	Dragline
	2009	Maria de Luz Guebuza	263	200	1.3	Dragline
	2009	Hoyo-Hoyo	189	150	1.3	Dragline
	2009	6 de Janeiro/ Colo	74	200	0.4	Dragline
	2009	Maholele Macamo	72	4	18	Dragline
	2009	Buna	218	110	2.0	Dragline
	2009	Olhar de Esperança/ Facasize	107	250	0.4	Dragline
	2009	Maholele G 1st Stage	266	6	44.3	Dragline
	2010	Chichuco	95	150	0.6	Dragline
	2010	Maholele Mutombene	56	4	14.0	Dragline
	2010	Tres de Fevereiro D	133	10	13.3	Dragline
	2010	Mucombo Est.	70	80	0.9	Pivot
Total			2,091	1,539	1.4	

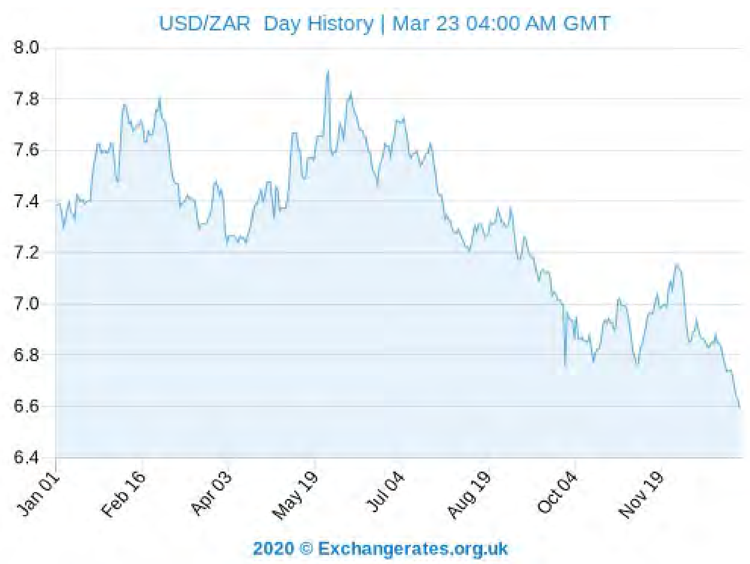
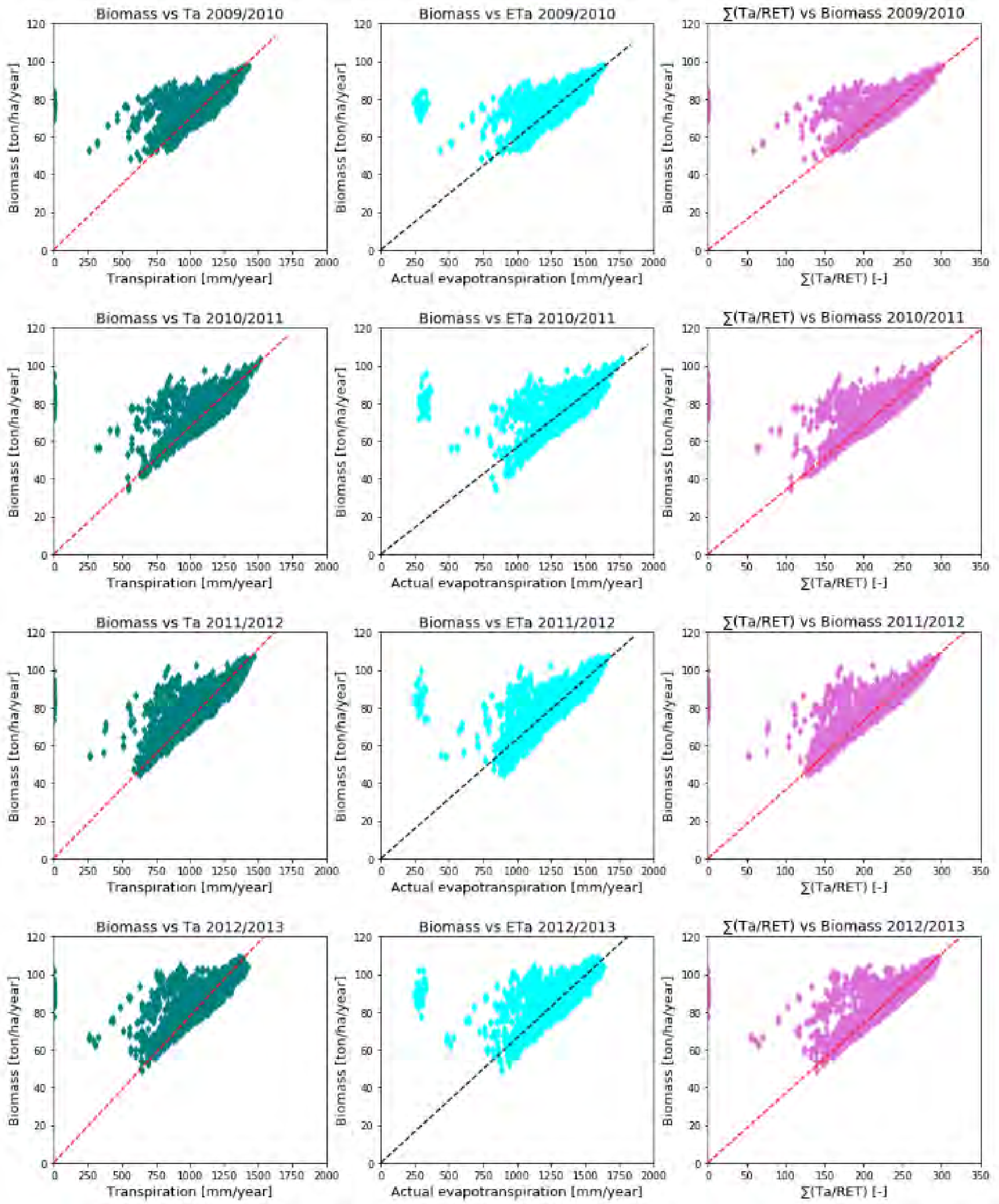
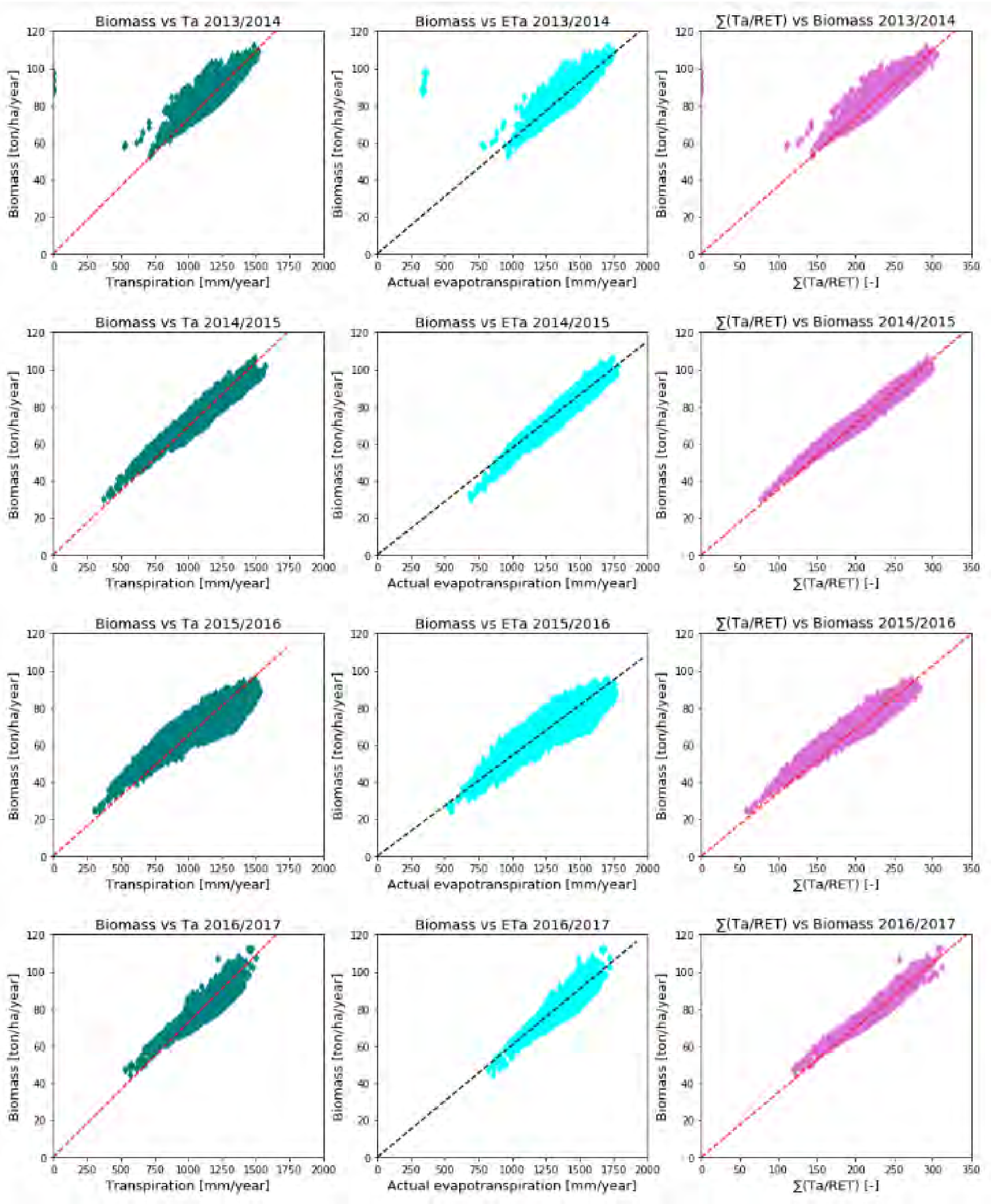


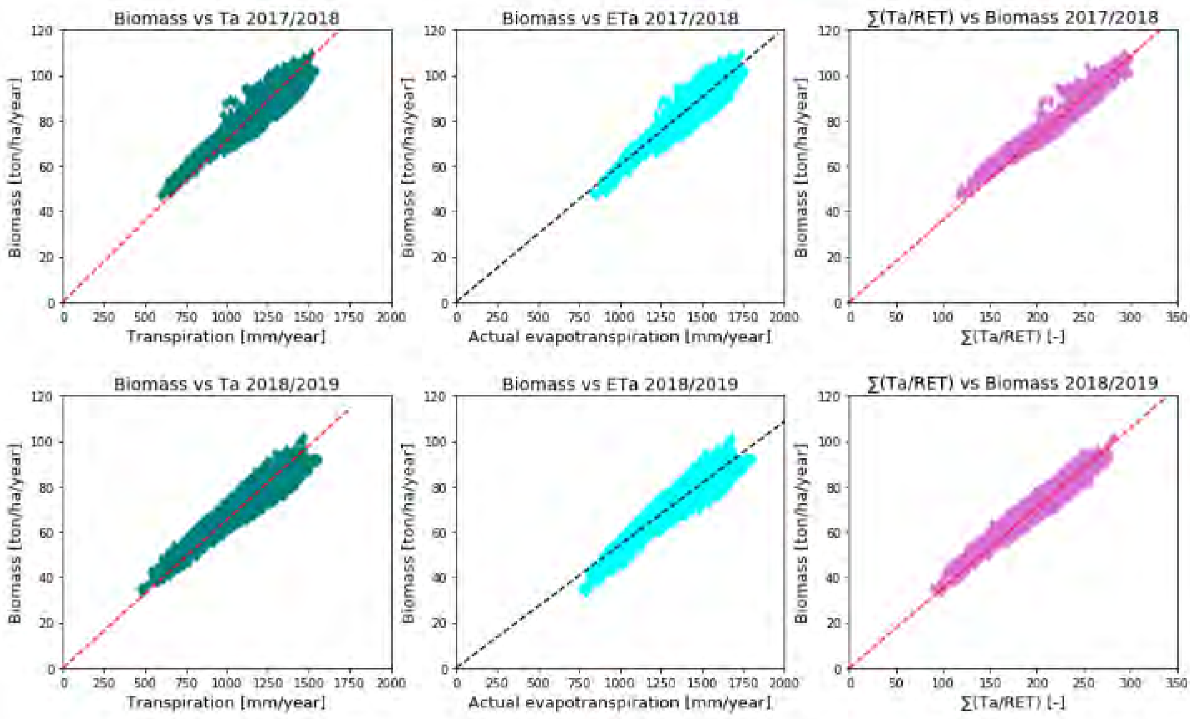
Figure A-1: US Dollar to South African Rand Spot Exchange Rates for 2010

Appendix B Relationship of Biomass vs T_a, and Biomass vs ET_a

The relationship between biomass vs transpiration (T), biomass vs ET_a and $\sum(T_a/ET_{ref})$ vs biomass of sugarcane production at Xinavane from 2009/2010 to 2018/2019

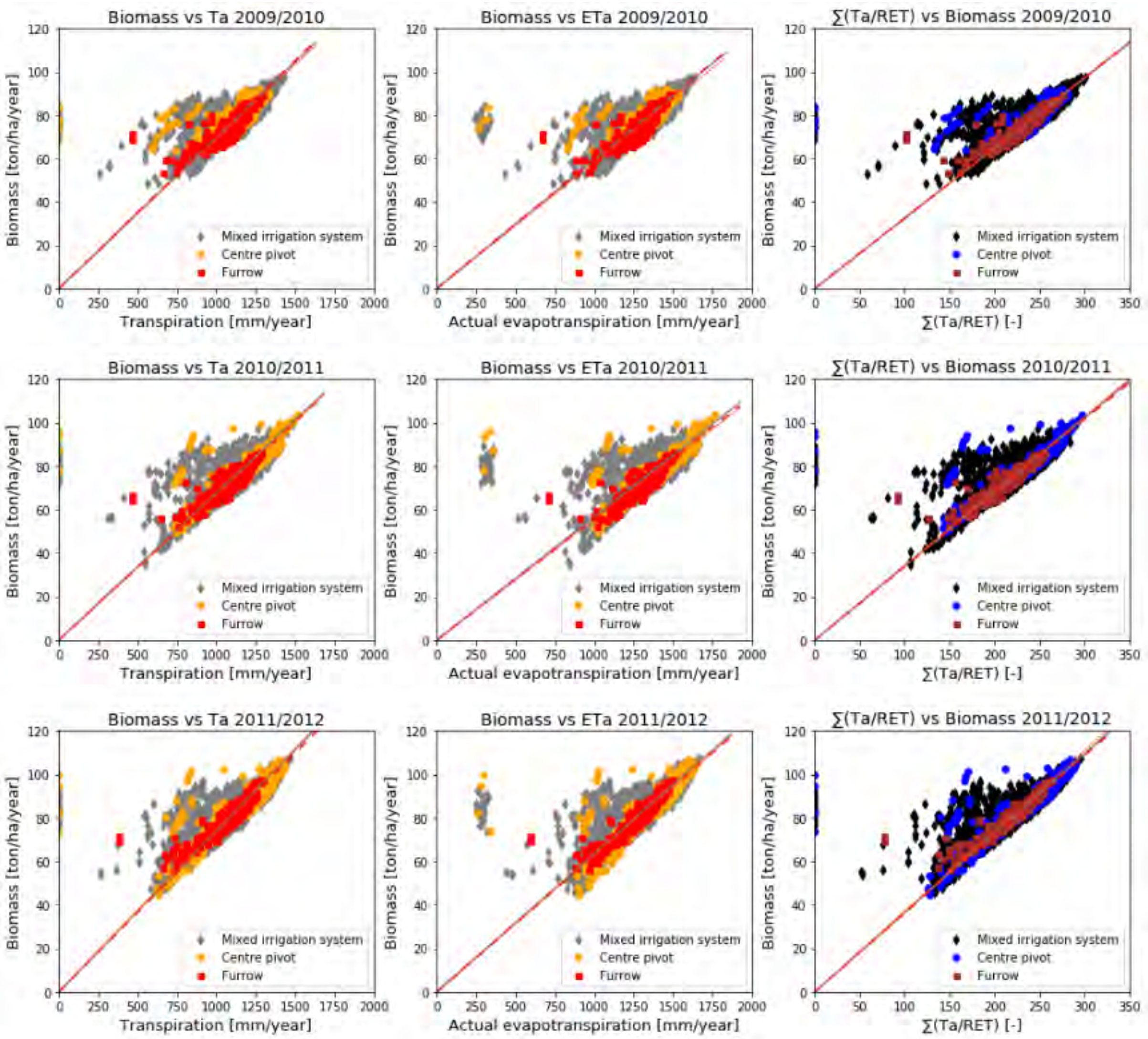


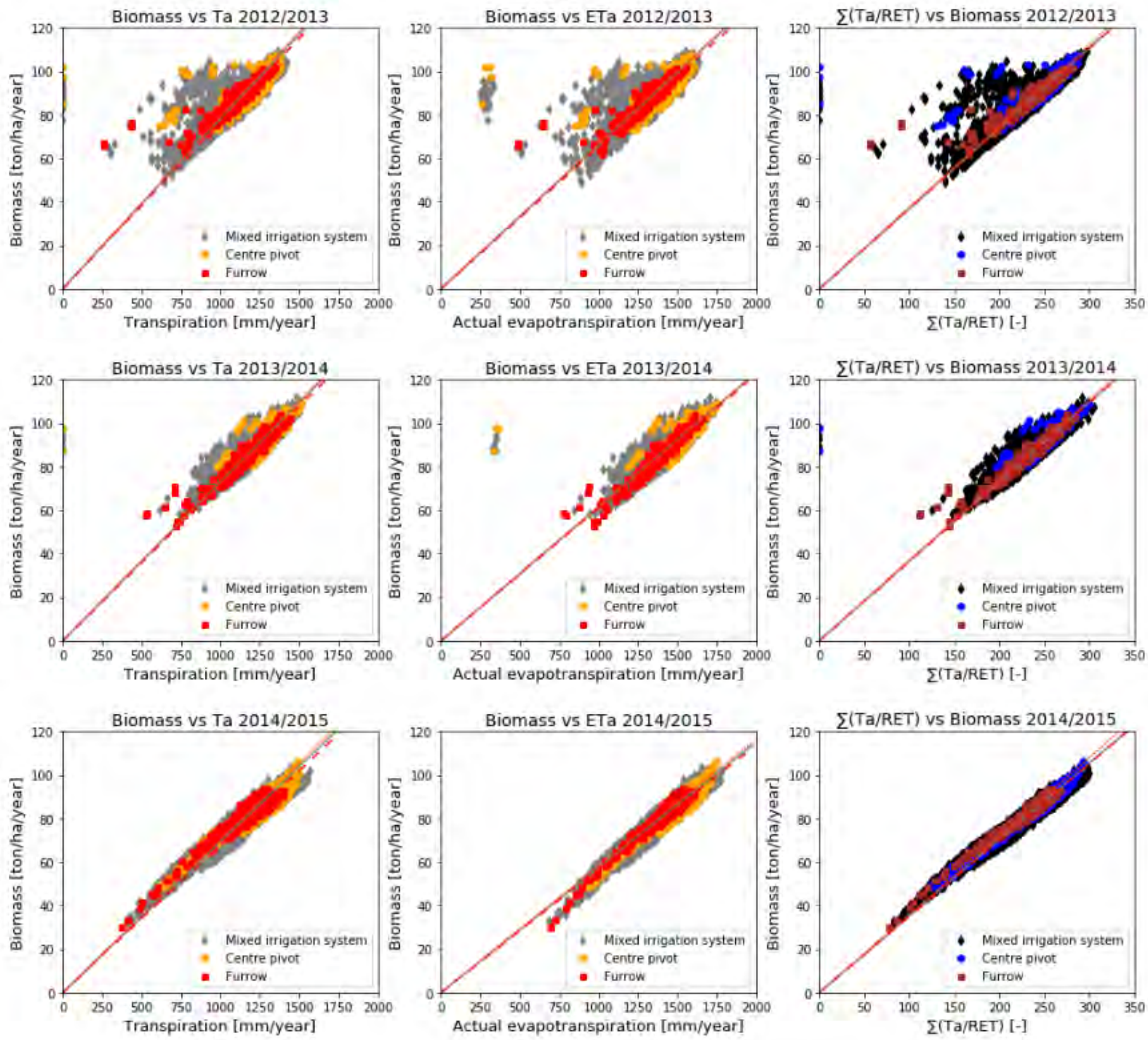

Biomass vs Ta 2013/2014
Biomass vs ETa 2013/2014
∑(Ta/RET) vs Biomass 2013/2014
Biomass vs Ta 2014/2015
Biomass vs ETa 2014/2015
∑(Ta/RET) vs Biomass 2014/2015
Biomass vs Ta 2015/2016
Biomass vs ETa 2015/2016
∑(Ta/RET) vs Biomass 2015/2016
Biomass vs Ta 2016/2017
Biomass vs ETa 2016/2017
∑(Ta/RET) vs Biomass 2016/2017
Biomass [ton/ha/year]
Transpiration [mm/year]
Actual evapotranspiration [mm/year]
∑(Ta/RET) [-]

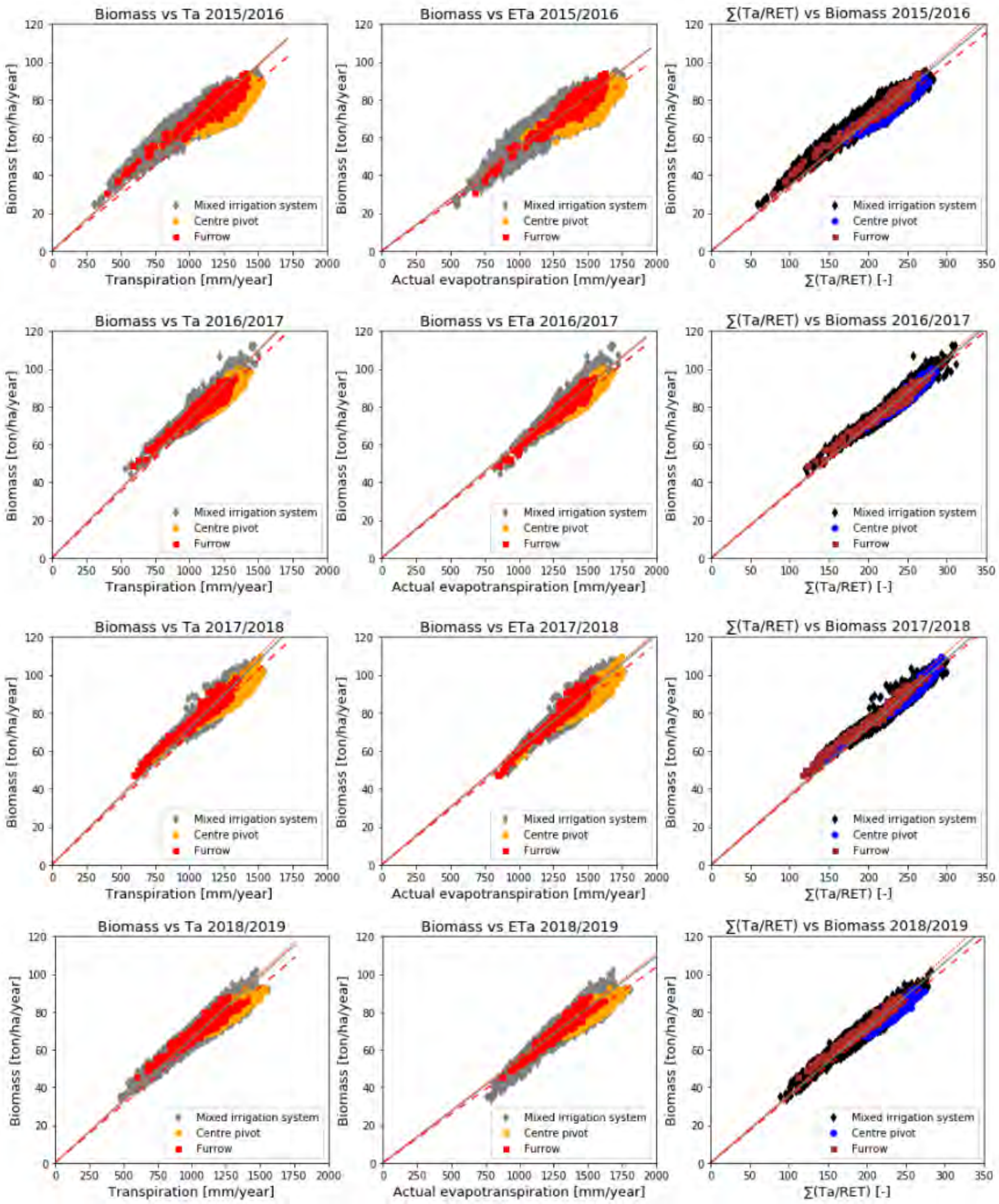

Biomass vs Ta 2017/2018
Biomass vs ETa 2017/2018
∑(Ta/RET) vs Biomass 2017/2018
Biomass vs Ta 2018/2019
Biomass vs ETa 2018/2019
∑(Ta/RET) vs Biomass 2018/2019
Biomass [ton/ha/year]
Transpiration [mm/year]
Actual evapotranspiration [mm/year]
∑(Ta/RET) [-]

Appendix C Relationship of Biomass vs T_a, and Biomass vs ET_a *at Xinavane categorized by irrigation methods*

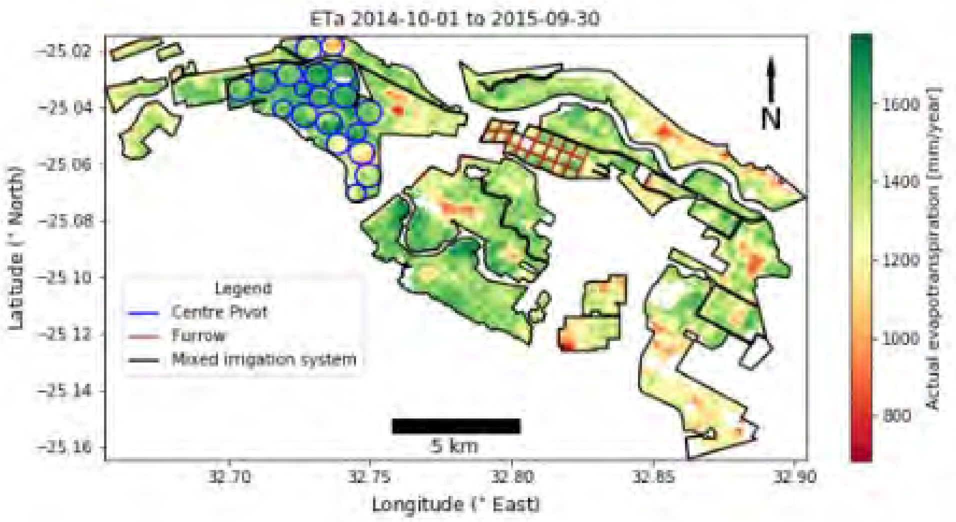
The relationship between biomass vs transpiration (T), biomass vs ET_a and $\sum(T_a/ET_{ref})$ vs biomass of sugarcane production under centre pivot, furrow and combination of mixed irrigation system at Xinavane from 2009/2010 to 2018/2019.

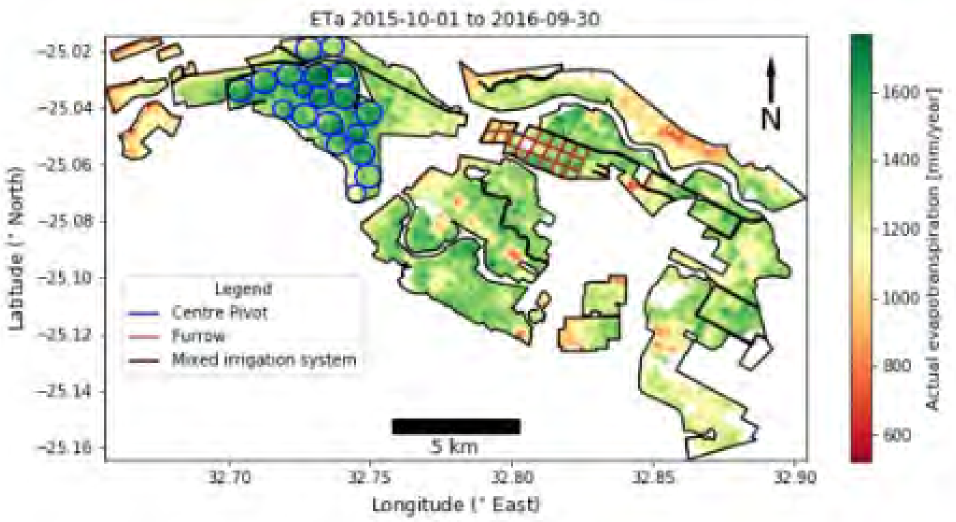


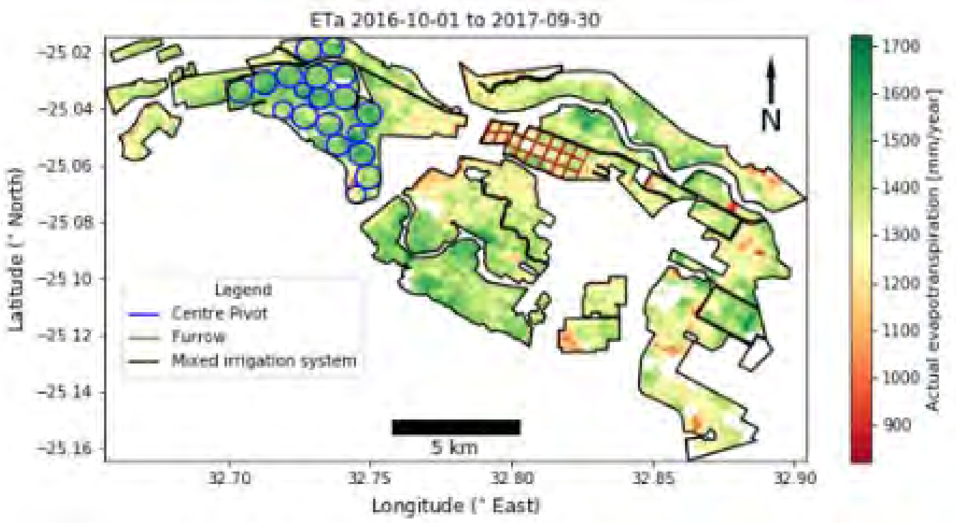

Biomass vs Ta 2012/2013
Biomass vs ETa 2012/2013
∑(Ta/RET) vs Biomass 2012/2013
Biomass vs Ta 2013/2014
Biomass vs ETa 2013/2014
∑(Ta/RET) vs Biomass 2013/2014
Biomass vs Ta 2014/2015
Biomass vs ETa 2014/2015
∑(Ta/RET) vs Biomass 2014/2015
Biomass [ton/ha/year]
Transpiration [mm/year]
Actual evapotranspiration [mm/year]
∑(Ta/RET) [-]
Mixed irrigation system
Centre pivot
Furrow

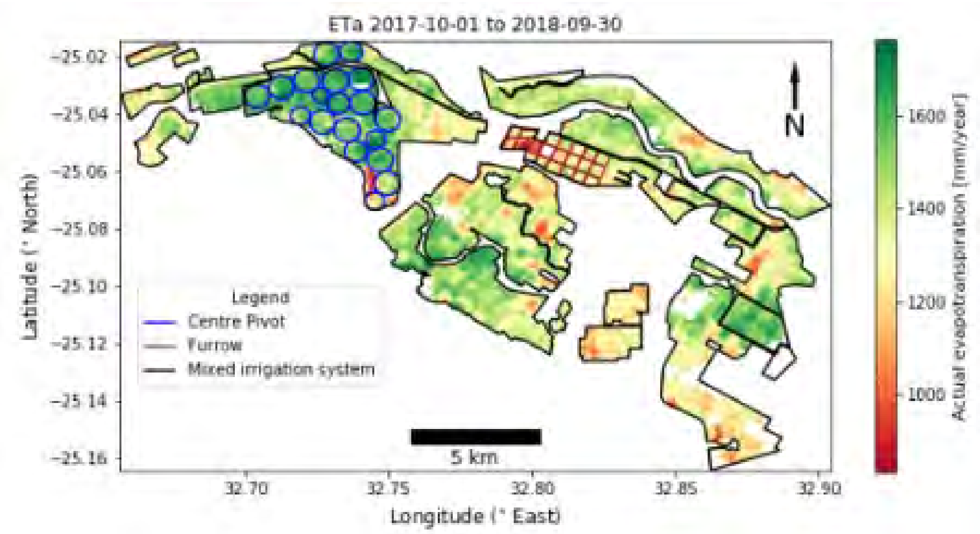

Biomass vs Ta 2015/2016
Biomass vs ETa 2015/2016
∑(Ta/RET) vs Biomass 2015/2016
Biomass vs Ta 2016/2017
Biomass vs ETa 2016/2017
∑(Ta/RET) vs Biomass 2016/2017
Biomass vs Ta 2017/2018
Biomass vs ETa 2017/2018
∑(Ta/RET) vs Biomass 2017/2018
Biomass vs Ta 2018/2019
Biomass vs ETa 2018/2019
∑(Ta/RET) vs Biomass 2018/2019
Biomass [ton/ha/year]
Transpiration [mm/year]
Actual evapotranspiration [mm/year]
∑(Ta/RET) [-]
Mixed irrigation system
Centre pivot
Furrow

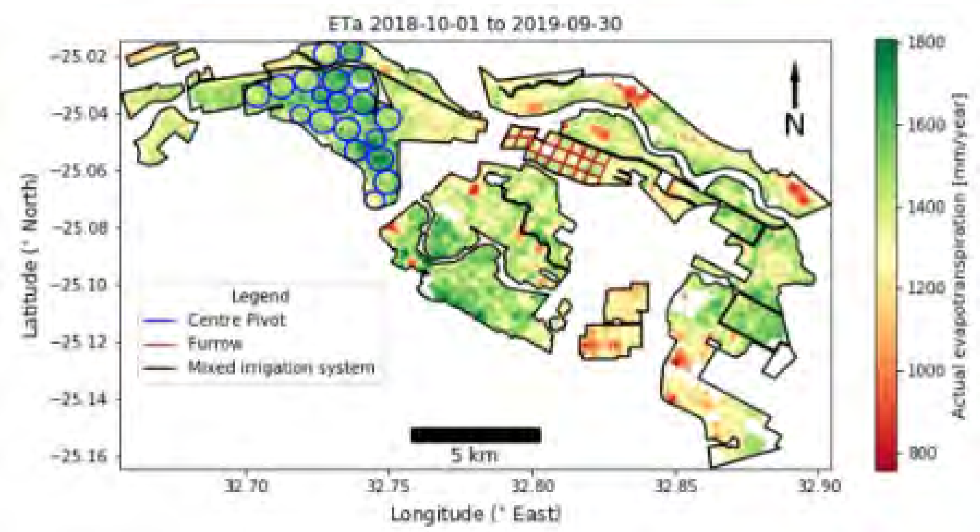
Appendix D Spatial distribution of actual ET of sugarcane at Xinavane from 2014/2015 to 2018/2019



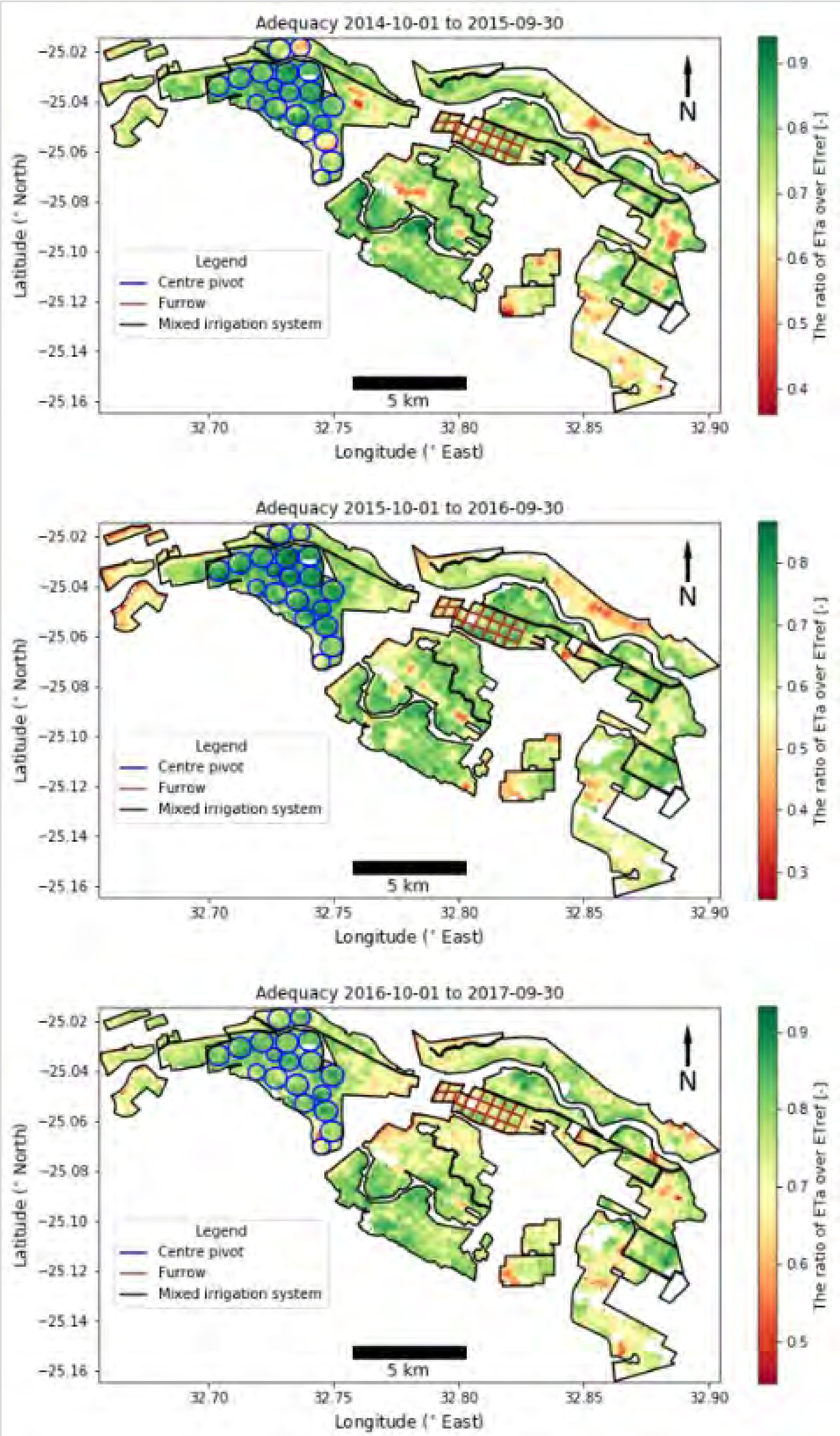


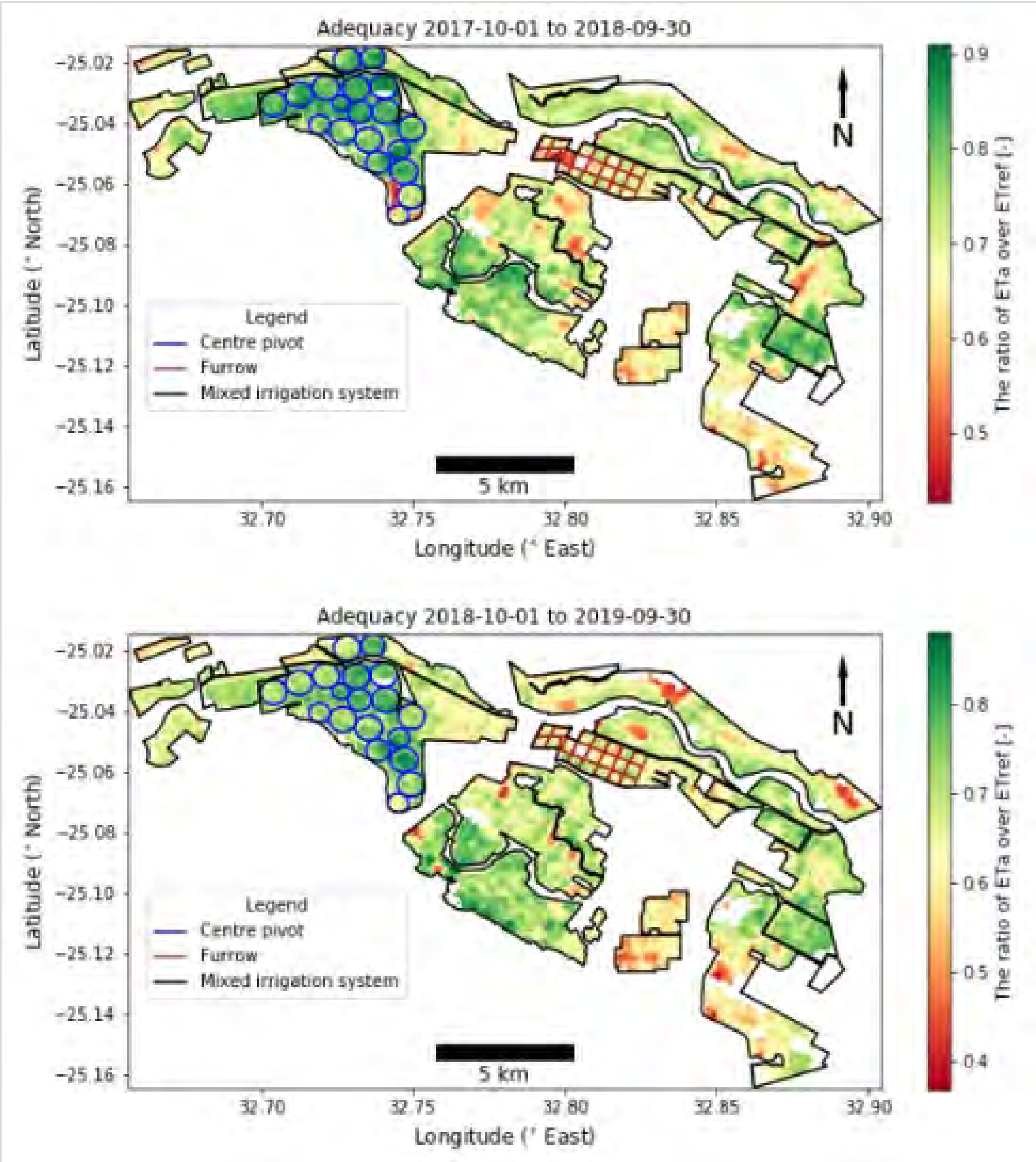



ETa 2017-10-01 to 2018-09-30
Legend
Centre Pivot
Furrow
Mixed irrigation system
5 km
N
Latitude (° North)
Longitude (° East)
Actual evapotranspiration [mm/year]

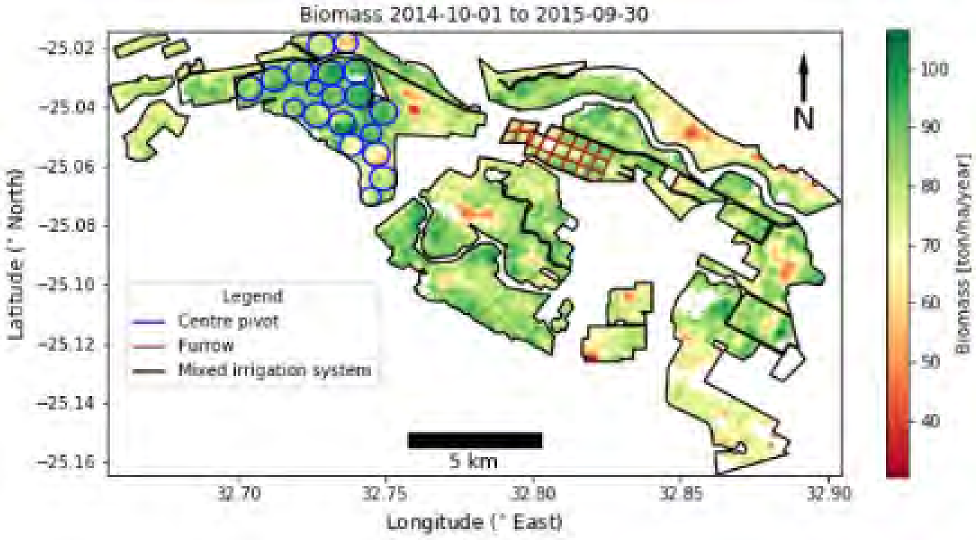

ETa 2018-10-01 to 2019-09-30
Legend
Centre Pivot
Furrow
Mixed irrigation system
5 km
N
Latitude (° North)
Longitude (° East)
Actual evapotranspiration [mm/year]

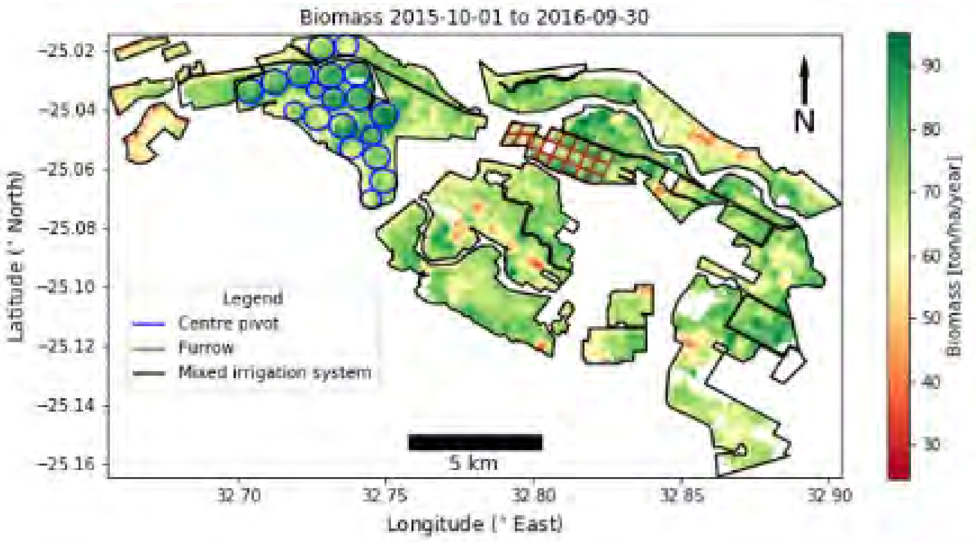
Appendix E Spatial distribution of relative evapotranspiration of sugarcane at Xinavane from 2014/2015 to 2018/2019

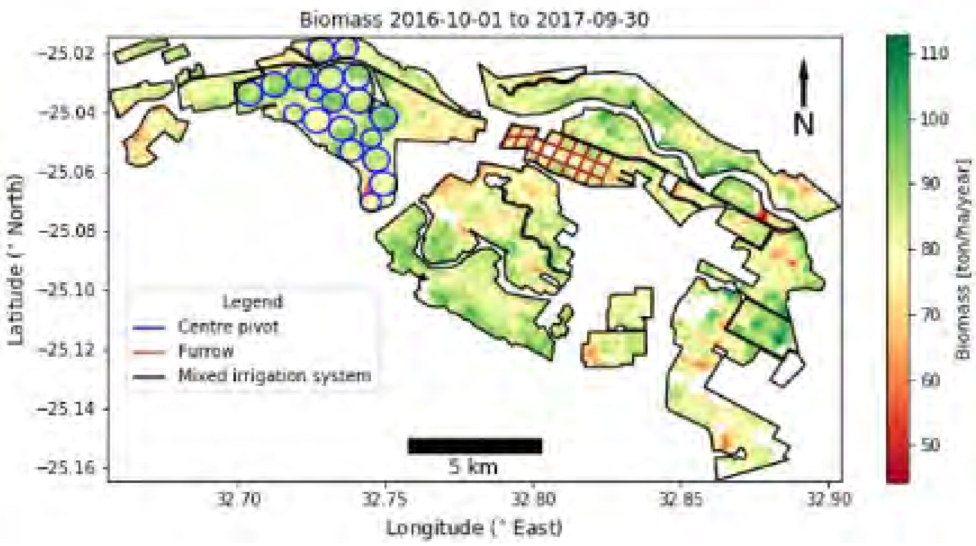


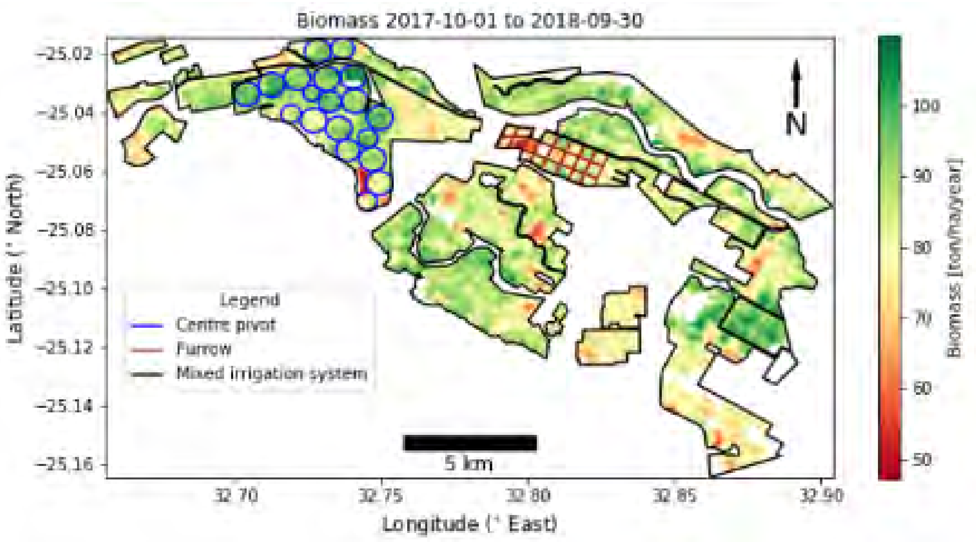

Adequacy 2017-10-01 to 2018-09-30
Latitude (° North)
Longitude (° East)
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N
The ratio of ETa over ETref [-]
Adequacy 2018-10-01 to 2019-09-30
Latitude (° North)
Longitude (° East)
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N
The ratio of ETa over ETref [-]

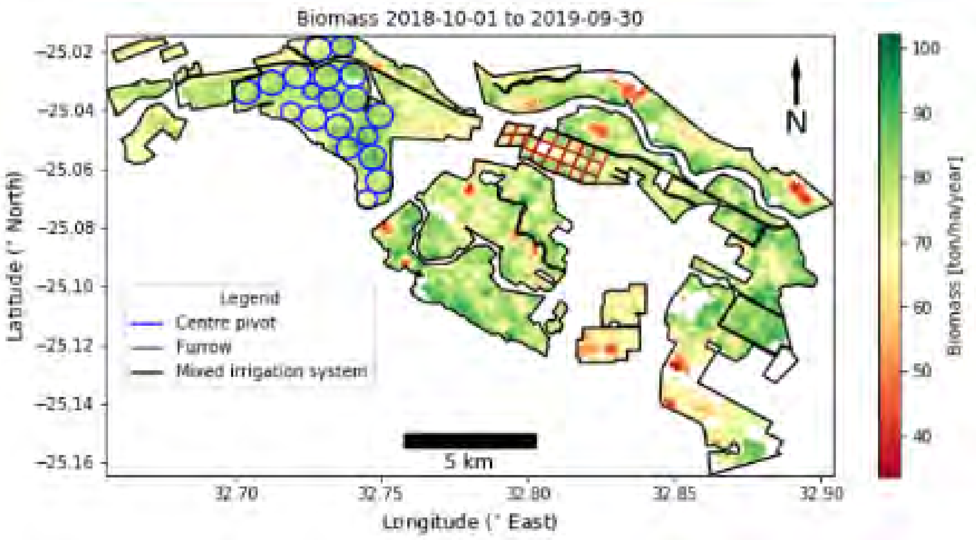
Appendix F Spatial distribution of biomass and biomass WP of sugarcane at Xinavane from 2014/2015 to 2018/2019

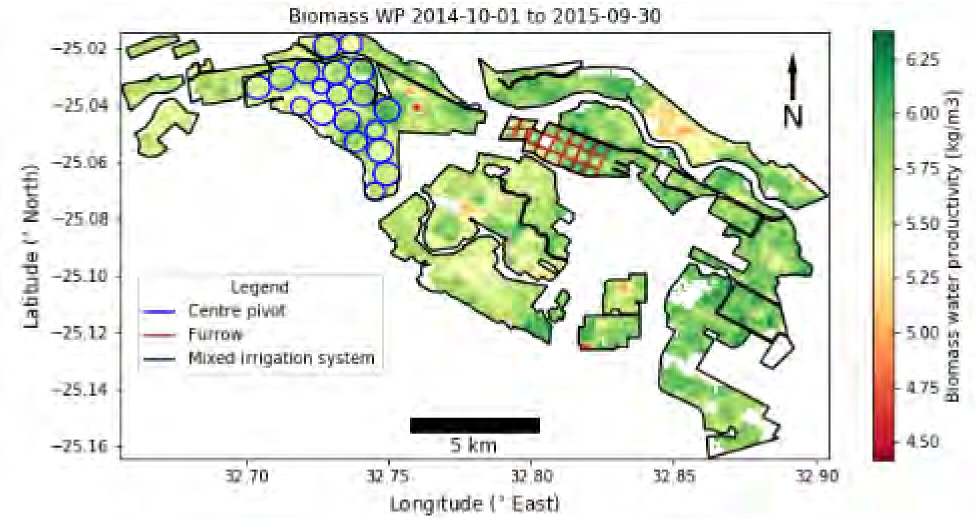


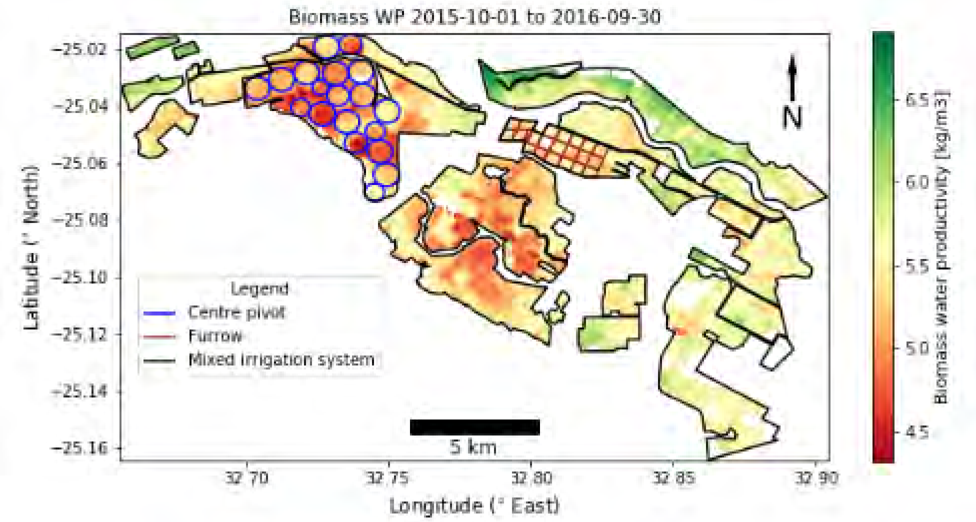


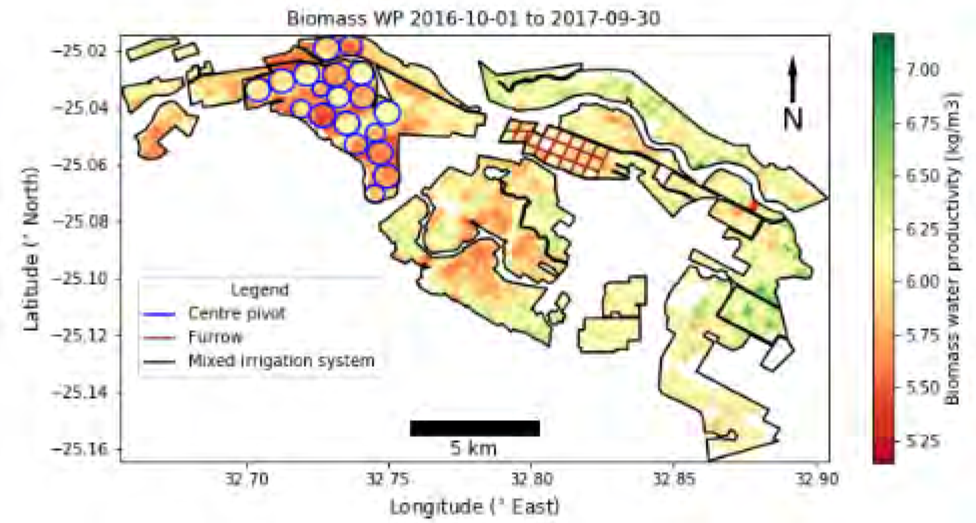


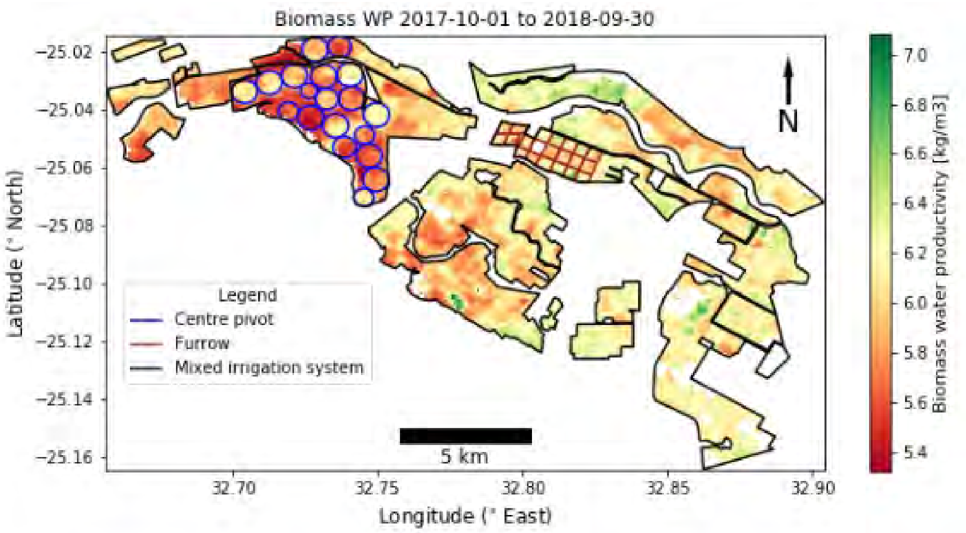

Biomass 2017-10-01 to 2018-09-30
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N
Latitude (° North)
Longitude (° East)
Biomass [ton/ha/year]

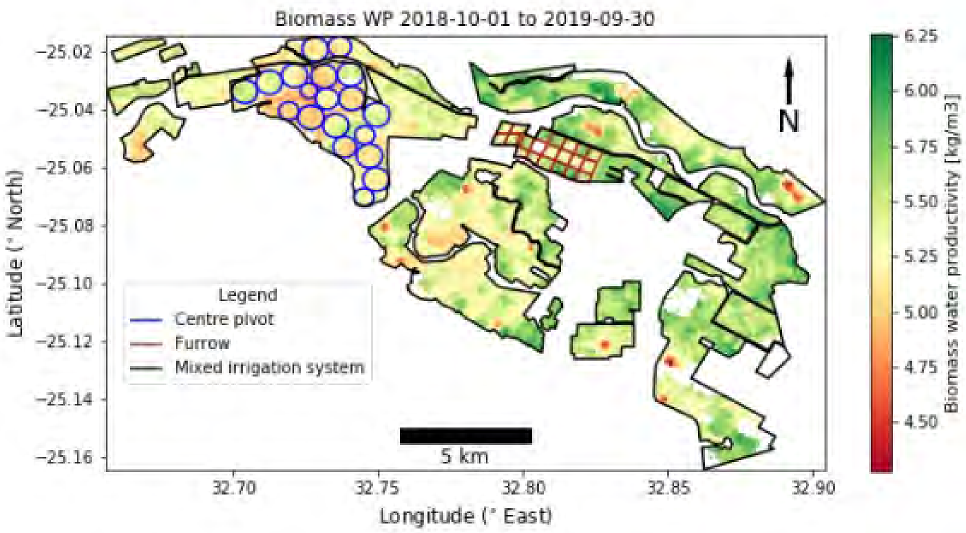

Biomass 2018-10-01 to 2019-09-30
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N
Latitude (° North)
Longitude (° East)
Biomass [ton/ha/year]


Biomass WP 2014-10-01 to 2015-09-30
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N
Latitude (° North)
Longitude (° East)
Biomass water productivity [kg/m3]

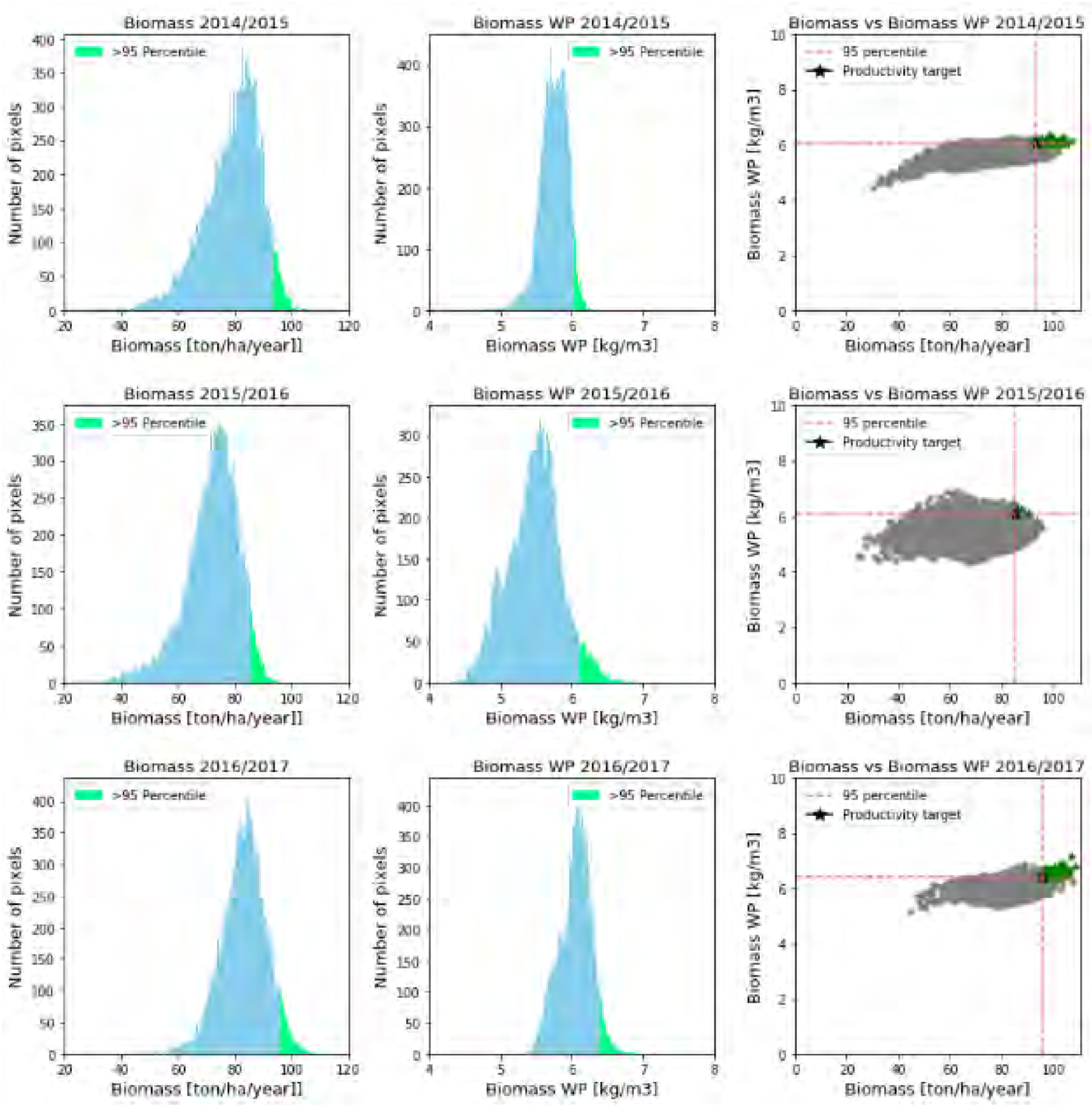

Biomass WP 2015-10-01 to 2016-09-30
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N
Latitude (° North)
Longitude (° East)
Biomass water productivity [kg/m3]

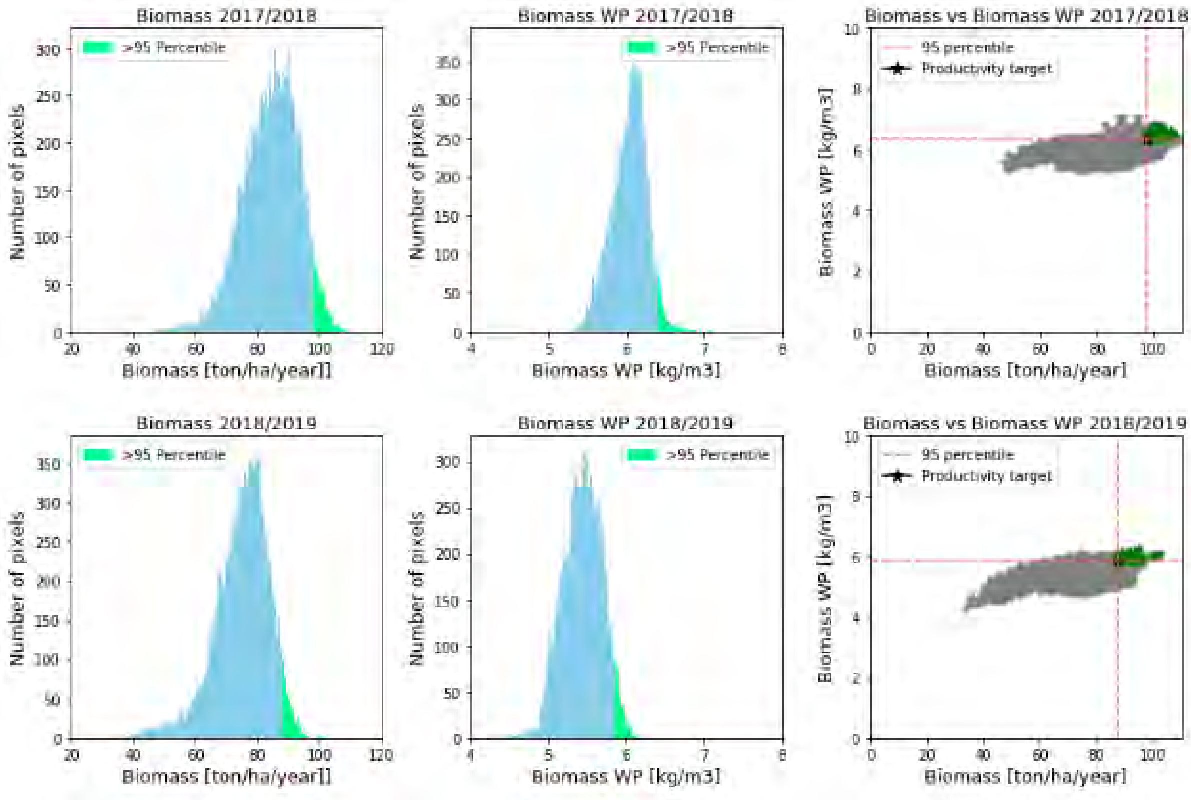

Biomass WP 2016-10-01 to 2017-09-30
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N
Latitude (° North)
Longitude (° East)
Biomass water productivity [kg/m3]


Biomass WP 2017-10-01 to 2018-09-30
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N
Latitude (° North)
Longitude (° East)
Biomass water productivity [kg/m3]
−25.02
−25.04
−25.06
−25.08
−25.10
−25.12
−25.14
−25.16
32.70
32.75
32.80
32.85
32.90
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4


Biomass WP 2018-10-01 to 2019-09-30
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N
Latitude (° North)
Longitude (° East)
Biomass water productivity [kg/m3]
−25.02
−25.04
−25.06
−25.08
−25.10
−25.12
−25.14
−25.16
32.70
32.75
32.80
32.85
32.90
6.25
6.00
5.75
5.50
5.25
5.00
4.75
4.50

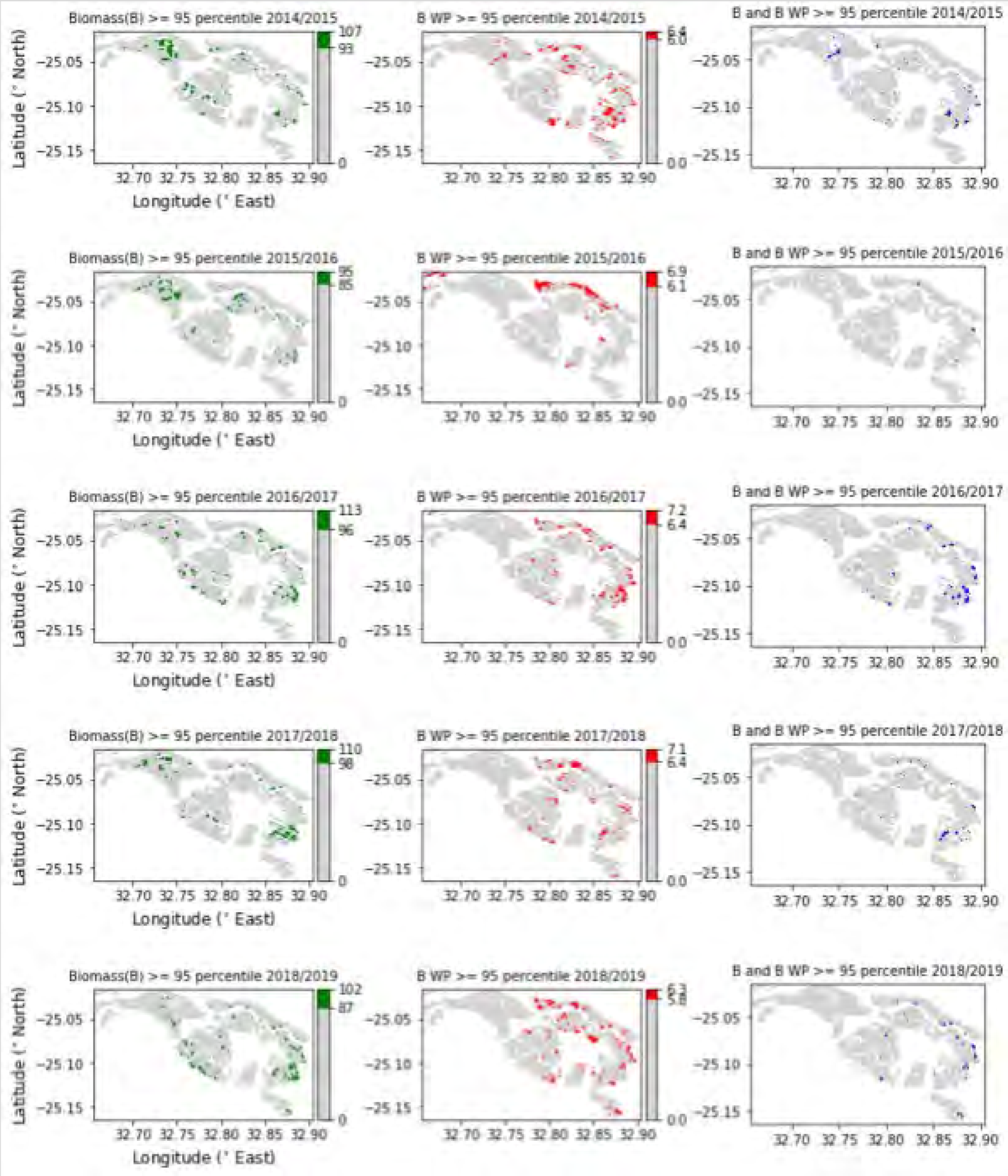
Appendix G Biomass and biomass WP targets at Xinavane from 2009/2010 to 2018/2019



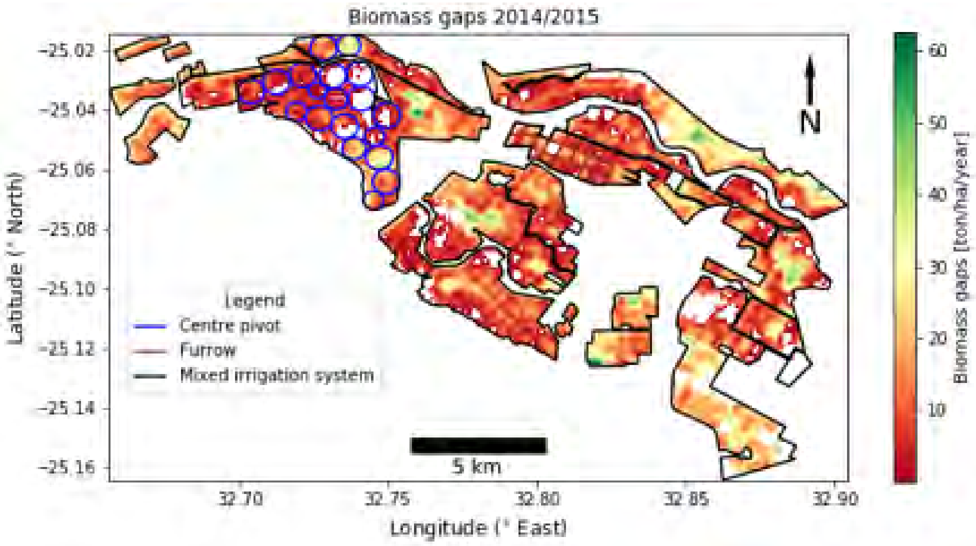


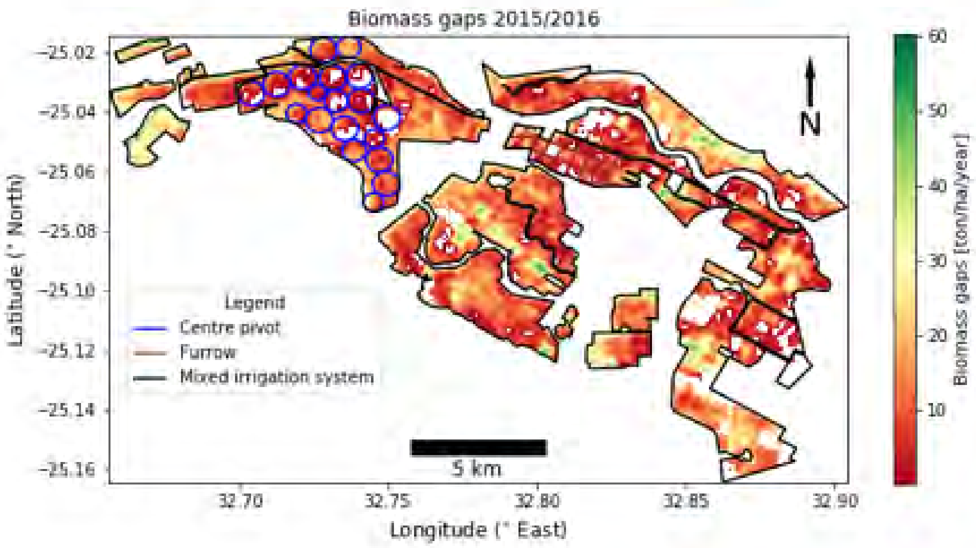
Biomass 2017/2018
>95 Percentile
Number of pixels
Biomass [ton/ha/year]]
Biomass WP 2017/2018
>95 Percentile
Number of pixels
Biomass WP [kg/m3]
Biomass vs Biomass WP 2017/2018
95 percentile
Productivity target
Biomass WP [kg/m3]
Biomass [ton/ha/year]
Biomass 2018/2019
>95 Percentile
Number of pixels
Biomass [ton/ha/year]]
Biomass WP 2018/2019
>95 Percentile
Number of pixels
Biomass WP [kg/m3]
Biomass vs Biomass WP 2018/2019
95 percentile
Productivity target
Biomass WP [kg/m3]
Biomass [ton/ha/year]

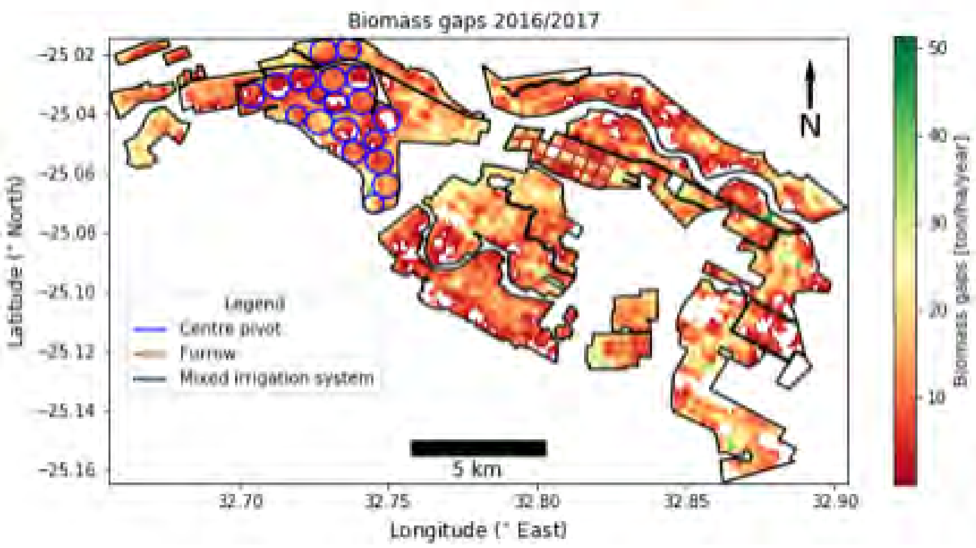
Appendix H Targets spots (areas where yield and WP greater than or equal to the 95 percentile) at Xinavane from 2014/2015 to 2018/2019.

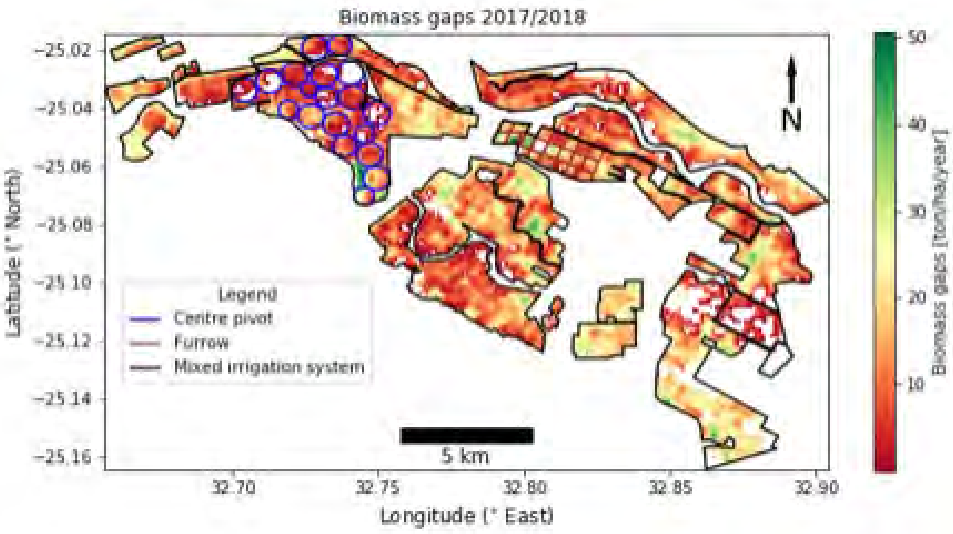


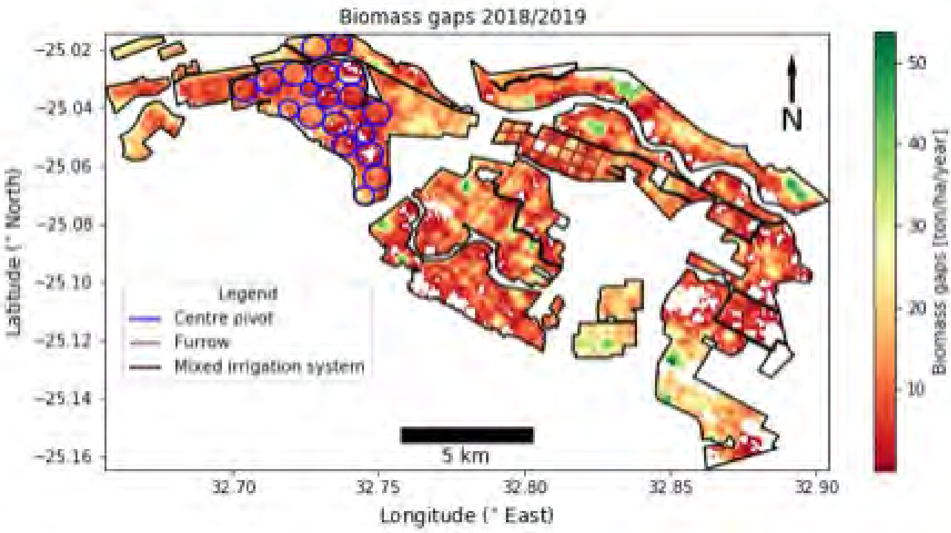
Appendix I Spatial distribution of biomass gaps and biomass WP gaps of sugarcane at Xinavane from 2014/2015 to 2018/2019

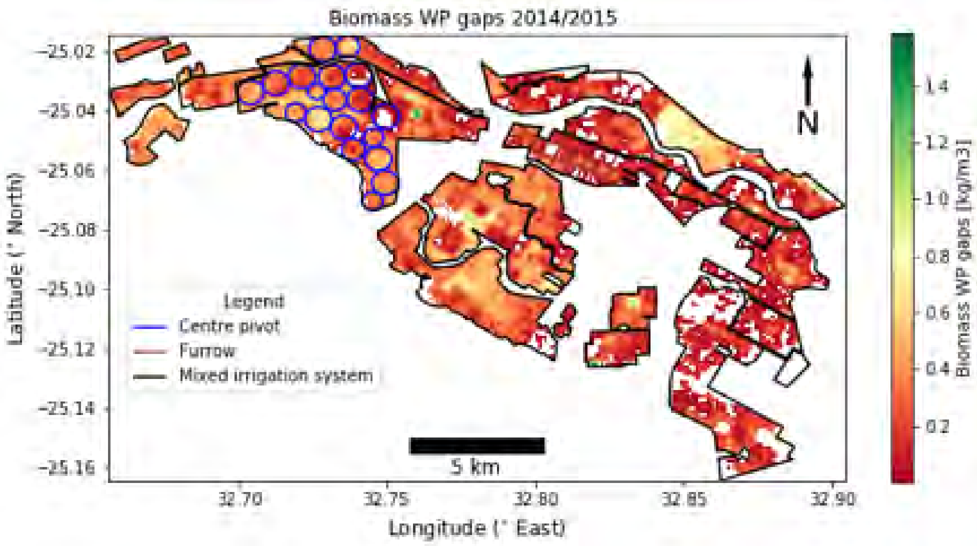


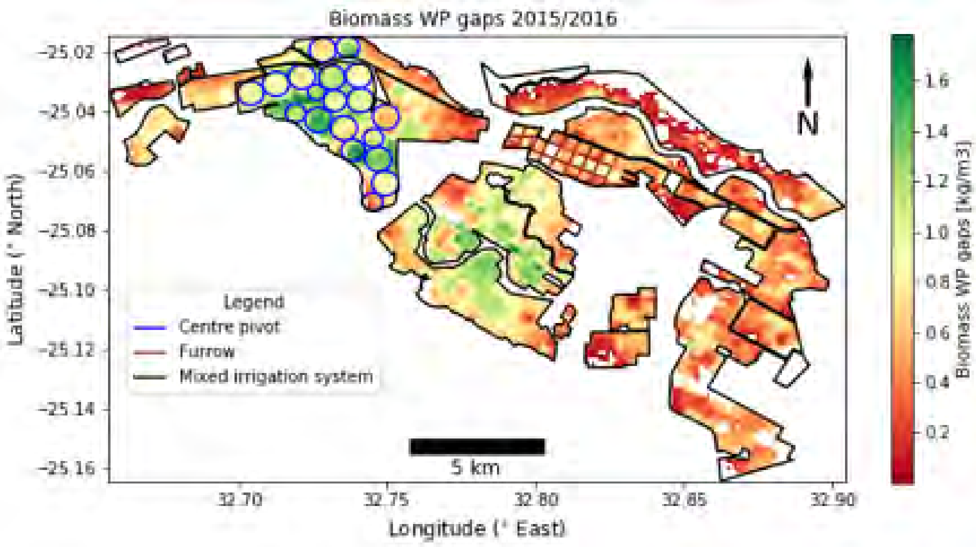


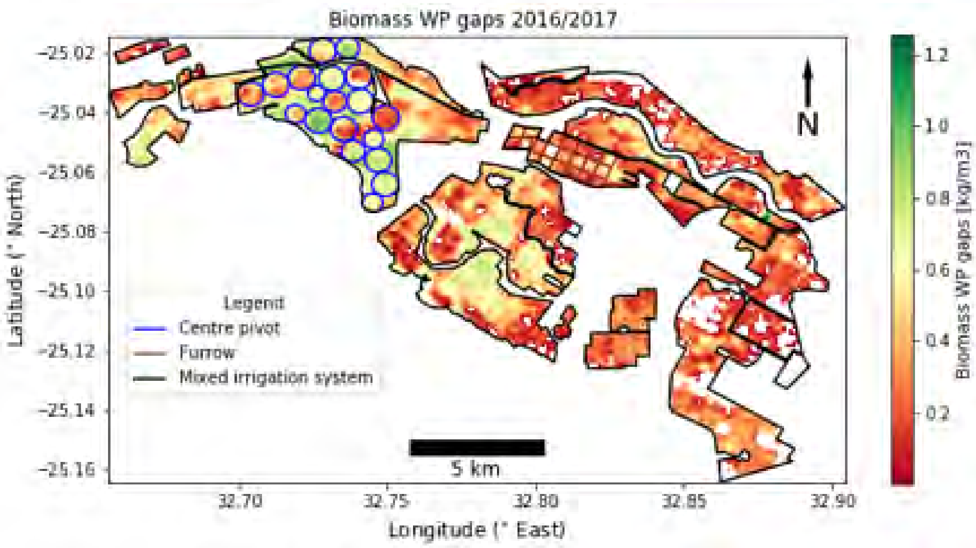


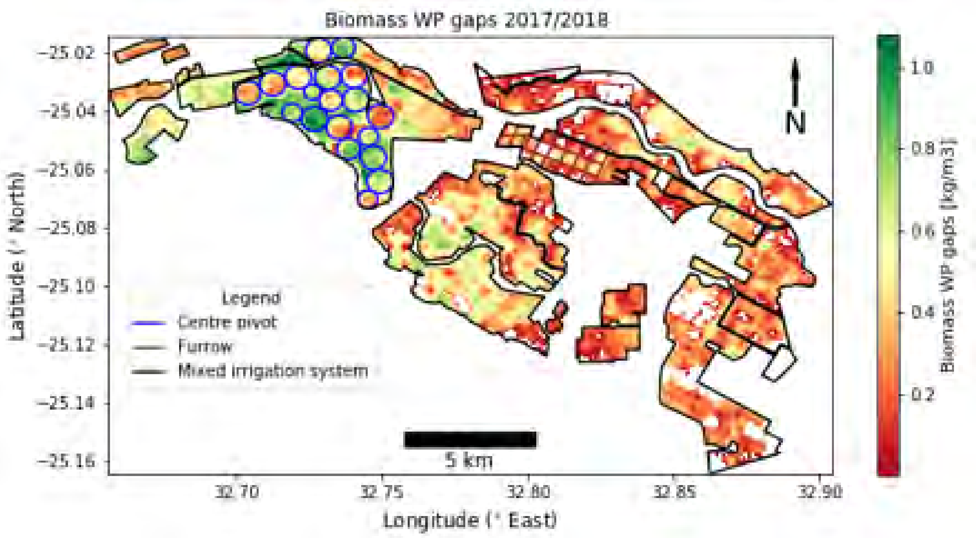

Biomass gaps 2017/2018
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N
Latitude (° North)
Longitude (° East)
Biomass gaps [ton/ha/year]

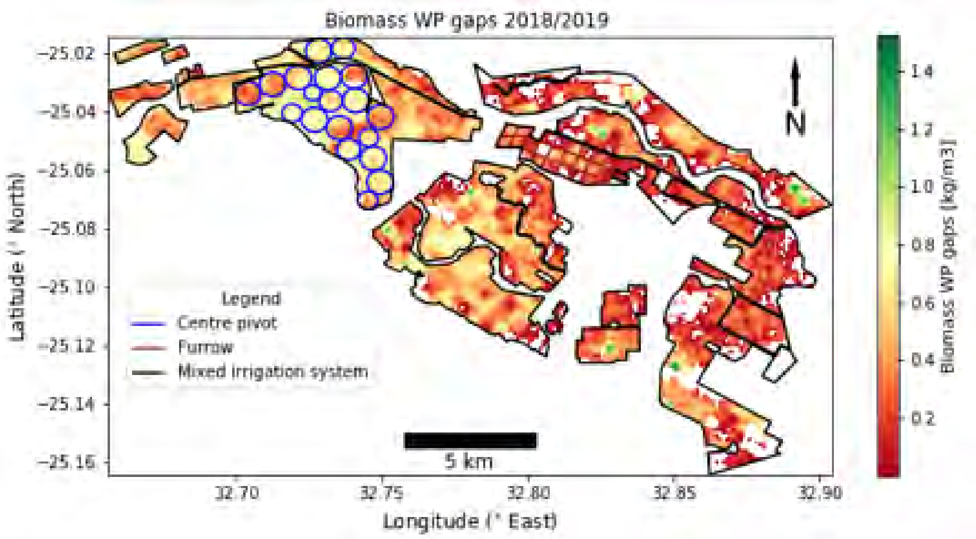

Biomass gaps 2018/2019
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N
Latitude (° North)
Longitude (° East)
Biomass gaps [ton/ha/year]


Biomass WP gaps 2014/2015
Latitude (° North)
Longitude (° East)
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N
Biomass WP gaps [kg/m3]


Biomass WP gaps 2015/2016
Latitude (° North)
Longitude (° East)
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N
Biomass WP gaps [kg/m3]


Biomass WP gaps 2016/2017
Latitude (° North)
Longitude (° East)
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N
Biomass WP gaps [kg/m3]


Biomass WP gaps 2017/2018
Latitude (° North)
Longitude (° East)
Biomass WP gaps [kg/m3]
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N


Biomass WP gaps 2018/2019
Latitude (° North)
Longitude (° East)
Biomass WP gaps [kg/m3]
Legend
Centre pivot
Furrow
Mixed irrigation system
5 km
N