MÉMOIRE DE FIN D'ÉTUDES

Présenté pour l'obtention du diplôme d'Ingénieur Agronome

Options de spécialisation : Gestion de l'eau, des milieux cultivés et de l'environnement

Guiding varietal choice for soybean in Africa: A comparison of bottom-up and top-down modelling approaches to assess water limited potential yields

par

Ugo Verlingue

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Organisme d'accueil : Unité mixte de recherche Fonctionnement et conduite des systèmes de culture tropicaux et méditerranéens (UMR SYSTEM)

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Ugo Verlingue

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Devant le jury :

Carole Sinfort

Hélène Marrou

Jean-Jacques Drevon

Armand Crabit

Lydie Guilioni

Organisme d'accueil : Unité mixte de recherche Fonctionnement et conduite des systèmes de culture tropicaux et méditerranéens (UMR SYSTEM)

Abstract:

Soybean [Glycine max (L) Merr.] represents an opportunity of improved incomes for small farmers in Sub-Saharan Africa. However, the low yields observed in this region act as a disincentive to the use of soybean by smallholders. Estimating soybean water-limited potential yields (Yw) for a range of climate and soil contexts in Africa is the first step to assess the gap between Yw and actual yields (Ya) of soybean under rainfed production. This gap, also called yield gap, can provide guidance for yields improvement. In this study, Yw were simulated thanks to the use of the crop model SSM-Legumes (Simple simulation model). The ability of SSM-Legumes to reproduce Yw in the African context was verified thanks to an evaluation of this model. Two approaches were used for the spatial representation of simulations. The first approach was the bottom-up approach; simulations were based on weather inputs from weather stations and results were up-scaled at climate zone and country scale thanks to rules of aggregation. The methodology was based on the Global Yield Gap Atlas methodology and results will be used to complete the atlas for the countries under study. The second approach was the top-down approach; simulations were based on gridded generated weather data that completely covered the area of the countries. The results of these two approaches were compared in Ethiopia, Kenya and Uganda at the same spatial unit level. Most of the simulations resulted in greater Yw for the top-down approach. Important differences between the results of the two approaches were detected when management inputs were slightly differing. In zone of abrupt climatic variation, the top-down approach resulted in greater yield. Lastly, in zone of homogeneous climatic condition, the two approaches gave practically similar results. The top-down approach was used to assess the effect of phenology and sowing dates on the simulated Yw. Combinations of phenology and sowing dates characterized as optimal were determined for the three countries under study.

Keywords:

Soybean, Water-limited potential yield, Bottom-up approach, Top-down approach, Simple Simulation Model, Sub-Saharan Africa, Yield gap analyses, N2Africa, Global yield gap atlas, rainfed crops

Résumé :

La culture du soja [Glycine max (L) Merr.] représente une opportunité d'amélioration des revenus pour les petites exploitations agricoles d'Afrique Sub-Saharienne. Cependant, les faibles rendements observés dans ce contexte sont un frein majeur à l'établissement à long terme de cette culture. L'estimation des rendements potentiels limités par l'eau (Yw) du soja pour une gamme d'environnements pédoclimatiques Africains est un prérequis à l'estimation de leurs écarts aux rendements observés en condition de culture pluviale. L'étude de ces écarts peut permettre d'orienter les recherches pour améliorer les rendements. Dans la présente étude, le modèle SSM-Legumes est utilisé pour simuler les rendements potentiels limités par l'eau. L'évaluation de ce modèle dans le contexte Africain a donné des résultats probants. Deux approches ont été mises en place pour sélectionner les unités spatiales simulées au sein des pays étudiés. La première est qualifiée de « bottom-up». La méthodologie est basée sur la méthode du « Global Yield Gap Atlas » et les résultats permettront de compléter l'atlas pour les pays concernés. L'unité spatiale est basée sur la localisation d'une station climatique dont les données sont utilisées pour simuler les Yw. Les résultats sont ensuite utilisés pour estimer les Yw à l'échelle des zones climatiques, puis des pays. La seconde approche est qualifiée de « top-down ». L'unité spatiale de simulation est basée sur des données climatiques simulées, présentées sous la forme de grilles, et couvrant la totalité des pays étudiés. Les résultats de ces deux approches ont été comparés en Ethiopie, au Kenya et en Uganda à chaque échelle spatiale de représentation. La tendance globale est à une surestimation des rendements par l'approche « top-down ». Les différences méthodologiques d'estimation des paramètres de gestion des cultures entre les deux approches ont joué sur l'établissement de ce résultat. Les résultats des simulations diffèrent de manière importante dans les zones de variation climatiques tandis que les zones plus homogènes présentent des résultats proches. L'approche « top-down » a ensuite été utilisée pour caractériser l'effet des variations des paramètres de gestion des cultures sur les Yw simulés. Une combinaison optimale entre une date de semis et un type de maturité a été ensuite sélectionnée pour chaque unité spatiale.

Mots-clés :

Soja, Rendements potentiels limités par l'eau, Approche « Bottom-up », Approche « Top-down », « Simple simulation model », Afrique Sub-Saharienne, Analyse des écarts aux rendements potentiels, N2Africa, « Global Yield Gap Atlas »

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Abbreviations and acronyms

BSG	Beginning seed growth
CN	Soil curve number
CPP	Critical photoperiod
CZ	Climate zone
DEP1	Soil first layer depth
DDMP	Daily dry matter production
DRAINF	Drainage factor
dtEM	Duration from sowing to Emergence
dtR1	Duration from Emergence to Flowering
dtR3	Duration from Flowering to Podding
dtR5	Duration from Podding to Seed growth
dtR7	Duration from Seed growth to Maturity
dtR8	Duration from Maturity to Harvest
DUL	Soil drained upper limit
E	Environment
EXTR	Extractable soil moisture
FRTRL	Fraction of total crop mass at beginning seed growth
G	genotype of the legume
G'	genotype of the rhizobia
GCC	Grain conversion coefficient
GYGA	Global yield gap atlas
IITA	International institute for tropical agriculture
IRUE	Potential RUE
KPAR	Extinction coefficient of photosynthetically active radiation
M	Management
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental prediction
PAR	Photosynthetically active radiation
PHYL	Phyllocron
PLACON	Plant leaf area when no node on the main stem
PLAPOW	Constant of the allometric relationship
PP	Photoperiod
ppsen	PP sensitivity coefficient
RUE	Radiation use efficiency
SALB	Soil albedo
SAT	Soil saturation limit
SLA	Specific leaf area
SOLDEP	Soil maximum depth
SPAM	Spatial Production Allocation Model

SSA	Sub-Saharan Africa
SSM	Simple Soltani model
TBD	Base TMP
TBRUE	Base TMP for radiation use efficiency
TCD	Ceiling TMP
TCRUE	Ceiling TMP for radiation use efficiency
TMP	Mean of the temperature
TP1D	Lower optimum TMP
TP1RUE	Lower optimum TMP for radiation use efficiency
TP2D	Higher optimum TMP
TP2RUE	Higher optimum TMP for radiation use efficiency
WISE	World Inventory of Soil property Estimates
WSSG	Water stress factor for dry matter production
WSSL	Water stress factor for leaf area index development
Ya	Actual yield
Yg	Yield gap
Yw	Water-limited potential yield

Introduction générale en Français

La culture du soja [Glycine max (L) Merr.] représente une opportunité d'amélioration des revenus pour les petites exploitations agricoles d'Afrique Sub-Saharienne (Giller, Witter et al. 2009). Sa capacité à fixer le diazote de l'air rend cette culture intéressante dans le cadre d'une amélioration de la fertilité des sols africains. Pour autant, les rendements atteints en Afrique n'engagent pas les petits producteurs à adopter le soja dans des systèmes de rotation. La notion d'écart des rendements potentiels aux rendements réels (Yield Gap) a été développée pour offrir un cadre à l'amélioration des rendements et de la production agricole à travers le monde (Neumann, Verburg et al. 2010; van Ittersum, Cassman et al. 2013). Ce rendement potentiel est déterminé comme le rendement atteignable lorsque les seules limitations appliquées à la culture sont le rayonnement solaire, la température, la concentration en dioxyde de carbone, et les caractéristiques génétiques (GYGA 2013). Puisque les cultures de soja en Afrique sont majoritairement caractérisées par le système pluviale, les limitations dues à la ressource en eau sont intégrées au calcul du rendement potentiel, alors appelé rendement potentiel limité par l'eau. Ce concept de rendement potentiel limité par l'eau n'a que peu d'applications physiques observables. Il est donc judicieux d'estimer sa valeur grâce à des outils de modélisation des cultures. Dans le cadre de l'étude, le modèle de culture SSM-Legumes (Simple Simulation model) (Soltani 2012) sera utilisé. SSM est un modèle mécaniste à base physiologique et dont tous les paramètres ont une signification biophysique et sont mesurables. Ce modèle a été testé en Amérique du Sud pour le soja ((Muchow and Sinclair 1986); (Sinclair, Salado-Navarro et al. 2007)) mais jamais en Afrique. Une évaluation de la qualité prédictive du modèle sera donc réalisée dans cette étude. Dans cette étude, la détermination des rendements potentiels limités par l'eau est réalisée à grande échelle. Afin de pouvoir caractériser les entrées du modèle, il est nécessaire d'appréhender l'espace comme constitué d'unités spatiales homogènes pour ces entrées. Deux approchent existent pour caractériser l'espace qui sont toutes deux basées sur le climat comme facteur de subdivision de la zone étudiée. La première est l'approche « bottom-up ». L'espace est subdivisé selon des zones climatiques prédéfinies, caractérisées comme climatiquement homogènes. Au sein de ces zones, les stations climatiques existantes sont utilisées pour réaliser les simulations. Les résultats de ces simulations sont agrégés à l'échelle des zones climatique puis du pays. L'avantage de cette approche est qu'elle se base sur des données climatiques réelles et s'affranchit des biais liés à l'utilisation de données climatiques simulées. Le principal inconvénient est que l'ensemble des subdivisions ne couvre pas la totalité de la zone. L'homogénéité des zones climatiques peut être questionnée et donc remettre en cause la méthode d'agrégation. La seconde approche est l'approche « top-down ». Celle-ci se base sur des données climatiques simulées. Des simulations climatiques réalisées pour des points répartis de manière homogène sur le territoire sont généralisées à des zones de même aire. L'ensemble de l'espace est donc couvert par ces données. Le principal inconvénient réside dans la fiabilité de ces simulations climatiques. De plus, la multiplication des unités qui doivent être renseignées rend la paramétrisation difficile, en particulier pour les données de gestion des cultures. Dans le cadre de cette étude, les deux approches seront réalisées et comparées. La différence de nature entre les deux approches implique des différences méthodologiques qui conditionneront cette comparaison. L'approche « bottom-up » sera réalisée selon la méthodologie du « Global Yield Gap Atlas » (GYGA 2013) et permettra de compléter cet atlas pour les pays concernés. Selon cette méthodologie le rendement potentiel limité par l'eau doit être simulé dans des conditions optimales de gestion des cultures. La définition d'une gestion optimale pose cependant problème et la plupart du temps les entrées du modèle sont basées sur la gestion effectivement réalisée par les agriculteurs dans la zone concernée. L'approche « top-down » sera utilisée pour caractériser l'effet des pratiques de gestion des cultures sur les niveaux de rendements potentiels limités par l'eau pour une gamme de contextes pédoclimatiques. Une sélection de la meilleure combinaison entre date de semis et type de maturité du soja sera réalisée sur la base des rendements atteints et du nombre d'années ou le semis est simulé comme effectif. Les niveaux atteints seront alors comparés à ceux observé pour des pratiques de gestion des cultures déterminées sur des bases biobibliographiques.

I Introduction

1 Supporting Soybean production in Africa

The major crop legumes cropped by smallholder in Sub Saharan Africa (SSA) are: groundnut (Arachis hypogaea L.), cowpea (Vigna unguiculata (L.) Walp.) and common bean (Phaseolus vulgaris L.). If soybean [Glycine max (L) Merr.] is still considered as a minor crop in SSA, the production is now expanding rapidly across the continent (**Figure 1**) (Giller, Murwira et al. 2011). Soybean is grown in 20 of the 45 Sub-Saharan countries and Sub-Saharan Africa (SSA) accounts for 1.3% of the total world cropped area of soybean and represents 0.6% of the world production. The biggest producer is Nigeria but commercial soybean production on large farms takes place mainly in Zambia, Zimbabwe and South Africa.

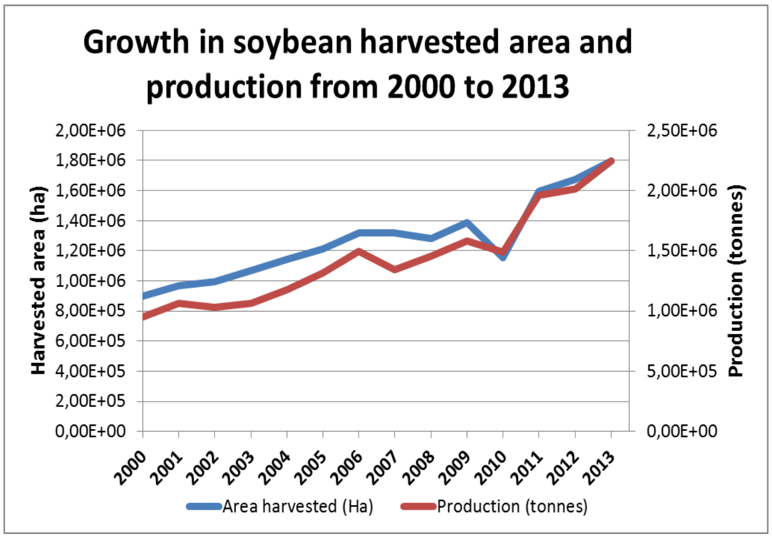


FIGURE 1 GROWTH IN SOYBEAN HARVESTED AREA AND PRODUCTION FROM 2000 TO 2013 (FAO STAT)

Yet, soybean yields in SSA are about 45% of the world average only (Abate, Alene et al. 2012). Indeed, most of the production in Africa relies on small holder farms, and is grown under rainfed conditions. Of the total 800 million inhabitants in SSA, around 500 million (63%) live in rural area. 80% of all farms in SSA are small farms (two ha or less). For some countries smallholders contribute up to 90% of the agricultural production (Wiggins 2009).

On this type of farms, an important part of the production is used at the farm level for food or feed (IITA 2009),while farmers cash income is very low. Two main factors slow down the development of soybean production on small holder farms. First, soybean is not traditionally consumed as food in this area of the world and would require a change in the cooking habits and diets. Second, limited adoption of soybean production by smallholders is mostly due to the uncertainty on open markets for small holder and on the possibility to earn secured incomes (Giller, Witter et al. 2009). According to Giller, Witter et al, the production of grain legumes can achieve a central role where a ready cash market exists.

Soybean represents an opportunity of improved incomes for small farms and to achieve a better nutritional security of the household at the same time. In addition, soybean production can represent an alternative to fertilizers that are too expensive for farmers (Vanlauwe, Van Asten et al. 2013). Its ability to fix the nitrogen of the air through the biological nitrogen fixation (BNF) could assist in solving the fertility issue in Africa. Its integration in rotations, before maize was shown to increase the maize yields in Zimbabwe (Mpepereki, Javaheri et al. 2000). In addition, soybean is perceived as being more resistant to local pests and diseases than other legumes such as the common bean or the cowpea (Giller, Murwira et al. 2011). Soybean also has a good potential for fodder. Roughly half of the consumed soybean in Africa comes from importation (IITA 2009), which make soybean appear as a ready market for smallholders. These multipurpose advantages for food, feed and incomes make soybean production adapted to small African farm situations.

The N2Africa project aims at "putting the nitrogen fixation to work in Africa" and "addresses agronomic and genetic options involving biological N2 fixation to improve the lives of smallholder in Africa". The N2Africa project is based on a (GxG')xExM approach, considering that the performance of grain legumes depends on the interaction between the genotype of the legume (G), the genotype of the rhizobia (G'), the environment (E) and the management (M) of the crop (Woomer, Huising et al. 2014). Among the five main objectives of the N2Africa project (Woomer, Huising et al. 2014), the one concerning the tailoring and adaptation of legumes technologies to close yield gaps is the base of the current study. Another objective of the N2Africa project is to collect experimental data and to stimulate their dissemination. The study benefited from these dynamic thanks to the rich collection of data available for soybean as well as the important network of country coordinators from N2Africa.

2 Assessing water limited potential yield

A Concept of water limited potential yield for yield gap calculation

Soybean yields in Africa are far below the average yields in the rest of the world. Increasing soybean yield is a priority to encourage soybean adoption by small holders in Africa.

The concept of Yield gap was proposed to offer a framework for improving yields and food production in the world (Neumann, Verburg et al. 2010; van Ittersum, Cassman et al. 2013). It relies on the hypothesis that, each crop genotype, grown in a given environment (determined by temperature and radiation from sowing date to maturity) can achieve a maximum yield when no biotic or abiotic factors affect the crop. This maximum yield is called "Potential Yield". In the case of rainfed cropping systems, where there is no options to bring water through irrigation, "Potential Yield" can appear as a useless reference. Instead, considering the maximum yield that can be achieved with the same cultivar in the same environment, without supplemental water could offer a more relevant reference as a maximum target. According to ((Lobell, Cassman et al. 2009)) Yw is "an idealized state in which a crop grows without any biophysical limitations other than uncontrollable factors, such as solar radiation, air temperature, and rainfall in rainfed systems".

Thus, the yield gap (Yg) for rainfed crops represents the difference between the water-limited potential yields (Yw) and the actual yields (Ya). In other terms, it represents the maximum yield gain that can be targeted for a given cultivar, planted at a given location, under rainfed conditions. The estimation of Yg provides guidance for improving yields worldwide. Areas in the world with large yield gaps can be identified as priority areas where to look for solutions to increase yield. Yield gap value can also orientate the strategy to improve yields, considering two possible pathways: 1) increasing water limited potential yield without increasing yield gap, or 2) reducing the Yield gap while Yw remains unchanged. For example, locations with large Yg and Yw, indicate a need for agricultural inputs or pest controls improvement. A low Yw indicates that crop cultivar improvement or adaptation to climatic conditions may be necessary.

B Contribution of modelling to the evaluation of Yg

While actual yield can be measured on field, it is hardly possible to determine Yw under field conditions. Therefore, Yw has to be estimated through crop modelling. From their apparition in the early 70's, crop models hare more or less popular in crop science and often denigrated for their disconnection from reality (Sinclair and Seligman 1996). However, considering that "limits of crop models as surrogates for reality should be recognized and accepted as inevitable consequences of simplification", crop models can provide insightful direction to improve agricultural production. This is all the most the case when trying to assess water-limited potential yield, which is a conceptual value that cannot be fully estimated, even with the help of heavily controlled experiments (van Ittersum, Cassman et al. 2013). Model can also provide ex-ante assessment of new genetic or agronomic options, and allow for an estimation of risk associated to these options. This is possible only when using transparent and physiology base models, in which changes in parameters or model equations can be directly related to biophysical changes of the system. Model parameterization and model evaluation are two crucial points for an enlightened use of crop models and thus occupy and important place in the study.

3 Modeling the water limited yield with the SSM model

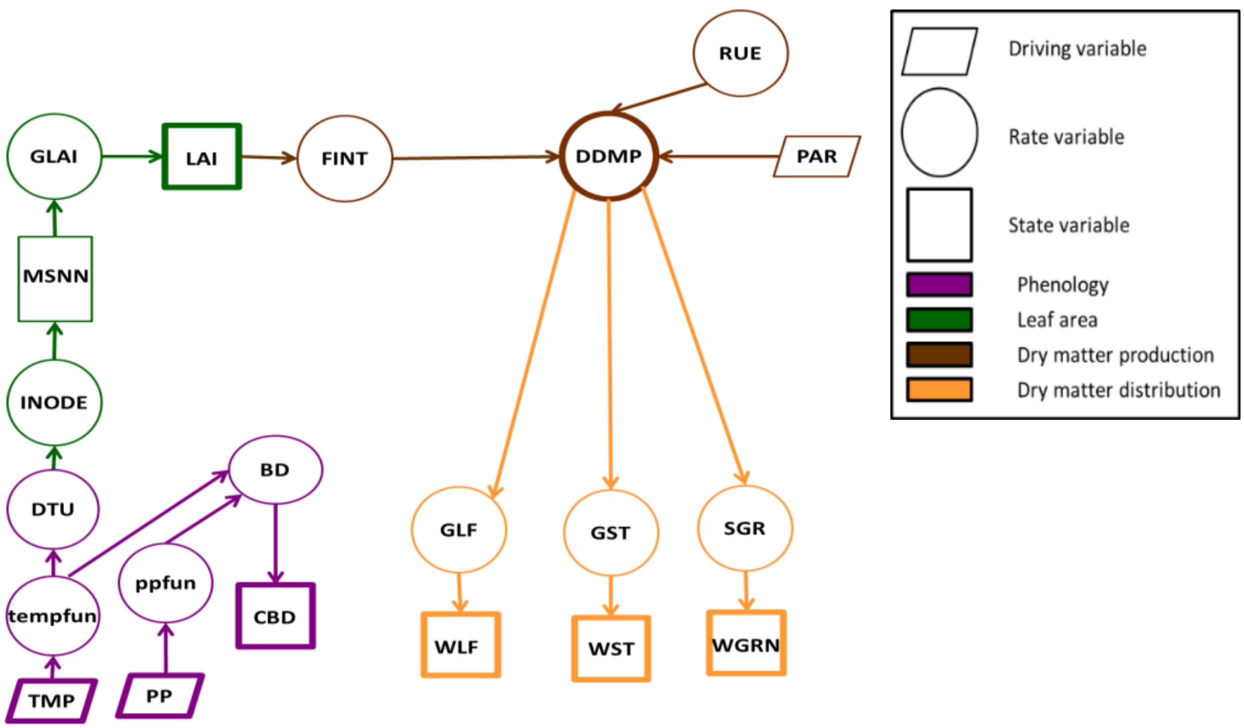
A General model description

The simple simulation model for legumes (SSM-Legumes) (Soltani 2012) is a mechanistic crop model for simulating growth and yield of crops. SSM is a transparent and physiology based model in which every parameters has a biophysical signification and is measurable. In addition, SSM is adapted to scarce data contexts as few parameters are needed to run a simulation. These two characteristics (being physiologically meaningful, and needing few parameters) makes this model a good candidate to simulate Yw over large geographic areas in Africa.

The SSM model has been developed in two separate versions to simulate legume crops (bean, soybean, chickpea, and lentil) on the one hand and cereal (maize, wheat, sorghum) (Soltani, Maddah et al. 2013) on the other hand. The ability of SSM to reproduce soybean yields has been demonstrated in several studies over a range of environment ((Muchow and Sinclair 1986); (Sinclair, Salado-Navarro et al. 2007)). However, SSM has never been evaluated for its predictive capacity in Africa. Part of the work in this study will be dedicated to the evaluation of the capability of SSM to simulate properly water limited yields for soybean in Africa.

The model is structured into modules (**Figure 2**). Within each module, water stress factor can be calculated to simulate water stress effect on different physiological processes, which allows to calculate water limited Yield (Yw). Four main modules are involved into the simulation of water limited yield. **The first module is phenology**: phenology can be seen as the timer of the plant. For a day, if mean temperature (TMP) and photoperiod **(**PP) are optimal then a day is effectively counted. Otherwise, only a fraction of day is counted depending on the level of temperature or photoperiod reached. New developmental stages involving different process start when a phenological stage is reached by cumulative biological days (CBD). **The second module is leaf area growth**. TMP influence the number of leaf on the main stem (INODE) through a relation involving the phyllocron. An allometric relationship allows the calculation of the daily leaf area index (GLAI) from INODE. In the second part of the cycle, leaf senescence is calculated according to sink demand for nitrogen. **The third module is**

dry matter production. The fraction of photosynthetic active radiation (PAR) intercepted (FINT) by the leaves is calculated thank to the leaf area index (LA**I**). The total LAI calculated for the day will intercept the PAR of the next day. Intercepted PAR is used through the process of photosynthesis to produce dry matter (DDMP). The process of photosynthesis is accounted for by the crop specific radiation use efficiency (RUE). Potential radiation use efficiency is constant along the cycle but actual RUE varies according to temperature and water availability. **The fourth module of the model is dry matter distribution**. The produced dry mater is distributed between three sinks: leaf, aerial parts (stem) or grain. Dry matter is not allocated to roots. The priority order for distribution depends on phenological stages and on the nitrogen balance between organs according to (Jamieson and Semenov 2000) approach. When seed growth begins, dry matter from vegetative organs as well as the daily amount of dry matter produced is transferred to the grains. Another module is assigned to soil water balance calculation, which allows to calculate water stress effects.



TMP: Mean daily temperature (°C), **tempfun**: temperature function (day), **DTU:** Daily temperature unit (°C), **PP**: Photoperiod (h), **ppfun:** Photoperiod function (day), **BD:** Biological days (day), **CBD:** Cumulative biological days (day), **INODE:** Daily increase in leaf number on main stem (#/day), **MSNN:** Total cumulative number of leaf on mains stem, **GLAI:** Daily increase in LAI (m^2/m^2.day), **LAI:** Leaf area index (m^2/m^2), **FINT:** The fraction of intercepted PAR**, RUE:** Radiation use efficiency (g/MJ), **PAR:** Photosynthetic active radiation (MJ/m^2), **DDMP:** Daily amount of dry matter produced (g/m^2.day), **GLF:** daily growth in leaf dry matter (g/m^2.day), **GST:** daily growth in stem dry matter (g/m^2.day), **SGR:** seed growth rate (g/m^2.day), **WLF:** Cumulative leaf dry matter (g/m^2), **WST:** Cumulative stem dry matter (g/m^2), **WGRN:** Cumulative grain dry matter (g/m^2)

FIGURE 2 GENERAL DESCRIPTION OF THE SSM MODEL

A more detailed representation of the model is presented in the appendix 1

B Calculation of phenology in SSM

Calendar time is not a suitable measure to characterize time for plant. Temperature has a large influence (Gilmore and Rogers 1958) and photoperiod is important too. To take this into account, Sinclair and Soltani use the concept of biological days.

Concept of biological days

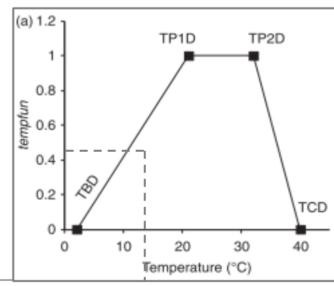
The duration in biological days is the duration of a developmental phase when temperature and photoperiod conditions are optimal. It is the minimum duration of a stage in calendar days. For a given calendar day, its duration in biological day is expressed as:

$$BD = tempfun * ppfun$$

Where tempfun and ppfun are temperature and photoperiod response of the crop. If both TMP and PP are optimal then BD is equal to one. If not, BD is between zero and one.

Temperature function:

$$\begin{aligned} \boldsymbol{tempfun} &= 0 \; if \; TMP < TBD \\ &= \frac{TMP-TBD}{TP1D-TBD} \; if \; TBD < TMP < TP1D \\ &= 1 \; if \; TP1D < TMD < TP2D \\ &= \frac{TCD-TMP}{TCD-TMP2} if \; TP2D < TMP < TCD \\ &= 0 \; if \; TMP > TCD \end{aligned}$$



With: **tempfun**: temperature function, **TMP**: mean daily temperature, **TBD**: Base temperature, **TP1D**: Lower optimum temperature, **TP2D**: Upper optimum temperature, **TCD**: Ceiling temperature

FIGURE 3: CROP RESPONSE TO TEMPERATURE

The temperature function is a linear approximation of the curvilinear response of plant relative rate of development to temperature (Loomis and Connor 1992; Sinclair 1994; Soltani, Robertson et al. 2006). Cardinal temperatures within a species are considered to be fairly constant across all development stages in this model even if (Piper, Boote et al. 1996) showed that certain variation could occur.

Photoperiod f unction:

For CBD < bdBRP

$ppfun = 1$

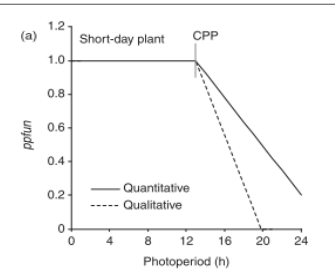
For bdBRP < CBD < bdTRP

$ppfun = 1 - ppsen * (CPP - PP) \; \boldsymbol{if} \; (PP > CPP)$

$\quad = 1 \; \boldsymbol{if} \; (PP < CPP)$

For CBD > bdTRP

$ppfun = 1$

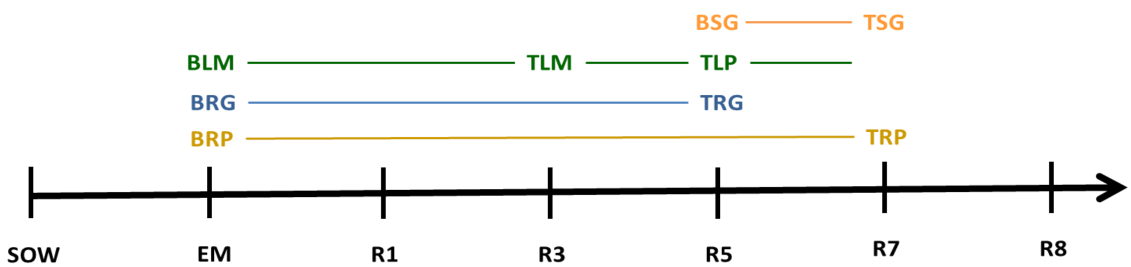


With: **ppfun**: photoperiod function, **ppsen**: photoperiod sensitivity coefficient, **CPP**: Critical photoperiod, **bdBRP**: Beginning of the response to photoperiod, **TRP**: Termination of the response to photoperiod

FIGURE 4: CROP RESPONSE TO PHOTOPERIOD

A 2 segment linear function is used (**Figure 4**) here but other more complex functions could be used as the quadratic function used in DSSAT model ((Jones, Hoogenboom et al. 2003). Soybean is a short day plant. Ppsen is the slope of the linear increase. The effect of photoperiod on plant development is accounted for only for a certain period.

The calculation of cumulative biological days allows starting physiological process such as seed growth or sensitivity to photoperiod **(Figure 5**). Main stages durations are to be input to the model as crop parameters



SOW: Sowing, **EM:** Emergence, **R1:** Flowering at any node, **R3:** Beginning podding, **R5:** Beginning seed filling, **R7:** Physiological maturity, **R8:** Harvest, **BSG:** Beginning seed growth**, TSG:** Termination seed growth, **BRP:** Beginning response to photoperiod**, TRP:** Termination response to photoperiod, **BRG:** Beginning root growth, **TRG:** Termination root growth, **BLM:** Beginning leaves development on main stem, **TLM:** Termination leaves development on main stem, **TLP:** Termination of leaves development

FIGURE 5: PHENOLOGICAL STAGES IN THE SSM MODEL

C Stress modeling in SSM

SSM allows for simulation of water limited yield for legumes. That means that Yw is determined by solar radiation, temperature, atmospheric CO2 concentration, genetic characteristics and water limitations. The effect of solar radiation is accounted for thanks to PAR, and genetic characteristics are taken into account thanks to maturity type (**Part II.3.A**). The effect of CO2 concentration is not accounted for in the model. Water and temperature stresses are accounted for in the SSM model for Yw by using reducing factors.

Temperature stress

In the SSM model, temperature impact on the RUE is calculated thanks to a three segment function close to the temperature function presented in **the part I.3.B**. Same cardinal temperatures are applied to calculate an adjusting factor (TCFRUE). This adjusting factor is applied to the potential radiation use efficiency (IRUE) to calculate the actual radiation use efficiency.

Water-related stresses

Water-deficit stresses can affect three processes in the SSM model which are: Transpiration/dry matter accumulation, leaf area development and phenological development. Different levels of the fraction of transpirable soil water (FTSW) will affect each of this process. The FTSW is the ratio between the actual transpirable soil water (ATSW) which is calculated thanks to the soil balance module and the total transpirable soil water (TTSW) which is calculated thanks to the soil extractable moisture and the depth of soil.

The WSFL (water-deficit stress factor for leaf area development) is activated when the FTSW is under 0.4. Between a FTSW of 0.4 and 0 the stress factor decreases linearly from 1 to 0. This factor affects the INODE (**Part I.3.A**) thanks to a multiplicative rule. The WSFD (WSF for development) is also activated when the FTSW reach 0.4. This factor can go from 1 to 1.4, it affects the value of biological days only during the grain filling period. Finally, the WSFG (WSF for growth) decrease linearly from 1 to 0 between a FTSW of 0.3 and 0. This factor impact the RUE. Water stresses impact yield through different pathway according to their timing of occurrence.

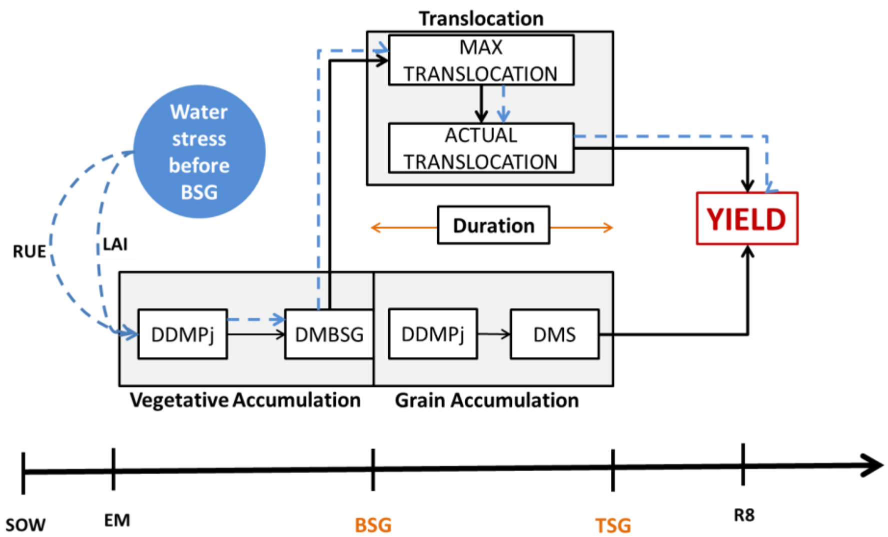


FIGURE 6: WATER STRESS EFFECT BEFORE THE BEGINNING OF SEED GROWTH

Depending on the level of water stress, daily dry matter production (DDMPj) of vegetative organs is impacted through a decrease of the IRUE and/or of the LAI. This decrease in daily production impacts the vegetative dry mater at the beginning of seed growth (DMBSG) (**Figure 6**). A fraction of the DMBSG is available for transfer to the grains. A decrease in DMBSG results in a decrease of the maximum amount of dry mater that can be translocated to the grain. This will impact the final level of grain dry matter and thus the final yield.

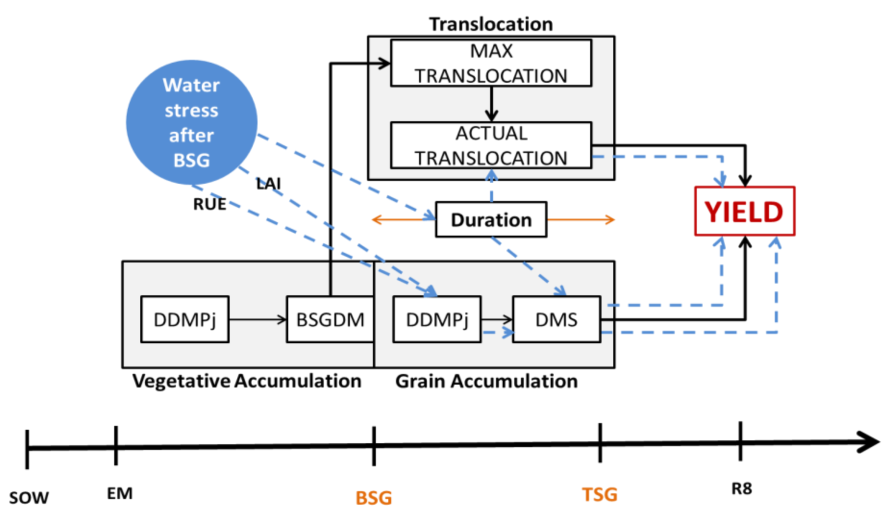


FIGURE 7: WATER STRESS EFFECT AFTER THE BEGINNING OF SEED GROWTH

Daily dry mater production is still possible after BSG because there are leaves left to undertake solar radiation absorption. This daily dry matter is distributed to grains (**Figure 7**). A decrease in DDMPj impacts the dry matter in grains at the termination of seed growth (TSG) and thus the final yields. Another effect of water stress is the hastening of the seed filling period. Less time is available for dry matter production and final dry matter in grains at the termination of seed growth is thus decreased. The maximum translocation is stable but the actual translocation is reduced and impacts the final value of the Yield.

D Model parameters

Efforts to determine parameters values for a model should be adapted according to two criteria:

- The sensitivity of the model to this parameter. The sensitivity measures the variation of the value of one parameter on the prediction of the variable of interest (here, water limited yield). Maximum effort should be put in determining the "right" value for parameters to which the model is highly sensitive

- The range of variation of a given parameter across the situations under study. Some parameters do vary with variety, species or geographical location. Parameters that are highly variable across the validity domain of the model require cautious estimation as extrapolation of their values from the literature can lead to wrong parameterization.

Crop and soil parameters of the model SSM have been classified according to these two criteria. Although no sensitivity analysis was carried out during this study, information from previous published reference (Sinclair, Marrou et al. 2014) and expert knowledge from the model authors allowed us to classify all model parameters into three classes of sensitivity: High, medium, or low.

Soil parameters

Soil parameters are mostly used in the model to run a water balance assessment for each day of the simulation. The curve number (CN) acts as a parameter of a relation between precipitation and runoffs as developed by the USDA-Soil Conservation Service (SCS) (Williams, Hanks et al. 1991). The drainage factor (DRAINF) characterizes the amount of extra-water that will drain in a day. It is used in a relation developed by Ritchie (Ritchie 1998). Soil saturation limit (SAT), soil drained upper limit (DUL) and soil extractable moisture (EXTR) are used to determine the soil water reservoir. DUL is defined as the maximum water that a soil can hold at a steady state of drainage. EXTR is defined as the total extractable soil water by the plant. SAT is defined as the maximum soil water content when all pores are filed.

CHART 1: SOIL PARAMETERS OF THE SSM MODEL

Name	Signification	Unit
SOLDEP	Soil maximum depth	mm
DEP1	Soil first layer depth	mm
SALB	Soil albedo	
CN	Soil curve number	
DRAINF	Drainage factor	
SAT	Soil saturation limit	$mm.mm^{-1}$
DUL	Soil drained upper limit	$mm.mm^{-1}$
EXTR	Soil extractable moisture	$mm.mm^{-1}$

Crop parameters:

The phenological crop parameters in blue on the **chart 2** are the one that were determined for each variety in the study. Experimental cardinal temperatures determination for each variety was not possible. According to (Soltani 2012) the cardinal values within a species are fairly constant across all developmental stages. Thus reference values for soybean cardinal temperature were used (Soltani 2012). The model shows medium sensitivity to CPP and ppsen. According to (Grimm, Jones et al. 1993), important variations among maturity groups exist for CPP and ppsen for soybean, and referenced values of CPP and ppsen exist for the American maturity group classification. However, varieties used in Africa have not been classified according to the American system. As a compromise, values of photoperiod parameters were referenced as an average of the three most represented group in Africa.

CHART 2: CROP PARAMETERS OF THE SSM MODEL

Name	Signification	Units	Sensitivity	Variations	Source for value
dtEM	Duration from sowing to Emergence	Biological days	High	Inter Maturity group	Experiments
dtR1	Duration from Emergence to Flowering	Biological days	High	Inter Maturity group	Experiments
dtR3	Duration from Flowering to Podding	Biological days	Low	Inter Maturity group	Experiments
dtR5	Duration from Podding to Seed growth	Biological days	High	Inter Maturity group	Experiments
dtR7	Duration from Seed growth to Maturity	Biological days	High	Inter Maturity group	Experiments
dtR8	Duration from Maturity to Harvest	Biological days	Low	Inter Maturity group	Experiments
ppsen	PP sensitivity coefficient		Medium	Inter Maturity group	(Soltani 2012)
CPP	Critical PP	Hour	Medium	Inter Maturity group	(Soltani 2012)
TBD	Base TMP	° Celsius	High	Inter Species	(Soltani 2012)
TP1D	Lower optimum TMP	° Celsius	High	Inter Species	(Soltani 2012)
TP2D	Higher optimum TMP	° Celsius	High	Inter Species	(Soltani 2012)
TCD	Ceiling TMP	° Celsius	High	Inter Species	(Soltani 2012)
PHYL	Phyllocron	° C/node	High	Inter Species	(Soltani 2012)
PLAPOW	Constant of the allometric relationship		High	Inter Species	(Soltani 2012)
PLACON	Plant leaf area when no node on the main stem	cm²	High	Inter Species	Personal Communications
SLA	Specific leaf area	m²/g	Low	Inter Species	//
KPAR	Extinction coefficient of PAR		High	Inter Species	//
IRUE	Potential RUE	g/Mega Joule	High	Inter Species	//
TBRUE	Base TMP for RUE	° Celsius	High	Inter Species	//
TP1RUE	Lower optimum TMP for RUE	° Celsius	High	Inter Species	//
TP2RUE	Higher optimum TMP for RUE	° Celsius	High	Inter Species	//
TCRUE	Ceiling TMP for RUE	° Celsius	High	Inter Species	//
FLF1A	Partitioning fraction of DDMP for leaf at low WTOP	g/g	Low	Inter Species	//
FLF1B	FLF at high WTOP	g/g	Low	Inter Species	//
FLF2	FLF between TLM and TLP	g/g	Low	Inter Species	//
WTOPL	Crop mass when FLF shift to FLF1B	g/m²	Low	Inter Species	//
FRTRL	Fraction of total crop mass at BSG		Medium	Inter Species	//
GCC	Grain conversion coefficient	g/g	Medium	Inter Species	//
WSSL	Water stress factor for LAI development			Inter Species	//
WSSG	Water stress factor for dry matter production			Inter Species	//

Management parameters

Management parameters are plant density (PDENS), sowing date (PDOY) and the choice of the variety under use. The variety under use affects all the crop parameters, including phenological parameters. Sowing date is crucial in order to start the crop development. Density has an important effect on the final results as it influences greatly the leaf area index. A model option also allows to input sowing date as a fixed value, or to let the model search for the appropriate sowing date within a sowing window. In this case, sowing is triggered when soil water content is found to be higher than a minimum threshold. If this condition is not satisfied before the end of the sowing window, the crop is not sown and crop cycle is considered to fail.

Initialization

The initialization of the simulation takes place before the sowing date. At the date of initialization, the state of soil water must be known for the total depth of soil (MAI) as well as for the surface layer (MAI1). The initialization is crucial as it has an important influence on the soil water balance calculation and thus on the final dry matter production. Thus, the beginning of the simulation has to be set at a date, before sowing (or at sowing) when the soil water status is known.

3 Spatial mapping of Yw

Another delicate aspect of the Yield Gap approach to improve yield across the world is the spatial representation of estimated Yw and Yg. When drawing geographic maps of a simulated variable, two approaches can be adopted. The bottom-up and the top-down approach:

A Bottom up approach

The bottom-up approach relies on the identification of spatial units that are considered to be homogenous regarding all the factors that can make Yw vary: the genotype locally grown, the sowing date, the local soil characteristics and the climate (radiation, rainfall and temperature) from sowing to maturity. Once units have been delimitated, an average value of the variable(s) of interest (here Yw) is estimated for each of them, according to their respective average properties.

The bottom up approach is used in the Global Yield Gap Atlas (GYGA) project. This international projects aims at mapping Yp, Yw and Yg of the main food crop across the world. A precise methodology has been elaborated and has to be rigorously implemented for each new region to be added to the Atlas (GYGA 2013). In this methodology, homogenous spatial units (climatic zone) are defined on the basis of existing weather stations regarding climatic variable. Only spatial units of interest are selected. This selection is made with respect to the crop distribution within the geographical zone. Within each climate zone (CZ), a buffer zone around each weather station is characterized regarding soil properties and cropping system (variety and sowing date). Yw is simulated for each weather station with its local soil and agronomic characteristics for a large number of years. Finally, each CZ is assigned one single value of Yw and Yg, calculated as the weighted average of Yw and Yg estimated around each weather station of the CZ.

The advantage of the bottom–up approach is that it avoids dealing with uncertainty of generated weather data. However, the implementation of this approach is very difficult when weather station records are scarce, as it is often the case in Africa. Another limitation relies on the assumption of homogeneity within each climate zone. Actually, each climate zone covers a diversity of climatic (van Wart, van Bussel et al. 2013) and soil situations, and Yw variation within these CZ is seldom evaluated.

Thus, this type of representation doesn't always allow identifying variation in the environment and in the Yg at small scales. However, this type of approach allows delimitating agro-ecologic areas with quite a holistic approach. These CZ can be then addressed as case study areas, within the limit of which alternative cultivation modes can be investigated.

B Top down approach

The top-down approach relies on the vision of a map as the juxtaposition of a high number of points that can be has closed to each other as desired. Thus, the method to build such Yw maps with this approach consist in simulating Yw for a high number of location, evenly spred over the country or the world region of interest. The particularity of top down approach is the use of generated weather data to perform simulations. The generated data are most of the time gridded data defined at a specific spatial resolution. Each cell of the grid is defined as a spatial unit for model simulation. No standardization of top down approaches exists. Some studies were performed by using empirical models (Mueller, Gerber et al. 2012). Some of them did not account for soil heterogeneity (Licker, Johnston et al. 2010). Most of these methods were used because the aim of these studies was to assess yield gaps at very large spatial scales and for an important range of crops.

The main advantage of this approach is to give a complete coverage of the geographical zones under study, using exact characteristic of each grid cell or point. In addition, weather data collection for this type of map is much easier, since all climatic data are generated. The main critical against this type of approach are that 1) it relies entirely on generated climate, and thus add a layer of uncertainty in the estimation of Yg 2) it doesn't offer any comprehensive zonation for field agronomists to test and evaluate ex post simulated scenarios.

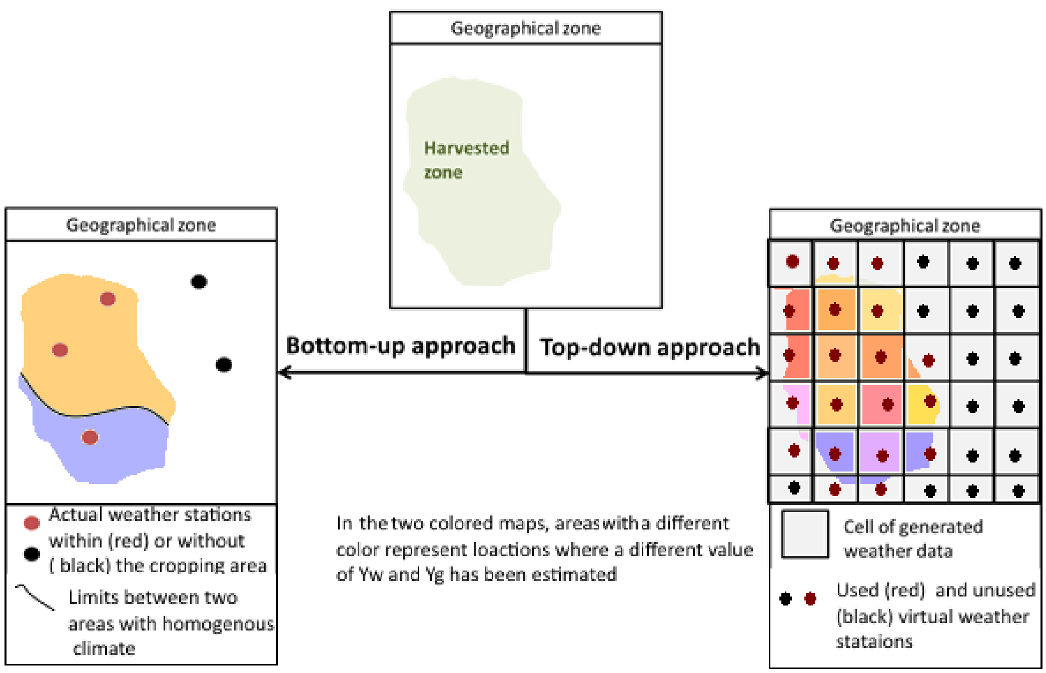


FIGURE 8: DIFFERENCES IN WEATHER ESTIMATION BETWEEN BOTTOM-UP AND TOP-DOW APPROACHES

The differences between these approaches make their comparison uneasy and sometime unjustified (van Ittersum, Cassman et al. 2013). In the study, similar methodologies were used for the soil determination of top-down and bottom-up approaches.

4 Agronomic and genetic levers to increase water limited potential yield (Yw)

Genetic improvement is usually foreseen as the only way to increase potential yields (Specht, Hume et al. 1999). However, it is important to consider that potential yield is directly determined by the radiative and thermic environment experienced by the crop all along its crop cycle. Thus, some management options, such as sowing date can have a direct impact on potential yield. In the case of water limited yield, management is even more determinant. For example sowing date impacts water availability for crop through initial soil water content and can thus modify Yw. As a consequence, crop management has to be characterized prior to every localized estimations of Yw.

According to the GYGA methodology, Yw must be simulated by using optimal agronomic management practices as inputs. Agronomic management is defined in this methodology as the combination of the sowing date, the varietal maturity and the density. Optimal parameters can be diverse according to the goal of each farmer. One will focus on yields while another will prefer low crop cycle duration in order to maximize profit for the entire cropping system rather than the profit of an individual crop, and so on. Because of the difficulty to define optimal management inputs, it is considered that actual practices have been selected by farmers as being the current optimum. Still, defining management practices for each unit can be an arduous task and rely on a combination of expert source, management rules reported in the literature. Another approximation of the methodology is that practices are supposed to be fixed for the period of time covered by simulations, which can represent up to 30 years.

5 Research questions

The objectives of this study are **i)** to evaluate the ability of the SSM model to reproduce Yw in the African context, **ii)** to complete the Global Yield Gap Atlas with Yw values calculated for East African countries thanks to a bottom-up approach, **iii)** to assess Yw at the spatial unit level thanks to a top-down approach, **iv)** to define optimal management among a range of practices for each spatial unit.

Bottom-up and top-down approaches are very different in aim and methodology. The comparison between them is thus uneasy. The use of the two approaches in this study must help answering the following questions:

Do the important differences in aims and methodologies between bottom-up and top-down approaches allow a consistent comparison of the results of the two methods? If so, do the two approaches show different results, and what are the factors involved in this differences?

Potential yield is determined by radiative and thermic environment experienced by the crop all along its crop cycle. Management parameters like the sowing date and the varietal choice impact crop cycle duration. They should thus influence the final water-limited potential yields. The study of the effect of a range of management parameters on the final water-limited potential yield must help answering the following question:

Does the use of different phenology influence the level of water-limited potential yields for a same spatial unit? If so, does optimal management practices can be defined thanks to crop simulations?

II Material and methods

1 General approach

The countries used in the different steps of the study are Ethiopia, Kenya, Mozambique, Nigeria, Uganda and Zambia. These countries are well distributed between Western Africa, Eastern Africa and South Eastern Africa (**Figure 9**).

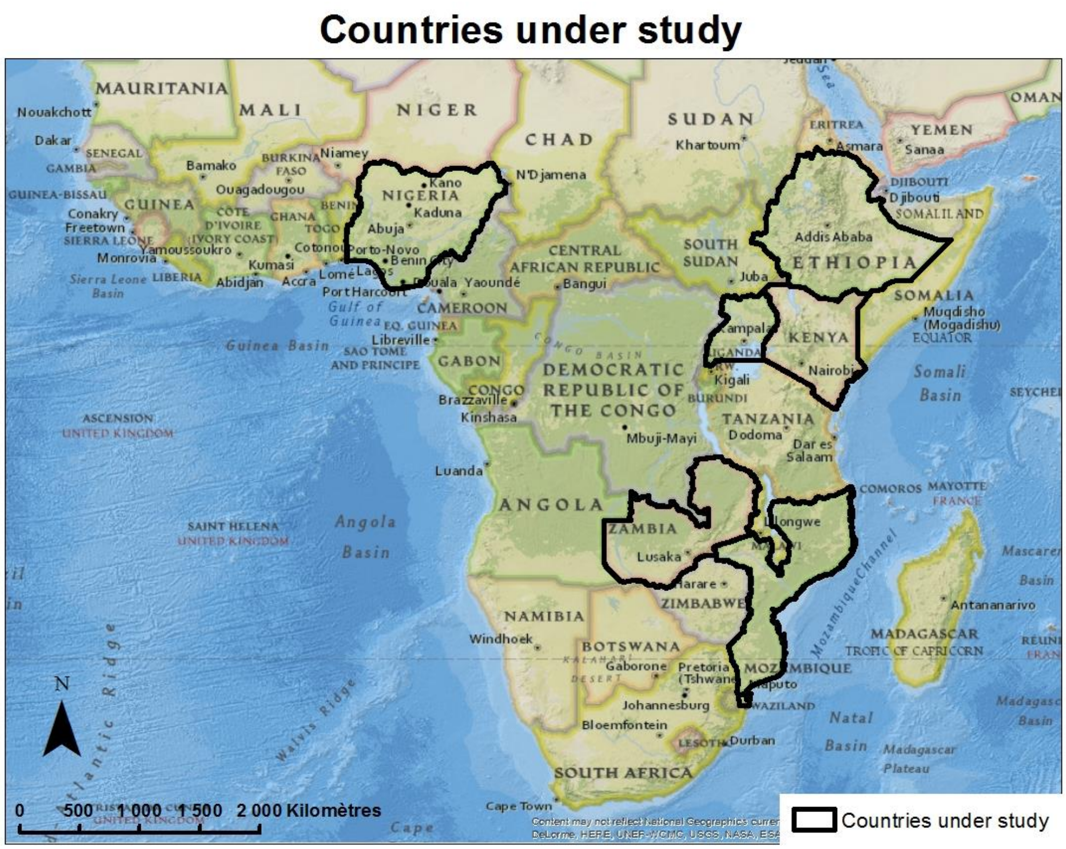


FIGURE 9: COUNTRIES UNDER STUDY

The goal of the study is to assess and map water limited potential yields (Yw) under current management according to both the bottom up approach and the top-down approach. The effect of a range of sowing dates and maturity types on the Yw determined for the top-down approach will allow the assessment of best crop management inputs. To achieve these objectives, the SSM model was used to run simulations on a range of agronomic situations, geographically referenced. The ability of the model to simulate adequately Yw over the entire range of situations had to be assessed beforehand. Water-limited yield potential (Yw) is the yield of a crop cultivar when nutrients are non-limiting and biotic stress effectively controlled (Van Ittersum and Rabbinge 1997).

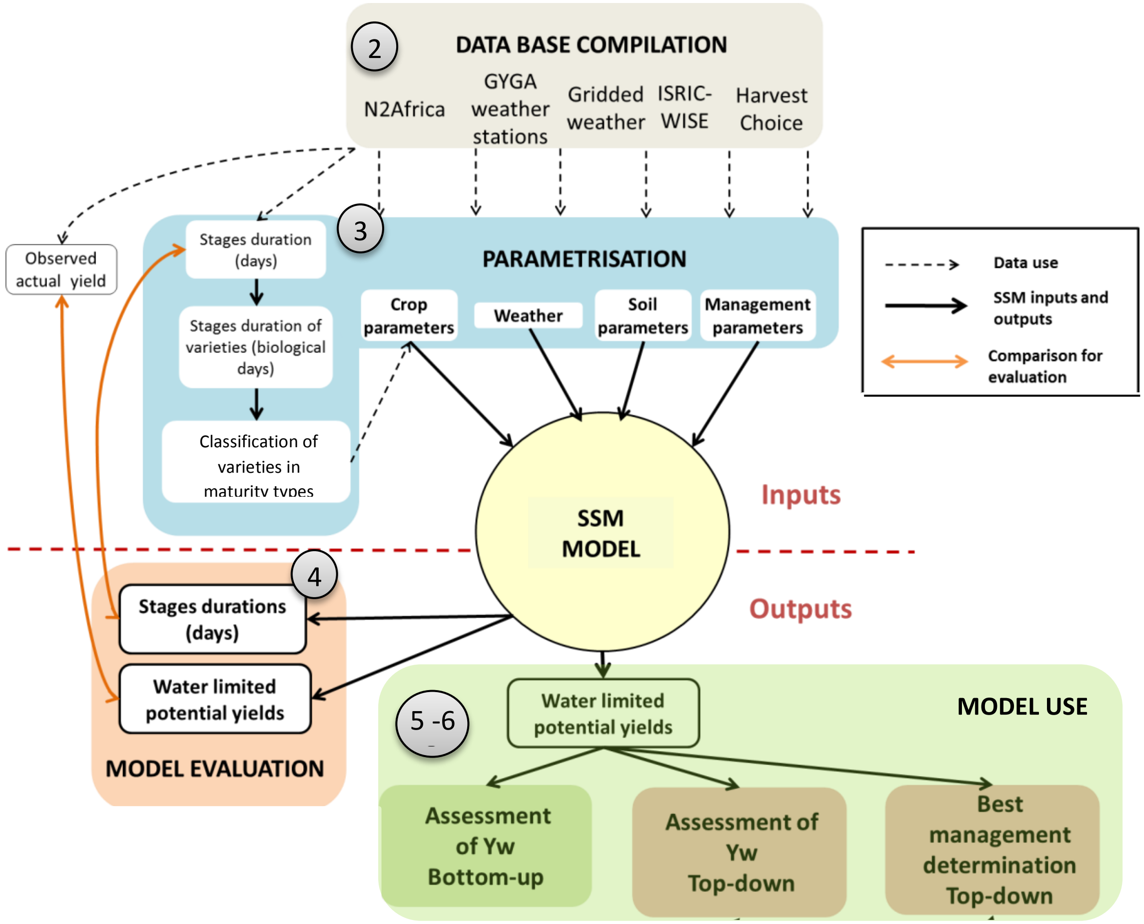


FIGURE 10: GENERAL APPROACH OF THE STUDY

The modelling study relies on an important work of data collection as required to parametrize the model for each location, and to evaluate it. Parameters have to be determined per each location and agronomic situation. Model inputs can be classified according to four types: Weather, soil, crop and management. Weather data are daily entry variable for the model while the three other types of inputs contain only fixed parameters. Soil parameters are mostly used to characterize the water balance. Management parameters reproduce mainly the sowing date and the sowing density. Crop parameters are composed of phenological parameters, physiological parameters, and crop reaction to stress parameters. Weather inputs, soil parameters and management (including variety choice) are likely to vary between each location. Regarding crop, the hypothesis that phenology is the main difference between cultivars had been made. Thus, maturity groups have been simulated rather than actual cultivar. All parameters, except phenological parameters, were kept the same for all maturity groups.

Different source of data were mobilized at each step of the modeling pathway. Accuracy of parametrization was adapted to spatial scale and objectives. For example information on management practices come from local data in the case of model evaluation. For the assessments of Yw under actual management, this information comes from literature and discussions with local agronomists because the spatial scale is wider. In order to facilitate the work of detailing which source is used for which topic, the next part presents an inventory of available dataset, presented by class of input. The availability of good quality dataset is an important determinant to the choice of countries under study.

2 Data source and data base inventory

A Data bases

The SSM model required climatic data that include daily values for minimum temperature, maximum temperature, precipitation and solar radiation. Two types of weather data were used in this study: actual records from weather stations from the GYGA database and daily generated weather data at 1° x 1° based on National Center for Environmental prediction (NCEP) and National Center for Atmospheric Research (NCAR) (Uppala, Kållberg et al. 2005; Dee, Uppala et al. 2011; Sinclair, Marrou et al. 2014). Records from actual weather stations were used for model evaluation (**Part II.4**), Yw assessment according to the bottom-up approach (**Part II.5**) and for the characterization of stages duration of maturity types in biological days (**Part II.3.A**). Matching a location with a suitable weather station is another crucial step on the pathway to map Yw with the bottom-up approach: climate can vary at very small spatial scales and approximation on the location of data measurement can be responsible for significant modelling uncertainties. The generated weather data were used for the assessment of both Yw and best management practices according to the top-down approach.

All simulations were run after parametrizing soil in SSM according to the ISRIC-WISE database. The ISRIC-WISE data base contains soil description on 5 by 5 arc minute global grid (Batjes 2006), and informations on the composition and properties of the different soil horizons are reported. The quality of this database could be considered as being medium to low. However, this dataset is adapted to SSM model simulations as all the soil parameters could be defined thanks directly or by mean of simple calculations from the variables stored in the dataset. This database is commonly used in modelling study using equivalent crop model (Gijsman, Thornton et al. 2007).

B Experimental database

The experimental data used in the study come from many sources. An important work of harmonization and data selection has been necessary before use. Data collected on field experiments in Africa are used for two purposes: the characterization of maturity types stages durations (**Part II.3.A**), and the model evaluation (**Part II.4**). The minimal information that had to be available for an experiment to be eligible for use in the modeling is listed in the chart 3.

CHART 3: MINIMAL INFORMATION NEEDED IN EXPERIMENTAL DATABASE FOR MODEL EVALUATION AND MATURITY TYPE CHARACHTERIZATION

Model evaluation	Maturity type characterization
Location	
Weather station	
Soybean variety	
Sowing date	
Plant density	
Stage duration in days (whatever stage duration)	Stages durations in days (SOW, EM, R1, R3, R5, R7)
Actual yield	

C Information on crop management

In the phase of model evaluation, the data for management parameterization (sowing date, plant density and varieties) come from cropping conditions in the corresponding experiment. For mapping Yw, management information had to be collected over the entire countries. In order to do so, two combined sources of information were carried out. The first source, which is recommended by the GYGA protocol, consists in a survey from N2Africa coordinators in order to determine the main practices in the region under study. The second one is based on average management as published in the literature. This second option is activated when the first one is not possible. Management information for the top down approach was interpolated from the description of management as collected for the bottom up approach (**Part II.5.B**).

E Summary of used datasets

As reported above, data availability is the main limiting factor to carry comprehensive modelling studies in Africa. **The chart 4** summarize the step in the methodology that could be achieved (green) or not (red) for each country.

CHART 4: COUNTRY SELECTED ACCORDING TO EACH STEP OF THE METHODOLOGY

Country	Maturity group definition	Model evaluation	Yw assessment bottom-up	Top-down
Ethiopia	Missing Observed stages durations	Missing Observed yields		
Kenya				
Mozambique	Missing Climatic data		Climatic data < 10 years	Missing Gridded climatic data
Nigeria				
Uganda	Missing Observed stages durations	Missing Observed yields		
Zambia	Missing Observed stages durations	Missing Observed yields		Missing Gridded climatic data

3 General method for model parametrization

A Identification of maturity classes

The identification of maturity classes is an important work as the finality of the study is to assess the effect of a range of different phenology on the potential yield establishment for various African environments. In addition the study is based on the assumption that phenology is the main driver of inter cultivar variations. Being able to cluster varieties into groups with identical phenologies is thus crucial. Various local classifications exist in Africa and were provided in the available dataset. An important number of Tgx varieties were referenced by the International Institute of Tropical Agriculture (IITA) (Tefera 2011) thanks to a classification made in the Guinea savanna of Nigeria. The seed co varieties were classified in Zimbabwe.

Local classifications of maturity type are used by farmers and breeders in each country. However, these classifications are based on stage durations in days. Since they have been defined from observations in small geographic areas, for a given temperature and photoperiod, they cannot be extended to other country. Indeed, a same variety can be classified as “medium” type in Central Kenya, and “early” type in Western Kenya or in Nigeria. New maturity classifications were established in this study, based on stages durations in biological days. Two classifications were performed, one for East Africa and another for West Africa, using the following protocol

1. Determination of stage duration in biological days, combining phenological stage observation as reported in day and local climate records.

2. Classification of varieties into maturity class on the basis of stages durations in thermal units. Three classes are constructed, late, medium and early varieties. The final stage duration of a class is the average stage duration of each variety belonging to this class. Each class is characterized by a set of durations in biological days: Sowing to Emergence (dtEM), Emergence to R1 (dtR1), R1 to R3 (dtR3), R3 to R5 (dtR5) and R5 to R7 (dtR7).

3. Consistency check of the new variety classification versus the local ones. It was verified that no variety jump from early to late class (or the opposite) between the local and the new classification, and the re-classification rather resulted in drift of variety from one maturity class to the next one.

Among the available experimental datasets, only the ones that recorded both sowing dates and stage duration in days were selected. After the selection of experiments, only two countries could be analyzed: Nigeria and Kenya.

Kenyan Experiments

Kenyan experiments were located in Butere, Butula, Gem, Kisumu west and Rarieda. Nearly all stages are referenced expect the seed filling stage which is difficult to record. The weather stations linked to the sites were referenced thanks to proximity rules and advices from local experts. The types of varieties used for these experiments were mostly Tgx varieties, Seed co varieties, Kari varieties and Makere varieties for a total of ten varieties used for maturity class building.

As no information on the R5 stage was available, it has been necessary to estimate this stage. According to expert knowledge and field observations, the duration from R3 to R5 was set at 3 biological days.

The **Figure 11** show the cumulative biological days at each crop stage for the three maturity types. As expected, the “Late” type had a longer cycle in average than the “Early” and “Medium” types. Early and Medium type had nearly the same duration from sowing to flowering, but the duration of seed growth (from R5 to R7) was longer for medium type than from the early type. The late type had both a vegetative phase and a reproductive phase longer than the early type.

The standard deviation calculated for the duration of each stage within the “Late” type never exceeded 3 biological days (***Appendix 2)***: the group was considered to be homogenous. For medium and early maturity types, standard deviations were higher and could go up to 10 biological days for the duration from R1 to R3 stage. However, it was observed that for a same variety (e.g. Tgx 1740-2F), calculation of the duration of phenological stages in biological days using data from different experiments could lead to a variation of up to 10 biological days, for the sowing to podding stage. This uncertainty on the estimation of the duration of phenological days can be caused by several approximations: the difference in appreciation of phenological stage by different experimentators, or the difficulty to note the exact date of occurrence of a stage.

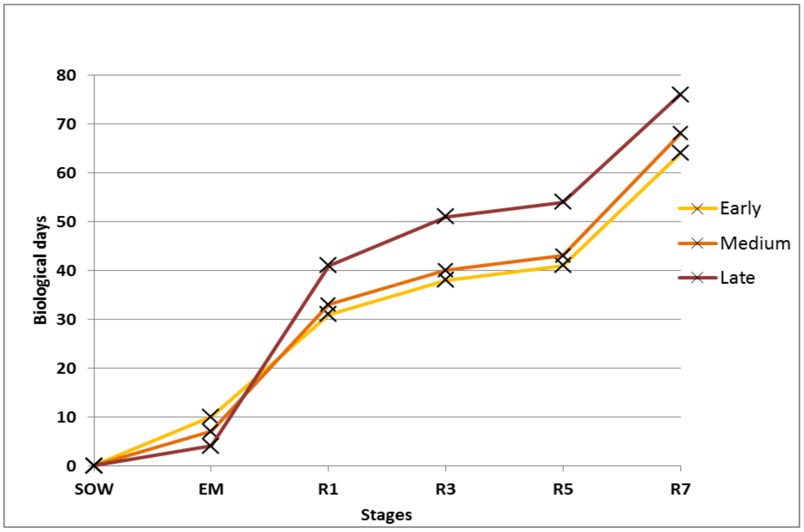


FIGURE 11: CUMULATIVE BIOLOGICAL DAYS AT EACH CROP STAGE FOR KENYAN MATURITY TYPES

Nigerian experiments

Nigeria experiments were located in Ibadan, Kano, Mokwa and Zaria. The types of varieties used were Tgx. Only two stages (Flowering – R1, and Maturity- R7) were recorded which were flowering and maturity. Characterization of maturity type in Kenya was used to estimate the duration of missing intermediary phenological stage. Duration from sowing to emergence was considered to be the same for all maturity types in Nigeria, and set equal to the duration from sowing to emergence, averaged over the three maturity types as defined in Kenya. The duration from R1 to R3 was also supposed to be equal to 10 biological days for all maturity types. This 10 day duration corresponded to the average duration of R3-R5 phase, as observed in Kenya, in average for all maturity types. R5 was supposed to occur 5 biological days after R3, as for Kenya.

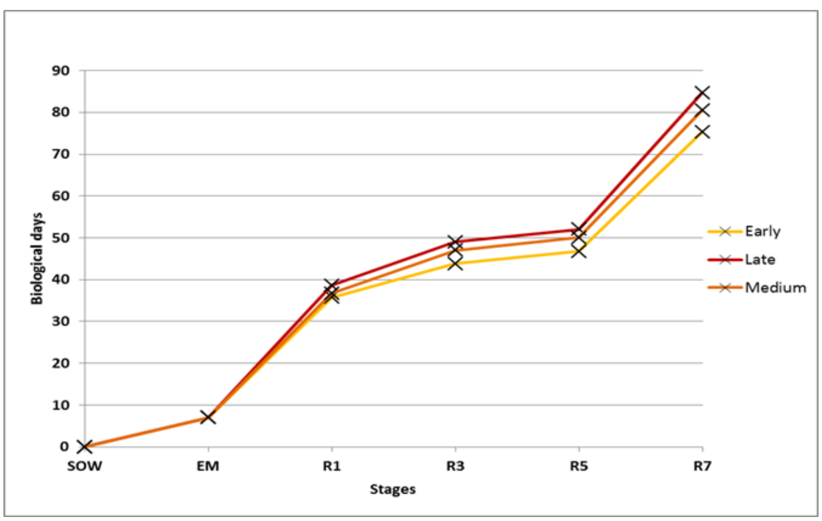


FIGURE 12: CUMULATIVE BIOLOGICAL DAYS AT EACH CROP STAGE FOR NIGERIAN MATURITY TYPES

Finally, the difference between maturity types results mostly from the duration of the seed filling phase (**Figure 12**). Maturity was reached at 75 biological days after sowing for early type, 81 for medium and 85 for late. The standard deviations (***Appendix 3***) for observed stages within each maturity group were always less than 5 biological days despite the large number of varieties clustered within each maturity group.

B Soil parameters

The same method was used to estimate soil parameters for all the simulations performed along this study. The data used for soil parametrization is the ISRIC-WISE database: this data base provides soil description for each cell on a 5 by 5 arc minute global grid (Batjes 2006). Each cell of the data base contains different soil types with their respective proportions. Each soil type is composed of five 20 cm thick layer. These layers are the minimal units of the dataset. Determining parameters value for SSM simulation, required to aggregate descriptors of different layers and different soil types, according to the location to be simulated. Each location to be simulated was assigned to a WISE cell. The average value of soil parameters for this cell was calculated from the weighed means of the soil characteristics as recorded for each soil type within this cell. The calculation of soil parameters from this dataset is adapted from the work of Gijsman and Thornton (Gijsman, Thornton et al. 2007).

Drainage factor

Drainage class were qualitatively recorded in the Wise database and scored with a 7 class scale, ranking from very poorly drained to excessively drained. These qualitative classes were converted into numeric drainage factors value, using the correspondence table established in (Ritchie, Godwin et al. 1989)

Runoff Curve number

In (Ritchie, Godwin et al. 1989) soils were classified by slope and hydrological groups in order to define runoffs classes. The slopes have not been taken into account in this study by lack of information on this characteristic of soils. Hydrological groups were defined by Ritchie according to the texture of the soil layer as well as depth of the soil as recorded in the Wise database. The textural class of each soil layer had to be determined from percentage of sand, silt and clay as recorded, by use of a textural triangle. This treatment was automated through an excel macro because of the number of soil type to be described. Finally, each cell of the WISE data base was assigned a run-off class and a Curve Number.

Soil water holding capacity

Soil water content at saturation and drainage upper limit, as well as soil water holding capacity were estimated from soil texture, following the methods described in (Ritchie, Gerakis et al. 1999; Soltani 2012).

C Initialization

Initialization of the model for model evaluation and for calculation of Yw using the bottom up approach was performed using the following methodology:

Defining soil water content before sowing in order to initialize the simulation is important and impact strongly the simulation results. It is most of the time very difficult to access precise information on soil water content at sowing date. However, it is possible to find a date, before sowing were soil can be reasonably estimated to be dry , or filled with water up to the drainage upper limit. Then the water balance of the model is run until sowing date to determine soil conditions at sowing. The limit of this method is that the model considers a bare soil before sowing. We considered that the maximal fallow duration between two crops in the tropics was around 4 months. It is thus dangerous to begin the initiation outside this window as the soil water balance could be highly influenced by the previous crop.

Soybean is sown at the beginning of the rainy season in Africa. Thus, it gets to be very dry in the four last month of dry season before soybean sowing in lots of countries under study. For each location, monthly precipitations were calculated (averaged over 30 years). If there was a dry month (less than 50 mm of rainfall), within the four month period before sowing date, the simulation was initialized on the last day on this month, with a dry soil. When no dry month was found in the four month period, very wet (more than 100 mm/month) months were looked for in the same period. If such a month was found, the simulation was started on the last day of this month, and the soil water level was considered to be at 90% of the total extractable water capacity. For a few location were none of the two situation above applied, the simulation was started 2 months before sowing date with a hall full soil extractable water capacity.

In the case of the top-down approach, too many initiations were needed to set specific initiation for each simulation. A unique initialization was set for all the locations: simulation was started 60 days before the sowing date with a soil water level of 10% of the total extractable water capacity.

4 Model evaluation

The model evaluation consists in the comparison between simulated yields and observed yields as well as simulated phenological stages durations in days with the observed phenological stages. In order to run these comparisons, an important set of experimental data is needed. This set should include results of observed yield and phenological stages as well as information on experimental conditions.

A Units of the evaluation

Experimental unit

We call experimental unit the smallest physical unit that correspond to one agronomic situation in the field. Most of the time, it is a field plot corresponding to one repetition, for one modality of the factors tested in the experiment.

In Kenyan datasets, information on experimental conditions was extensive and complete. Most of the experimental units present information on the type of potassium treatment and on the inoculation of soybean. The experimental unit for Kenyan experiments could be described as follow: “**Location X Maturity type X Sowing date X Density X Treatment X Inoculation x Repetition”.**

In the case of Nigeria and Mozambique, experimental units were described more roughly than in Kenya. No information is available on treatment and inoculation and sometimes density was also missing and was estimated to a fix averaged value based on experiments. In these countries, experimental units can be described as follow:

Location X Maturity type X Sowing date x Repetition

Simulation unit

A simulation unit is the model translation of an actual experimental unit. Since the model cannot describe all management choices, simulation units are less refined than experimental units. The simulation unit that can be modeled with SSM is summarized as follow**: "Location X Maturity type X Sowing date X Density"**. Thus, a simulation unit, defined by a unique set of parameters and entry variables (climate) can represent different experimental units.

The location of the experimental site allows to immediately identify the corresponding cell in the WISE data base and to determine soil. Weather inputs were provided by weather station located on site or within a short distance (**Appendix 4**). As far as variety name was available in the experimental records, it was possible to determine the corresponding maturity class thanks to the classification work done previously (**Part II.3.A**). Sowing dates and density parameters were also provided in the experimental description.

Some of the experimental data used for the model evaluation had been already used to build maturity classes (**Part II.3.A**). A particular attention was paid to the variation of quality of the model when comparing simulations with observed data from dataset that were used to define maturity group or not. The **chart 5** below describes the composition of the dataset.

CHART 5: COMPOSITION OF THE DATASET USED FOR MODEL EVALUATION

	Experimental units	Total repetitions	Number of repetitions used for maturity type assessment	Number of experimental units used for maturity type assessment
NIG	54	3006	3006	54
KEN	55	788	351	39
MOZ	12	366	0	0

B Quality indicators

During the evaluation phase, simulation were run with the SSM model to observe whether water limited yield simulated on each simulation unit matched the average yield observed on the corresponding experimental units. However, in most of the cases, the experiments were run in local farmers fields, with little control on nutrient limitation as well as biotic stress. Thus, observed yields on experimental units are expected to be equal or lower than simulated yields on the corresponding simulated unit, and evaluation criteria have to be revised according to this. The two performances listed below are expected to validate partially the ability of the model to reproduce water limited yields for soybean in Africa.

- The model should predict Yw values equal or greater than the values of actual yield of their respective experiments.
- The model should simulate properly phenological stages durations in days.

Ideally, only experimental situation where cropping conditions exclude any limiting factor, except rainfall, would have been used for this evaluation step. However, there is virtually no information on pest and disease level or soil nutrient content in the different experiments.

To cope with this lack of information and with poor growing conditions in Africa, a more elaborated methodology for model assessment was developed. For each experimental unit (characterized by its water availability calculated as the sum of rainfall all along the crop cycle and the initial soil water content), the corresponding Yw was estimated using the Yw envelop curve. First, this envelop curve was determined by fitting a log regression to the "highest" points in the graph obtain when plotting observed yields vs. water availability. "Highest" points were selected using the method described in (Shatar and

McBratney 2004) (**Figure 13**). Second, the theoretical value of Yw corresponding to each observed yield was read on the curve: it is the orthogonal projection of this point on the envelop curve. This method relies on the assumption that a minimum of points on the graph correspond to situation where water is actually the only limited factor. If this was not the case, the shape of the cloud of point would not show any yield increase when the water availability increase, and maximum observed yield would remain very low.

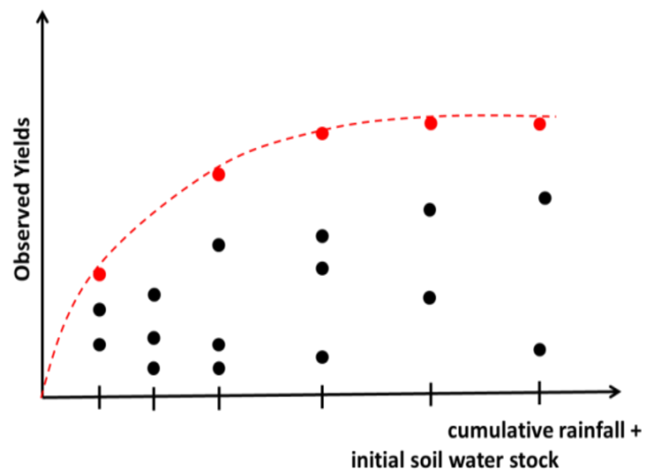


FIGURE 13: SELECTION OF THE "HIGHEST" POINTS AND ENVELOPE CURVE DETERMINATION FOR MODEL EVALUATION

The estimation of Yw value was calculated for each observed amount of available water. These results were then compared with simulated yields. The difference between simulated and estimated Yw values would represent the model error. Conversely, the difference between actual observed yield and estimated Yw represent the error due to poor experimental conditions (**Figure 14**).

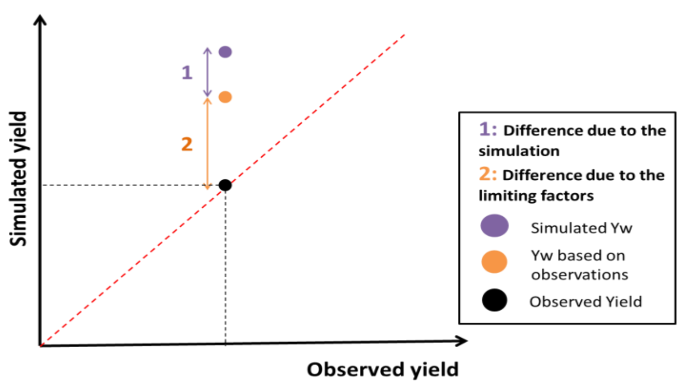


FIGURE 14: REPRESENTATION OF THE ERRORS FOR MODEL EVALUATION

5 Bottom up approach for Yw assessment

According to the GYGA protocol, Yw assessment is performed in three steps: choice of representative locations to be simulated, simulations, and results upscaling (van Bussel, Grassini et al. 2015). Indeed, with the bottom up approach, estimates of Yw at large scale emerge from the upscaling of estimation at smaller scale. In the GYGA methodologies, simulations are performed at the weather station level and Yw are then up-scaled at the climate zonation level and finally country level.

A Spatial unit in the GYGA methodology

The choice of locations to be simulated is closely linked to the repartition of soybean rainfed harvested area. In order to determine this area, a cropping area map provided by Harvest Choice was used. This map, composed of 5 arc-minutes grid cells was elaborated thanks to the Spatial Production Allocation Model (SPAM) (HarvestChoice 2014) for data of 2005. For each cell of the map, the value of the corresponding harvested area is provided.

The climate zonation used is The Global Yield Gap Atlas Climate Zones (GYGA-CZs). It is defined on three categorical variables: Annual global degree days (1), temperature seasonality (2) and aridity index (3). This method resulted in reasonable climate homogeneity within the zones (van Wart, van Bussel et al. 2013). We used the world wide climate zone map from the GYGA project, cropped to the countries considered in this study. Thanks to the spatial join function in ArcGis, the two maps (cropping area and climate zone) were overlapped and intersected. Cells of harvested area were linked to a climate zone if their center fell within the climate zone. The cropping area within each climate zones was calculated by doing the sum of the harvested area of each cell linked to this climate zone. In order to reduce the number of simulations, only climate zones that contained more than 5% of the national harvest area were kept for the rest of the study.

Weather stations

Selection

Each climate zone has to be characterized by a sufficient but minimal number of weather stations. The selection of weather station was operated for each climate zone in each country of interest following the GYGA methodology from the entire list of weather station referenced in the GYGA data base. The quality of the weather station (no missing daily records, no missing variable) is a first criteria to discriminate stations. Weather stations which records have been completed with interpolated values were considered as second choice. Only weather stations situated in previously selected climate zones were to be selected. A 100km circular buffer zone was built around each of these stations. This buffer zone was cropped to the limit of the climate zone in which the weather station was situated when necessary. The area within this buffer zone was considered to be under the influence of climatic conditions described by the weather station. If this weather station was covering a soybean area that represent more than one percent of the national area, the buffer zone was selected for further simulations. Then weather stations were selected successively, starting with the ones that had larger buffer zones, and avoiding to pick weather stations that were less than 180 km apart from each other (to avoid overlapping and redundancy of information). If the total area covered by selected buffer zones of a country did not reach 50% of the national soybean area, new hypothetical stations had to be created in the zones of interest according to the GYGA protocol. However the creation of hypothetical stations is a long process and requires a precise methodology that was not undertaken in this study. As an alternative, stations that covered only 1 to 5% of the harvested area were also picked to increase the total coverage of the production area. Finally, optimal localization for hypothetical stations was assessed and provided to the partners of the global yield gap atlas team.

Number of years

Each weather file contains climatic information for a particular number of years. The minimum number of year needed is ten years. Weather records have to be anterior to 2009. All the weather files used in this work meet the minimum quality feature needed according to the GYGA methodology.

Choice of soil to be simulated

According to GYGA methodology, the map of WISE soil is intersected with the buffer zones of each selected weather station. The percentage of the buffer zone covered by each soil unit was calculated. Only soil units that were covering more than ten percent of the buffer zone area were selected for each buffer zone. This allowed a reduction of the number of simulations.

Final selection

CHART 6: HARVESTED AREA COVERED BY SELECTED BUFFER ZONES

Country	Harvested area of the country (ha)	Percentage of harvested area covered by buffer zones	Number of buffer zones
Ethiopia	3996	62%	7
Kenya	2938	72%	2
Nigeria	605752	34%	13
Uganda	144294	89%	4
Zambia	38221	36%	6

In Uganda, the buffer zone around Lira station represented 68% of soybean harvested area of the country. In Kenya, the buffer zone around Kakamega station represented 67% percent of soybean harvested area of the country. These two stations had a great impact on final results by country. In Ethiopia, the repartition of coverage percentage between weather stations is more uniform and there is no stations covering more than18% coverage. Buffer zones of Nigeria and Zambia altogether covered only respectively 34 and 36% of the total countries harvested area. Thus, virtual weather stations needed to be created in the zones of interest for these two countries. A prospective work to assess the optimal position of virtual stations was done and transmitted to the GYGA team but no hypothetical stations were to be built during this study.

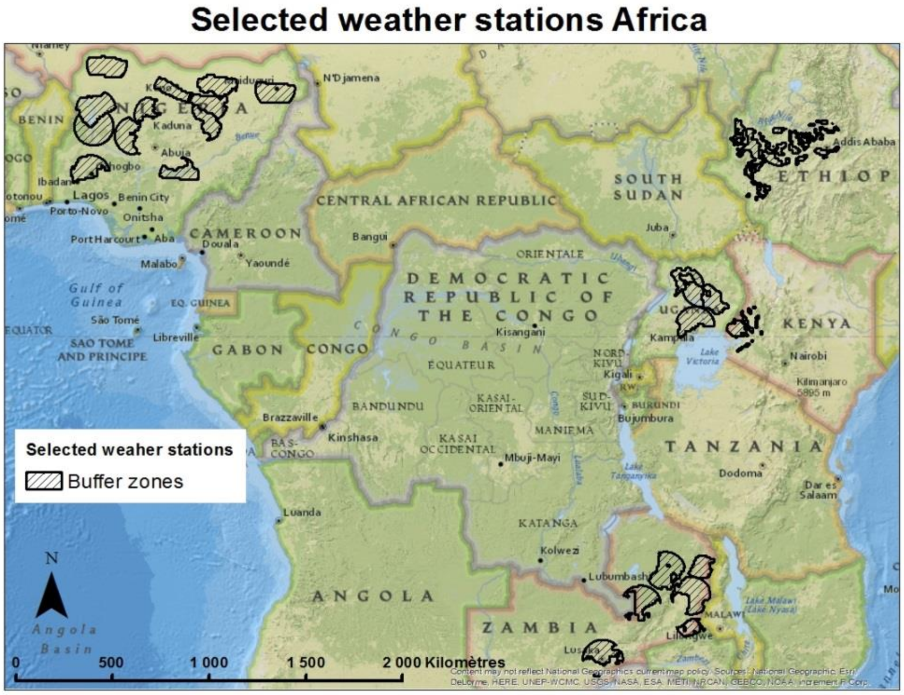


FIGURE 15: SELECTED WEATHER STATIONS IN COUNRTIES UNDER STUDY

B Determination of crop and management parameters for the simulations

The definition of management practices was based on bibliography as well as on discussion with country coordinators of N2Africa. This parametrization was done for all the buffer zones under study. Most frequently, only one cropping system (defined as the combination of sowing date, maturity group, and sowing density) was identified per buffer zone.

Sowing date

Sowing windows were determined for each buffer under study. The middle of every sowing window recorded in the literature or reported by experts was taken as the exact sowing date to run simulations. According to literature, sowing had to occur at the beginning of a rainy season (Dugje, Omoigui et al. 2009). Therefore, in the case of Kenya and Uganda where there are two rainy seasons per year, two sowing windows had to be determined.

Ethiopia: There was only one cropping season. The determination of sowing windows was based on discussion with N2Africa country coordinators (**Appendix 5**). The country was divided in three management zones, western Ethiopia, north-western Ethiopia and the rest of the country where soybean is not sown. Each management zone was assigned with one major window. Buffer zones were assigned the sowing window of the management zone in which they are located.

- **Nigeria:** There was only one cropping season. The determination of sowing window is based on literature (Dugje, Omoigui et al. 2009). The country is divided in four management zones, Sudan savanna, North Guinean savanna, south Guinean savanna and the forest zone where no soybean is grown. As for Ethiopia, each buffer zone is simulated with the sowing date of the management zone in which they are located.

- **Zambia:** There was only one cropping season. The determination is based on literature (G.Kananji 2013) for the whole country.

- **Kenya:** There was two cropping seasons per year. The determination of sowing date was based on discussion with N2Africa country coordinators (Appendix 6). The percentage of soybean production corresponding to each cropping season was also estimated according to local experts.

- **Uganda:** Two seasons are recorded. The determination is based on results from Kenya. The repartition of soybean production between the two sowing windows in Uganda was set to 50% each as no information was available in the literature.

Maturity type

According to technical guides (Dugje, Omoigui et al. 2009) harvesting must be done at the transition period between rainy and dry season, when precipitations are low or nonexistent. A late harvest can results in water stress occurring during the crop cycle and late season pest attacks while an early harvest can result in a low quality of grains due to moisture. As the sowing date is fixed for each buffer zone, the only way to adjust the timing of harvest is to choose an adapted maturity type. For each weather station, the maturity date was estimated for each maturity type by using average weather data (average over years), to calculate biological days. The average daily precipitations during a 20 day period centered on the date of maturity were also calculated. The appropriate maturity type was obtained from two successive selections:

First, among the three possible maturity types, the two maturity types that resulted in the lowest cumulative precipitation during the 20 days around maturity were selected. Second, the pattern of rainfall during the 20 days period around maturity was observed to determine the most appropriate maturity type. Low rainfalls had to occur at the beginning of the 20 days period and harvesting had to take place when no rain was detected. This selection was effective for all the country except Kenya and Uganda where the transition between heavy rainfall and dry climate was not clear. In this case, the maturity type with the lowest amount of precipitation during the 20 day period around maturity was selected.

Density

Density is referenced in technical guides as well as in documents transmitted by N2Africa country coordinators. For the buffer zones where no sowing density was reported, the value was set to 35 plants by hectare, which is the most common sowing density in East Africa. The total set of management parameter for bottom up simulations is reported in **Appendix 7**.

C Upscaling simulation outputs

From Yw per soil units to Yw per buffer zone

Each buffer zone was assigned with a cropping system (maturity group x sowing date x sowing density) spread over different soil units. Average Yw of each cropping system, for a given year was calculated as the weighted average of simulated Yw. The weights represented the percentage of each soil units in the buffer zone under study.

$$Y_{w\ crop\ cyle} = \sum_{i=1}^{n} \frac{Y_{w\ simu\ i} * Soil_{Weight\ i}}{\sum_{i=1}^{n} Soil_{Weight\ i}}$$

A cropping system could not contain two successive soybean cropping cycle. For this reason, in the case of Kenya and Uganda, the two cropping seasons were considered and treated as two cropping systems coexisting within a same buffer zone. In this case, average buffer zone Yw was calculated as the weighted average of Yw in the two cropping systems corresponding to the two cropping season. The weights corresponded to the proportion of the production grown during each cropping season. When this proportion was uncertain, it was fixed at 50%.

From Yw by station to Yw by climate zones

If different stations were contained in the same climate zone the average Yw weighted by the harvested area covered by each buffer zone in the climate zone was calculated.

From Yw by stations to Yw by country

Finally the Yw of the country was determined thanks to the calculation of the weighted mean of Yw calculated by each buffer zone. The weights were related the respective areas of the buffer zones..

6 Top-down approach for Yw and best management practices assessment

A Yw assessment

Weather data

The gridded data are composed of temperature, rainfalls and solar radiations. The cells are defined at 1° x 1° and each cell contains weather data for 30 years, from 1979 to 2009. This data were not available for Nigeria and Zambia.

Management parameters

Management parameters were based on parameters determined in the bottom-up approach. The most represented maturity type and sowing dates in the buffer zones of each country was selected to run the simulations (**Chart 7**).

CHART 7: BASELINE MANAGEMENT PARAMETERS FOR THE TOP-DOWN APPROACH

Country	Geographical zone	Rainy season	Sowing date	Maturity type
Ethiopia	North Western		15-juin	Late
Ethiopia	Western		15-juin	Medium
Kenya		1	01-mars	Medium
Uganda		1	01-mars	Medium
Kenya		2	15-sept	Medium
Uganda		2	15-sept	Medium

Sowing date

The sowing date was not fixed as it was done for the bottom-up simulations. In the current case, a window of 10 days beginning at the specified sowing date was created. A rule was set in the model which specified that sowing was effective only if soil water content was equal or superior to 20 mm in this window. When the soil water did not reach this level, sowing was not possible and the simulation was identified as "non-sown". This rule was set mainly to differentiate management features for the best management practices assessment (**Part II.6.B**). This difference between Yw assessment for the two approaches results in a difficult comparison between the results of the two approaches. This fact is discussed in the **Part IV.2** of the discussion.

Initiation

For all the simulations, the initiation was set at 60 days before the baseline sowing date. The level of water in the soil was set at 10 % of the total transpirable soil water as in most of the situation this date is situated in the dry season. This is another limitation to the top-down approach where the number of units that must be simulated is too important to make a specific initiation possible.

B Best management practices assessment

The management as parameterized above is representative of farmer practices, and was called baseline management. After simulation of the baseline management, a virtual experiment was set up to test the effect of changing maturity type and sowing date on Yw across the countries under study.

Sowing date variation

In the alternative scenario, sowing was still simulated within sowing windows, with the same condition for the model to trigger sowing. The beginning of the sowing windows varied from 30 days before the baseline sowing date to the 30 days after with a step of ten days as presented in the **Figure 16**. In total, 7 sowing windows (including the baseline) were tested. This allowed a large screening of the possible sowing dates around the baseline sowing date.

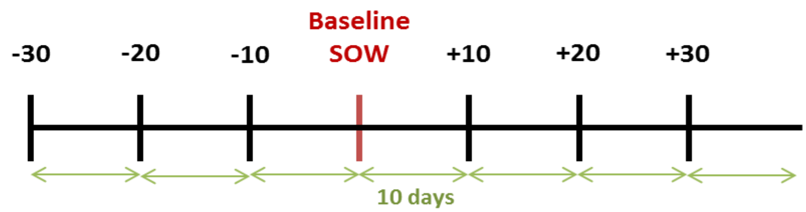


FIGURE 16: RANGE OF ALTERNATIVE SOWING WINDOWS SIMULATED

Maturity variation

The three maturity types determined for East Africa were tested alternatively, with each sowing window.

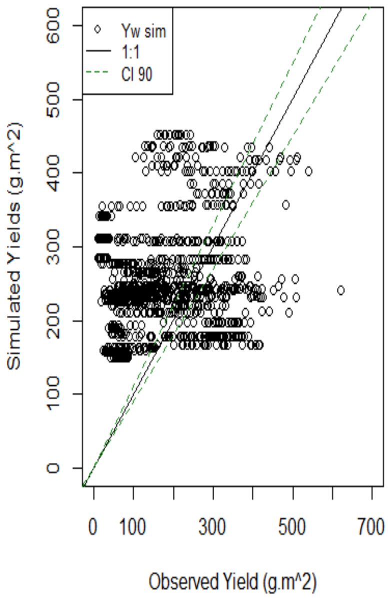
Selection of best management practices

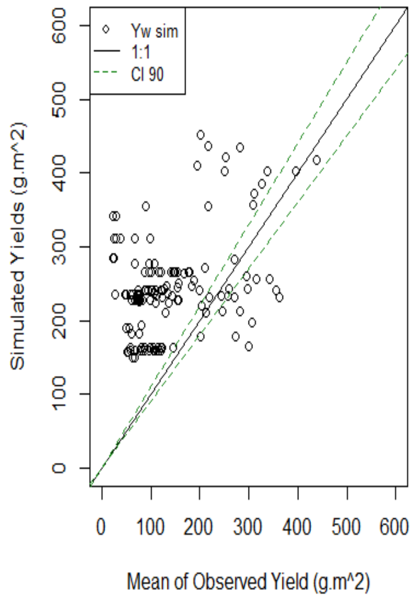
The mean of Yw by year was calculated in order to obtain average results on the 30 years simulated for each management situations. The number of years when sowing was not possible was determined for each management situation of a unit. For each unit, the selection of best management practices was based on two factors, the value of Yw and the number of years when sowing was not possible. Among the results of the 21 potential management situations, only the one showing the fewer years without sowing were selected. Among these results, the ones with the best average yield were selected. The best management was then compared with the baseline management.

III Results

1 Model evaluation

A East Africa





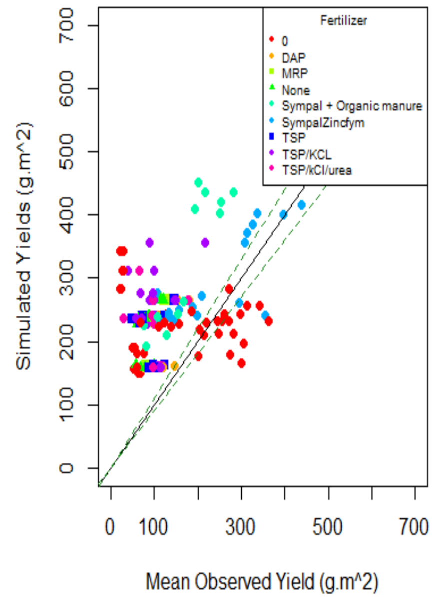
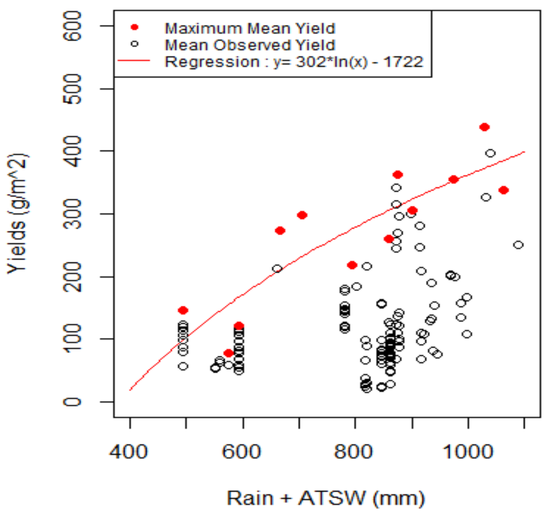


FIGURE 17: SIMULATIONS VS OBSERVATIONS, YIELD, EAST AFRICA
FIGURE 18: SIMULATIONS VS MEAN OF OBSERVATIONS, YIELDS, EAST AFRICA
FIGURE 19: SIMULATIONS VS MEAN OF OBSERVATIONS BY FERTILIZER

The **Figure 17** represents the simulated yield of each simulation unit against the observed yields on the corresponding experimental unit. Simulated yields are mostly greater than observed yields: bias between simulated and observed yield is of +73 (g/m^2). Most of points fall outside the 20% variation interval around the graph bisector. In order to ease the analyses of these results, the mean of observed yields on the experimental units corresponding to a same simulation unit was calculated. On the **figure 18**, simulated yields are compared with the mean of observed yields. Most of the simulated yields are greater or equal to the observed one. This result is coherent with the fact that many experiments may have not been conducted under optimal conditions regarding nutrient supply and pest and diseases control. Still, a majority of points are scattered outside the 20% variation interval around the bisector. Observed yields, averaged by simulation unit, range between 50 and 400 g/m^2 while the simulated yields vary between 150 and 450 g/m2 For most of the experimental observation there was no information on the treatment applied .Therefore it is difficult to interpret the causes for the difference between observed and simulated values. Observations that were better reproduced by the model correspond to experiment where “Sympal Zinc” was applied (**Figure 19**). “Sympal Zinc” is a fertilizer containing phosphorus, calcium, sulfate, potassium and magnesium. It is possible that this treatment, applied on low phosphorus and N soil, allow better N fixation rate, and to reach Yw, provided pest and diseases are controlled.

These results are in favor of an interpretation of the prediction error as the result of the uncertainty of the cropping conditions, rather than from a model structure error.

Model evaluation against re-estimated Yw



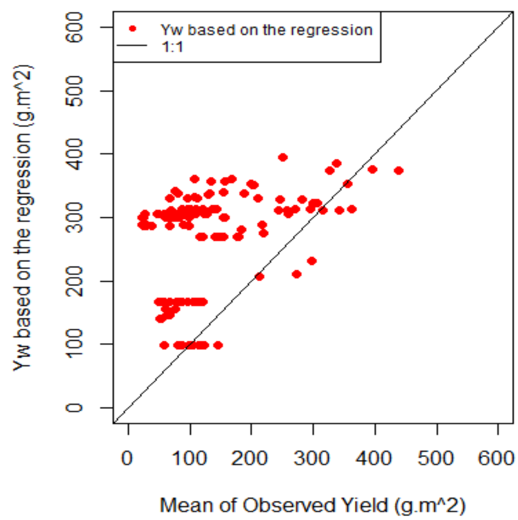
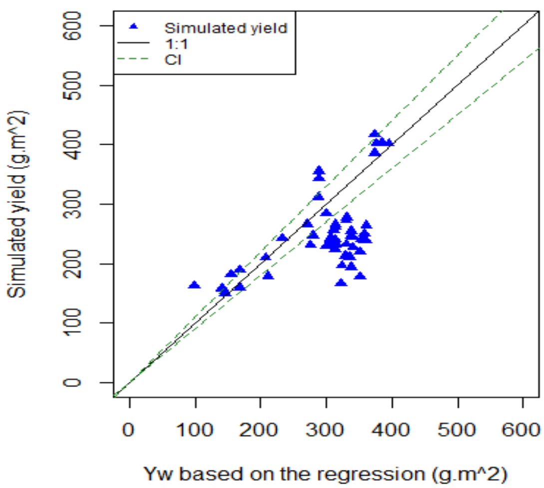


FIGURE 20: HIGHEST POINTS SELECTION AND REGRESSION CURVE

FIGURE 21: CORRECTED OBSERVATIONS VS OBSERVATIONS

The **figure 20** above show the observed yields plotted versus water resource. For each experimental unit, water resource was calculated as the sum of soil water stock at sowing and cumulative rainfall all along the crop cycle. A logarithmic regression was adjusted on the highest points of the point cloud, as detailed in Part II.4.B with a good fitness (R^2=0,73). This regression was assimilated to water limited potential yields. Estimated water limited yield was calculated for each yield observation as the y coordinate of the projection of the corresponding point on the regression curve. Yield correction resulted in higher values of yields (**Figure 21**), which is coherent with the method and the objectives. In average, the difference between estimated Yw yields from observation and actual yields is 138 g/m² which is an important value in comparison with the yield values (between 150 and 500 g/m²).

Model was then reevaluated, by comparing simulated yield with the water limited yield estimated from observed yields. The **figure 22** shows the comparison between simulated yields and water limited potential yields defined on the regression. The bias is -36 g/m² and the RMSE is 55 g/m². The estimated RMSE is moderate in comparison with observed water-limited potential yields that go mostly from 150 to 500 g/m².



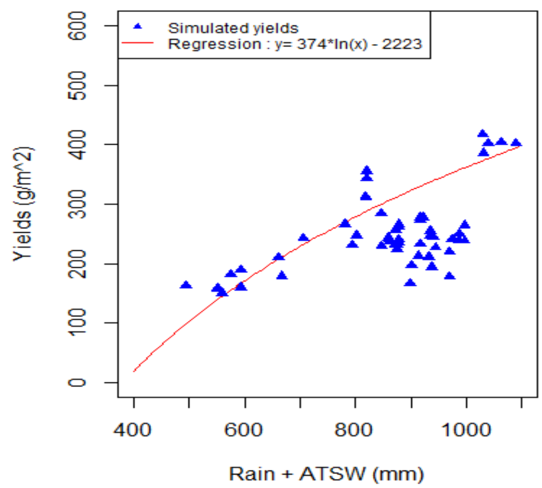


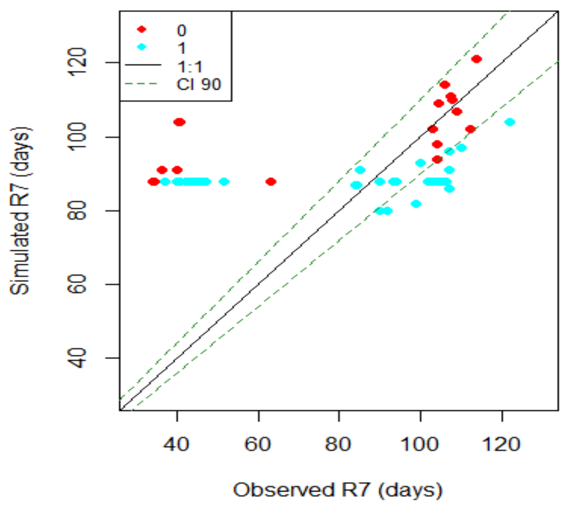
FIGURE 22: SIMULATED YIELDS VS YW DETERMINED ON THE REGRESSION, EAST AFRICA

FIGURE 23: REGRESSION CURVE VS SIMULATED YIELDS, EAST AFRICA

Thus, the quality of the prediction is improved when comparing simulations with estimated Yw, instead of rough observation. However, the model tends now to underestimate water limited potential yields. Plotting simulated yields against water availability (**Figure 23**) bring some insight on the cause of differences between model prediction and estimated Yw. It seems that model underestimate Yw for high water availability. Two hypothesis can be brought to explain this error 1) model structure and parametrization lead to slight underestimation of potential yield, 2) most likely, Yw estimation with the envelop curved method is overestimated for high values of water availability. Indeed a log curve was used to fit the envelop curve. However, log function doesn't have an asymptote, which does not correspond to a production vs resource answer, and can lead to overestimation of Yw for high water availability.

Phenology

The **figure 24** shows simulated values of the maturity stage R7 in days against the mean of observed value. Blue dots represent the data that were used for maturity type definition, while red points represent data from new experiment. Results for other phenological stages (R1 and R3) are quite similar to the ones presented by the figure 24 (**Appendix 8**), but are not presented here as there is more uncertainty on the observed values of these stages. It seems that the model predicts very well the occurrence of flowering and maturity dates, even for experiments that have not been used for the parametrization of maturity type. However, a group of points correspond to a number of situation were the duration of the cycle is significantly overestimated by the model.



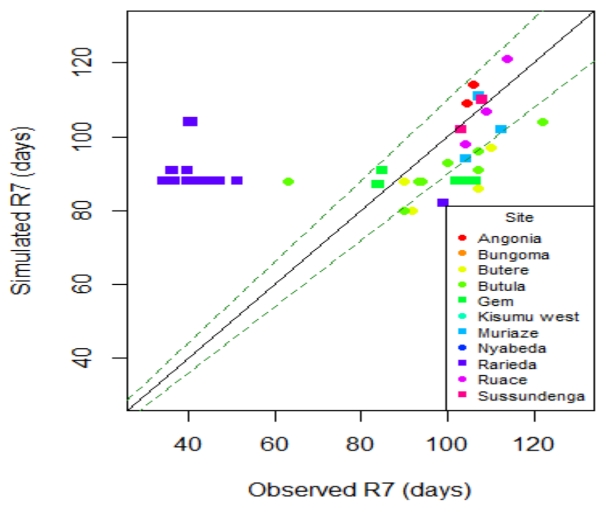


FIGURE 24: SIMULATIONS VS OBSERVATIONS, DURATION FROM SOW TO MATURITY, EAST AFRICA

FIGURE 25: SIMULATIONS VS OBSERVATIONS, DURATION FROM SOW TO MATURITY BY SITE, EAST AFRICA

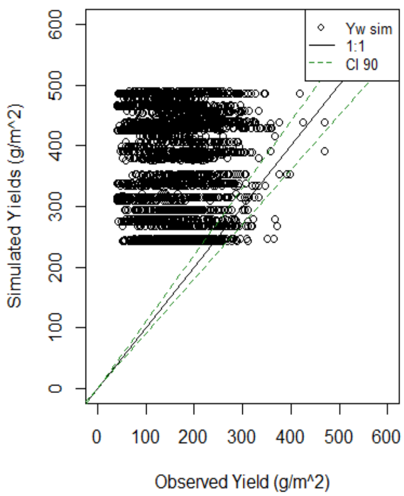
As shown on the **figure 25**, these points all come from the Rarieda site. The observed values for R7 in Rarieda were very low, between 35 and 60 days. The average difference between simulated and observed values was 45 days. The developmental delay between observed and simulated crop development appears between emergence and flowering and grows all along the crop cycle. No stage participates in the error more than other. The difference between observed and simulated does not seem to be the result of a violent stress like water stress that could have shorten the cycle, and that would not be represented by the model, as no violent stressing event could be identified from the climate file and from model simulation outputs. The error could rely in observed data quality: Kisumu weather station was used to determine the weather in Rarieda, although the two sites are quite distant and may have different climate.

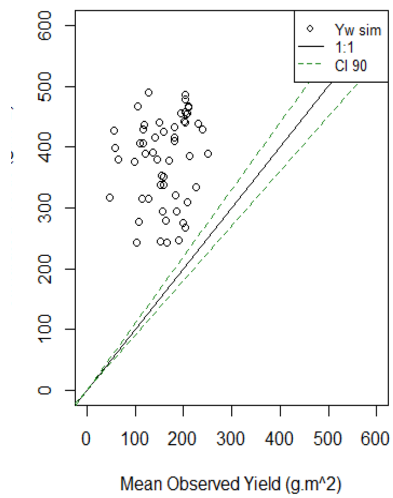
B Nigeria

Simulations against observations

Simulated yields were higher than observed yields for most of the observations (**Figure 26 and 27**). The model bias was 218 g/m².

For Nigeria, it was not possible to go further in model evaluation, using the envelop curve method. Indeed, observed yield are very low, and observations do not present a particular trend **(Figure 28**). Probably, most of the experiments in Nigeria were limited by other factor than water. Thus, the calculation of water use frontier based on observed value was not possible.





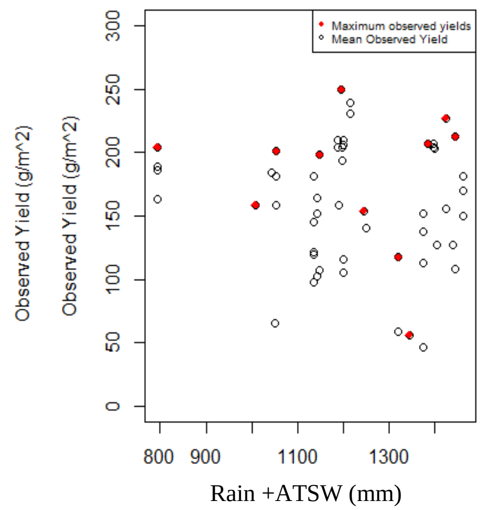


FIGURE 26: SIMULATIONS VS OBSERVATIONS, YIELDS, NIGERIA

FIGURE 27: SIMULATIONS VS MEAN OF OBSERVATIONS, YIELDS, NIGERIA

FIGURE 28: HIGHEST POINTS SEELECTION, YIELDS, NIGERIA

Phenology

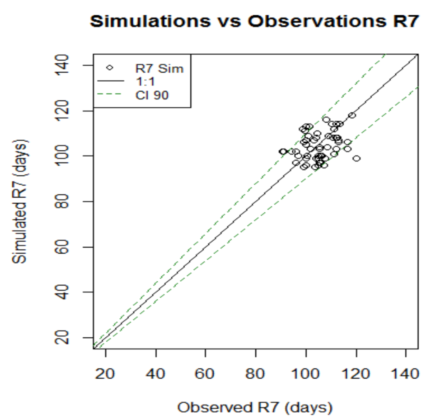


FIGURE 29: SIMULATIONS VS OBSERVATIONS, DURATION FROM SOW TO MATURITY, NIGERIA

Simulation of the crop cycle duration fit the observation (**Figure 29**). Although a very narrow range of cycle duration was explored, it can be concluded that model predicts phenology in Nigeria correctly, with an average error below 20%.

The SSM model is able to reproduce water limited yields and phenological stages for different locations in Eastern and Western Africa. It can be used in order simulate Yw across these countries in Africa. Ideally, experiments were limiting factors other than water are rigorously controlled should be carried out to confirm these results.

2 Yw assessment, bottom-up approach

A Nigeria

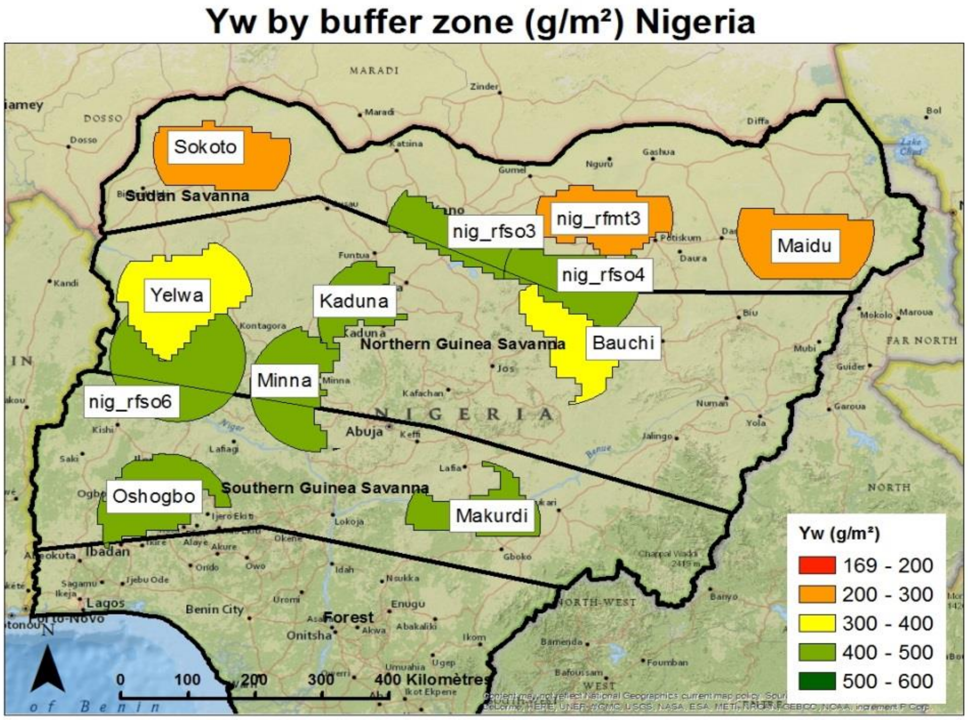


FIGURE 30: MAP OF YW BY BUFFER ZONES, NIGERIA, BOTTOM-UP APPROACH

Yw values in Nigeria range between 222 and 455 g/m² (**Figure 30**). Yields in the Sudan Savanna zone seemed lower than the yields in the Northern Guinea savanna and the Southern Guinea savanna. This North-South gradient on simulated Yw was certainly influenced by the climatic gradient observed in Nigeria. Climate is hot semi-arid in the North and tropical in the South. Indeed, the average daily rainfall during crop cycle were lower in the south Sudan zone (~ 6,5 mm/day) than in both Northern and Southern Guinea savanna (between 7,5 and 9,5 mm/day). However, some stations like Yelwa and Bauchi had lower yields (347 and 372 g/m²) than the ones observed for the other stations of the same geographical zone (~ 430 g/m²). For these two stations, the duration of the crop cycle was the same as in other stations and rainfalls during the crop cycle. In addition both stations were characterized by shallow soils (850 and 730 mm) and low simulated maximum LAI (7,87 and 8,87 mm/mm). It is possible that low water storage capacity in soil lead to water stress at the beginning of the crop cycle, reducing both LAI and yields for these two locations.

B Eastern Africa

Ethiopia

Yw values in Ethiopia range between 322 and 507 g/m² (**Figure 31**). Stations situated in the high plateau of Ethiopia received important rainfalls (7,7 to 9,8 mm/day) and were the ones with the highest yields. For example, the station Eth_rfwt4 was the one that received less rainfall (5,7 mm/day) and the simulated yield were 322 g/m² only. Crop cycle durations were very long, with maturity stage that could occur up to 170 days after the sowing date. This long crop cycle duration was due to the low temperature observed in this region which delayed crop termination. The maximum mean temperature observed in Gore was 19°C while, at the same latitude in Nigeria the minimum mean temperature of the Bauchi station was 21°C. Thus, more time was available for solar radiation interception and as rainfalls persists late in the season (Appendix 9), higher yield could be yields.

Kenya and Uganda

Low Yw were observed for both Kenya and Uganda (**Figure 31**). Rainfalls in Uganda were low to medium (5,8 to 6,2 mm/day). Conversely, in Western Kenya, the rainfalls reached 7,40 mm/day at Kakamega station and 3 mm/day at ken_rfmz1 station. Very low LAI values were simulated in this region, with all the buffer zone except rfmz3 and Namulongue having maximum LAI between 4 and 6 mm/mm. Crop cycle durations for Soroti and Lira were short (~ 89 days) while other stations had medium crop cycle duration (102 to 113 days). Average daily rainfalls in Soroti and Lira are similar to the one observed for other stations of Uganda. Soroti and Lira were the only stations in which no late type was used neither for the first nor the second rainy season.

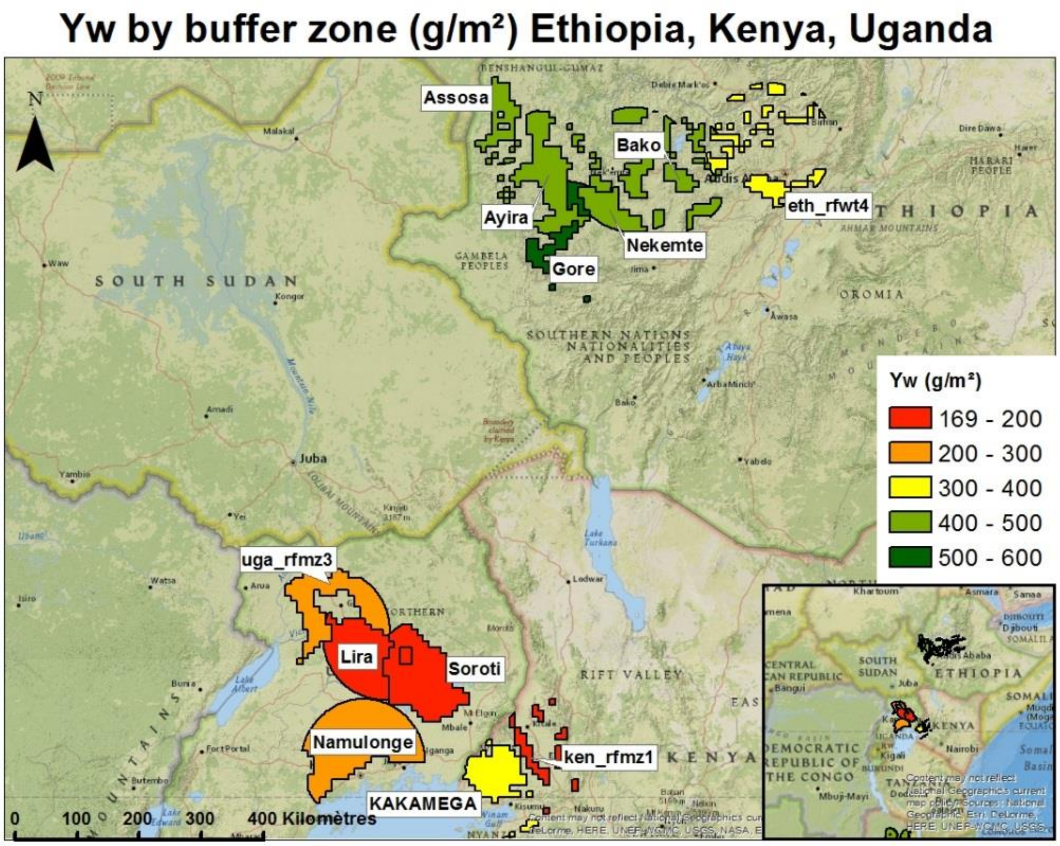


FIGURE 31: MAP OF YW BY BUFFER ZONE, ETHIOPIA, KENYA, UGANDA, BOTTOM-UP APPROACH

Zambia

Yields in Zambia ranged from 277 to 450 g/m² (**Figure 32**). Rainfalls in Lusaka City (6,6 mm/day) were low in comparison with the other stations of Zambia (7,8 to 10,2 mm/day). Chipata station showed the best rainfalls (10,2 mm/day) but also the most important runoff among all the stations (19% of the rainfalls).

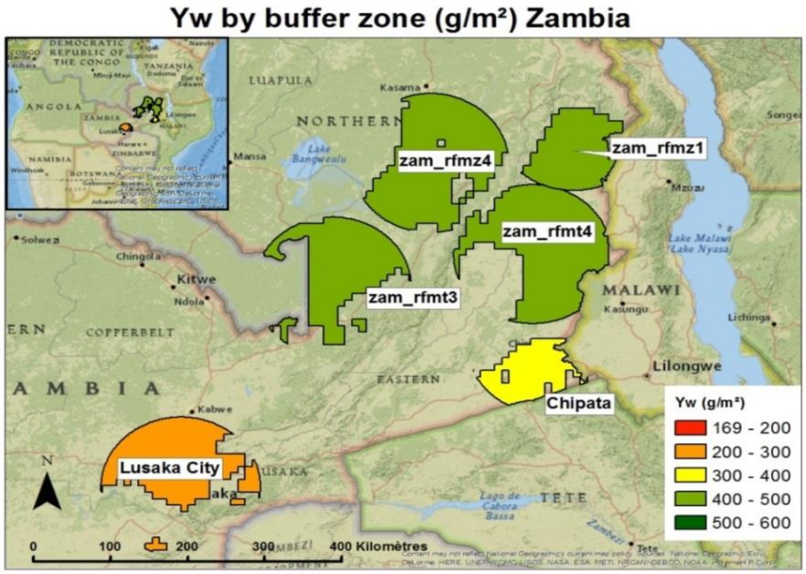


FIGURE 32: MAP OF YW BY BUFFER ZONE, ZAMBIA, BOTTOM-UP APPROACH

D Climate zone

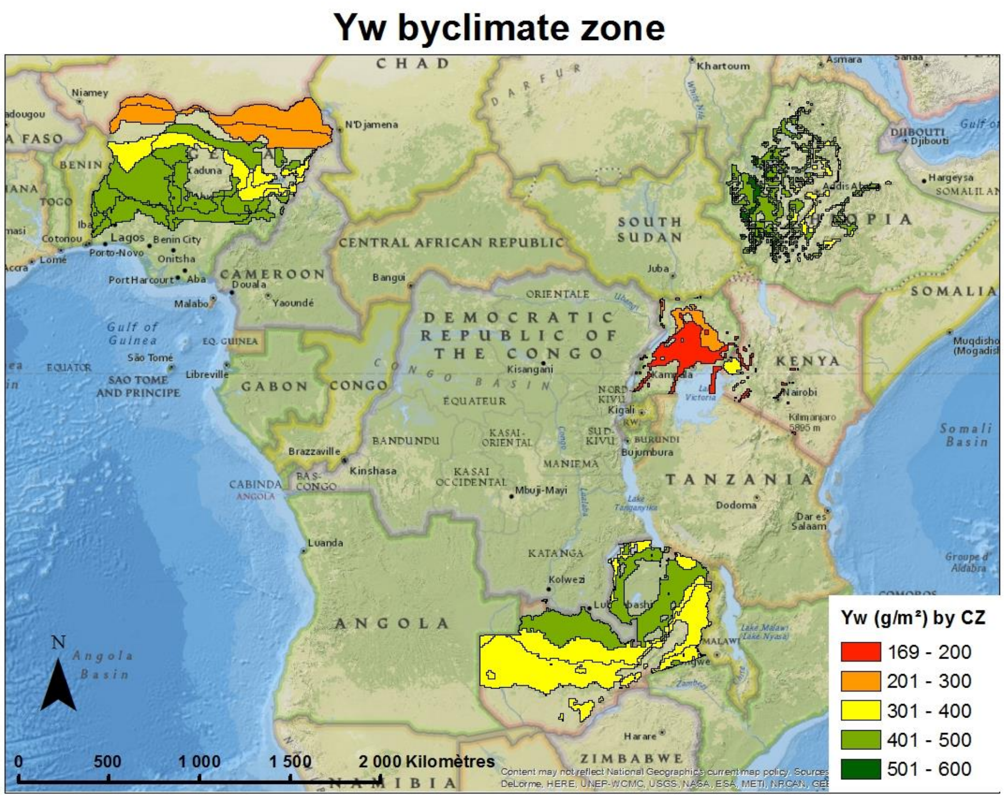


FIGURE 33: MAP OF YW BY CLIMATE ZONE, BOTTOM-UP APPROACH

The aggregation of results from the buffer zone level to climate zones resulted in an highest coverage of the country area. This representation brings to light the yields gradient observed in Nigeria and Ethiopia (**Figure 33**).

E Country

Countries were classified according to the average Yw calculated thanks to the aggregation method. Results for Uganda were well below the results simulated for the other countries (**Figure 34**). In Uganda, the harvested area was mainly concentrated in the Lira buffer zones which impact greatly the final results. The determination of the maturity type used for each buffer zone was made according to the method described in (**Part II.3.A**). However, the determination of the maturity type for Uganda and Kenya was uncertain. In Lira, no late maturity was used, which may have resulted in short cycles, and low yields. This could explain the low yields simulated for this station, and thus estimated at the country scale.

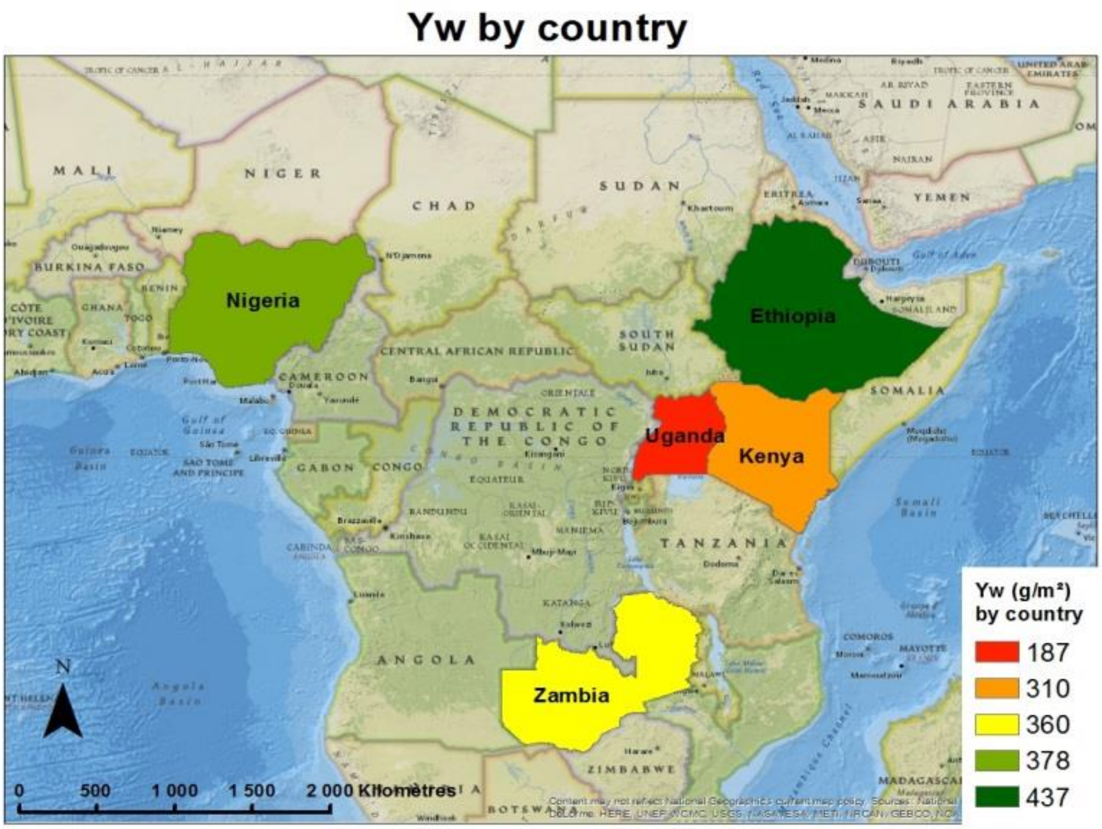


FIGURE 34: MAP OF YW BY COUNTRY, BOTTOM-UP APPROACH

Results were presented at three levels: Buffer zone, Climatic zone and Country. In Kenya and Uganda, results at the country level were mostly influenced by one buffer zone of importance. In other countries, the homogeneous repartition of harvested area among buffer zones smoothed the individual impact of each buffer zone. The results in Uganda seem unrealistic and must be compared to the results given by the top-down approach.

In order to determine if better productivity is possible thanks to the use of other sowing dates or maturity types, the next part focuses on the impact of a range of new management situations on the levels of water limited potential yield.

3 Top down approach

A Ethiopia

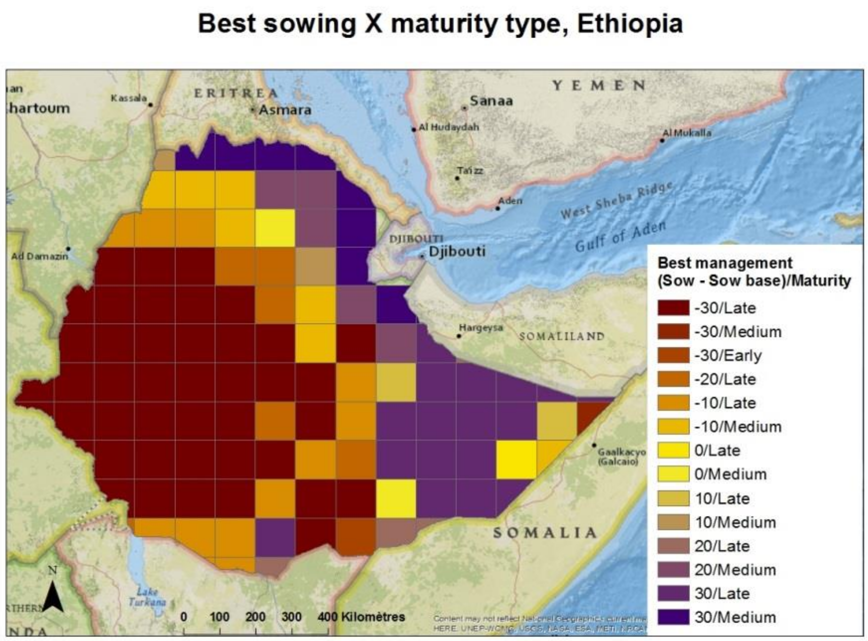
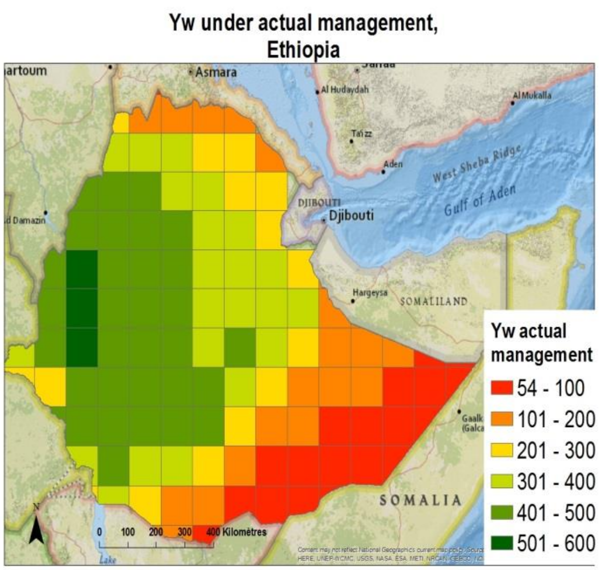


FIGURE 35: BEST SOWING X MATURITY TYPE, ETHIOPIA, TOP-DOWN APPROACH



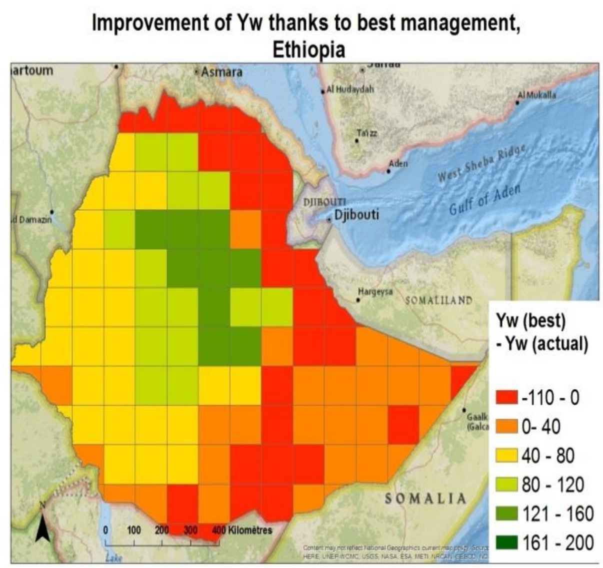
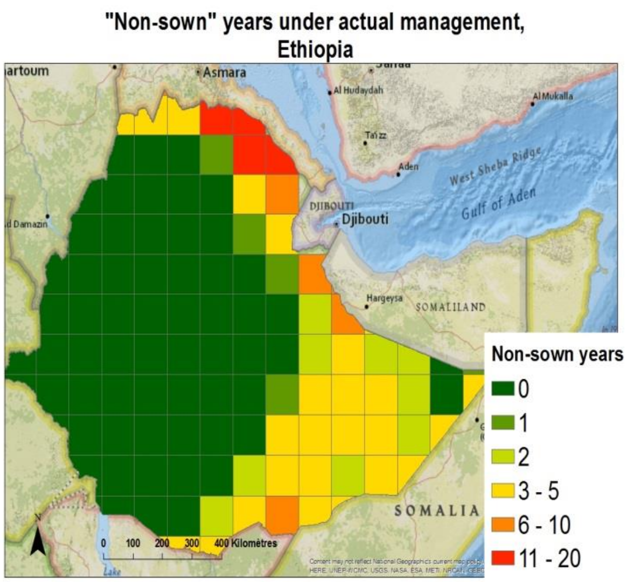


FIGURE 36: YW UNDER ACTUAL MANAGEMENT, EYHIOPIA, TOP-DOWN
FIGURE 37: IMPROVEMENT OF YW DUE TO BEST MANAGEMENT, ETHIOPIA, TOP-DOWN

By using different maturity type and sowing date, yield gain varying up to 200 g/m2 could be obtains (**Figure 37**). Management baseline in Ethiopia was set at the 15th of June for the sowing date with medium or late maturity type. For most of the cells situated in the high plateau of Ethiopia, best situations where found to begin 30 days before the baseline sowing date with a late maturity type

(**Figure 35**). Rainfalls allowed a good development of the plant earlier in the season and yields were improved as shown on the **figure 37**. The most predominant best management practices for lowlands consist in a later sowing and the use of medium or late maturity type. This improvement does not result in an important increase of Yw but in the reducing of the number of years when sowing is not possible. The number of years when sowing is not possible was reduced thanks to new management practices (**Figure 39**). At the border with Eritrea, the new management practices resulted in lower yields. That is an artifact caused by the fact that the number of years when sowing was possible decreased with improved management, but the average yield on this particular years when it was possible to sow with the new practices was low.



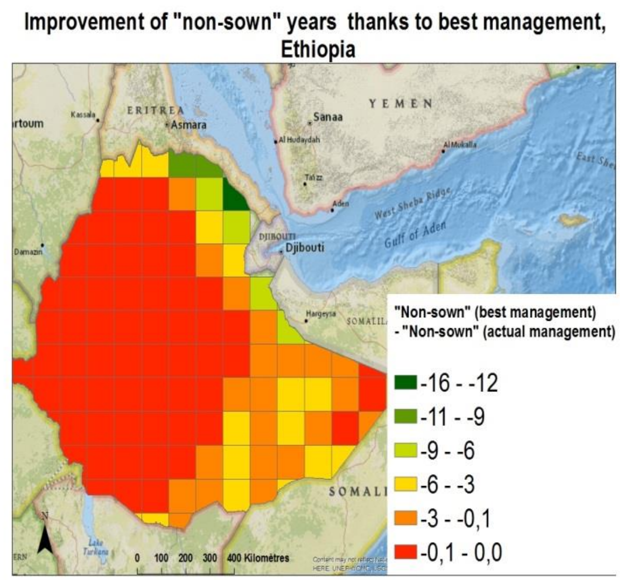


FIGURE 38: "NON SOWN" YEARS UNDER ACTUAL MANAGEMENT, ETHIOPIA, TOP-DOWN
FIGURE 39: IMPROVEMENT OF "NON SOWN" YEARS DUE TO BEST MANAGEMENT, ETHIOPIA, TOP-DOWN

B Kenya and Uganda

1st Rainy season

The baseline management for the first rainy season in Kenya and Uganda was set at the 1st of March for the sowing date with a medium maturity type. The most predominant best management practice consists in sowing the 1st of April with a late maturity type (**Figure 40**). The yields were slightly improved by this change in management practices (**Figure 42**) but the most important effect concerned the number of non-sown years. Baseline management results showed that a majority of cells present 11 to 25 non-sown years on the 30 possible for the ten days between the 1st and the 10th of March (**Figure 44).** The improvement of management practices resulted in an increase of yields of 160 g/m² with a decrease in non-sown year of 12 years in the south-east of Kenya.

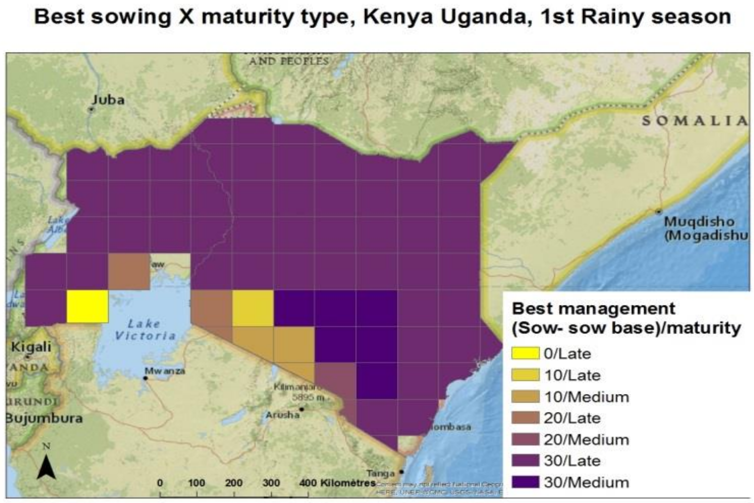
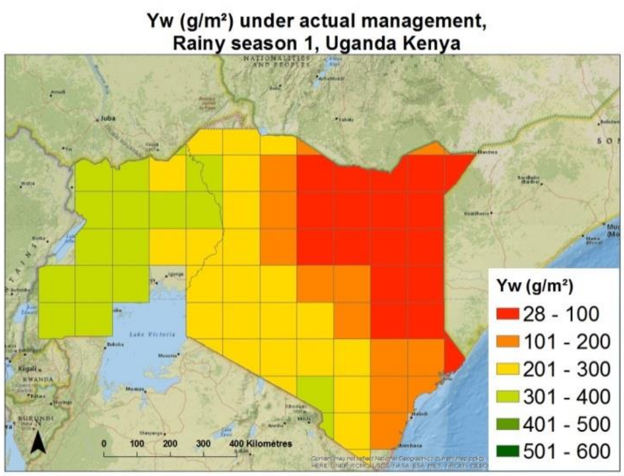


FIGURE 40: BEST SOWING X MATURITY TYPE, KENYA AND UGANDA, RAINY SEASON 1 TOP-DOWN APPROACH



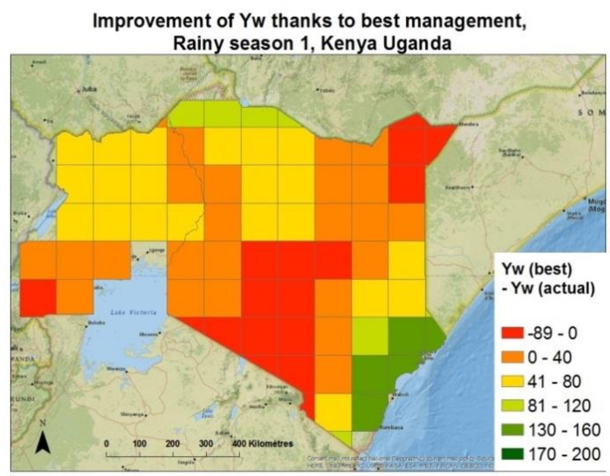
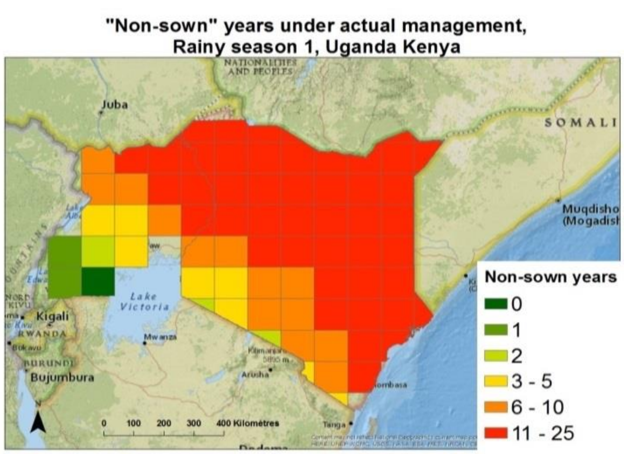


FIGURE 41: YW UNDER ACTUAL MANAGEMENT, KENYA AND UGANDA, RAINY SEASON 1, TOP-DOWN
FIGURE 42: IMPROVEMENT OF YW DUE TO BEST MANAGEMENT, KENYA AND UGANDA, RAINY SEASON 1, TOP DOWN



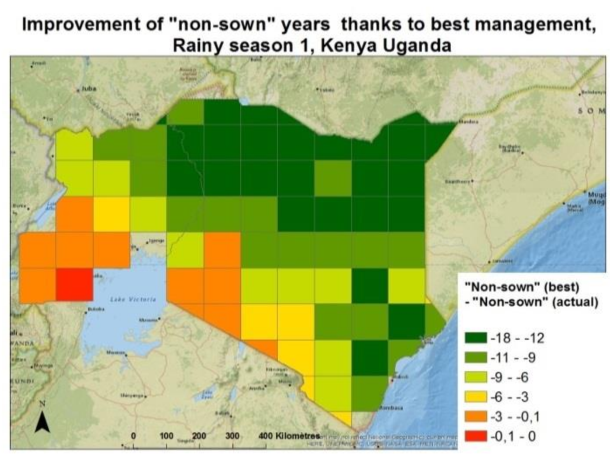


FIGURE 43: "NON SOWN" YEARS UNDER ACTUAL MANAGEMENT, KENYA AND UGANDA, RAINY SEASON 1, TOP-DOWN

FIGURE 44: IMPROVEMENT OF “NON SOWN” YEARS DUE TO BEST MANAGEMENT, KENYA AND UGANDA, RAINY SEASON 1, TOP-DOWN

2nd Rainy season

Best sowing X maturity type, Kenya Uganda, 2nd Rainy season

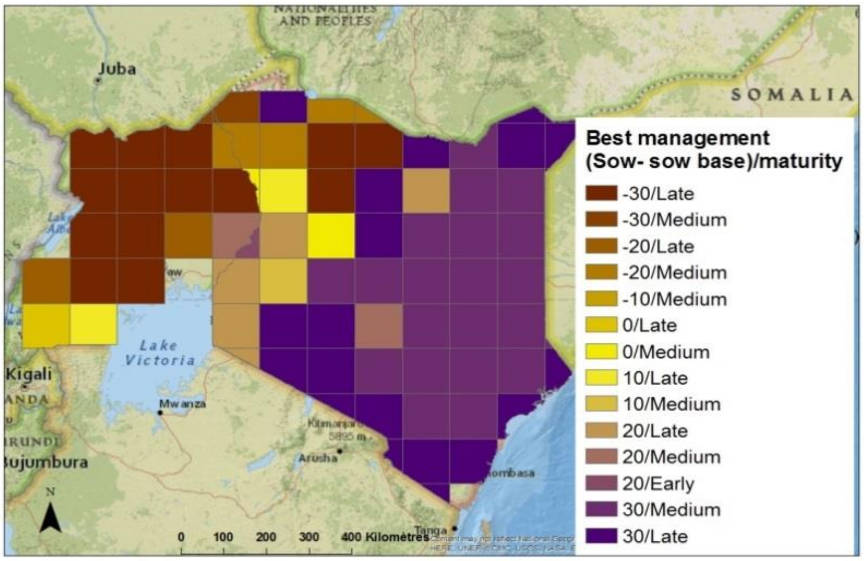
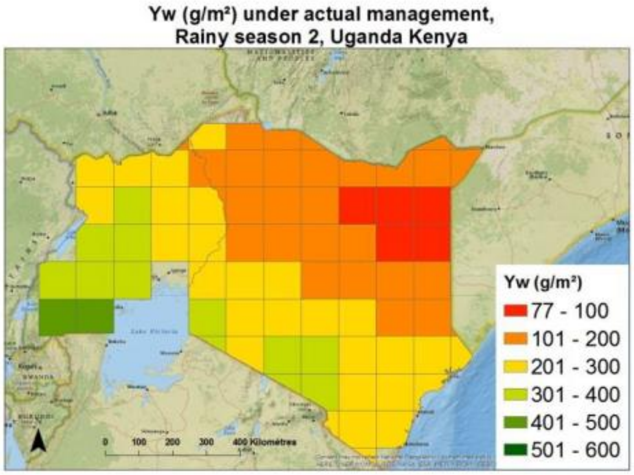


FIGURE 45: BEST SOWING X MATURITY TYPE, KENYA AND UGANDA, RAINY SEASON 2, TOP-DOWN APPROACH

The baseline management for the second rainy season in Kenya and Uganda was set at September 15th with a medium maturity type. The most predominant best management practice for Uganda corresponded to an early swing, set at August 15th for a late maturity type (**Figure 45**). This change resulted in higher yields for a majority of cells in Uganda (**Figure 47**). The number of year when soybean was sown is kept optimal by this change in management (**Figure 49**). Kenyan map of yields with new best management could divided into two parts: a narrow strip in the west of Kenya with a diversity of management techniques as best management, and Eastern Kenya where mostly late sowing dates and medium or late maturity types were recommended. In the north of western Kenya the best sowing dates ranged mostly between August 15th and September 5th of while in the south, the optimal sowing dates ranged between September 15th and October 15th . No particular distribution of optimal maturity types was observed. In the western Kenya, most of optimal sowing dates were situated between the 15th and the 25th of October with medium and late types. These changes in management practices resulted in a general decrease of year with no sowing in Kenya. Finally only slight increase of yield (0-40 g/m²) was predicted with best management practices for this second rainy season in Kenya.



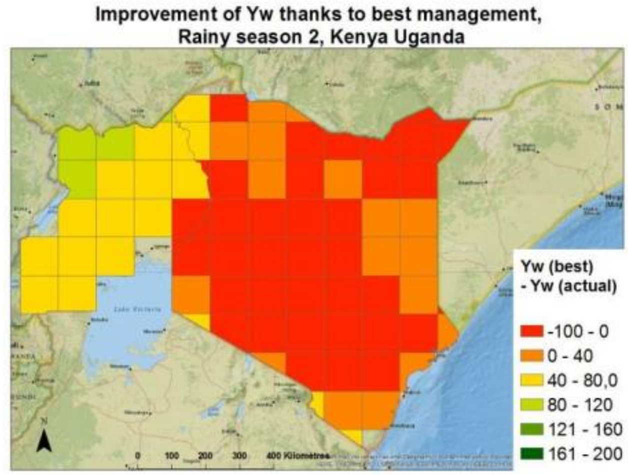
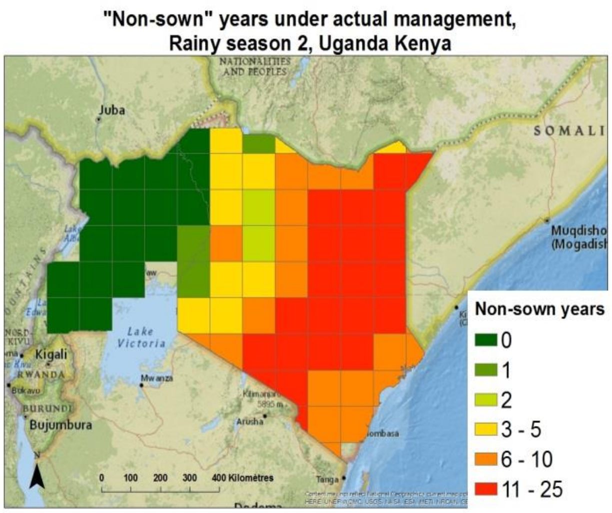


FIGURE 46: YW UNDER ACTUAL MANAGEMENT, KENYA AND UGANDA, RAINY SEASON 2, TOP-DOWN

FIGURE 47: IMRPROVMENT OF YW DUE TO BEST MANAGEMENT, KENYA AND UGANDA, RAINY SEASON 2, TOP-DOWN



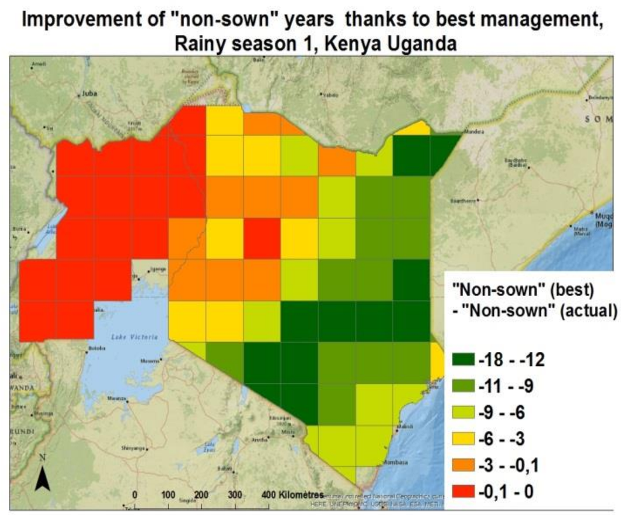


FIGURE 48: "NON SOWN" YEARS UNDER ACTUAL MANAGEMENT, KENYA AND UGANDA, RAINY SEASON 2, TOP-DOWN

Figure 49: improvement of "Non sown" years due to best management practices, Kenya and Uganda, Rainy season 2, tOP DOWN

The variation in management practices resulted in yields increase mostly in the high plateau of Ethiopia. For both rainy seasons in Kenya and Uganda, the main effect of the change in management inputs was a decrease of "non-sown" years.

In order to characterize the differences between results from the bottom-up approach and the top-down approach, an important part of the discussion is focused on comparison of water-limited yield estimations.

IV Discussion

1 Model evaluation

The experiments that were used to evaluate the model on its ability to predict Yw were not designed for this purpose. The cropping conditions were sometimes reported, but most of no information on nutrient limitations or pest control was available. The range of variation of observed yields, even for a same amount of water available and close location, let us suspect that most of the time crops suffered from other limiting factors, in addition to water.

In this study, new approach to discriminate the global model error between –actual model error and “error on data” was proposed. By errors on data, we mean the difference between actual observed yield, and Yw as it would have been observed in this region. The method proved to be easy to implement in Eastern Africa, and allowed to re calculate a lower predictive quality for the model. However, the method is still perfectible and showed a few limits:

The simulated yields for East Africa were fitting the regression line representing Yw estimated from experiment rather well for situation where water availability range between 500 and 800 millimeters and between 1000 and 1100 millimeters. In the case where water availability ranged between 800 and 1000 millimeters, the model seemed to underestimate Yw. It was not possible to identify a factor (location, treatment, variety) matching the situations where Yw was underestimated by the model. It seems that this discrepancy would rather rely on some imperfection of the method used to re-estimate Yw.

In the case of Eastern Africa experiments, the re-estimation of Yw values based on observation was done thanks to fitting a logarithmic regression between water availability and maximum observed yields. The R-squared of the regression was 0,73 and it was considered that the regression represented well variations of the maximum yields with water availability. However, the shape of the logarithmic curve may not be adequate: resource/ product relations are better represented with asymptotic relations, which is not the case of the logarithmic function. Other curve shape could have been tested, like the modified Mitscherlich (Harmsen 2000), or the Gompertz equation. In Nigeria, it was not possible to use this method, which required a minimum of situations, within the dataset where water was actually the only limiting factor.

Our method contributed to overcome the difficulty of assessing models in context of scarce and low quality data that have been acquired for different purposes. It is an interesting methodological progress for the modelling community. Still, the realization of strictly controlled experiments will remain necessary for a comprehensive evaluation of crop models.

2 Comparison of bottom-up and top-down approaches

A Two approaches based on a different vision of the area of study

The two approaches differ conceptually and methodologically. Conceptually, the top-down approach can be considered as a continuous vision of the geographical space to study, while the bottom up approach relies on a discretization of space into sub ensembles that are considered as homogenous. The top-down approach aims at scanning large scale to spot out geographical situation that have better performance or react better to a change of management for example. Conversely, the bottom up aims at delimitating and characterizing ensemble, within which agronomic and genomic solution can be looked for and applied to the entire sub-ensemble.

Regarding the method, the main difference relies in different weather datasets to simulate Yw. Other differences are due to the determination of the set of parameters. In the top down approach, management parameters have to be set at a same value for all the cells of a same country, or simple rules have to be enunciated to determine parameters according to the geographic location of the cell where the simulation is run. For example, initiations of simulations were all set at the same value for the top-down approach because the number of situation to characterized was to important. The use of a sowing window of ten days for the top-down approach was necessary for the further study of the effect of management practices variations on the values of yields, while the use of fixed sowing date for the bottom up approach was required by the GYGA methodology. Management practices for the top-down approach were characterized as average of what was observed at the buffer zone level. The comparison of results is thus sensitive to these methodological differences.

B That bring different answer to research questions

In this part, we want to compare the result obtained with the bottom up and the top down approach. To do so, a spatial entity suitable for comparison between the two approaches was to be found. The spatial units are buffer zones and climate zones for the bottom-up methodology and weather cells for the top-down approach. In order to compare these two results, the mean Yw of cells from the top down approach that are situated in a buffer zone (or in a climate zone) was calculated. The two mean of Yw obtained respectively with the bottom up and the top down approach were then compared, for each buffer zone and climate zone. To also take into account the difference in term of variability between the two methods, maximum and minimum Yw estimated with the top down approach was also compared to mean Yw obtained with the bottom up approach, for each climate zone.

Ethiopia

In Ethiopia, for most of the buffer zones, results show little differences. The mean of the difference between top-down results and bottom-up results is 33 g/m². Only rfwt4 show a difference greater than 50 g/m² (**Figure 50**).

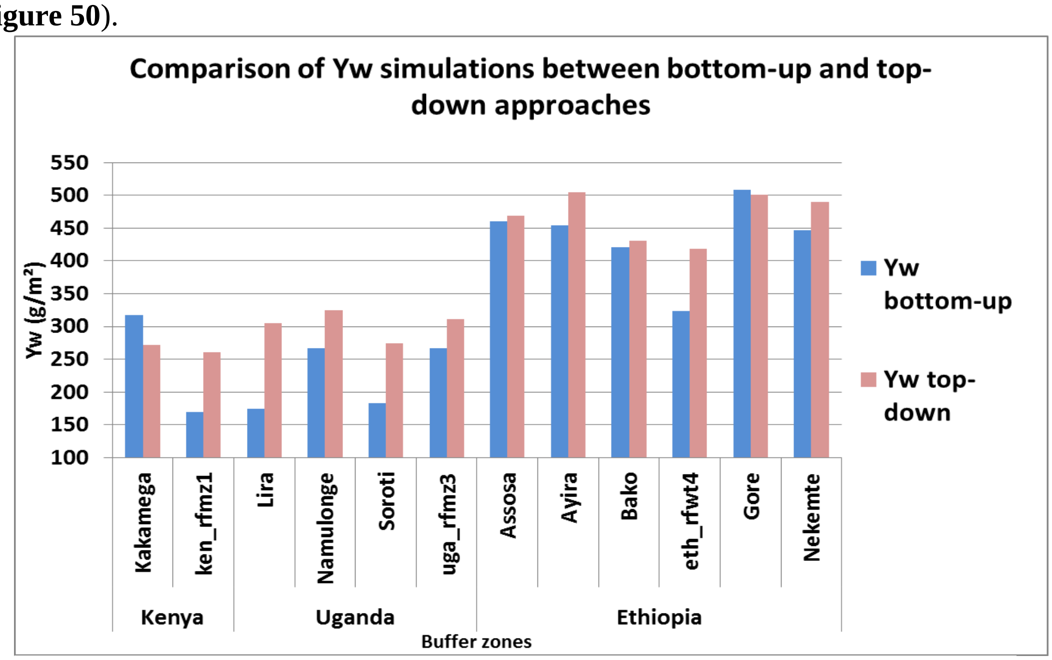


FIGURE 50: COMPARISON OF YW SIMULATIONS BETWEEN BOTTOM-UP AND TOP-DOWN APPROACHES, BUFFER ZONES LEVEL

Several explanations can be proposed to explain the slight over estimation of Yw with top down approach compared to the bottom up. The initiations were quite different with most of the initializations of the bottom-up approach that were done one month before the sowing date with the maximum amount of soil moisture while the initiation was made two month before the sowing date for the top-down approach, with the soil moisture at the lowest point. The initialization for the top-down approach was a bit severe (initial soil water content set at 10% of the water holding capacity) as weather station records show that rainfalls occur during the period just before the beginning of the simulation. However, the main differences between the approaches consisted of the use of different weather dataset. By looking at the average monthly weather generated with the climate simulator (top-down) to actual weather (bottom-up) at the rfwt4 station, these difference seemed to be explained by a higher amount of rainfall in the generated data (**Figure 51**).

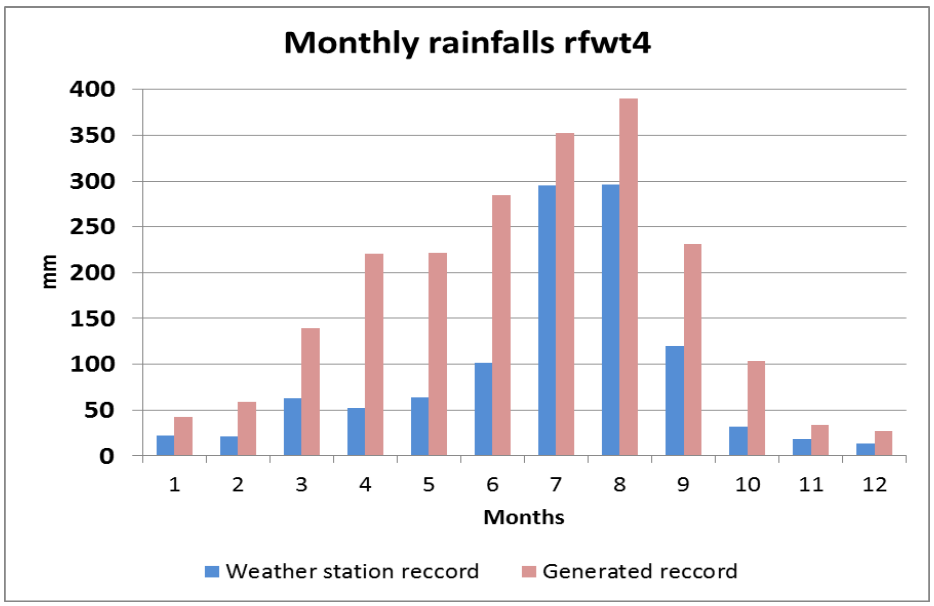


FIGURE 51: AVERAGE MONTHLY RAINFALLS IN THE BUFFER ZONE "RFWT4" ACCORDING TO WEATHER STATION RECORDS AND GENERATED WEATHER DATA

Other actual weather stations from the GYGA database that are close to rfwt4 show a pattern of rainfall very different than the one of rfwt4 (**figure 52**). Rfwt4 is situated at the limit between the Ethiopians high plateau and the lowlands, in zone of climatic transition. It is thus possible that the abrupt transition in climate observed in the area of rfwt4 station was not simulated by generated weather stations. This had resulted in an overestimation of Yw for the top-down approach. Therefore, in area where climate changes abruptly, the use of a small number of actual stations may artificially accentuate variation of yield between one buffer zone and the neighboring ones, applying to the entire buffer zone a microclimate observed locally. This can also impact significantly the results at the climate zone scale, especially if only a small number of buffer zones are used to describe the climate zone.

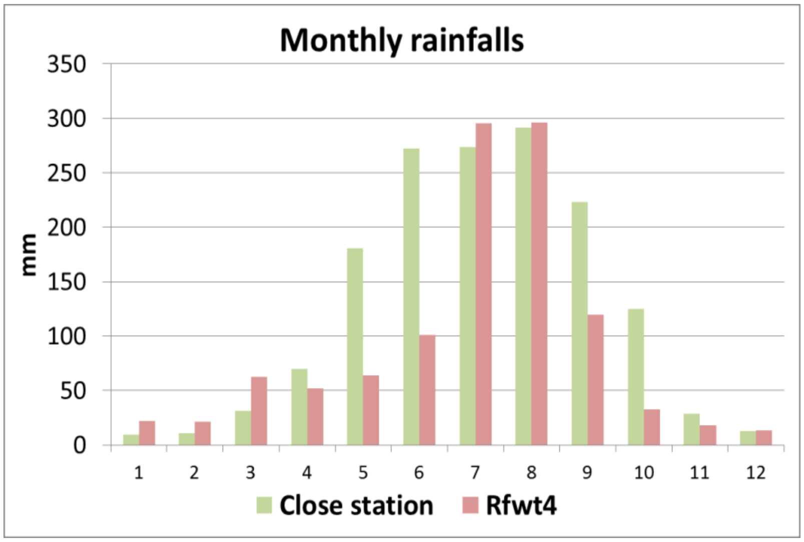


FIGURE 52: AVERAGE MONTHLY RAINFALLS, RFWT4 WEATHER STATION AND NEIGHBORING WEATHER STATIONS

Finally, in zones of stable climatic conditions, the generated data give Yw close to the one simulated for weather stations. However, referencing the model with accurate inputs is more difficult when using generated data, mostly because of the continuous description of space, and number of simulations to perform. The top-down approach involves most of the time more significant simplifications than the bottom-up approach and is less connected to the actual practices. However, this approach gives a good opportunity to prospect the effect of new practices on a large range of spatial units among the country under study. .

Kenya and Uganda

In Kenya and Uganda, the top down approach strongly overestimate average Yw at buffer zone level compared to the top down approach. In Uganda, Lira station covers 68% of the total harvested area of the country, thus this station greatly influenced the result at the country level. In Lira, the top-down simulations resulted in an average of 3 years with no sowing. In the bottom-up approaches, because of slight difference in the set of management parameters, crop was sown in the simulation for these same years and could have resulted in low yield values due to early water stress. On the contrary, in Ethiopia, were little difference was observed between the two approaches, no “non-sown” years were detected. This could explain why the average Yw calculated with the bottom up approach for these buffer zones is lower than with the top down approach. Other factors could also have contributed like the difference in weather data, or even differences of initialization.

C Comparison of results at climate zone level

At the climate zone scale, the top down approach still tends to slightly over estimate average Yw (**Figure 53**). Like at the buffer zone scale, differences are important in Uganda where the mean of the differences is 100 g/m². In Kenya, no particular trend was noticeable. Except for the climate zone 6401, differences are negligible in Ethiopia; the mean of the differences is 24 g/m².

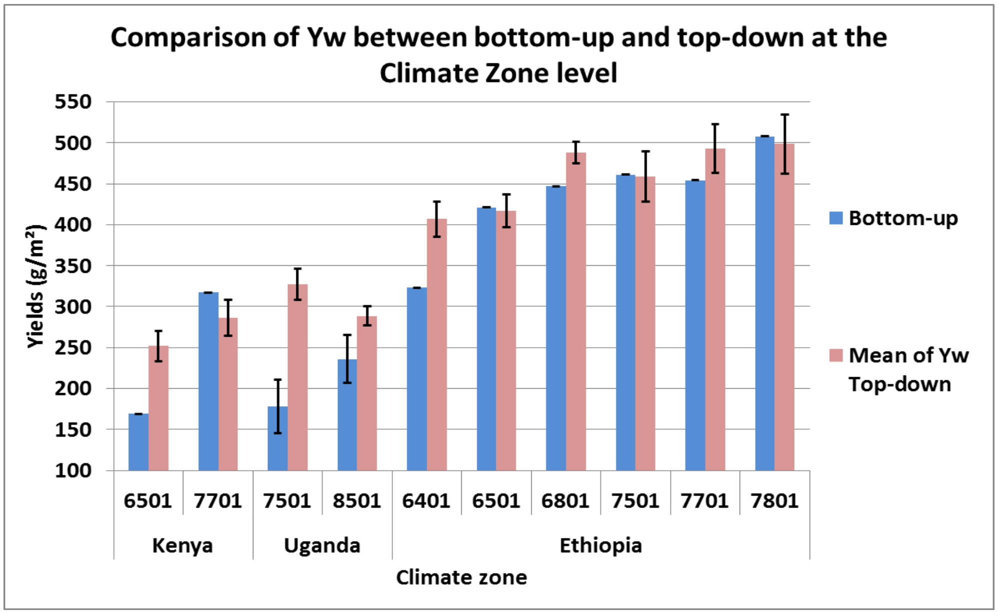


FIGURE 53: COMPARISON OF YW BETWEEN BOTTOM-UP AND TOP-DOWN APPROACHES, CLIMATE ZONES

Differences between top-down and bottom-up approaches were referenced at the buffer zone and climate zone level in the **Figure 54**. In most of the case, the difference does not seem to be influenced by the aggregation from the buffer zone scale to the climate zone scale. The mean of the variations of differences between the two scales is 14 g/m². For the bottom-up approach, **the figure 54** showed that standard deviations of the estimation of Yw at the climate zone scale are small (average of 44 g/m²). Yw of each cell within a climate zone are thus quite similar. For the bottom-up approach, most of the climate zone results are based on results from one buffer zone. Only the two climate zones in Uganda are based on results from two buffer zones. Results of the bottom-up approach at both scales are thus quite similar. In the particular case under study, the aggregation does not result in a significant variation of the difference between the bottom-up and the top-down approach. The fact that only few buffer zones are used to determine the results at the climate zone level probably influences this result.

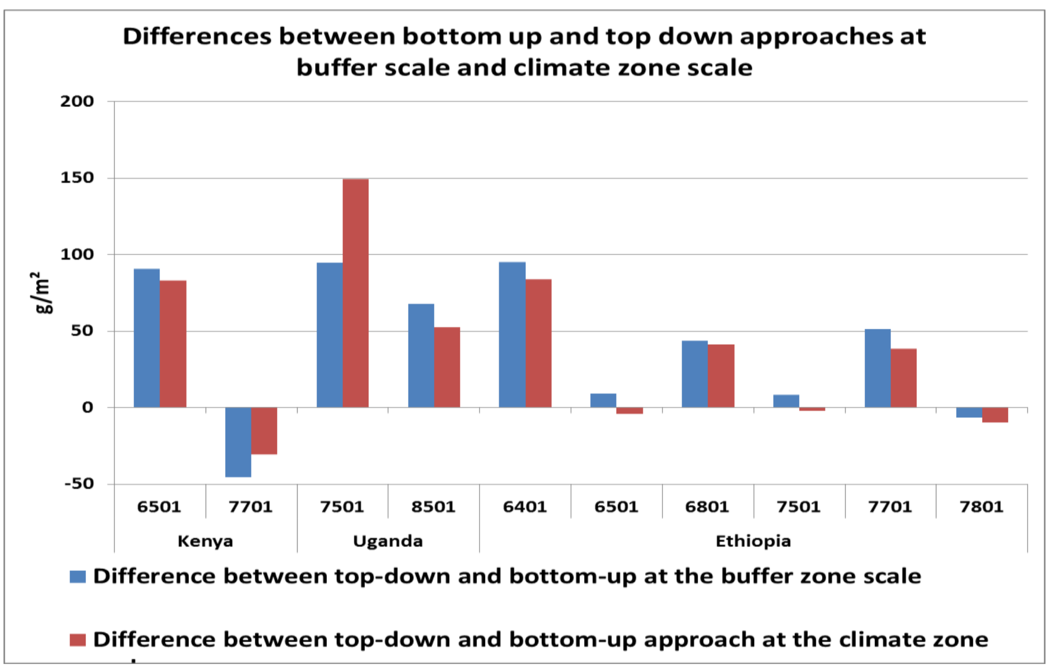


FIGURE 54: COMPARISON OF DIFFERENCES BETWEEN YW OF TOP-DOWN AND BOTTOM APPROACH AT THE BUFFER ZONE SCALE AND AT THE CLIMATE ZONE SCALE

V Conclusion

The first output of this work is the addition of 5 new African countries to the GYGA Atlas regarding soybean production. Our model assessment showed that there were high variations in the potential yield that can be expected for Soybean in Africa. While Ethiopia seems a suitable area to promote and develop this crop, Kenya and Uganda were found to have low potential yield. Comparison between water limited potential yield and actual yield will be carried out in a near future.

We have presented two approaches to estimate water-limited potential yields and compared them regarding methodologies and results. Most of the time, higher values of Yw were simulated with the top-down approach compared to the bottom up approach. Our work allowed identifying the reason for this over estimation of yield with the top down approach compared to the bottom up. Most of the difference would rely in the estimation of parameters to run the model in the two approaches. Indeed, the biggest differences on Yw between the methods were observed at locations were management parameters differed between the two methods. Although efforts have been made to harmonize methodologies, inherent differences between the two approaches resulted into different parameterization for some locations. Besides, in zones of homogeneous climatic conditions, when slightly similar management inputs are used, the two approaches give similar results. In zones of abrupt climatic transition, the use of different weather data sources impact final results. Climatic transitions are smoothed by generated data while the use of weather stations situated in the zone of abrupt transition may accentuate its effect. The aggregation of estimated Yw from buffer zone into larger geographic units (climate zones) did not result in an increase of the differences between the two approaches. To conclude, the level of differences between the two approaches is highly linked to the particularities of each spatial unit. Finally, data availability and study objective should lead scientist to pick or another one approach, with acceptable discrepancy in the outcome of the study.

The study of the effect of management practices on Yw values have been implemented according to the top-down approach. The use of different combinations of sowing dates and maturity types influence the Yw levels and the number of years when the crop is simulated as not sowed. The best combination always results in a decrease of the number of years when the crop is not sown, except in zones were the number of “non-sown” years was already optimal under “baseline” management. Most of the time, no significant increase of Yw levels is detected. The increase of Yw was observed in zones were Yw are already important under “baseline” management (e.g. Ethiopian high plateaus). These results are probably influenced by the choice we made to privilege management strategies with low risk for farmers, based on the number of years when the crop is sown and on yield level, when identifying best management. However, feasibility of implementation has not been considered and should be addressed in the next steps through exchanges with local farmers. In particular, our study concluded that long cycle varieties should be adapted more widely, which may not be adapted to local cropping and farming system calendars. The use of the bottom-up approach to characterize the effect of management variation on final results would ease the characterization of management practices feasibility. Comparison of results provided by the two approaches for improvement of crop management should help to consolidate our findings.

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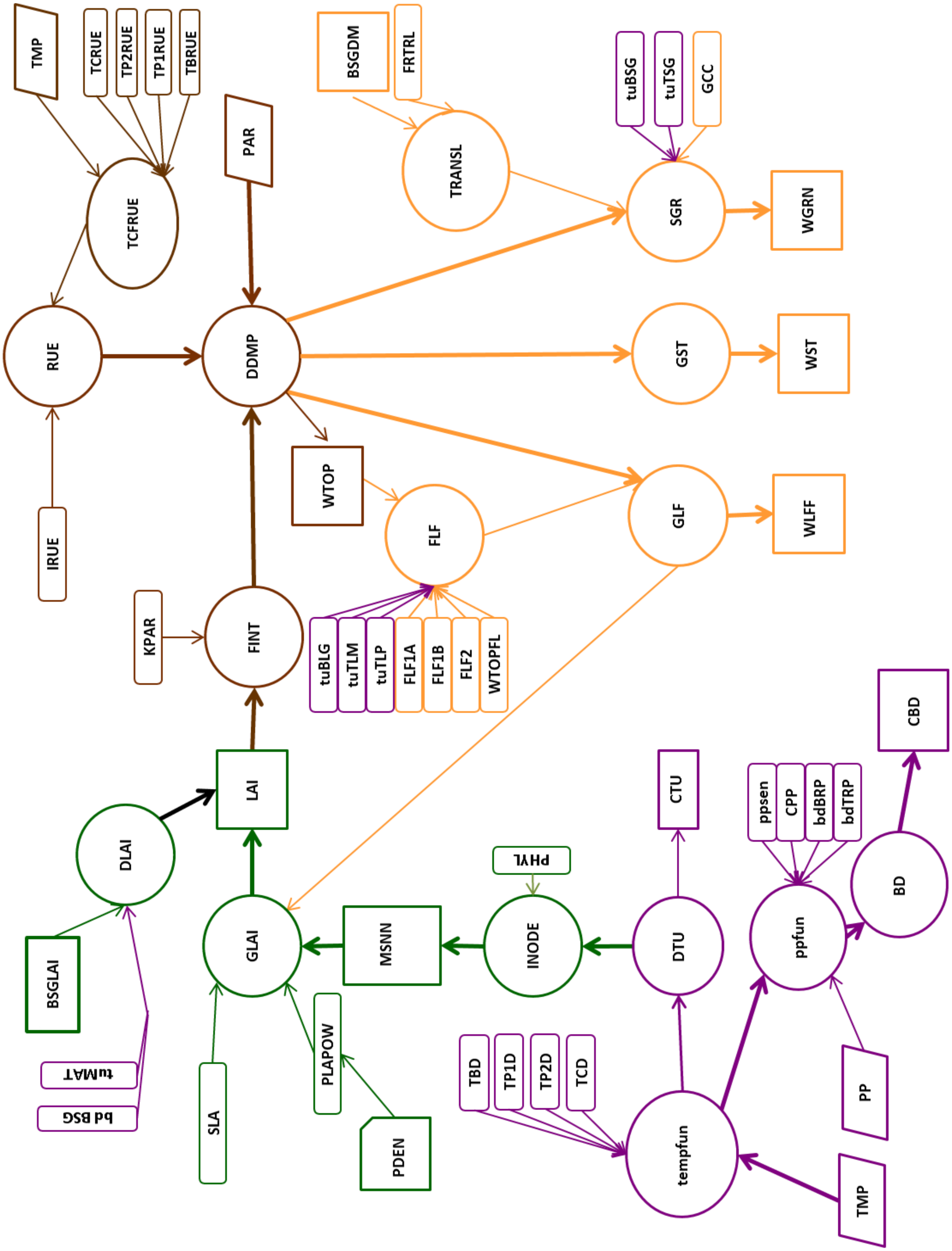
Appendixes :



Appendix 1: Detailed description of the SSM model

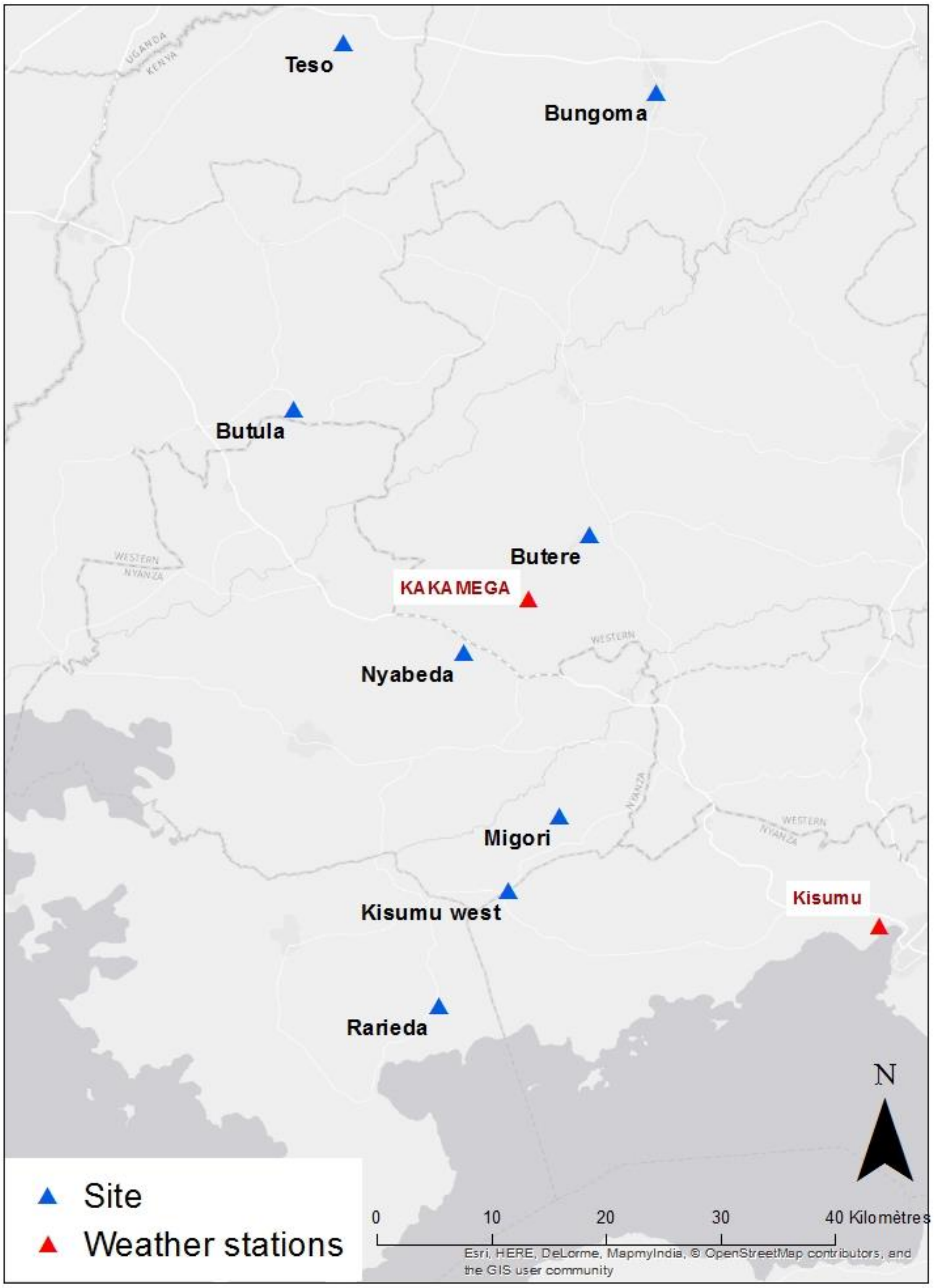
	Maturity	EM	R1	R3	R7
Duration	Late	4	41	51	77
	Medium	7	33	40	68
	Early	10	31	38	64
Standard deviation	Late	2	4	4	2
	Medium	3	10	10	5
	Early	6	8	10	5

Appendix 2: Standard deviation of maturity type in Kenya for each stage

	Maturity type	SOW	EM	R1	R3	R5	R7
Duration	Late Nigeria	0	7	39	49	52	85
	Medium Nigeria	0	7	37	47	50	81
	Early Nigeria	0	7	36	44	47	75
Standard deviation	Late Nigeria			2			7
	Medium Nigeria			3			3
	Early Nigeria			3			5

Appendix 3: Standard deviation of maturity type in Nigeria for each stage

Weather stations and experimental sites of Kenya



Appendix 4 : Distance between weather stations an experimental sites

Appendix 5: Management in Ethiopia according to N2 Africa local experts

Ethiopia

	Bako and Western Ethiopia , Oromia region							
	Sowing			Phenology				Density
	Sowing window	**Percentage of each practice in the buffer zone**	**Sowing rule**	**Variety name**	**Maturity group**	**Crop cycle duration (days)**	**Crop cycle duration (GDD)**	**Plant density (plant/m^2)**
A	End of May	20	After effective first rain	Ethio-ugozilavia, Keta and Korme	Long	140-150	-	17-34
	In June	80	After effective first rain	Boshe, Jalale, Didessa, Cheri	medium and short	120-140	-	25-40

	Jimma (South Western Ethiopia, Oromia region)							
	Sowing			Phenology				Density
	Sowing window	**Percentage of each practice in the buffer zone**	**Sowing rule**	**Variety name**	**Maturity group**	**Crop cycle duration (days)**	**Crop cycle duration (GDD)**	**Plant density (plant/m^2)**
A	June 17-24 (long rains)	-	After effective rains	Clark- 63k	medium	120	-	33

	Pawe (North Western Ethiopia, Beni-shangul & Gumuz region)							
	Sowing			Phenology				Density
	Sowing window	**Percentage of each practice in the buffer zone**	**Sowing rule**	**Variety name**	**Maturity group**	**Crop cycle duration (days)**	**Crop cycle duration (GDD)**	**Plant density (plant/m^2)**
A	June (Long rain)	95	After first rains	*Belessa 95*	Long	120	-	33
	August, end of long rain	5	Before the last one month rain	Nova	Very Short	60	-	50

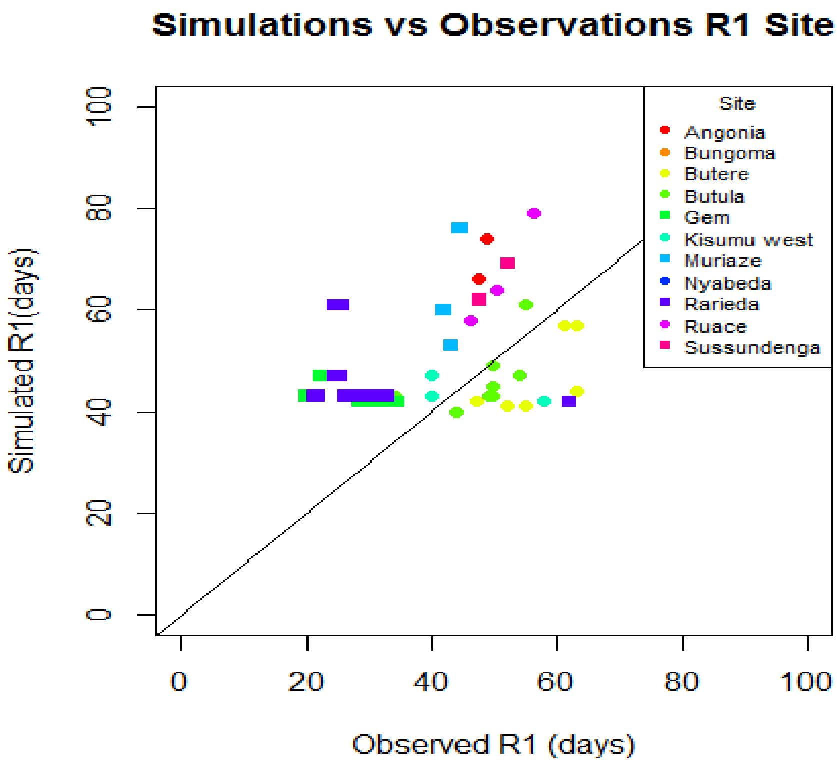
Remark; Belessa 95 variety is the best adaptive and high yielder variety in the area. Nova is an alternative var when needed to cover the farm lately at about the 1st week of August (often practiced when crop failure occurs or the June planting is missed because of workloads)

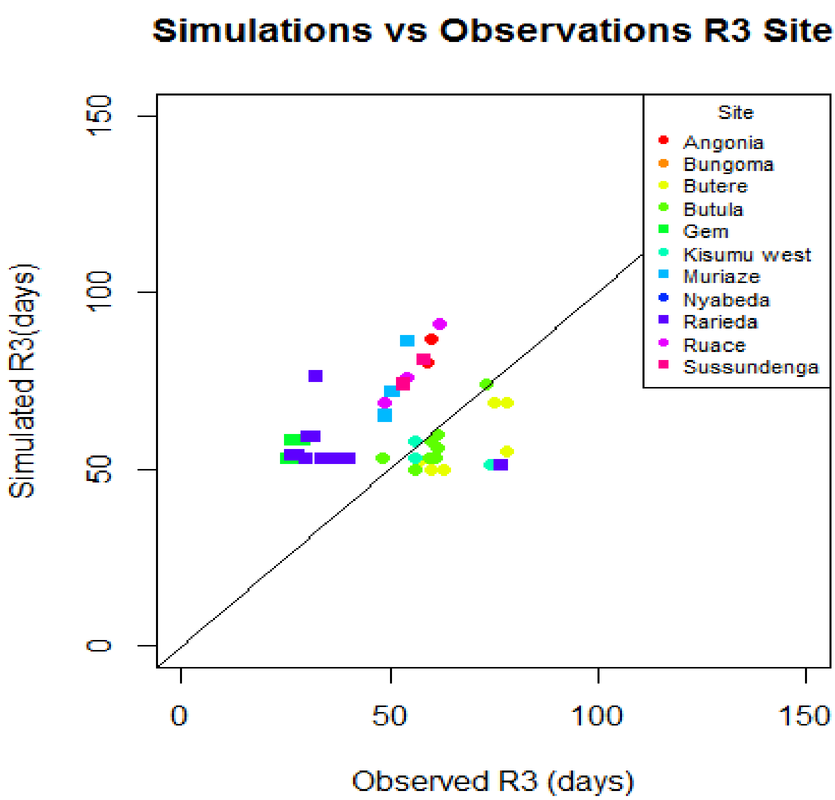
Kenya								
	Sowing			Phenology				Density
	Sowing window	Percentage of each practice in the buffer zone	Sowing rule	Variety name	Maturity group	Crop cycle duration (days)	Crop cycle duration (GDD)	Plant density (plant/m^2)
A	March (Long Rains)	12	After first rains	SeedCo Squire	Medium	110	Need other source	32
	September (Short Rains)	10	After first rains	SeedCo Squire	Medium	110	Need other source	32

Appendix 6: Management in Kenya according to N2 Africa local experts

Country	Station	Zone	Sowing date	Maturity group	Initiation date	MAI	Pourcentage
Ethiopia	Assosa	North Western	15-juin	Late	15-avr	0,1	100
	Nekemte	North Western	15-juin	Late	30-mai	0,9	100
	Ayira	Western	15-juin	Medium	10-mai	0,9	100
	Gore	Western	15-juin	Late	15-mai	0,9	100
	rfwt4	Western	15-juin	Early	01-juin	0,9	100
	Bako	Western	15-juin	Medium	15-mai	0,9	100
Kenya	Kakamega		01-mars	Medium	20-févr	0,5	55
	Kakamega		15-sept	Medium	15-août	0,9	45
	Kisumu		01-mars	Late	30-janv	0,5	55
	Kisumu		15-sept	Medium	30-juil	0,5	45
Nigeria	Bauchi	Northern Guinea	22-juin	MediumW	20-avr	0,1	100
	Kaduna	Northern Guinea	22-juin	MediumW	01-juin	0,9	100
	rfso4	Northern Guinea	22-juin	MediumW	30-avr	0,1	100
	Yelwa	Northern Guinea	22-juin	LateW	30-mars	0,1	100
	Makurdi		01-juin	LateW	01-avr	0,1	50
			01-juil	MediumW	20-juin	0,9	50
	Minna		01-juin	LateW	30-mars	0,1	50
			01-juil	MediumW	20-juin	0,9	50
	Oshogbo		01-juin	LateW	20-mai	0,9	50
			01-juil	LateW	20-juin	0,9	50
	rfso6		01-juin	LateW	30-mars	0,1	50
			01-juil	EarlyW	20-juin	0,9	50
	Maidu	Sudan Savanna	06-juil	EarlyW	01-mai	0,1	100
	Nguru	Sudan Savanna	06-juil	EarlyW	30-avr	0,1	100
	rfmt1	Sudan Savanna	06-juil	EarlyW	30-avr	0,1	100
	rfmt3	Sudan Savanna	06-juil	EarlyW	30-avr	0,1	100
	rfso3	Sudan Savanna	06-juil	EarlyW	30-avr	0,1	100
	Sokoto	Sudan Savanna	06-juil	EarlyW	30-avr	0,1	100
Uganda	Lira		15-sept	Medium	15-août	0,9	50
			01-mars	Early	20-févr	0,5	50
	Namulonge		15-sept	Late	31-août	0,9	50
			01-mars	Medium	01-févr	0,5	50
	Soroti		15-sept	Medium	31-août	0,9	50
			01-mars	Medium	01-févr	0,1	50
	uga_rfmz3		15-sept	Medium	31-août	0,9	50
			01-mars	Late	01-févr	0,1	50
Zambia	Chipata		15-déc	Medium	25-oct	0,1	100
	LusakaCity		15-déc	Early	30-oct	0,1	100
	Zam_rfmt3		15-déc	Early	30-oct	0,1	100
	Zam_rfmt4		15-déc	Late	30-oct	0,1	100
	Zam_rfmz1		15-déc	Medium	30-oct	0,1	100
	Zam_rfmz4		15-déc	Early	30-oct	0,1	100

Appendix 7 : Management for each buffer zone



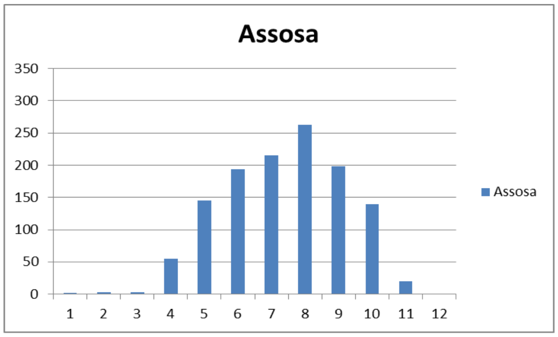


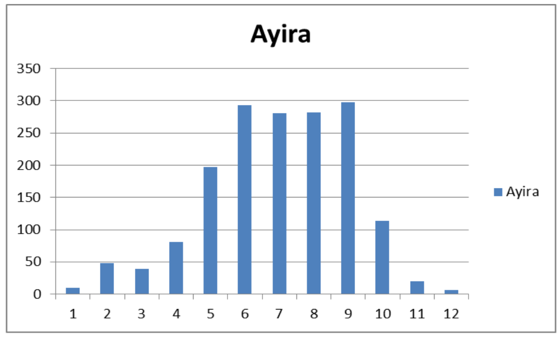
Appendix 8 : Observed stage duration in days against simulated in Kenya. Classified by site

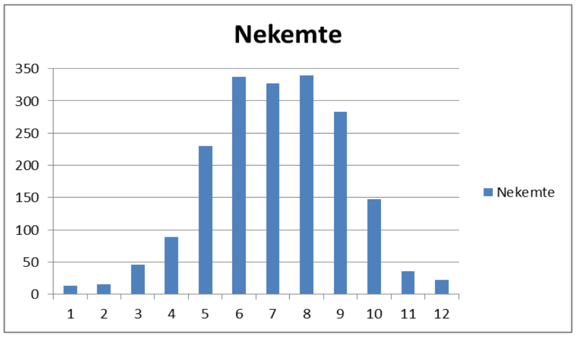
Ethiopia

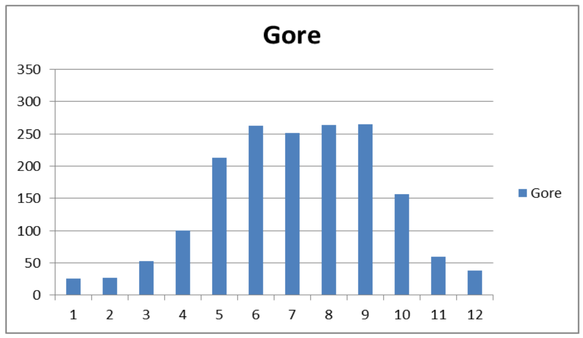
North Western

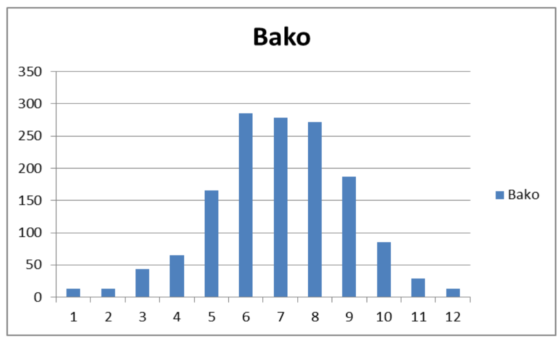
Western

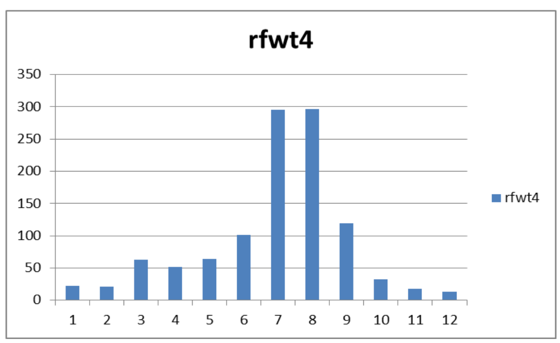






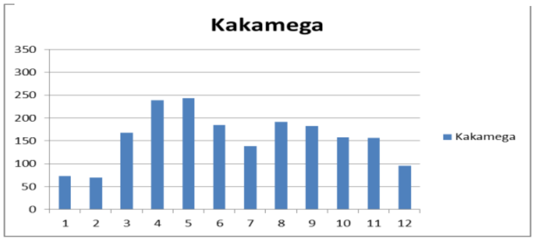


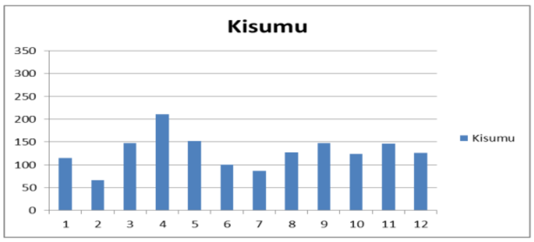




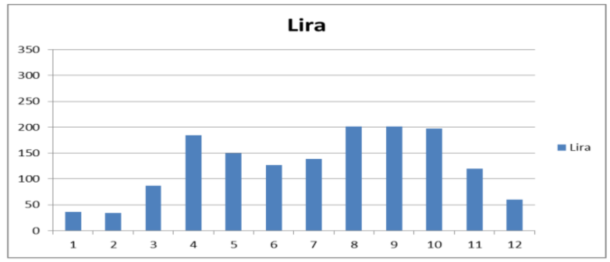
Appendix 9 : Average of monthly rainfall in Ethiopia

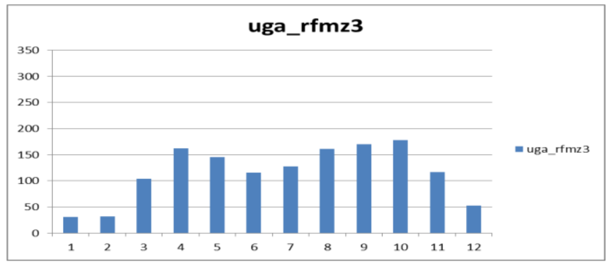
Kenya

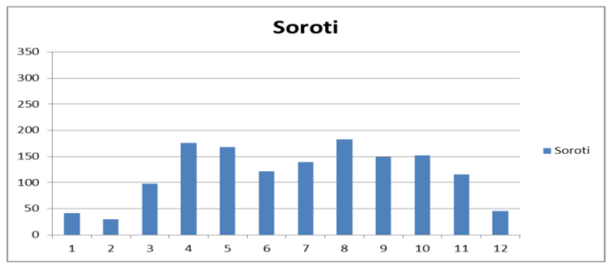


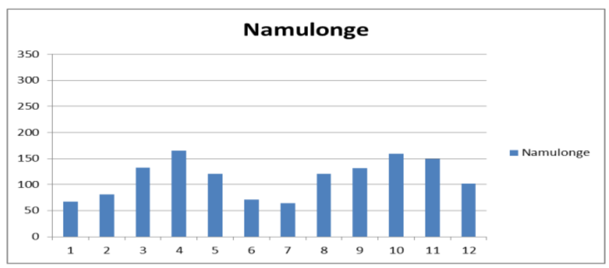


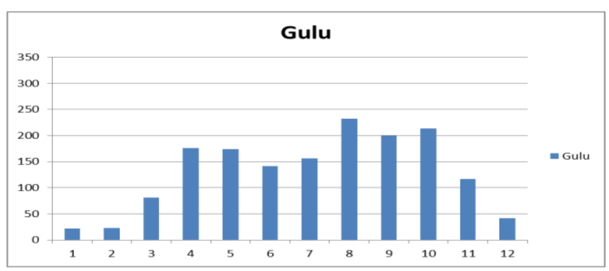
Uganda

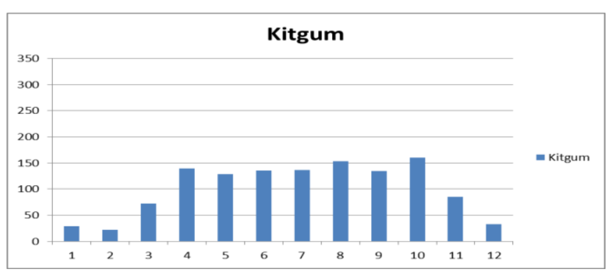








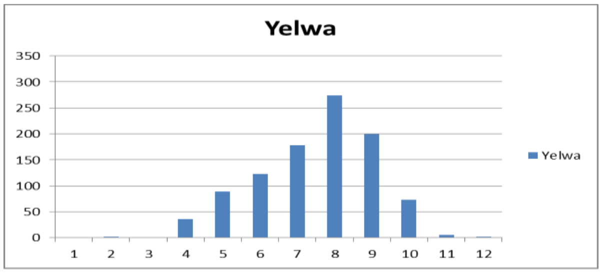


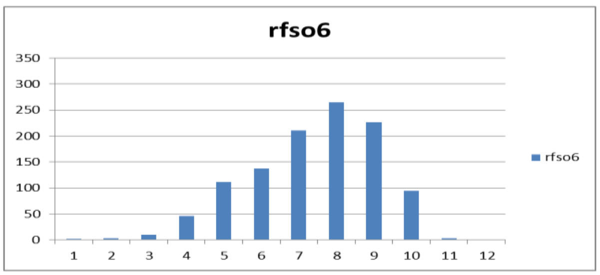


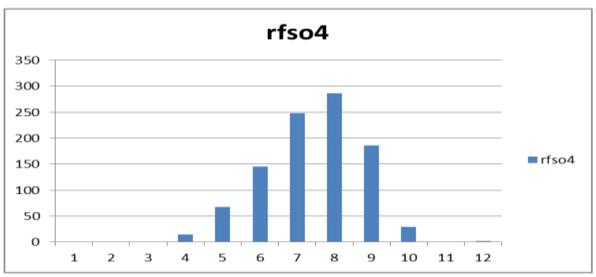
Appendix 10 : Average of monthly rainfall in Kenya and Uganda

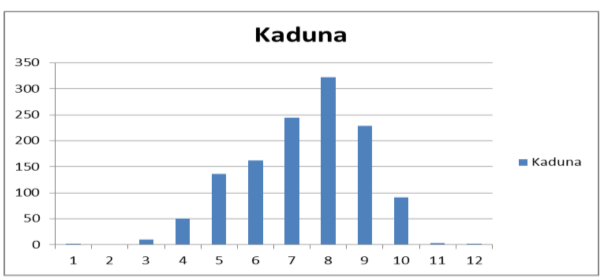
Nigeria

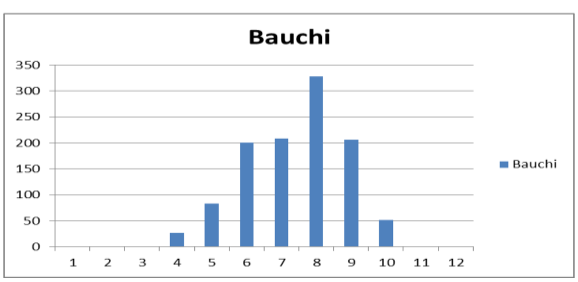
Northern Guinea zone



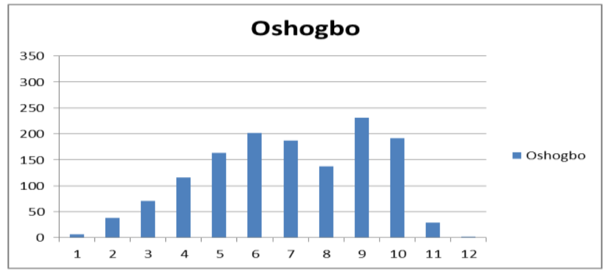


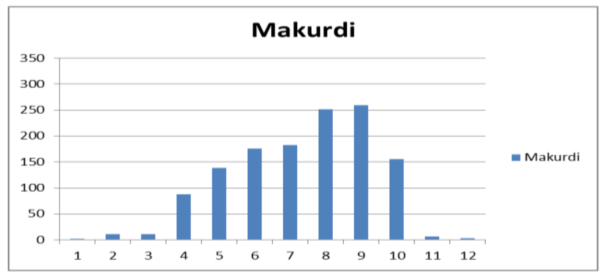


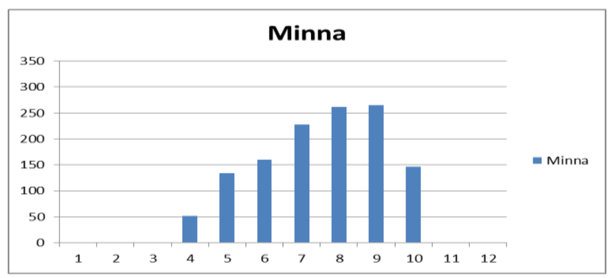




Southern Guinea zone

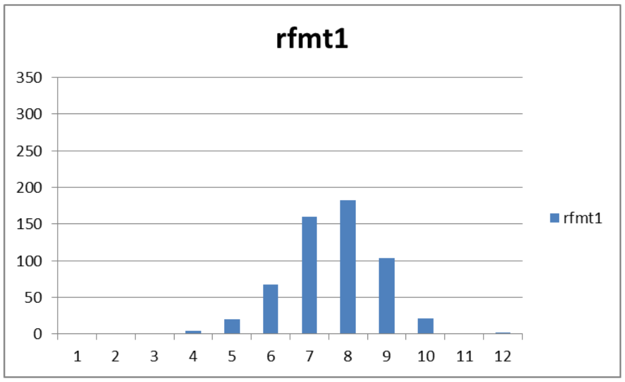


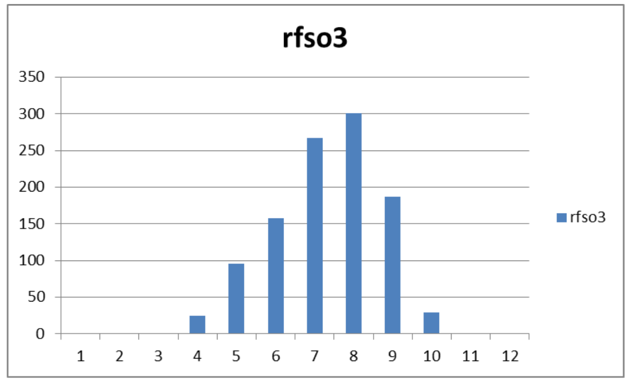


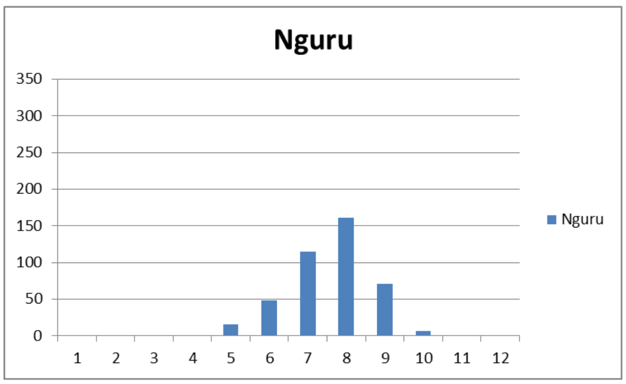


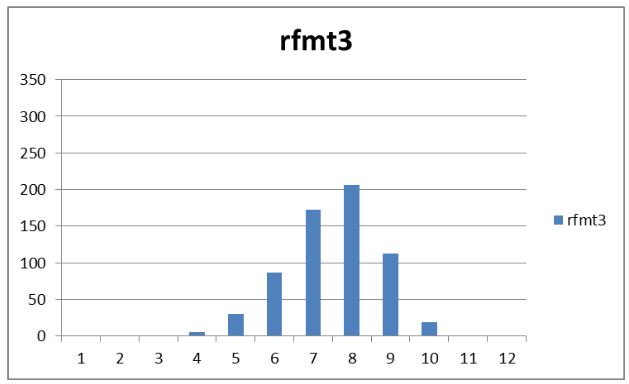
Nigeria

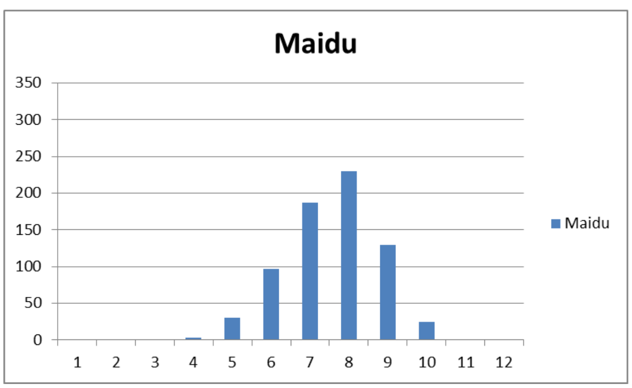
South sudan zone

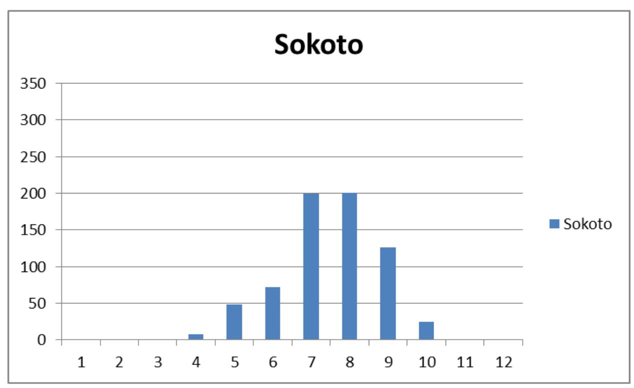












Appendix 11 : Average of monthly rainfall in Kenya and Uganda