The Assessment of Crop Water Productivity Behaviour in Humid Climate Region for Nasho Irrigation Scheme and Rainfed Area in Rwanda

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Abstract

The study quantified and analysed Agricultural Crop Water Productivity Indicators such as Transpiration, Actual Evapotranspiration and Interception, Net Primary Productivity, Total Biomass Production, and Gross Biomass Water Productivity. And Crop Water Productivity (CWP) of irrigated crops was normalised from climate constraints to evaluate the level of climate effects for C3 (are the plants which fix carbon dioxide using Calvin cycle and producing a 3-carbon molecule) and C4 (plants fix carbon dioxide into a 4-carbon molecule) crops. Comparative analysis indicated that the beans as C3 crops are more affected by the climate than maize, the C4 crops in both seasons which has a significant meaning due to the different biological properties of both beans and maize. The findings indicate that the average seasonal transpiration values for maize and beans during the winter season are 364 and 420 mm/season, respectively, while during the summer season, they are 306 and 323 mm/season. During the summer, the average seasonal evapotranspiration for maize and beans is 415 and 399 mm/season, respectively, and during the winter, it is 493 and 538 mm/season. Also, summer beans and maize produced 2.50 and 2.43 kg/m3 of crop water productivity, whereas beans and maize produced 2.67 and 2.70 kg/m3 as gross crop water production for winter. For the summer beans and maize, the average seasonal Total Biomass Production (TBP) was 10534 and 11169 kgDM/ha/season; for the winter crops, it was 12440 and 13349 kgDM/ha/season. Additionally, summer crops such as beans and maize have gross crop water productivity of 2.67 and 2.70 kg/m3, respectively, whereas winter crops have 2.50 and 2.43 kg/m3. During the evaluation of climate effects on crop water productivity, the climatic normalization of crop water productivity technique was examined for irrigated beans and maize. For winter beans, the average CWP and CWPc values are 2.5 and 3.2 kg/m3, while for summer beans, they are 3.0 and 3.0 kg/m3. Additionally, the 2.4 and 2.4 kg/m3 of CWP and CWPc are indicated for winter maize, whereas 2.7 and 2.0 kg/m3 are for summer maize.

1. Introduction

Food insecurity became a global issue due to climate change and the high demand for rapidly growing population; it is the most crucial problem in the 21st century (Vladimirova et al., 2018). Food is not only the affected sector, but water resources are also stressed especially for African countries due to the water management problems in agricultural domain (Sharma et al., 2018). The major problem for future generations in Rwanda and globally is to provide enough food for the rapidly increasing population under stressed environments. Address the problems of food insecurity and water scarcity, requires growing enough food to feed the population and improving water use efficiency especially in the agricultural sector and sustaining the disturbed environment (Kang et al., 2009). To solve the problems, modern agriculture should consider the monitoring of land and water productivity to improve the usability of water resources. This study was evaluating how modern agriculture can uses remote sensing technology, GIS and climate normalisation of Crop Water Productivity (CWPc) approach to solve the above-mentioned problems.

2. Method and Approach

The Nasho irrigation scheme and surrounding rainfed areas were selected as a specific study area located in Rwanda, eastern province, Kirehe district, Nasho sector along the Lake Cyambwe from which the irrigation water is pumped. It has an area of 1,206 ha irrigated using a centre pivot irrigation system.

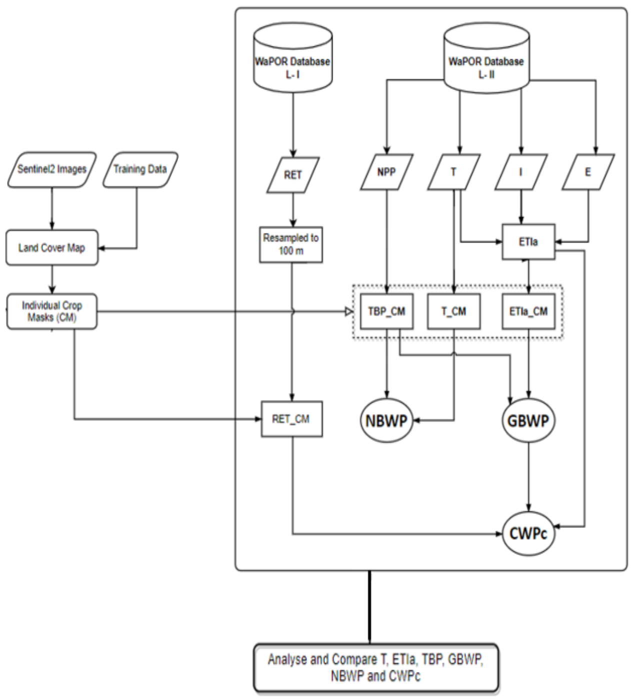

Figure 1. Methodological Flow Chart

The main crop types cultivated in the scheme are maize, French bean, and soybeans. The study had extracted water productivity indicators from remotely sensed data such as WaPOR (Water Productivity for Open access Remotely sensed data: an online geoportal developed by FAO to monitor land and water productivity) level 2 with spatial resolution of 100 m and 10 days of temporal resolution, in combination with Sentinel 2 images, ECMWF ERA5 and in-Situ data. The image classification performed in SNAP (Sentinel Application Platform), Wapor datasets were processed using ILWIS (Integrated Land and Water Information System) software, and quantified Crop Water Productivity (CWP) was normalised from climate effects and the results analysis was conducted in Python, and Geographical Information System (GIS).

3. Results

3.1 Land Cover Classification and Creation of Crop masks

Land cover classification was also performed for Nasho irrigation and rainfed areas using Sentinel 2A images of 19/06/2019 and 15/12/2020 for summer and winter growing seasons. Classified images were evaluated for accuracy and reported as the correct predictions, RMSE, and Bias for the summer season of 2020 with the value of 97.81, 0.73, and 9.59, respectively with total samples of 8335. The winter season of 2019 has total samples of 8033 with 97.95, 0.598, and -0.036 of correct predictions, RMSE, and Bias, respectively. Classified images are considered to be the same for the remaining growing seasons with the assumption of crop rotation between summer and winter seasons. In the appendices, figure 2 shows the results for classified land cover and crop masks for summer and winter seasons

3.2 Quantification of Crop Water Productivity Indicators

The study quantified and analysed Agricultural Crop Water Productivity Indicators such as Transpiration, Actual Evapotranspiration and Interception, Net Primary Productivity, Total Biomass Production, and Gross Biomass Water Productivity. And Crop Water Productivity of irrigated crops was normalised from climate constraints to evaluate the level of climate effects for C4 and C3 crops.

3.2.1 The results obtained for Irrigated Area: The results for crops grown under the Nasho irrigation scheme show the average seasonal transpiration for the summer months of 306 and 323 mm for beans and maize, and for the winter months, it is 364 and 420 mm. The average seasonal evapotranspiration for the summer season is 399 mm, while the average for the winter season is 493 mm and 538 mm for maize and beans, respectively.

The overall seasonal transpiration fractions were also calculated, and the results show higher values for C3 crops compared to C4 crops in both winter and summer seasons with the values of 0.77 and 0.78 for beans and maize of summer season, respectively and values of 0.74, and 0.78 for beans and maize of winter season. Summer season crops have a higher transpiration fraction compared to the winter season crops in humid climate regions. The study concludes the higher water consumption of C4 crops compared to C3 crops, higher water consumption of summer compared to winter seasons of semi-arid climate region, higher water consumption of winter seasons compared to summer seasons of humid climate region, respectively. The total average of TBP for the summer crops under the Nasho irrigation scheme is 10534 and 11169 kgDM/ha/season for beans and maize, while for the winter crops, it is 12440 and 13349 kgDM/ha/season. Additionally, the gross crop water productivity of Nasho irrigated crops is 2.67 and 2.70 kg/m3 for summer crops like maize and beans, and 2.50 and 2.43 kg/m3 for winter crops like maize and beans.

3.2.2 The results obtained for Rainfed Area: Overall average seasonal transpiration values for Nasho rainfed crops are 332 and 345 mm/season for beans and sorghum throughout the winter, and 303, 666, and 297 mm/season for beans, bananas, and sorghum throughout the summer. In contrast, the summer season yields an overall average seasonal evapotranspiration of 389, 849, and 380 mm/season for beans, bananas, and sorghum, respectively, and the winter season yields 443 and 449 mm/season for beans and sorghum. Comparative analysis between Nasho rainfed and irrigated crops shows that rainfed transpiration and evapotranspiration values are lower compared to irrigation transpiration and evapotranspiration values. Additionally, the average TBP for Nasho rainfed agriculture is 10745, 22723, and 10549 kgDM/ha/season for summer crops like beans, bananas, and sorghum, and 11435, and 11564 kgDM/ha/season for winter crops like beans and sorghum, respectively. Furthermore, the gross crop water productivity of Nasho rainfed crops is 2.83, 5.3, and 2.63 kg/m3 for summer crops like beans, full-season bananas, and sorghum, and 2.47 and 2.63 kg/m3 for winter crops like beans and sorghum.

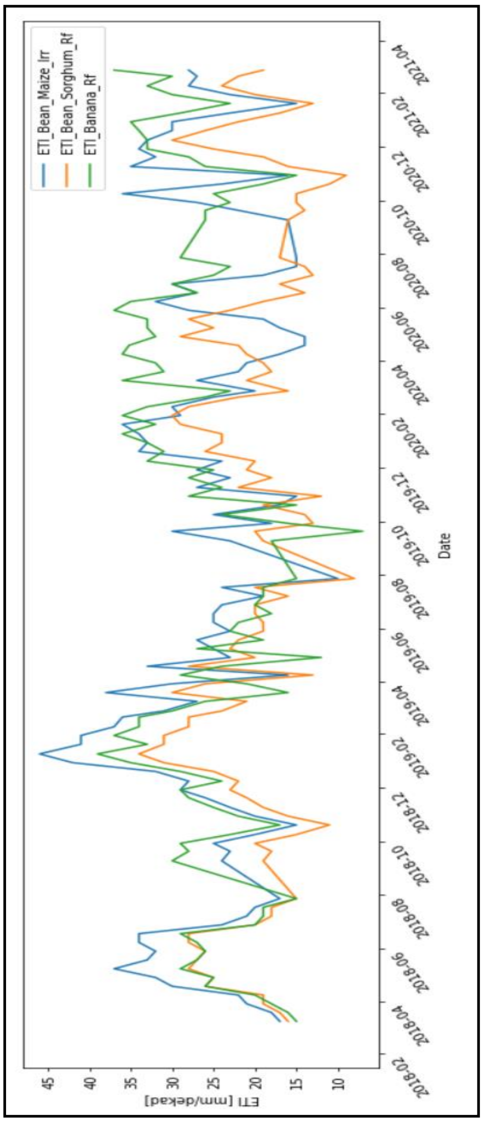

Figure 2. Seasonal average CWP and normalised CWP (CWPc) values of Nasho Irrigated beans and maize for winter season

3.3 Seasonal Comparison of Crop Water Consumption

The study compared Crop Water Indicators such as Transpiration, Actual Evapotranspiration and Interception to analyse the water consumption factor of the area for winter and summer seasons.

3.3.1 Comparison of crop water consumption between irrigated crops for winter season: The irrigated maize had higher water use than beans in all seasons with the average evapotranspiration values of 599, 495 and 522 mm/season for maize and 557,465, and 456 mm/season for beans. Transpiration values were 467, 383 and 410 mm/season for maize and 415, 353 325 mm/season for beans for 201,2019 and 2020, respectively. This has a significant mean due to the higher transpiration of maize as a C4 crop type. The season of 2018 had higher transpiration and evapotranspiration compared to the other two seasons for all crops. The season of 2019 is the lowest crop water use. Crop water consumption is almost the same for rainfed crops in every season. The transpiration values of each crop are proportionally higher with respect to its values of evapotranspiration as indicated above.

3.3.2 Seasonal comparison of crop water consumption for the irrigation crops of summer season: The study indicated the irrigated maize had higher water use than beans in all seasons with the average evapotranspiration values of 399, 437 and 396 mm/season for maize and 389,437, and 371 mm/season for beans. Transpiration was 300, 363, and 307 for maize and 290, 353 and 278 mm/season for beans for 2018,2019, and 2020, respectively. This has a significant mean due to the higher transpiration of maize as a C4 crop type. The season of 2019 had higher transpiration and evapotranspiration compared to the other two seasons for all crops. The season of 2020 is the lowest crop water consumption compared to the other seasons.

3.3.3 Comparison of crop water consumption for the rainfed crops of winter season: The observations found that crop water consumption is almost the same for rainfed crops in three seasons. All crops have almost the same transpiration and evapotranspiration, but sorghum has higher values in 2019 and 2020 seasons. The average values of evapotranspiration are 504, 410 and 432 mm/season for sorghum for 2018, 2019, and 2020, respectively. And 896, 811, and 839 mm/season for banana (full season), and 510, 402, and 432 mm/season for beans. Transpiration values are 380, 319, and 298 mm/season for beans, 687, 647, and 663 mm/season for banana and 376, 327, and 333 mm/season for sorghum for 2018, 2019 and 2020, respectively. The higher values of banana due to the long duration of their growing season. Beans have almost the same evapotranspiration, but lower transpiration compared to the sorghum. The season of 2018 had higher evapotranspiration and transpiration compared to the other two seasons for all crops and season 2019 is the lowest crop water use season.

3.3.4. Seasonal comparison of crop water consumption for the rainfed summer season: The observations made found that crop water consumption is almost the same for rainfed crops in three summer seasons. All crops have almost the same transpiration and evapotranspiration, but beans have higher values of water consumed in 2018 and 2019 seasons. The average values of evapotranspiration are 393, 391, and 385 mm/season for beans and 375, 388, and 376 mm/season for sorghum. Transpiration values were 304, 303, and 302 mm/season for beans and 292, 304, and 294 for sorghum for 2018, 2019, and 2020, respectively. This has not significant mean due to the higher transpiration and evapotranspiration of sorghum as a C4 crop type. This may be caused by intercropping systems of beans and other crop types such as maize and soyabeans.

3.4 Relationship between Total Biomass Production and Evapotranspiration

3.4.1. Relationship between Total Biomass Production and Evapotranspiration for irrigated crops for the winter season: Figure 3 shows linear relationships between TBP and ETI of winter crops from 2018 to 2020. The linear relationships between TBP and ETI were assessed for beans and maize. There were positive linear relationships between TBP and ETI to both crops. Total biomass production increasing with respect to the increase of ETI. The higher relationships were found higher for irrigated beans compared to the irrigated maize with a coefficient of determination R^2 of 0.77 and 0.63 for beans and maize, respectively.

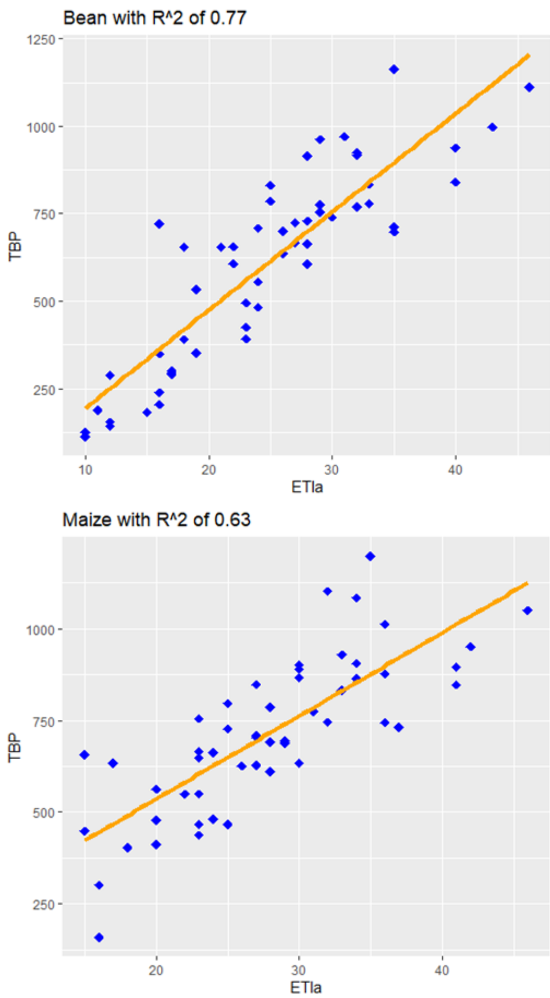

Figure 3 Relationship between TBP and ETI of irrigated beans and maize

3.4.2. Relationship between Total Biomass Production and Evapotranspiration for the rainfed crops winter season: The linear relationships between TBP and ETI were assessed for rainfed beans, banana, and sorghum. There were positive linear relationships between TBP and ETI to all three crops. Figure 4 illustrating the relationships between TBP and ETI for rainfed crops. Banana was found with high relationship with R^2 of 0.70 compared to beans and sorghum with R2 of 0.64 and 0.59 as indicated in figure 4.

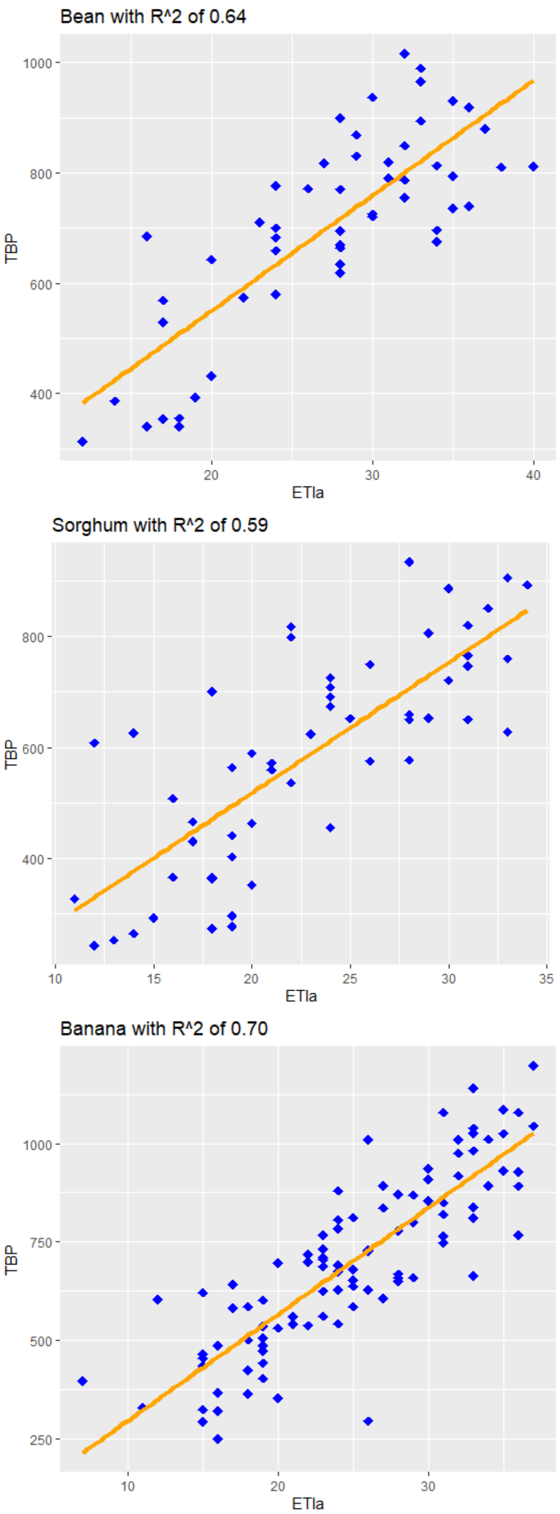

Figure 4. Relationship between TBP and ETI of rainfed beans, banana, and sorghum for winter season.

3.5 Climate normalisation of crop water productivity for Irrigated Crops

During this study, the climate normalisation of crop water productivity approach was also tested for irrigated crops such as beans and maize. A comparative analysis done for the summer values of CWP and CWPc shows that the CWP values are 2.4, 2.7 and 4.0 kg/m^3; and CWPc values are 2.37, 2.78, and 3.88 kg/m^3 for beans for 2018, 2019 and 2020, respectively. The study also indicates that the CWP values are 2.5, 2.5, and 3.1 kg/m^3; and CWPc values are 1.88, 1.97, and 2.29kg/m^3 for maize for 2018, 2019 and 2020, respectively as well. winter season, it also shows the values of CWP and CWPc with CWP of 2.2, 2.5, and 2.8 kg/m^3; and CWPc of 2.79, 2.98, and 3.70 kg/m^3 for beans for 2019, 2020, and 2021, respectively. And CWP of 2.2, 2.5 and 2.6kg/m^3 and CWPc of 2.17, 2.43, and 2.70 kg/m^3 of maize for 2019, 2020, and 2021, respectively.

3.5.1 Comparison of Crop Water Productivity (CWP) and normalised CWP (CWPc) values for Maize and Beans for winter seasons: The observations made from the figure 5 shows that the beans are more affected than maize. In the 2018 season, beans have 2.2 and 2.7 of CWP and CWPc values, this means 0.5 kg/m^3 is crop water productivity gap from the expected normal value from climate effects. For the season of 2019, beans have 2.5 and 2.98 of CWP and CWPc values, respectively. This means that CWP is less than CWPc for this season with a gap of 0.5 kg/m^3. The CWP and CWPc values of 2.8 and 3.7 kg/m^3 for beans of 2021 season with a gap of 0.9 kg/m3. This means that CWP is less than CWPc for this season. There are crop water productivity gaps occurred on beans for the winter season. The winter season of 2021 was more affected than other winter seasons (Refer to figure 5).

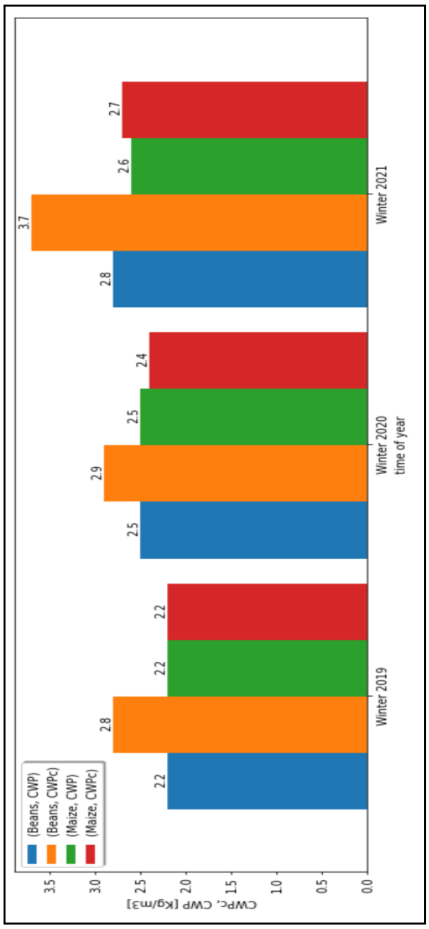

Figure 5. Seasonal average CWP and normalised CWP (CWPc) values of Nasho Irrigated beans and maize for winter season

3.5.2 Comparison of Crop Water Productivity (CWP) and Normalised CWP (CWPc) values for Maize and Beans for summer season: Figure 6 shows the differences between CWP and CWPc values for maize and beans as C4 and C3 crops of the summer season for Nasho irrigation scheme. CWP values of maize are greater than CWPc values for all three summer seasons of 2018, 2019, and 2020. In the season 2018, maize has 2.5 and 1.9 of CWP and CWPc values, this means 0.6 kg/m^3 is crop water productivity beyond the expected normal value without climate effects. For the season of 2019, maize has 2.5 and 1.9 kg/m^3 of CWP and CWPc values, respectively. This means that no CWP gap occurs for this season. The CWP and CWPc values of 3.1 and 2.3 kg/m^3 for maize of 2020 season were obtained. There is a positive CWP of 0.8 kg/m3 beyond the expected values without climate effects. The observations from the figure-6 show that the beans are much affected than maize. In 2018 season, beans have 2.4 and 2.37 of CWP and CWPc values, this means 0.1 kg/m^3 is crop water productivity beyond the expected normal value from climate effects. For the season of 2019, beans have 2.7 and 2.78 of CWP and CWPc values, respectively. This means that CWP equals to CWPc for this season. And the CWP and CWPc values of 4 and 3.9 kg/m^3 for beans of the 2020 season, means that CWP equals to CWPc for this season. There are no crop water productivity gaps that occurred for the summer season of humid climate.

3.5.3 Calculation and Evaluation of crop water productivity levels: To know the degree of climate effects on crop water productivity, percentage of crop water productivity (%CWP) were determined from normalised CWP to evaluate the level of CWP of specific crop under climatic constraints for Nasho irrigation schemes. Crop water productivity level was calculated using the formula below.

$$\%\mathbf{CWP} = \frac{\boldsymbol{CWP}}{\boldsymbol{CWPc}} \times \mathbf{100}, \quad (1)$$

where %CWP = percentage of crop water productivity
CWP = Crop Water Productivity
CWP*c* = Normalised Crop Water Productivity

Crops	Beans		Maize	
Indicators	CWPc	**%CWP**	CWPc	**%CWP**
2019	2.8	**79**	2.1	**102**
2020	2.9	**84**	2.4	**103**
2021	3.7	**76**	2.7	**96**
Overall Avg.	3.1	**79**	2.4	**100**

Table 1. Statistics of CWP and CWPc for the winter seasons

Crops	Beans		Maize	
Indicators	CWPc	**%CWP**	CWPc	**%CWP**
2018	2.4	**100**	1.9	**132**
2019	2.8	**96**	1.9	**132**
2020	3.9	**102**	2.3	**135**
Overall Avg.	3.0	**99**	2.0	**133**

Table 2. Statistics of CWP and CWPc for the summer seasons

The evaluation of crop water productivity levels was made based on the following scenarios:

1) Level 1: %CWP less than 100%, means CWP is lower than CWPc; there is a crop water productivity gap.

2) Level 2: %CWP equal to 100%, means CWP equals to CWPc; this means no crop water productivity gap.

3) Level 3: %CWP greater than 100%, means CWP is greater than CWPc; crop water productivity is beyond the expectations.

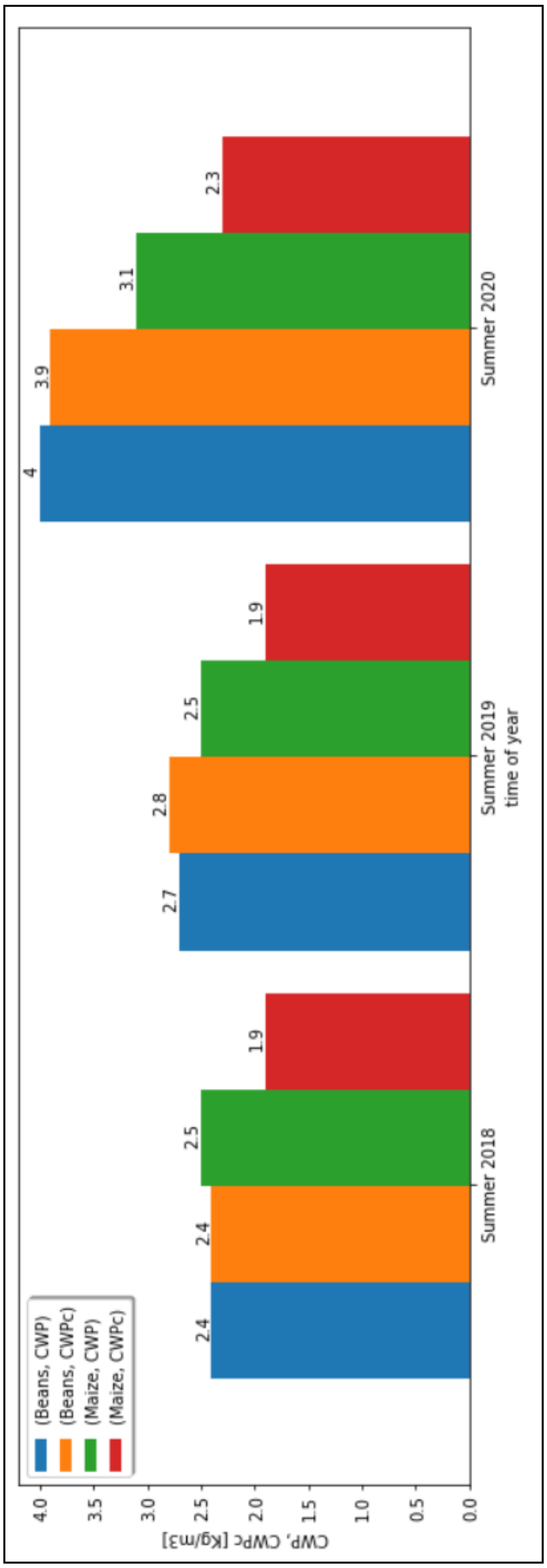

Figure 6. Seasonal average CWP and CWPc values of Nasho Irrigated beans and maize for summer season

4. Conclusion

The study concludes that both C3 and C4 crops are affected by climate constraints in humid region. The climate effect is highly occurred on C3 crops than C4 crops. Additionally, the impact is greater during the winter (season A) than the summer (season B). According to the study's findings, the climatic normalization of crop water productivity technique can aid in assessing the seasonal variability of agricultural water production gaps within irrigation schemes at the regional level.

5. Recommendation

The comparative analyses made for crop water consumption between irrigated and rainfed crops for Nasho study area and the study finds some unnecessary irrigation activities that may result into poor management of water resources. Nasho irrigation managers and engineers are recommended to improve irrigation services, especially in season A (winter) which shows higher differences in crop water use but almost the same productions.

Normalised crop water productivity (CWPc) is not only a helpful approach at a global scale but also at a regional scale to evaluate irrigation performance and mapping crop water productivity gaps within the schemes. Local authorities (agricultural sector, planners, irrigation engineers and other related organisations) are recommended to adapt CWPc approach for water resources management, planning and decision making. However, there are few critical CWP values that need the improvement for much better performance, the findings of CWPc applied in this study show that irrigation managers and engineers have to improve CWP to grow more food.

This study did not consider the causes of crop water productivity gaps rather than climate constraints. Other factors such as used fertilizers, irrigation management information, soil types and other practices which may influence crop water productivity indicators require further investigations to know their effects on crop water productivity. The other researchers are recommended to do further investigations on how they can influence crop water productivity in both semi-arid and humid climates.

6. References

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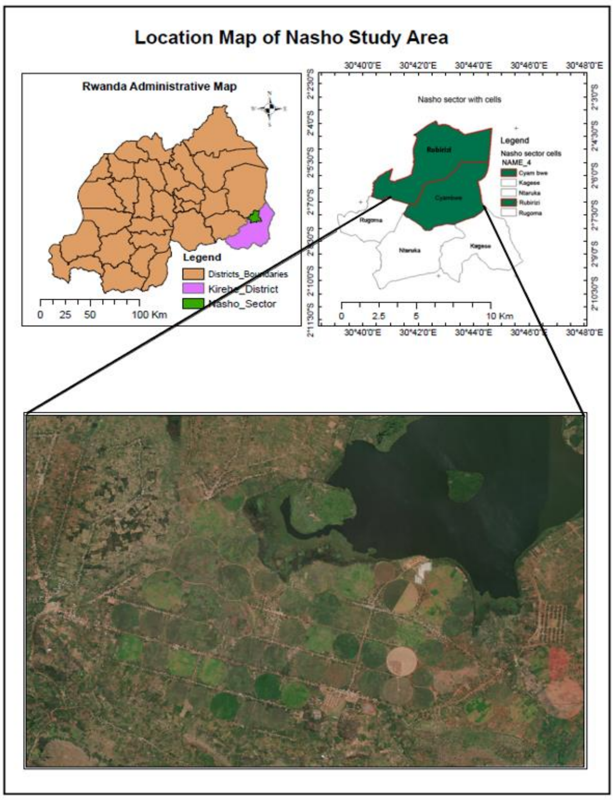
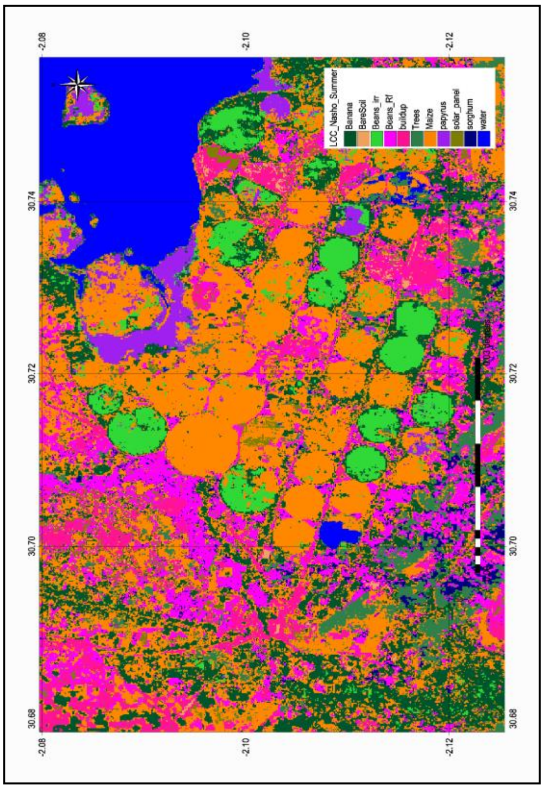
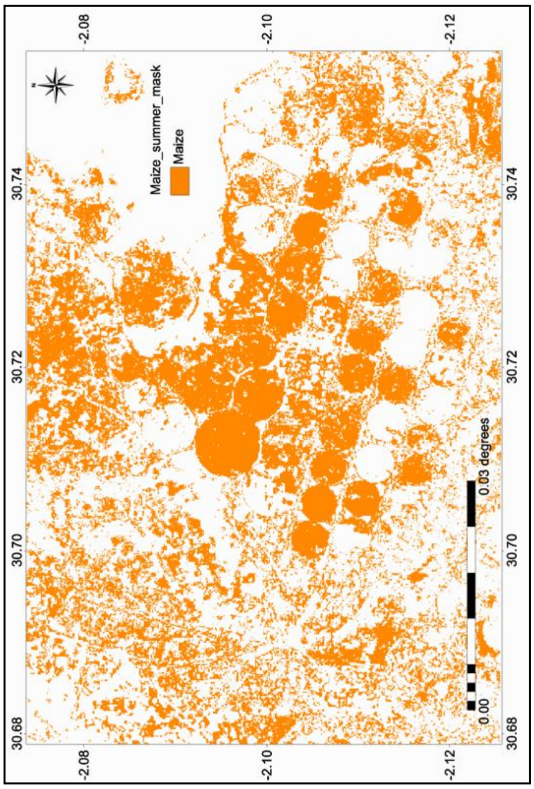
Appendix



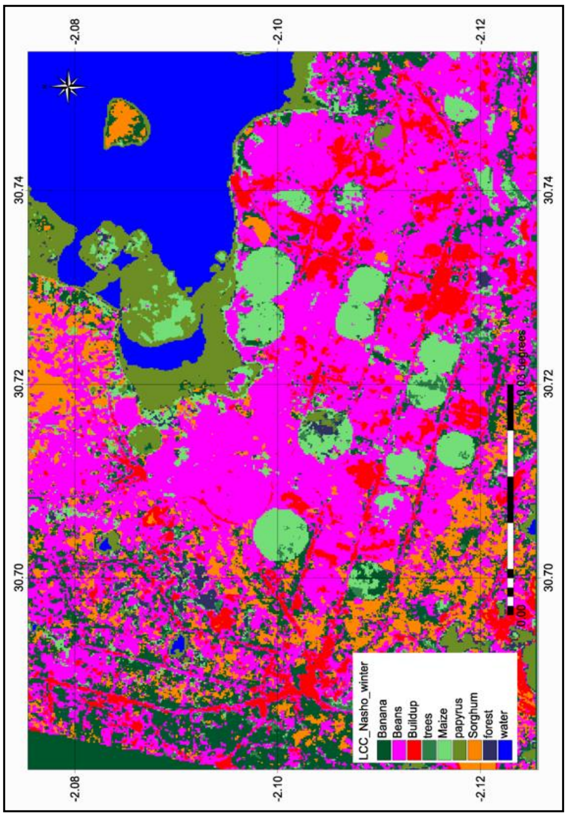
Appendix 1: Location Map of Study Area



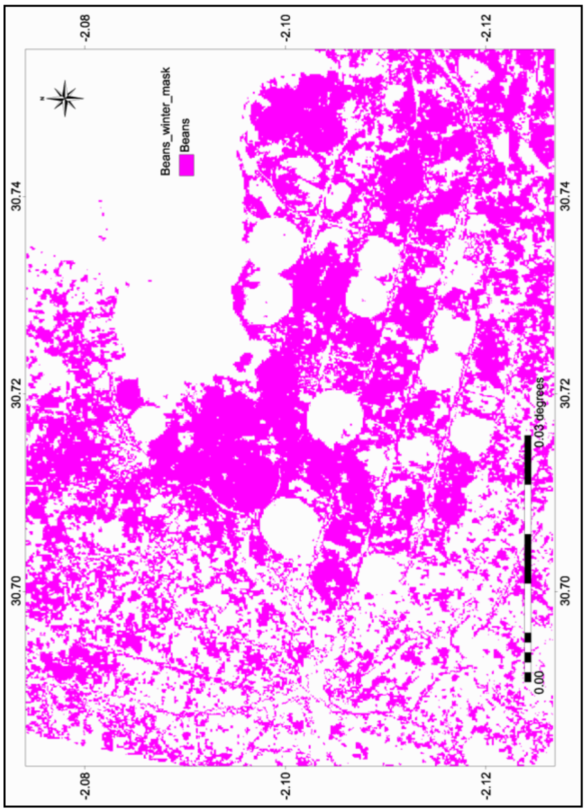
Appendix 2: Land cover classification of Nasho study area summer season



Appendix 4: Maize Mask for summer season



Appendix 3: Land cover classification of Nasho study area winter season



Appendix 5: Beans Mask for winter season