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Research Application Summary

Analysis of potato yield gap using aquacrop simulation Model

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Abstract

Water scarcity and food shortage worldwide is a major concern globally. In crop production, water stress affects yield if not managed properly. *Solanum* potato is the second most important food crop in Kenya after maize and is sensitive to water deficits. The main objective of this study was to estimate yield gaps for various water regime strategies so as to contribute to increasing potato yields in order to close the nation's yield gap and achieve a food secure country. Field trial was conducted in the period of March 2016-July 2016 in Uswo location under Keiyo highlands climatic conditions and obtained results used to calibrate and validate AquaCrop simulation model. The model was then used to simulate the yield output under the various irrigation treatments with and without mulch for the selected years representing wet, normal and dry seasons for full supply (FS) (100%ETc) and deficit irrigation (DI) (80%ETc) for main and off-seasons. The difference between the water stressed yields and potential yields (FS) showed the potato tuber yield gap. Results showed that yield reductions (gap) were realized in DI treatments as compared to FS during both main and off-seasons. The supplemental irrigation yield percentage decline ranged from 0.7%-1.5% and 1.1%- 2.6% for main and off season during a dry year. Normal year declain ranged from 2.1%-2.5% and 1.5%-4.1% for main and off season, respectively. Wet year losses were 0.3%-2.1% and 0.8%-7.4% for main and off seasons, respectively. Rainfed yield losses ranged from 18.9%-22.2%, 6.0%-14.1% and 2.1%-3.2% for dry, normal and wet years during main season. Off-season yields were 68.1%-87.9%, 79.6%-86.1% and 36.1%-36.8% for dry, normal and wet years, respectively. In conclusion AquaCrop is a robust model that can be used to predict potato yield gaps with acceptable accuracy under various water regime strategies and this would aid in decision-making at farm levels.

Key words: Irrigation, mulching, *Solanum tuberosum*, water use efficiency, yield gap

Résumé

La pénurie d'eau et la pénurie alimentaire dans le monde sont une préoccupation majeure à l'échelle mondiale. Dans la production agricole, le stress hydrique affecte le rendement s'il n'est pas géré correctement. La pomme de terre *Solanum* est la deuxième culture vivrière la plus importante au Kenya après le maïs et est sensible aux déficits hydriques. L'objectif principal de cette étude était d’estimer les écarts de rendement pour diverses stratégies de régime d’eau afin de contribuer à l’augmentation des rendements de pommes de terre afin de combler l’écart de rendement et d’assurer la sécurité alimentaire du pays. L’essai sur le terrain a été mené entre mars 2016 et juillet 2016 à Uswo dans les conditions climatiques des hautes terres de Keiyo et a obtenu des résultats utilisés pour calibrer et valider le modèle de simulation AquaCrop. Le modèle a ensuite été utilisé pour simuler le rendement de rendement sous les différents traitements d’irrigation avec et sans paillis pour les années sélectionnées représentant les saisons humides, normales et sèches pour l’approvisionnement complet (FS) (100% ETc) et l’irrigation déficitaire (DI) (80% ETc) pour les saisons principales et hors saison. La différence entre les rendements sous stress hydrique et les rendements potentiels (FS) a montré l’écart de rendement des tubercules de pomme de terre. Les résultats ont montré que des réductions de rendement (écart) ont été réalisées dans les traitements DI par rapport au FS pendant les saisons principales et hors saison. La baisse du pourcentage de rendement de l’irrigation supplémentaire a varié de 0,7% à 1,5% et de 1,1% à 2,6% pour la saison principale et hors saison pendant une année sèche. La baisse de l’année normale variait de 2,1% à 2,5% et de 1,5% à 4,1% pour la saison principale et hors saison respectivement. Les pertes des années humides étaient de 0,3% -2,1% et 0,8% -7,4% pour la saison principale et la saison morte, respectivement. Les pertes de rendement des cultures pluviales variaient de 18,9% à 22,2%, 6,0% à 14,1% et 2,1% à 3,2% pour les années sèches, normales et humides pendant la saison principale. Les rendements hors saison étaient de 68,1% -87,9%, 79,6% -86,1% et 36,1% -36,8% pour les années sèches, normales et humides, respectivement. En conclusion, AquaCrop est un modèle robuste qui peut être utilisé pour prédire les écarts de rendement des pommes de terre avec une précision acceptable dans diverses stratégies de régime hydrique, ce qui faciliterait la prise de décision au niveau des exploitations.

Mots clés : Irrigation, paillage, *Solanum tuberosum*, efficacité de l’utilisation de l’eau, écart de rendement

Introduction

Global food production needs to increase to 70% by 2050 in order to produce 60% more food to contribute to food security therefore a need for improvement of sustainable agriculture (Sadras *et al*., 2015). Globally, the area under irrigation is only 20% and contributes 40% crop production (Turral *et al*., 2010) while Sub-Saharan Africa crop production systems involving irrigation accounts only for 3% and rainfed accounts for 97%. Utilizing the scarce water resources efficiently due to high demands is important in order to feed the ever increasing population. Deficit irrigation with mulching is a strategy that can help to curb agricultural water challenge by producing more food with less water (Springer and Duchin, 2014). With proper irrigation scheduling, higher yields can be achieved (Monjardino *et al*., 2013).

According to Kenya Food Security Steering Group, KFSSG and UN (2017) for arid and semi-arid lands (ASAL) it is evident that farmers depend much on rain-fed agriculture. As such, a large number of people, 2.6 million to 3.5 million in these agroecologies need food donations each year.

Potato (*Solanum tuberosum* L.) is the fourth most important food crop after rice, wheat and maize in the world and over a million people eat potatoes (Devaux *et al*., 2014). In Kenya, it is the second most important crop after maize and plays a major role in national food, nutritional security and income generation (Muthoni and Nyamongo, 2009). Potato is a water stress sensitive tuber crop with shallow roots. It grows in high altitude areas where maize does not do well and its high nutritional value makes it a valuable crop.

Asia and Europe are the world's major potato producing regions, accounting for more than 80% of world production. Africa is the least producing region accounting for about 5% and lags at about 10 t/ha (FAO., 2008). In Sub-Saharan Africa (SSA) 70% of the growth is concentrated in eastern Africa (FAO, 2010). In Kenya, the production ranges between 4.4-15 t/ha with an average of 6.7 t/ha. These yields are far less than the amount produced by some developed countries. However, approximately 25-40 t/ha can be attained under research conditions (Muthoni and Nyamongo, 2009).

Water scarcity has become a challenge in crop production and this calls for short season crops which do not use a lot of water. Uswo location in Elgeyo Marakwet County and under Keiyo highlands climatic conditions, as the study area has been experiencing irregular rainfall patterns especially from May-July. This has led to low crop yields that result in food insecurity in the area as well as poverty. Potato can be considered as an option to reduce this problem since it is a short season crop which can mature within a short period compared to maize crop. Scarcity of the crop in the area is experienced during dry seasons, especially between the months of November and March.

There is need to do a deeper investigation in order to understand the main causes of potato yield gaps at the farmers' fields which is lower than the potential expected yield. Various constraints can lead to potato decline including, erratic rainfall, lack of clean seeds, pests and diseases, among others. Rainfall variability has been a major challenge in the study area due to water scarcity. To address this problem, potato yields can be obtained by increasing the land under irrigation and mulch especially during the off-seasons. Properly managed land and water resources can help minimize the yield gaps.

Analysing yield gap provides a measure of untapped food production capacity (Van Wart *et al*., 2013). Few studies have been carried out for crops like potato on yield gaps as opposed to cereal crops. The Global Yield Gap Atlas (GYGA) is one of those initiatives that is dealing with grain crops. Different crops respond to water stress differently due to different climatic conditions. It is therefore important to understand the gap yield in order to help in improving crop yields. Crop simulation mathematical models are valuable tools for yield gap analysis. They can help in assessing the interaction of climatological factors with crop response (CIP, 2014).

Lack of enough data is the main challenge affecting application of these models in Sub-Saharan Africa (SSA) but use of simulation models like AquaCrop could assist (CIP, 2014). Some of the available crop models include CROPSYST, DSSAT, CROPWAT and AquaCrop. AquaCrop model outweighs other crop models due to its features of simplicity, robustness and accuracy (Panday, 2014). The objective of the study was therefore to analyse of potato crop yield gaps for various water regime strategies and field management so as to contribute to increasing potato yields and closing Kenya's national yield gap as a strategy of achieving food security.

Materials and methods

Study area description. The field trial was carried out in the period of March 2016-July 2016 in Uswo location in Elgeyo Marakwet County under Keiyo highlands climatic conditions. The meteorological data for the period of the study were obtained from Elgeyo Saw Mills Station located 2 km from the trial site. The monthly maximum temperature ranged from 19.1^{0}C -28.7^{0}C while minimum temperature ranged from 8.2^{0}C -14.2°C. A total rainfall of 497.7 mm was received during the period of April 2016 - July 2016. This area is characterised by long rains between April - June and short rains between October - December. The soil in the study area was sandy loam.

Model simulations for yield gap. The historical data were used to carry out statistical analysis in order to generate the irrigation schedules for various growing seasons. Frequency analysis was done using RAINBOW software (Raes *et al*., 1996) to determine the homogeneity test for the different years. Probability of exceedance for wet (20%), normal (50%) and dry (80%) based on rainfall data from 2001 to 2015 for main growing season (March to July) and off-season (November to February) were derived and used to select representative type of seasons: wet, normal or dry.

The calibrated and validated AquaCrop model (Kiptoo, 2018) was run for each of the selected years representing wet, normal and dry seasons to determine the irrigation schedules for each growing stage for the main potato growing season (March to July) and for the off-season (November to February). Simulations were run under rainfed for both main and off-season without irrigation and then with irrigation under full water supply. Further deficit irrigation (DI) strategies were also designed according to the water stress sensitivity of the crop growing stages. Drought sensitive stages were avoided during DI in order to reduce the yield decline. Finally, AquaCrop model was used to simulate the yield output under the various irrigation treatments for the selected years representing wet, normal and dry seasons. There were a total of 36 simulations carried out for the following six conditions:

1. Six rainfed simulations for non-mulch (3: Dry, Normal and Wet and for main season and off season) representing no intervention.
2. Six full supply with irrigation and rainfall for non-mulch (3: Dry, Normal and Wet and for main season and off season) representing intervention by irrigation.
3. Six selected optimal DI level of irrigation and rainfall for non-mulch (3: Dry, Normal and Wet and for main season and off season) representing intervention by deficit irrigation and no mulch.
4. Six rainfed simulations for mulch (3: Dry, Normal and Wet and for main season and off season) representing intervention with mulch.
5. Six full supply with irrigation and rainfall for mulch (3: Dry, Normal and Wet and for main season and off season) representing intervention by irrigation and mulch.
6. Six selected optimal DI level of irrigation and rainfall for mulch (3: Dry, Normal and Wet and for main season and off season) representing intervention by deficit irrigation and mulch.

Yield gap is considered as the difference between two levels of yield. For mulch treatment yield gap was based on the maximum expected yield from the average temperature in the upper 100 m (T100M) treatment under full irrigation and mulch. Then yield gap for the other 17 simulations was computed in percentage based on the maximum yield under T100M. For non-mulch (NM) treatment yield gap was based on the maximum expected yield from T100NM treatment under full irrigation and no mulch. Then yield gap for the other 17 simulations were computed in percentage based on the maximum yield under T100NM.

Results and discussion

Yield gap for potato crop under varying water stresses. Under rainfed conditions for main season (March-July) in a wet year, the harvestable tuber yields were 13.154 t/ha and 11.554 t/ha for mulch and no mulch treatments, respectively. During a normal year, the tuber yields were 12.630 t/ha and 10.250 t/ha for mulch (M) and non-mulch (NM), respectively. Also dry season yields were 10.901 t/ha and 8.563 t/ha for M and NM, respectively. The off-season (Nov-Feb) under rainfed yields were 8.585 t/ha and 7.538 t/ha for M and NM, respectively for wet year. The normal year yields were 2.736 t/ha and 1.657 t/ha for M and NM, respectively while dry year registered 2.149 t/ha and 1.447 t/ha for M and NM in that order.

Applying supplemental irrigation and rainfall under the average temperature in the upper 100 m (T100M), main season yields were 13.342 t/ha and 11.931 t/ha for mulch (M) and non-mulch (NM), respectively during dry year. The 80% water level was selected due to optimal yields and water productivity attained (Kiptoo, 2018). Comparison of full sprinkler (FS) and Deficit irrigation (DI) showed a slight difference in yield. Deficit irrigation (80%) with rainfall yields were 13.241 t/ha and 11.765 t/ha for M and NM, respectively during dry year. During the off-season, the yields were 13.255 t/ha and 11.798 t/ha for M and NM under full sprinkler (FS) and rainfall and 13.088 t/ha and 11.657 t/ha for M and NM, respectively under DI and rainfall. Considering normal year main season, FS plus rainfall yields were 13.162 t/ha and 11.685 t/ ha for M and NM and deficit irrigation (DI) plus rainfall were 13.113 t/ha and 11.633 t/ha for M and NM, respectively. The off-season yields were 13.438 t/ha and 11.747 t/ha for FS and rainfall and 13.218 t/ha and 11.442 t/ha for DI and rainfall for M and NM treatments, respectively.

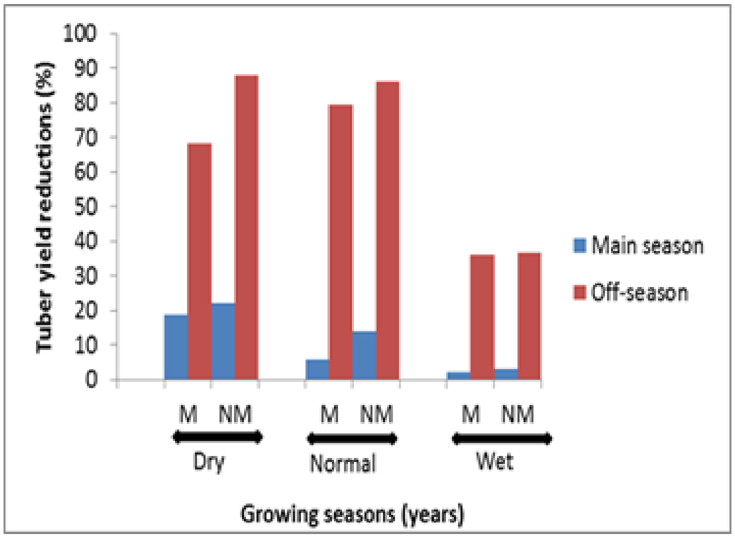
Results further reveal that the wet year yields for the main season under FS and rainfall were 13.394 t/ha and 11.827 t/ha for M and NM, respectively. For the off season the yields were 13.135 t/ha and 11.832 t/ha for M and NM. The DI with rainfall registered 12.438 t/ha and 11.832 t/ha for M and NM, respectively.

Highest tuber yield was 13.438 t/ha obtained at T100 M during the off season of the normal year. Comparing this with the yields of the other 35 simulated treatments for both rainfed and irrigated, it registered 0.0% yield reduction. The highest yield loss was 87.9% obtained during a dry off-season without mulch for rainfed treatment. The least yield decline for this treatment was 2.1% achieved when mulch was applied during the wet year main season (Fig. 1 a).

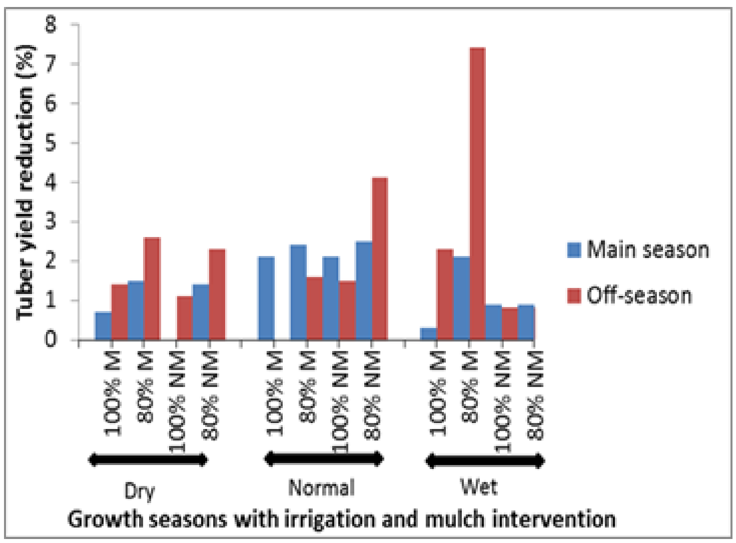
Provision of irrigation and mulch reduced potato yield loss as compared to rainfed treatments. The yield losses during a dry year ranged from 0.7%-1.5% at T100M and T80NM respectively during main season and 1.1%-2.6% for the off-season. Normal year losses were 2.1%-2.5% for the main season and 1.5%-4.1% for off-season at T100M and T80NM, respectively. Also the yield losses during a wet year were 0.3%-2.1% for main season and 0.8%-7.4% during off-season for FS and DI treatments respectively (Fig. 1 b).

Practically, with increasing water application the yields are expected to increase which applies to 100% water supply and yield reduction for 80% water supplication. High water productivity for 80% treatment ranged from 2.80-3.44 kg/m^3 for mulch and 2.42-3.06 kg/m^3 for no mulch. For 100% water supply, water productivity ranged from 2.52-2.90 kg/m^3 and 2.21-2.59 kg/m^3 for M and NM treatments, respectively.

From the potato variety catalogue 2017, the theoretical yield for Tigoni variety is 35-45 tons/ ha for for medium to high yields. For the purpose of this study, medium yields of 35 tons/ha was considered (Fig. 2). Comparison of the theoretical with the potential and actual showed some difference in yield as shown in Figure 1. Low yield gaps were realized in irrigated treatments during both main and off-seasons. However under rainfed conditions, huge yield reductions were registered especially during off-season. Combination of irrigation and mulch is expected to improve potato yields as compared to rainfed without mulch. Also better yields can be achieved under irrigation as compared with rainfed only.



a)



b)

Figure 1. Percentage tuber yield reduction under rainfed (a) and irrigated (b) treatments for mulched (M) and non-mulched (NM) plots

Discussion

Yield gap shows the difference between the yield that could be achieved by farmers and water limited potential yield. The rainfed potato yields are normally low and not stable. The calibrated and validated AquaCrop model was used to determine the possibility of reducing the yield gap. There is a high potential to increase potato production if only yield limiting factors are put into considerations. Yield gap during a rainfed season was high as compared to in irrigated treatments.

Major crop failure was registered in rainfed crops during off-season as compared to in a dry year with irrigation. Also irrigated treatments for main and off-seasons recorded a low crop reduction for both tuber and biomass yields during the wet years. Assuming a farmer planted potatoes during main season, normal year under irrigation without mulch, the yield increase of 1.435 t/ha would be realized as compared to during rainfed treatments. On applying mulch for the same conditions, more yields of 2.912 t/ha would be achieved. If the planting was done during the off season with intervention of mulch and irrigation, more yields of 11.598 t/ha would be achieved. The tuber yield difference between a wet year off-season under irrigation and mulch (FS and DI) and wet year under rainfed was 4.294 t/ha.

From the above, application of mulch and irrigation is advisable during off season in order to improve crop yields. Therefore, even in a wet season, supplemental irrigation is recommended in order to improve potato yields. Also a significant amount of water can be saved during wet seasons through DI for use during a dry season for better crop yields. Overall, the yield gap analysis showed a difference in potato yields under rainfed and deficit irrigated treatments under same environmental conditions. The largest difference was seen during the normal year and also the dry year. The rainfed yields were low compared to under irrigated treatments during the dry year. Further, more efforts should be put to boost rainfed agriculture by improving farming technologies like using drought resistant crops in drought prone areas and through mulching Therefore, irrigation and mulching is needed even during a wet year in order to conserve soil moisture and boost crop yields. Further, water harvesting can be practiced and used for supplemental irrigation to increase potato yields. With AquaCrop model, attainable against actual tuber yield can be predicted where water is a major limiting factor of production.

Recommendations

Potato yield gap analysis should be carried out to help the country address the issues of food insecurity by applying better production methods with well- planned irrigation strategies. To bridge the yield gap, AquaCrop model is recommended to estimate the yield gaps and also climate potential yield due to climate change. It is therefore recommended that the AquaCrop model be used to predict yield especially in areas where water is a major limiting factor. Further, as irrigation requires high capital investment, the Ministry of Agriculture is required to allocate more resources to boost this sector.

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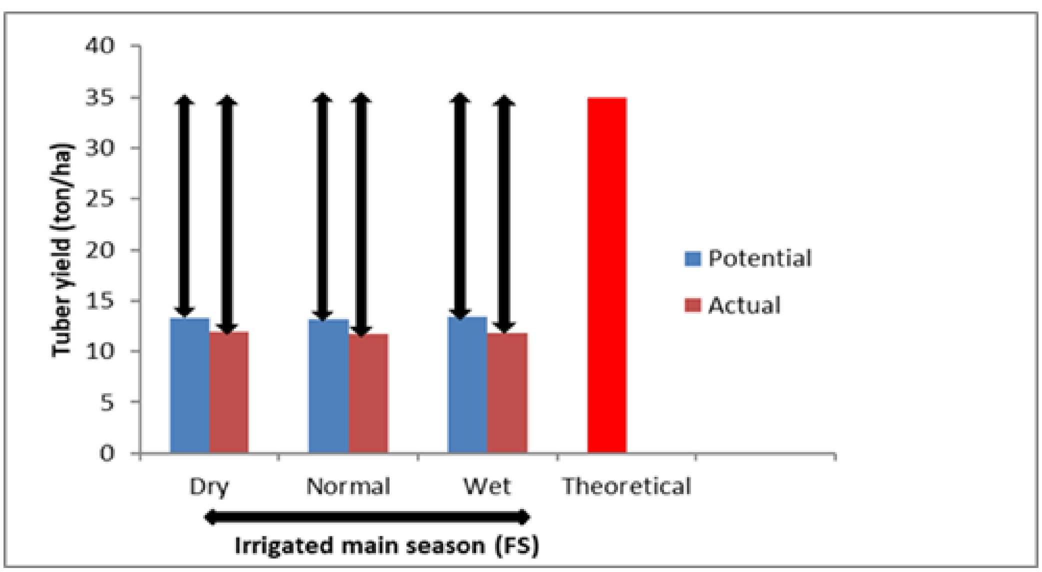
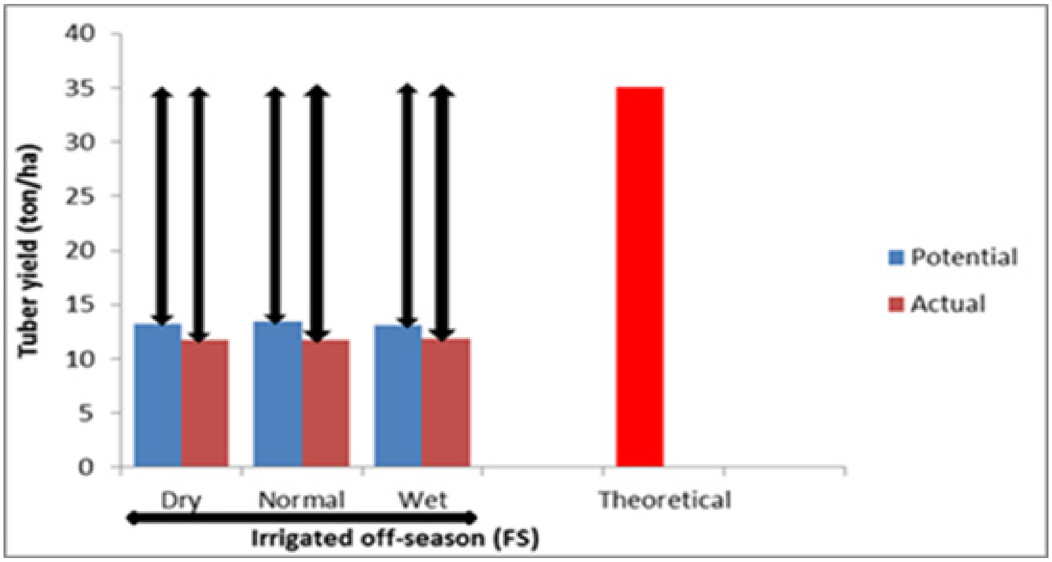
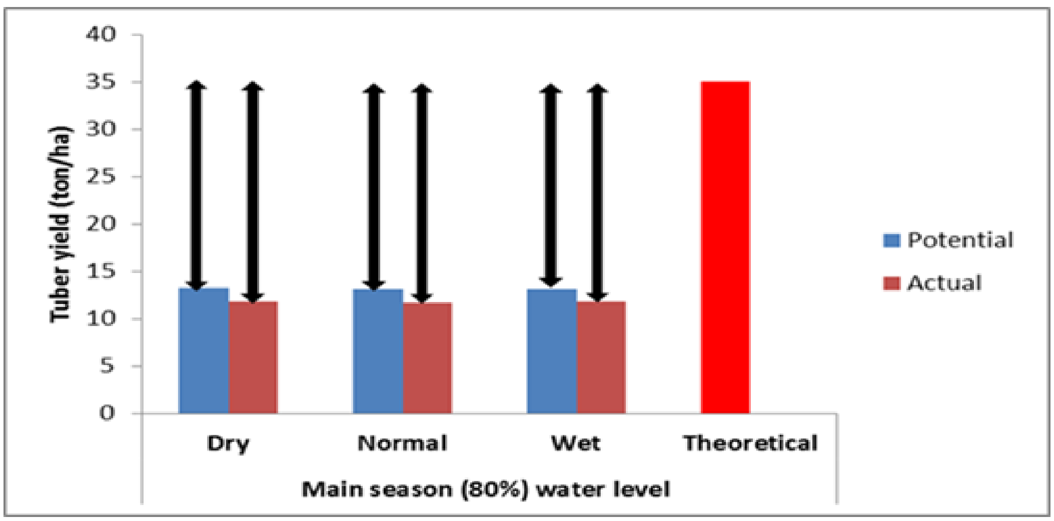
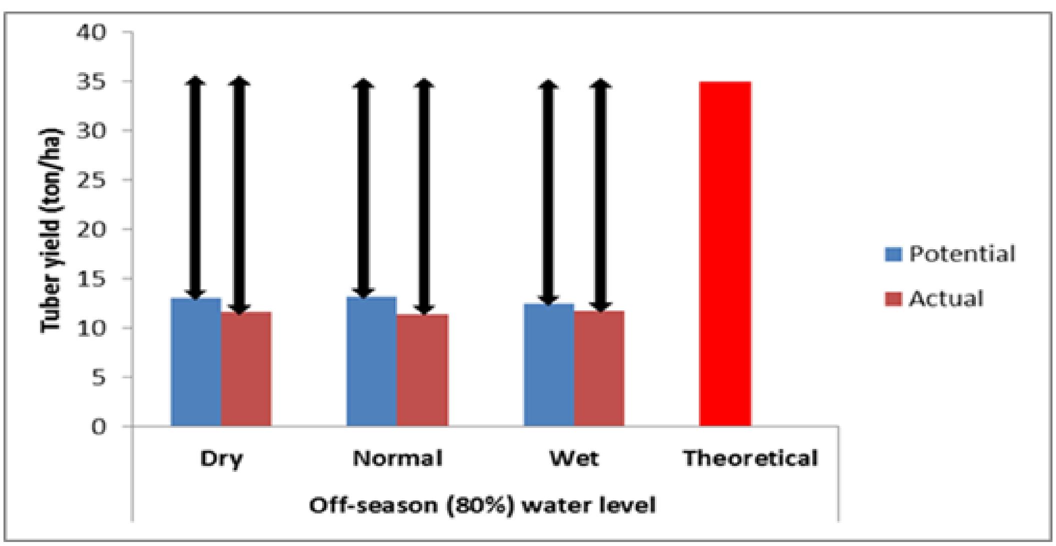




Tuber yield (ton/ha)
40
35
30
25
20
15
10
5
0
Dry
Normal
Wet
Theoretical
Irrigated off-season (FS)
Potential
Actual



Tuber yield (ton/ha)
40
35
30
25
20
15
10
5
0
Dry
Normal
Wet
Theoretical
Main season (80%) water level
Potential
Actual



Tuber yield (ton/ha)
40
35
30
25
20
15
10
5
0
Dry
Normal
Wet
Theoretical
Off-season (80%) water level
Potential
Actual

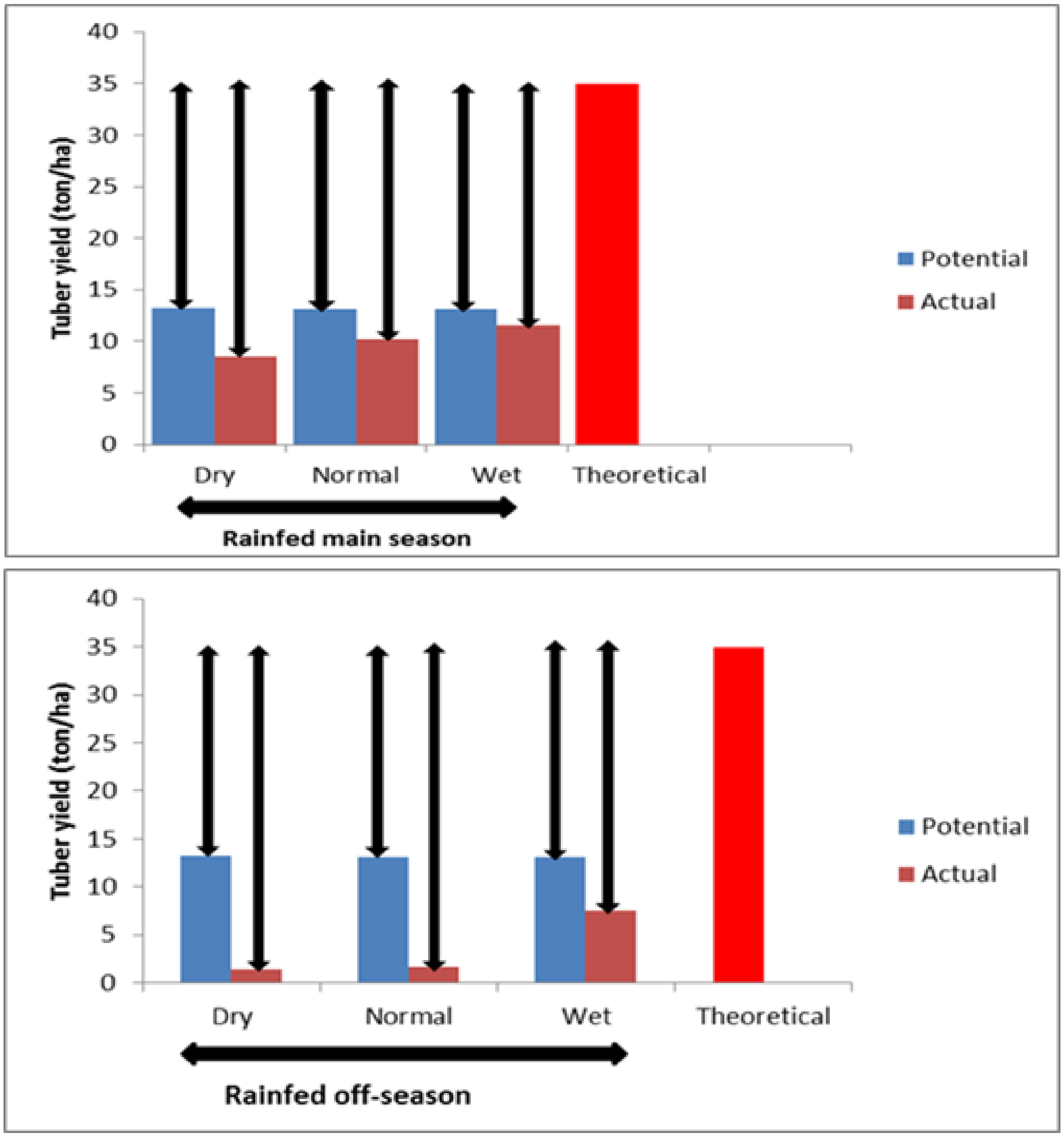


Figure 2. Illustrations of yield gap analysis, vertical arrows indicate tuber yield gaps.

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