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Analysis of field data and modeling with the faq aquacrop model, in the framework of a study on the resistance of two rice cultivars to irrigation deficiency in Cambodia

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LERFEL DÉBORAH

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ACADEMIC YEAR 2021-2022

SUPERVISOR: AURORE DEGRE

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Host organism

Institute of Technology of Cambodia, Phnom Penh

Research unit: Water and Environment (WAE), Soil laboratory

Scorlarship

Erasmus + mobility scholarship

Jury

- Pr. Haïssam Jijakli (President)
- Pr. Aurore Degré (Supervisor)
- Dr. Pinnara Ket
- Dr. Joost Wellens
- Dr. Caroline De Clerck

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Abstract

This study was dedicated to the analysis of the water-use efficiency of rice in Cambodia. We studied several scenarios depending on the parameters: soil and fertilization, irrigation regime and cultivar. We identified the most resistant cultivar to irrigation deficiency as CAR15, which is also the cultivar producing rice with the best WUE.

We also modeled these scenarios in AquaCrop to calibrate and validate a model, and especially with the objective to determine the accuracy of the model in stress scenarios. We had some struggles with the modeling as the irrigation records were flawed and we lacked information on some stresses that could impact the rice. Thus, we recommend a better and more rigorous data collection to be able to fit and validate the model properly in the future.

Keywords: AWD, irrigation, cultivars, water-use efficiency, AquaCrop

Résumé

Ce mémoire a été dédié à l'étude de l'irrigation du riz au Cambodge. Différents scénarios basés sur le sol et la fertilisation, le régime d'irrigation et le cultivar ont été étudiés et compares. Nous avons identifié le cultivar CAR15 comme étant le plus résistant au stress hydrique, et produisant du riz avec la meilleure efficience d'usage de l'eau.

Nous avons également créé plusieurs modèles sur AquaCrop pour représenter cette expérience. L'objectif de cette démarche était d'observer la précision d'AquaCrop dans des scénarios de déficit hydrique. Nous n'avons pas atteint la précision espérée lors de la modélisation. En effet, nous avons eu des difficultés à calibrer et valider les différents paramètres du modèle car les données d'irrigation étaient parcellaires et peu fiables. De plus nous manquions d'information sur d'autres stress qui auraient pu impacter le riz. Nous recommandons donc une collecte de données plus complète et plus rigoureuse lors de la reproduction d'une expérience de ce type dans le futur.

Mots-clés: Irrigation alternée, cultivars, efficience d'irrigation, AquaCrop

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List of acronyms and abbreviations

ANOVA	Analysis of Variance
AWD	Alternate Wet and Dry
ρ_b	Bulk density
CARDI	Cambodian Agricultural Research and Development Center
CC	Canopy Cover
CC_x	Maximum canopy cover
CN	Curve Number
CF	Constant Flooding
d	Willmott's index of agreement
DAT	Days after transplant
EF	Nash-Sutcliffe efficiency
ET_0	Reference evapotranspiration
FAO	Food and Agriculture Organization
FC	Field Capacity
HI	Harvest Index
HI_0	Reference harvest index
IPCC	Intergovernmental Panel on Climate Change
IRRI	International Rice Research Institute
ITC	Institute of Technology of Cambodia
Kc_{Tr}	Maximum crop transpiration coefficient
PWP	Permanent Wilting Point
R^2	Coefficient of Determination
RMSE	Root Mean Square Error
SAT	Saturation
SWC	Soil Water Content
Θ	Volumetric Water Content
WP*	Normalized crop water productivity
WUE	Water-Use Efficiency

Chapter 1

***

Contextualization

1.1. Rice production

1.1.1. General facts

Rice (*Oryza sativa*) is the fourth most produced crop in the world, as we can see in figure 1.

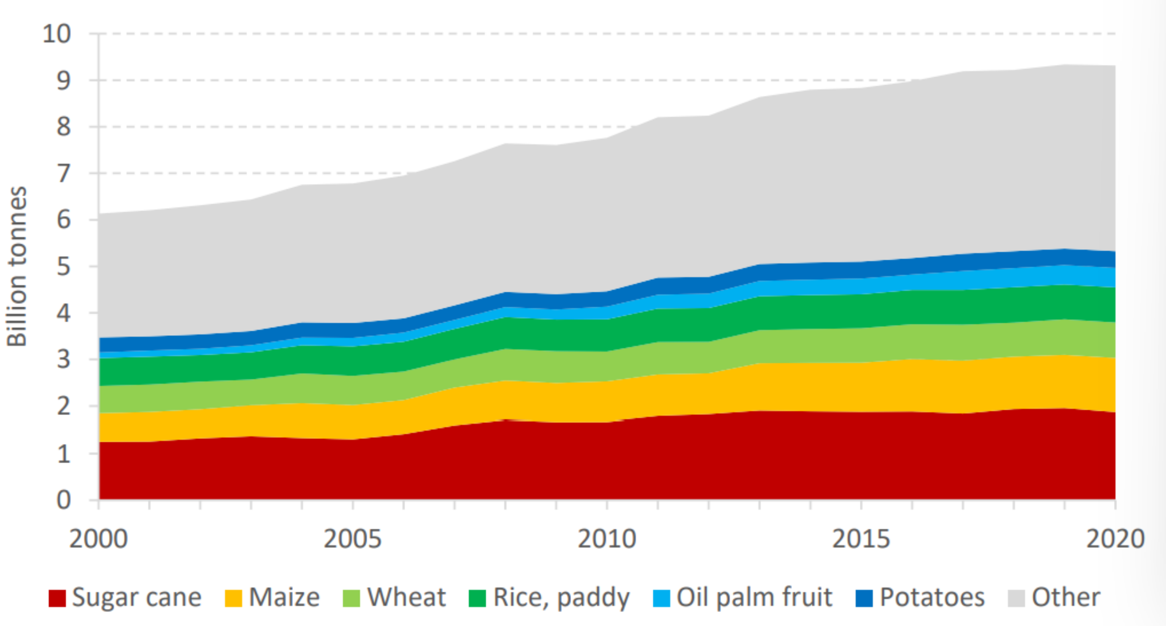

Figure 1 - Global production of crops by main commodities (FAO, 2022)

This plant, which belongs to the *Poaceae* family, produces a grain that is mainly used for human alimentation as is or transformed in products like noodles or alcohol. Most of its production takes places in Asia, with China, India and Indonesia being the leaders of rice production (FAO, 2020).

This cereal is said to provide 21% of per capita energy and 15% of per capita protein worldwide (IRRI, 2022). As we can see, this crop has a lot of importance, and constitutes a staple food of a lot of people around the world, especially poor people (IRRI, 2002).

Moreover, the production has globally increased in the last decades, as we can see on figure 2 below, to meet a growing demographic demand. It is then a crucial issue to ensure and optimize rice production.

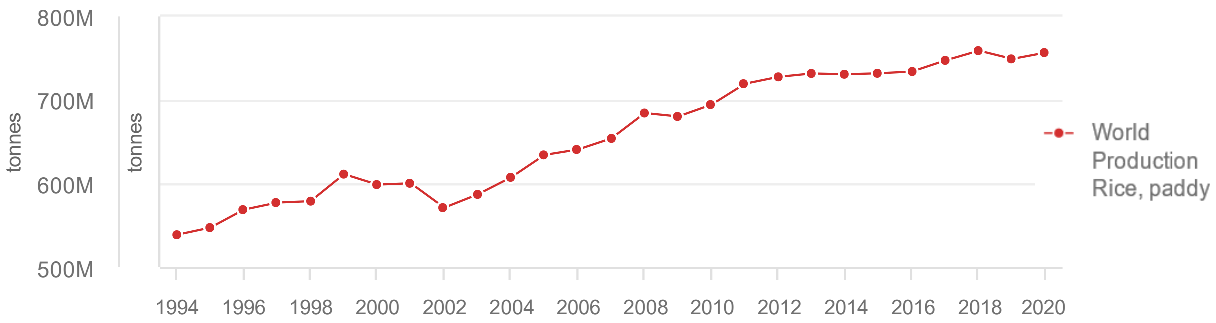

Figure 2 - Evolution of the global production of rice between 1994 and 2020 (FAO, 2022)

1.1.2. Rice anatomy

Rice is a grass plant with a complex anatomy. The figure 3 represents the main parts of a mature rice plant.

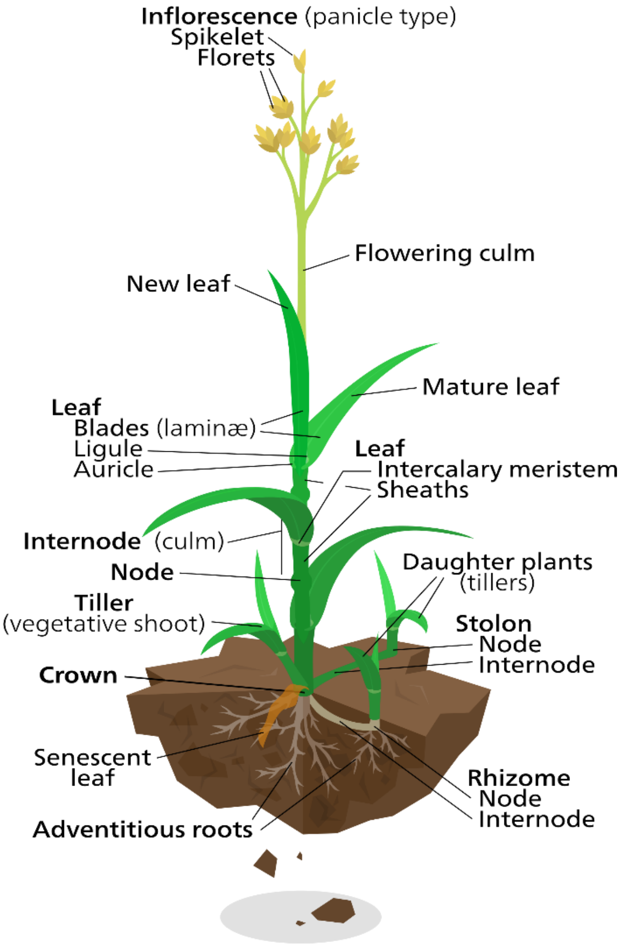

Figure 3 - Anatomy of a rice plant

The roots can have different architectures depending on the cultivar planted. The root is composed of the seminal root, and the lateral roots that are formed around it.

The rice plant produces tillers that are each an independent plant. There are primary tillers coming from the main culm. These tillers give rise to secondary tillers, and secondary tillers generate tertiary tillers. Tillers are produced during the vegetative growth stage.

The inflorescences of the rice tillers are the panicles, located at the top of the tillers. The panicle carries the spikelets, which grow into grains after fertilization (Richard Dunand et al., 2014).

1.1.3. Rice cultivation

1.1.3.1. Stages of rice cultivation

The development of rice goes through different phases represented on the figure 4 below.

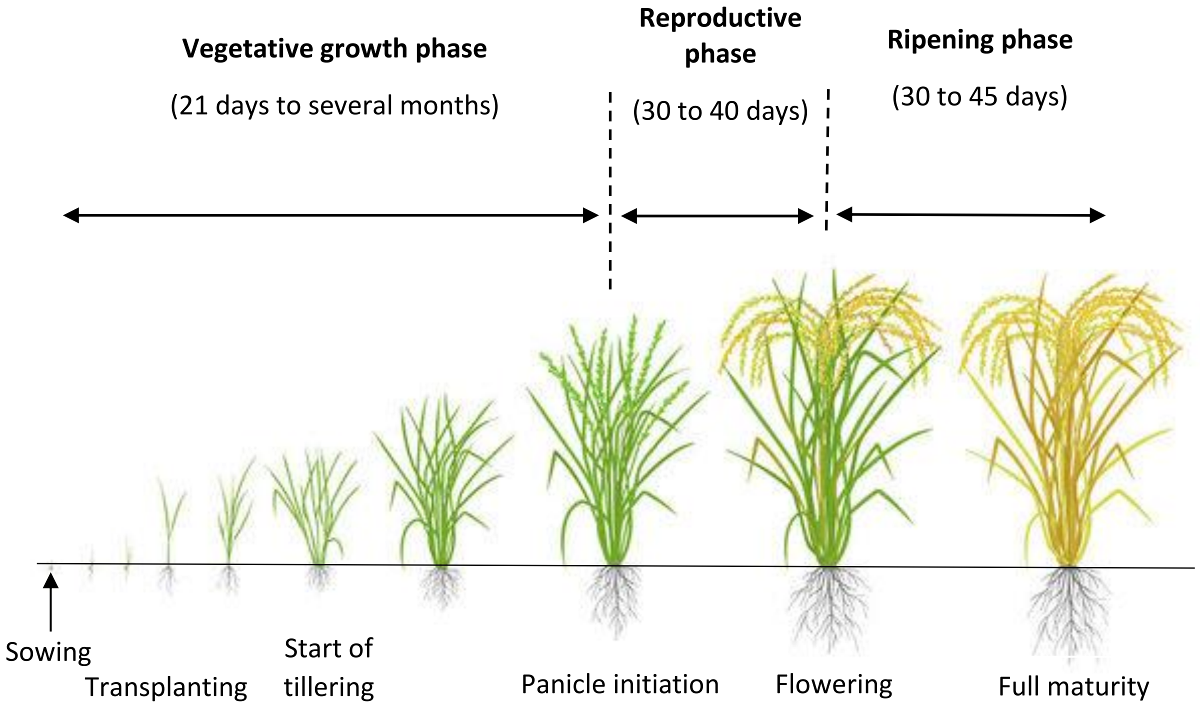

Figure 4 - Growth stages of rice

The vegetative phase starts with germination and ends with panicle initiation. This phase can be divided in several stages: emergence, seedling development, tillering and internode elongation. Let's also note that transplanting is not really a stage but it has an impact on the plant, because of the shock caused by this manipulation.

The reproductive phase starts with the panicle initiation and ends with the flowering. This phase can be divided in several stages as well: panicle initiation (at this time the panicle is not yet visible to the human eye), booting, when the internodes grow very rapidly, and heading, when the panicle emerges from the protective leaf.

Finally, during the ripening phase, the spikelets are filling and grains growing. We can cite the milky stage, when the spikelets are filled with a white liquid resembling milk. After this comes the soft dough stage, the hard dough stage and finally maturity when the grain is hard and ready to be harvested.

The duration of the different stages depends on the environmental conditions, and the cultivars used. There are usually two cycle of cultivation per year for rice (Karen Moldenhauer et al., 2021).

1.1.3.2. Needs of the rice during the cultivation

All throughout its cultivation cycle, rice has needs in terms of water, temperature, and nutrients. Rice needs high temperature and an important water input. Thus, it is usually cultivated in tropical climates and humid regions. However, temperatures that are too high can cause stress to the rice and for example decrease fertility during flowering. Soils with a good water retention and a big portion of clay are ideal, but rice can be cultivated in all types of soil. The soil must be prepared: it has to be plowed and levelled, so that water spreads evenly in the field (FAO, 2021). Rice also needs sufficient sun radiation, and nutrients. It is usually heavily fertilized with chemical substances or natural manure (JICA, 2016).

1.1.3.3. Rice irrigation

Rice cultures can either be rainfed or irrigated. Most times, the irrigated cultures have a higher yield because of the use of high-yield cultivars. They also allow more control on the amount of water that is brought to the crop.

1.1.3.3.1. Continuous flooding (CF)

The traditional and most common system of irrigation is Continuous Flooding (CF). It implies that the fields are constantly flooded, during all the cultivation cycle. In this scenario, the use of the water is not optimized, because a lot of water is lost by transpiration among others. Furthermore, the flooded fields create anaerobic conditions that allow a methane-emitting bacteria to thrive. The longer the floodings last, the more methane is emitted. According to the IPPC, rice paddies are a huge source of methane, which is a greenhouse gas that has a warming potential 28 to 34 times superior to carbon dioxide. It is estimated that rice agriculture is responsible for 11% of all anthropogenic methane emissions (Jiang et al., 2019).

As we can see, the CF method is not optimal in terms of water management, nor in terms of methane emissions.

1.1.3.3.2. Alternate wet and dry (AWD)

The Alternate Wet and Dry is another method of irrigation implying a cycle with applications of irrigation followed by periods where the fields are drying, as shown in figure 5. This method allows to reduce water use by up to 30% (which is very important in a global contest of climate change and water scarcity), and help farmers save money on pumping costs, as well as reduce by 48% the methane emissions without reducing the yield (Richards et al., 2014).

There are different types of AWD, based on different criteria. For example, it can be based on the appearance of the soil (if the soil is crackling) or the appearance of the plants, but the most common way to implement AWD is to install "water tubes" into the fields, that are performed and allow the monitoring of the water level. The fields are re-irrigated when the water level drops to a certain value, usually 15cm below the surface of the soil.

The AWD can be conducted from 1 to 2 weeks after the transplant up until the flowering stage. Indeed, the firsts and lasts stages of the cultivation cycle are sensible to water stress.

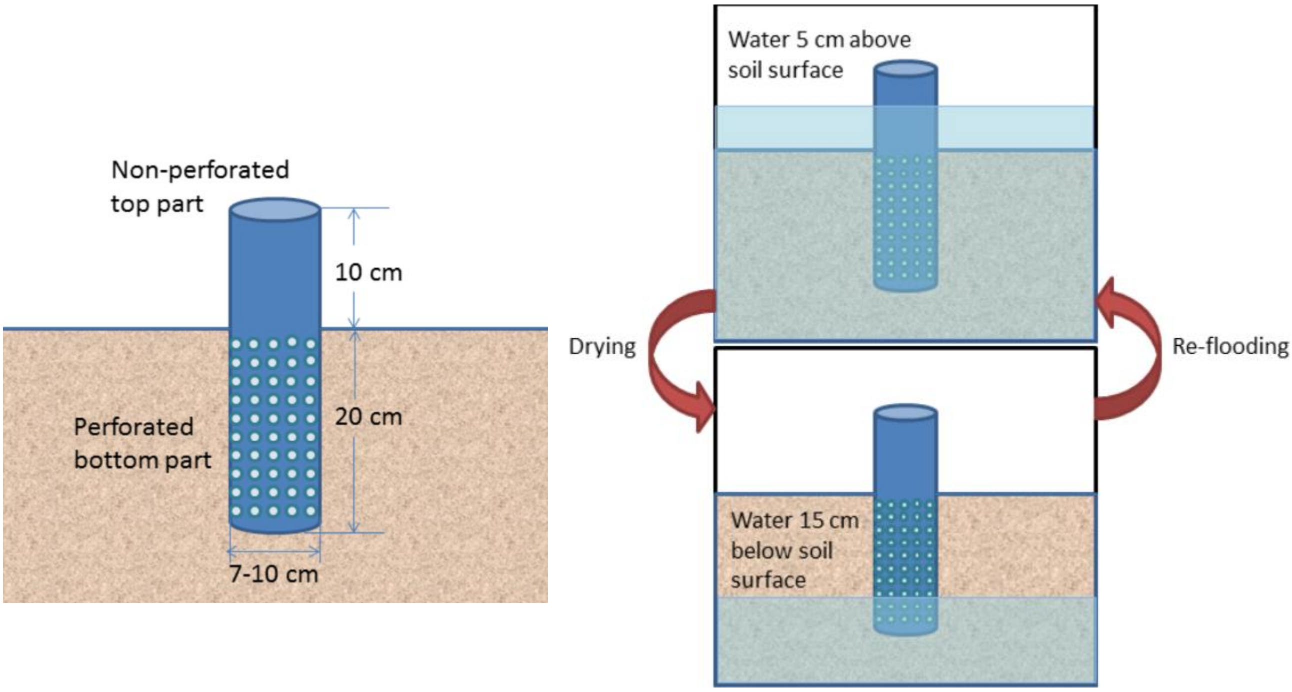

Figure 5 - Illustration of the AWD cycle with a “water tube”

1.2. Rice in Cambodia

1.2.1. General situation

In Cambodia, where our study is focused, rice production is very important. Indeed, the local climate and the location of the country on the course of the Mekong are great conditions for rice cultivation. In 2013, it represented 68% of all cropped areas. It is a very huge economic issue for farmers because they rely on their production to earn their income, and there are also big stakes at the national scale.

However, because of the conflict history of this country, its production restarted later than its neighboring countries as it is visible on figure 6).

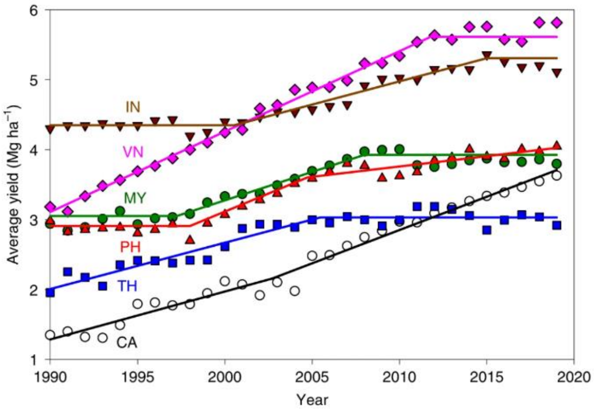

Figure 6 - Rice paddy yield of several South-East Asia countries between 2000 and 2019 (Yuan et al., 2022)

The agriculture is now developing rapidly, as other domains in the country. However, the country has one of the highest gap yields of South-East Asia, that is to say there is a very high difference between the actual yield, and the potential yield of rice, as we can see on figure 7.

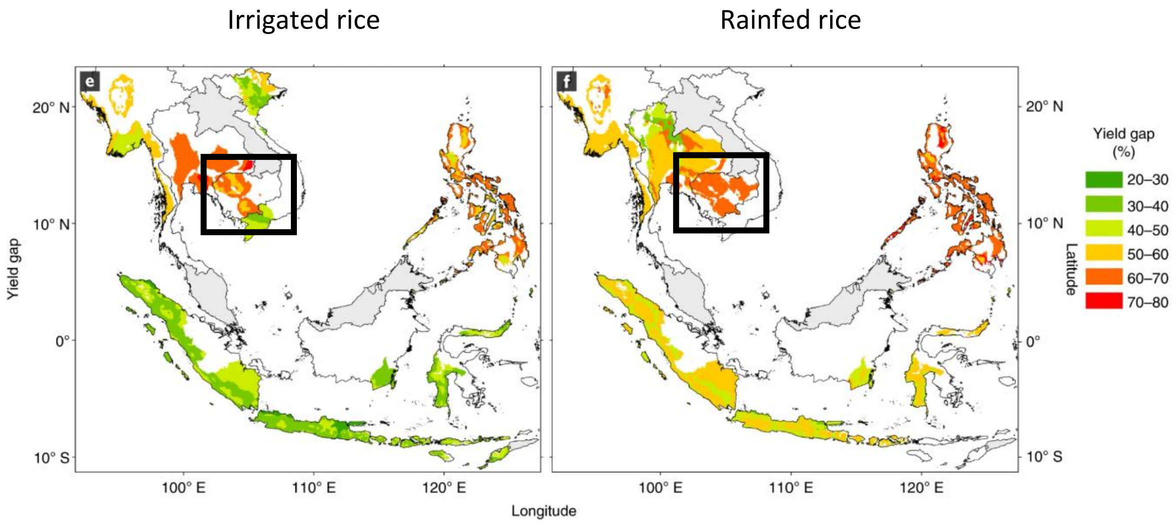

Figure 7 – Gap yield in South-East Asia (Yuan et al., 2022)

As the country is developing very rapidly in this post-war period, the government made a priority to encourage farmers to optimize their production and their yield to, for instance, reduce the gap yield.

1.2.2. Future issues

The policies that the government is trying to set-up also have another objective: to mitigate the effects of one of the biggest threats to Cambodia agriculture, climate change. Indeed, the country is very sensitive to climate change, and will face more and more high temperatures, droughts and unexpected floods because of the irregularity of rain. Several extreme meteorological events can even happen during the same rice cultivation cycle (Sok et al., 2021). Drought can limit the access to irrigation, and thus have an impact on rice production (Redfern et al., 2012). Floods are violent events that also reduce rice production, in addition to damaged housing, and risks for public health. Each of these events have a negative impact on rice cultivation and production, but also a more general impact economically for the farmers and the population.

According to the 6th Report of the IPPC, there is in the best-case scenario, a decrease of 4% in the rice potential yield, and in the worst-case scenarios, there is a 45% predicted decrease of rice potential yield for the year 2080. There is a very urgent need to set-up strategies to make rice cultivation more resilient in the face of climate change and ensuring harvests and incomes for farmers.

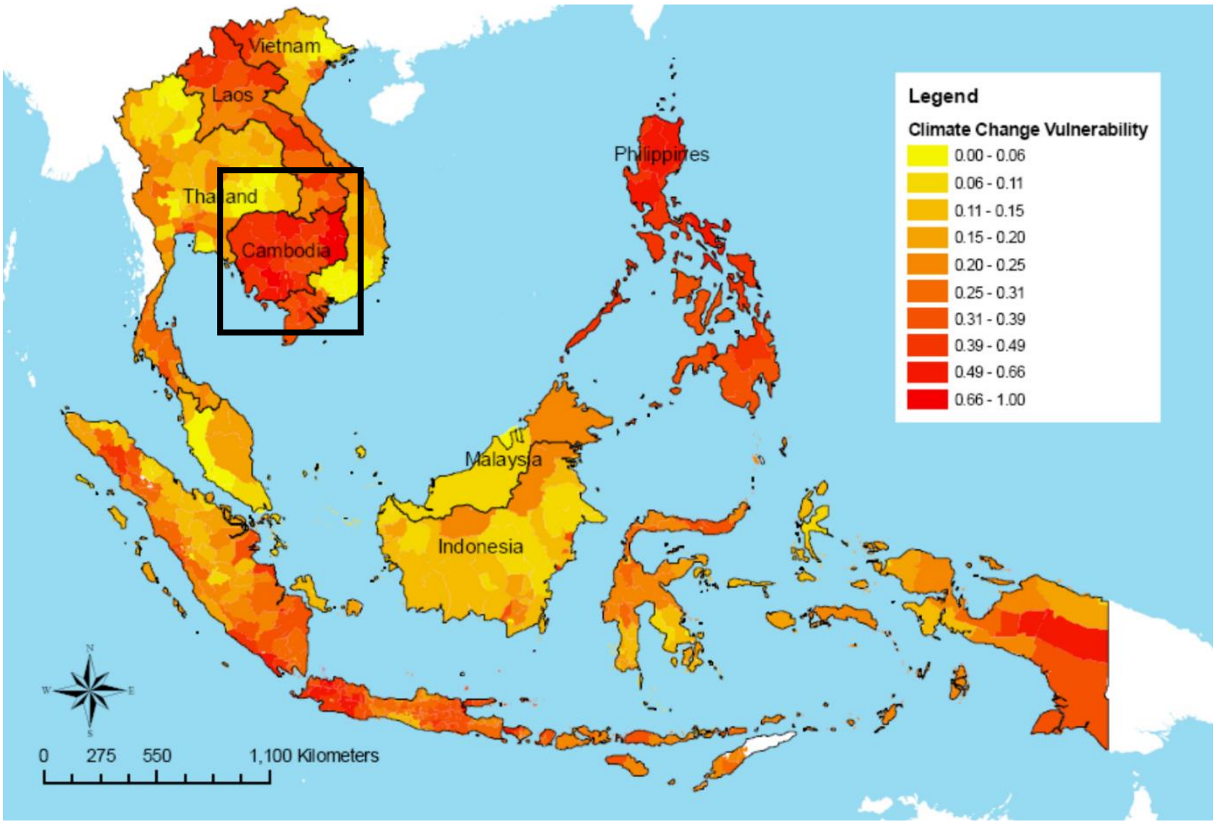

Figure 8 - Map of Climate Change Vulnerability in South-East Asia (IDRC, 2009)

In this light and with the objective to optimize the use of limited resources, especially water, modeling is very useful. It allows to simulate the outcomes of different inputs in the crop and find the best scenario to optimize the cultivation.

1.3. Modeling

1.3.1. AquaCrop

1.3.1.1. Introduction

In this study, we are going to use AquaCrop, a water-based model developed by the FAO to assess the effect of the environment on any crop. It was designed in a way that makes it very accessible and easy to use, so it can be used for research purposes, planification and policy making, but also directly by the farmers themselves.

AquaCrop is a good fit for our experiment because it is a very widely used and robust model. To function, it only needs a limited set of data, but it can function more precisely with a wider set of data. We could find all the data we needed to run the model precisely either from the litterature or from simple experiments.

1.3.1.2. Parameters

As shown in figure 9, the model is based on parameters about the soil-plant-atmosphere continuum, and the field management.

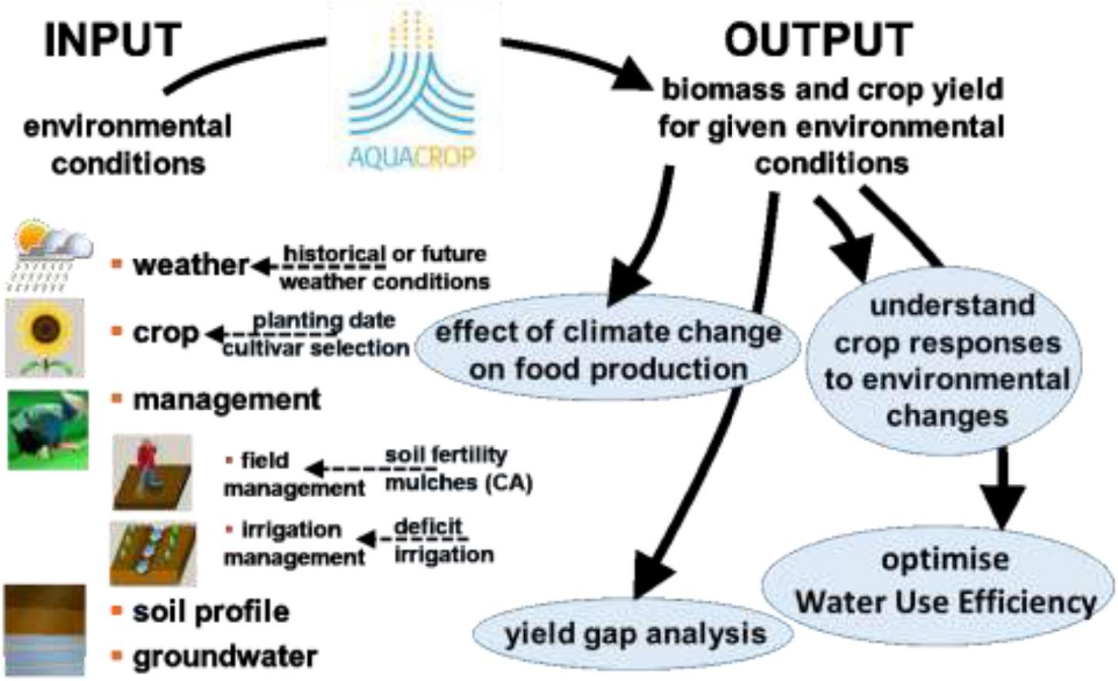

Figure 9 - Application of the AquaCrop model (UN, 2017. AquaCrop training Handbook)

AquaCrop estimates the yield thanks to a 4-steps calculation on a daily basis (if the data entered is of course daily): first, the development of green canopy cover is simulated, and the daily soil water content is useful to keep track of any water stress the plant might be encountering. Then, the crop transpiration is estimated, thanks to the reference evapotranspiration and a crop coefficient that is determined with the green canopy cover. With this data, the evolution of the above-ground biomass is calculated, and finally, with the harvest index the crop yield is calculated.

1.3.1.3. Literature review

AquaCrop is widely used for research purposes and has been calibrated and validated for many crops in many regions already. It usually has very good results and a good validation, for example Zhai et al. (2019) used it for rice in China, Amiri et al. (2022) about wheat in Iran, Sandhu et al. (2015) about rice in India, Ket et al. (2018) about lettuce in Cambodia, Farahani et al. (2007) about cotton in Syria, Saadati et al. (2011) about rice in Iran, etc.

However, some other studies also find that under water stress, AquaCrop can be less accurate. For example, according to Gimenez et al. (2017) who studied soybean in Uruguay, the actual evapotranspiration term $T_{c\,act}$ was underestimated, leading to some differences between the model output and the field data.

According to Chreok et al. (2017), a study lead in CARDI on maize, AquaCrop simulates fairly well the well irrigated scenario, but the performance of the model for the less irrigated treatments was not as good.

Several studies like these express the lack of accuracy of AquaCrop as the water stress intensifies: Greaves et al. (2016) say this about maize in Taiwan, Heng et al. (2009) about maize in Texas, Florida and Spain and they affirm that this lack of accuracy happens especially when the water stress happens during the senescence.

In our study we will focus on irrigated rice in Cambodia, and we will compare several irrigation regimes (with and without irrigation deficiency) and mod all the scenarios on AquaCrop. We will see how the water stress impact the output of the model and the crop in the field.

1.4. The study

1.4.1. Context

The practical part of the study was conducted in Cambodia, on three experimental sites that are represented with a red spot on the figure 10 below.

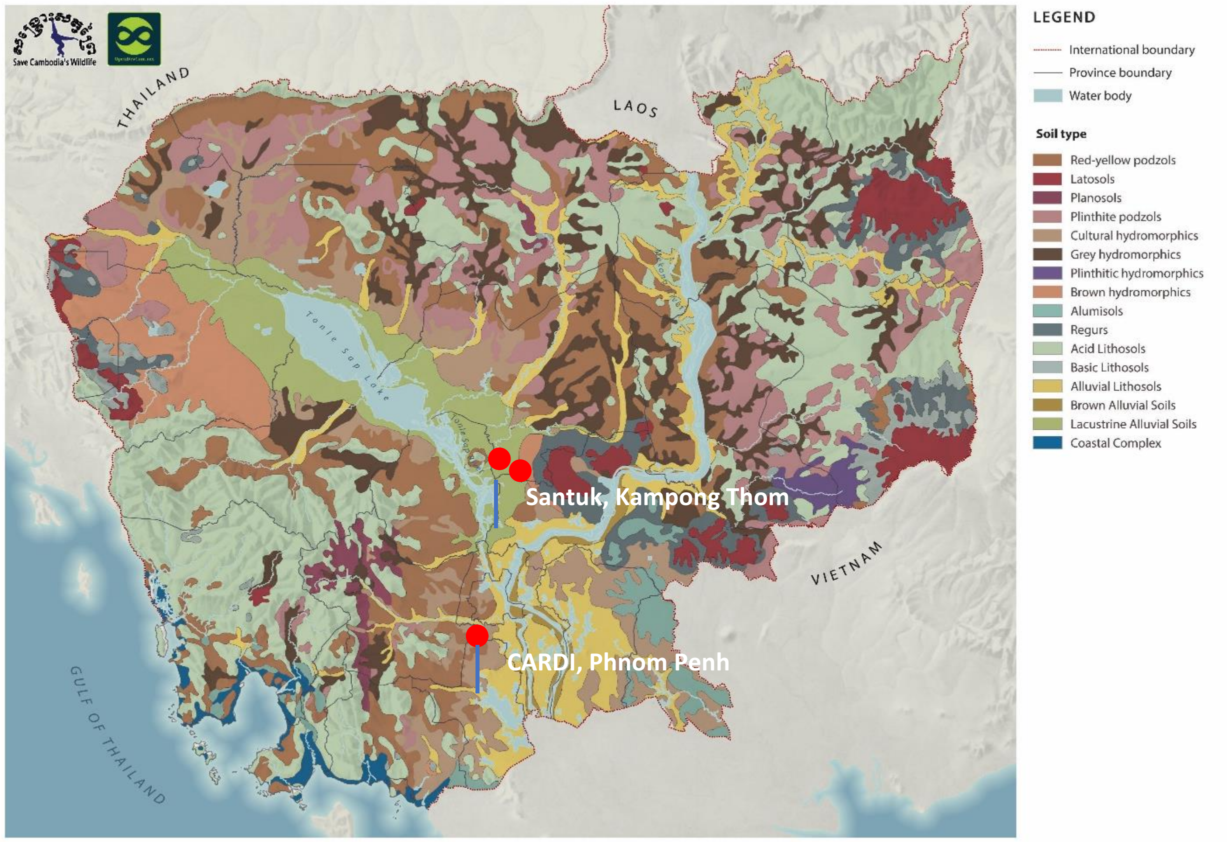

Figure 10 - Soil map of Cambodia (CROCKER, 1962)

The climate in Cambodia is a tropical climate, as shown on the ombrothermic diagram in figure 11.

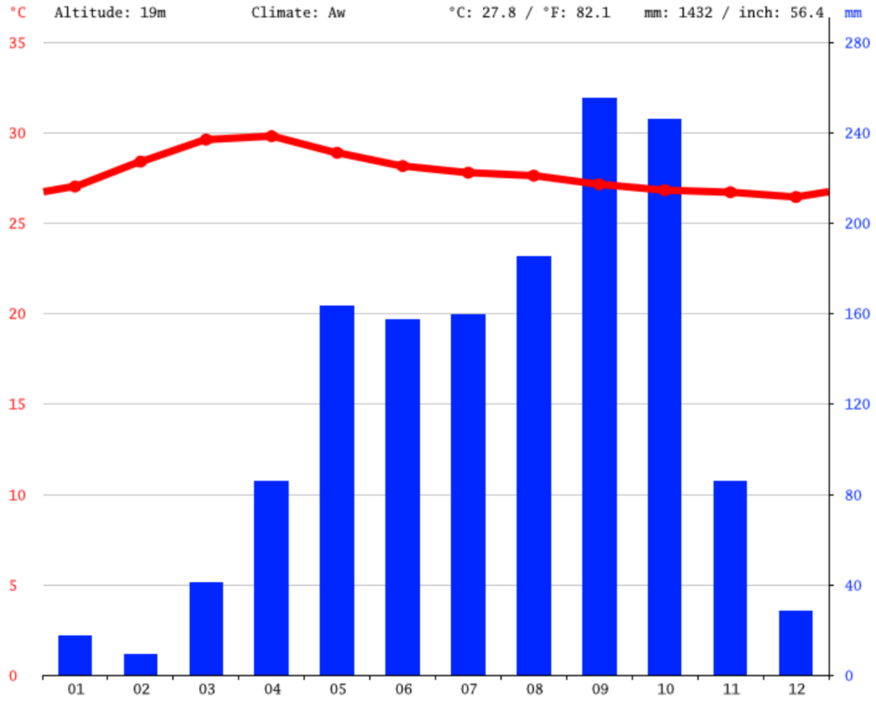

Figure 11 - Ombrothermic diagram of Phnom Penh (Climate data, 2022)

1.4.2. Objectives

In the earlier part of the PhD related to this study, it has already been shown in CARDI that AWD15 irrigation doesn’t cause a significant loss in yield compared to CF irrigation for four cultivars tested, and allows to save a lot of irrigation water.

The objective of the present study is to study different scenarios in CARDI and Kampong Thom with varying parameters: the irrigation regime, the cultivar and the soil.

One particular objective is to see how far it is possible to go in the AWD before suffering a yield loss. These scenarios are also modelled in AquaCrop to observe the fitting of the model and try to reach a better precision in the modelling of irrigation stress.

The main question that we will try to answer with this work is:

➔ Which scenario allows the best Water-Use Efficiency?

The specific objectives of this work are:

- Identify the most resistant cultivar to irrigation deficiency among the tested cultivars.
- Evaluate the precision of the AquaCrop model on growth and yield in a situation of deficit irrigation and try to find ways to refine the model.

These specific objectives are included in a more general framework with a general objective: Contribute to strengthen the resilience of rice agriculture and the food safety of Cambodia in a context of climate change.

Chapter 2

***

Material and methods

2.1. Material

2.1.1. Vegetal material

Four rice cultivars were used during this study, but we will focus the modeling part on the two cultivars that are known to be more resistant to irrigation deficiency: Sen Pidor and CAR15.

They were both developed by the International Rice Research Institute (IRRI) and released in Cambodia by CARDI, after some adaptation tests for the local climate. They are both high yielding varieties, which means that they produce a yield that is in average 18% superior to the mean farmers' yield.

The Sen Pidor cultivar is a non-seasonal aromatic rice, widely used in Cambodia. Indeed, it is one of the ten varieties promoted by the Cambodian government in their Rice policy since 2010, and currently represents 2% of all cropped areas in Cambodia (Pech, 2013). It is a fast-ripening variety (90 to 95 days) and it is adapted to dry conditions of cultivation. However, this cultivar isn't resistant to high heat. The yield potential of this cultivar (that is to say the yield that can be expected when the rice is grown in ideal conditions with no limits of water, nutrients and well controlled pests) is between 3,5 and 5,5 t/ha (Kimmarita, 2021).

The CAR15 (acronym of "Cambodian Rice") cultivar is also a high-yield variety that is increasingly used in several regions of Cambodia. It is also insensitive to water stress, and reaches maturity fast (90 to 95 days). This cultivar isn't resistant to high heat either. Still, it is resistant to many rice diseases including brown planthopper, rice blast and leaf blight which make this cultivar very interesting for cultivation. Its yield potential is up to 7,4 tons per hectare.

The cultivar OM5451 is a Vietnamese long grain rice, created by a crossbread combination of the varieties Jasmine 85 and OM2490. It is a high-yield variety, that reaches maturity fast (the growing cycle lasts 90 to 95 days) (Pinsei, 2021).

The latter, the Sen Kro Ob cultivar (which means "Fragrant" in khmer), also is a non-seasonal fragrant rice that is very demanded by consumers and thus allows a very good income to farmers. It currently represents 2% of total cropped areas in Cambodia and has a yield potential between 3,5 and 5,5 t/ha. Both of the last cultivars are known not to be resistant to dry conditions.

These four cultivars are very interesting as a group because of their growing importance in agriculture, and on an experimental point of view, their different characteristics will allow us to compare their resistance to several regimes of irrigation.

2.1.2. Measuring material

2.1.2.1. Sensors

2.1.2.1.1. Water level sensors

In addition to the manual measure of the water level, we had at our disposal four HOBO U20L-01 atmospheric sensors and data loggers to gain more information about what is going on in the soil. Three of them were placed in the experimental plots, and one was placed at the surface of the ground on the experimental site, for reference.

This model operates between 0 and 207 kPa, has a resolution of less than 0.02 kPa, which equals to 0.21cm. The average accuracy of this model is ±1cm, and the maximum error of this model is ±2cm. It has a factory calibration for a range of 69 to 207 kPa. Our measurements fall in this range so we didn't recalibrate the sensors in the lab.

2.1.2.1.2. Soil moisture sensors

We have used two Teros 12 sensors (visible in figure 12), produced by METER Group. These sensors measure the volumetric water content, the temperature and the electric conductivity. The Teros 12 sensors are based on the capacitance technique: the sensors will measure the dielectric permittivity of the soil thanks to an electromagnetic field. This value is then converted to the Volumetric Water Content (Θ) with a calibration equation that is specific to the substrate.

Figure 12 – Teros 12 sensor

The measurement frequency of these sensors is 70 MHz, and their volume of influence is 1,010 mL. The resolution of Θ measurement is 0.001 m^3/m^3, and the accuracy depends on the calibration. The manufacturer indicates that a soil specific calibration gives a better accuracy than the factory calibration, between ± 0.01 – 0.02 m^3/m^3. The soil specific calibration was conducted in the laboratory, following a detailed protocol featured in the annex.

The operational temperature range is -40 to 60°C with a resolution of 0.1°C and an accuracy of ± 1°C. Concerning the Bulk Electrical Conductivity (EC_b), the range of measurement is 0-10 dS/m, with a resolution of 0.001 dS/m and an accuracy of ± 5%.

2.1.2.1.3. Potential sensors

The second kind of sensors we used was the MPS-2, from Decagon Devices Inc. Since this company has been bought by METER Group, this sensor has been renamed Teros 21. It measures the water potential in the soil, as well as the temperature.

The water potential is the sum of the matric potential (that is to say the binding of water to surfaces), the osmotic potential (which is the binding of water by the solutes), the gravitational potential of the water and the pressure potential (in other terms the hydrostatic pressure on the water). It gives us information about the movement of water, because it always moves following a potential gradient, and also information about the energy that is necessary for the plant to extract the water from the soil. This data added to the soil moisture gives us information about the availability of the water to the plant.

The range of the sensor is -9 to -100000 kPa for the water potential and the resolution of the measurement is 0.1 kPa. The accuracy of the MPS-2 is ± (10% of the reading + 2 kPa) from -9 to -100 kPa. The measurements of this sensor are based on a dielectric measurement that is converted to water potential. The factory calibration of the MPS-2 is performed on the drying side of the hysteresis loop so the measurements are more accurate when the soil is drying than when the soil is wetting up. This phenomenon of hysteresis will imply that the measurements as the soil wets up are a little more negative than the reality of the water potential in the soil. The manufacturer affirms that this error is smaller than 10 kPa in the -20 kPa to -100 kPa range.

Concerning the temperature, the operating measurement range is 0°C to 60°C with a resolution of 0.1°C and an accuracy of ± 1°C.

Both the water moisture and potential sensors are connected to a Em50 datalogger from Decagon Devices Inc.

2.1.2.2. Soil data

2.1.2.2.1. Saturated hydraulic conductivity

We measured the saturated hydraulic conductivity with a KSAT instrument from METER Group (represented in figure 13). Firstly, we prepared and saturated our field samples, and placed them in the metal ring, in the device. The measurements were made with the falling head technique, which means that the burette is filled with water at the beginning of the experiment, and then the water goes through the sample, without the burette being refilled. The pressure sensor measures at very small intervals the pressure head and derives the K_{sat} value from it. The data was collected through the KSAT application.

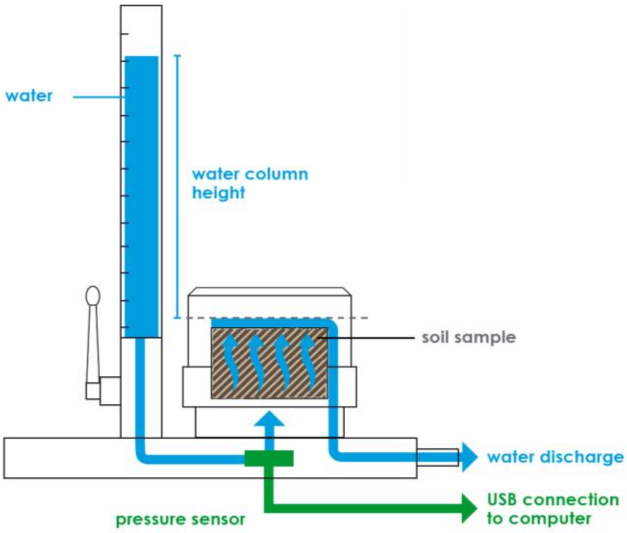

Figure 13 - Sketch of the principal elements and functioning of the Ksat machine (METER Group)

After a while, the Ksat measurement device started leaking due to some wrong use. It was then impossible to finish our measurements with this machine, so we built a device (in figure 14) that allowed us to measure the Ksat, with the constant head technique.

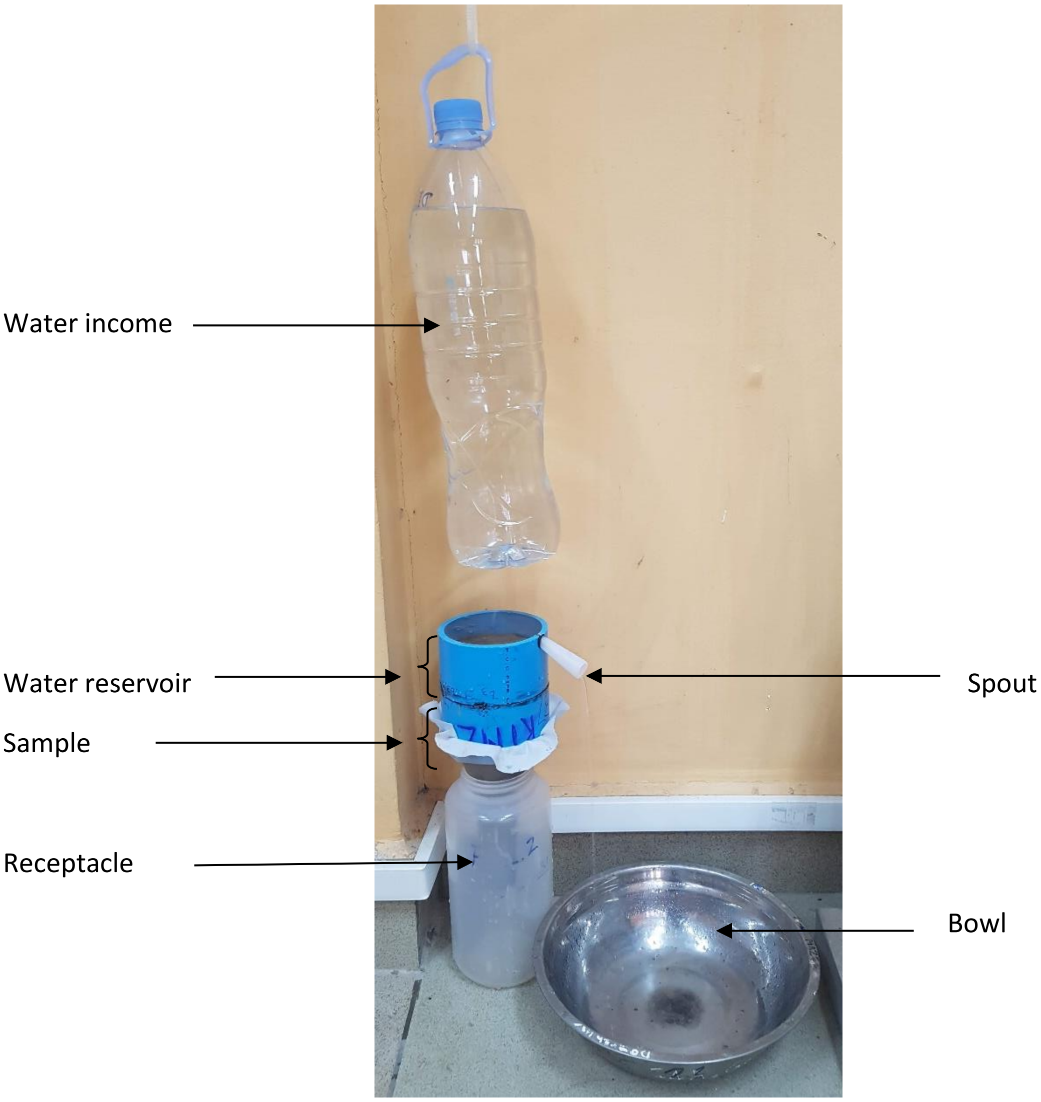

Figure 14 - Picture of the experimental set-up to measure the Ksat

In this set-up, the water comes down from the bottle very slowly, as in a drip irrigation system. To keep a constant level of water in the reservoir, we inserted a spout, and we made sure that the water is constantly flowing from it. Under this reservoir with a constant level of water and thus, a constant pressure, there is the previously saturated soil sample. The connection between the reservoir and the sample is watertight thanks to a silicone seal.

The water will flow through the sample and end up in the receptacle under. With the volume in the receptacle at the end of the experiment, and its duration, we can calculate the Ksat (in cm/day) with the Darcy equation (1856):

$$Q = \frac{KA(h_1 - h_2)}{L}$$

With Q being the total discharge, A the area of the sample, K the hydraulic conductivity, $(h_1 - h_2)$ the hydraulic head gradient along the flow direction, and L the length of the soil sample.

2.1.2.2.2. Water Retention Parameters

We also needed to determine some parameters about the water retention in the soil. The Permanent Wilting Point (PWP) is the moisture of the soil at -1500 kPa and it corresponds to the minimum amount of water needed in the soil for a plant not to wilt. The Field Capacity (FC) is the moisture of the soil at -33 kPa and it represents the moisture of the soil when the excess water has been drained by gravity. Finally, the saturation (SAT) is the moisture of the soil at 0 kPa of suction pressure.

Figure 15 - Samples in the pressure plates

We prepared our samples (see fig. 15) and saturated them. Then we put them under different pressures until they reached an equilibrium. At each stage, we measured their weight to see how the samples were conserving the water under different pressures. We worked with Θ to stay coherent with the measured data in the experiments and the model. We performed the experiment for the following pressures: 6.895 kPa, 13.79 kPa, 20.685 kPa, 27.58 kPa, 34.475 kPa, 48,265 kPa, 68.95 kPa, 103.425 kPa. These measures allowed us to build a water retention curve, and from it determine the PWP and the FC of our soils.

2.1.2.2.3. Bulk density

The bulk density was calculated with undisturbed samples taken from the field in metal rings. The samples were prepared and dried at 105°C during 24h. The bulk density was then calculated as:

$$\rho_b = \frac{m}{v}$$

With m being the dry mass of the sample in g and v being its volume in cm^3.

2.1.2.3. Other

To weight our samples, we used a OHAUS Pioneer balance with a precision to the thousandth and a linearity deviation of ± 0,002g.

2.2. Method

The cultivars that are studied here were cultivated on three different sites, which all have different soils. Three surface irrigation regimes are tested among these experiments: Constant Flooding (CF), Alternate Wet and Dry 15 (AWD15) and Alternate Wet and Dry 20 (AWD20), where the crop is re-irrigated when the water level reaches, respectively -15cm and -20cm below the ground.

In all the experiments, AWD was conducted during a restricted period between the stages of panicle initiation and flowering (around 30 days during the reproductive stage) as they are sensitive to water stress, so CF was conducted during these stages.

2.2.1. The experimental set-ups

2.2.1.1. Kampong Thom - Site 1

2.2.1.1.1. Experimental design

The first experimental site is located in the Kampong Thom province near the city of Santuk. It is a field owned by a local farmer who collaborates with ITC, and the whole plot is dedicated to the experiment. In figures 16 and 17 below is represented the experimental design of this site.

Figure 16 - Picture of the first experimental site in Kampong Thom (20/04/22)

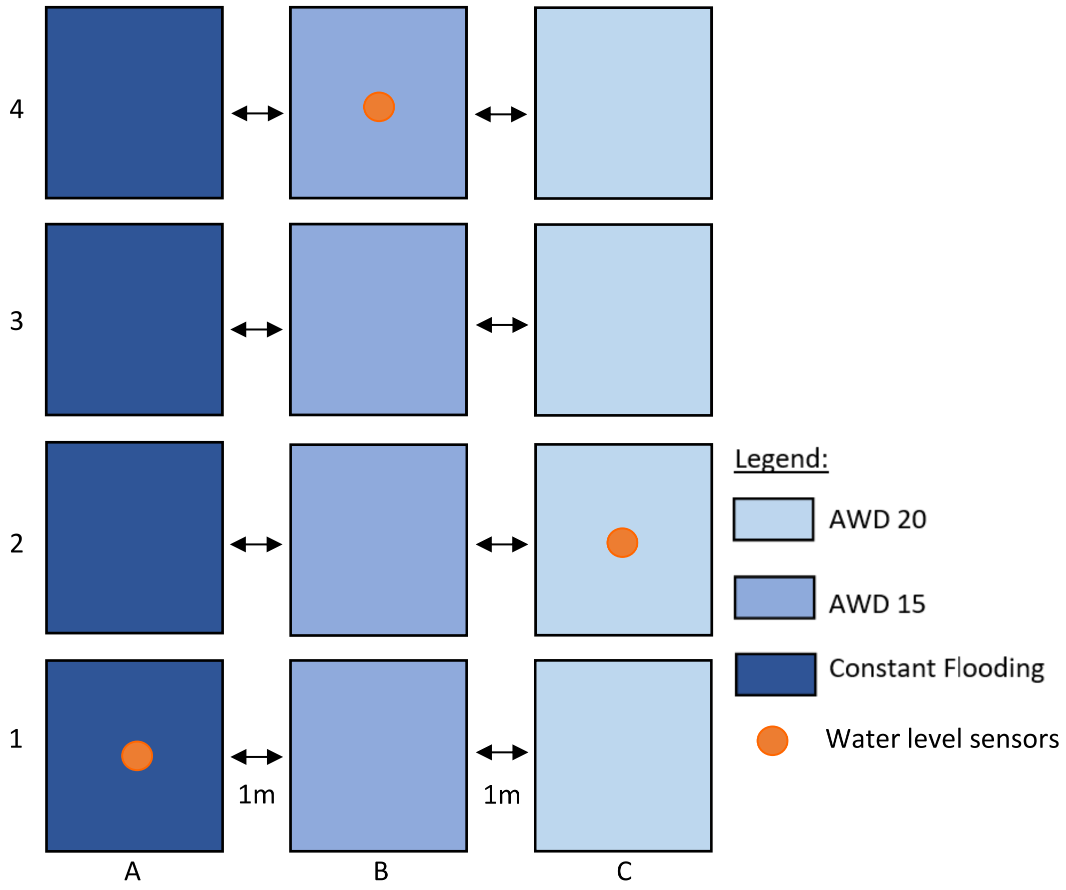

Figure 17 – Layout of the experiment in Kampong Thom, Site 1

In this experiment, three irrigation regimes are tested on the cultivar CAR15 which was planted in all the plots of 25m².

Two doses of fertilizer were applied during the span of the growth of the rice, as shown in figure 18. Both doses were 1,2 kg/plot of NPK 46:00:00.

Concerning the pesticides, one product was applied against the golden apple snail, which is an invasive species from South America that can cause a lot of damage in rice crops. The product was applied 1 day after the transplant, 7 days after the transplant and again 14 days after the transplant. Another product was applied against brown plant hopper 35 days and 45 days after the transplant.

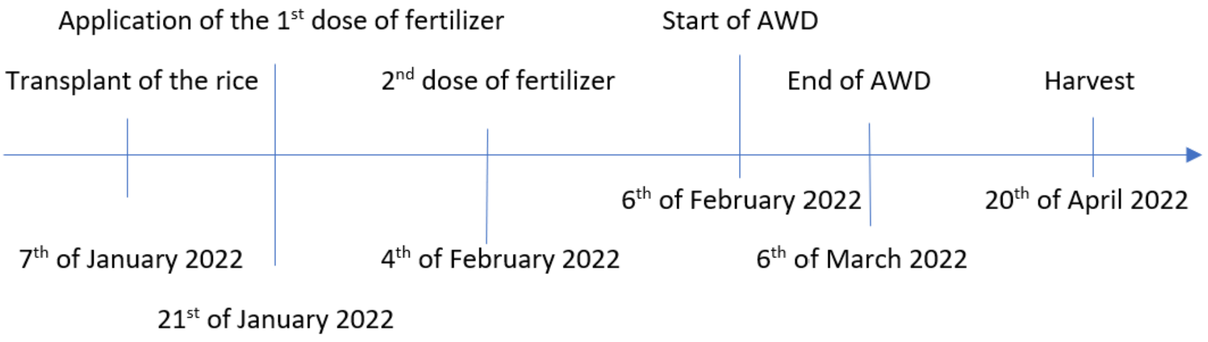

Figure 18 - Timeline of the experiment in Kampong Thom, Site 1

2.2.1.1.2. Soil properties

The soil of this site is composed of three horizons as shown in figure 19.

Figure 19 - Soil profile of the first experimental site in the Kampong Thom province (02/03/22)

In all the experimental sites, we took 3 undisturbed soil samples from each layer to perform analyzes in the laboratory. In order to get these samples, we dug carefully at the desired depth to take the samples. We then placed plastic rings ($\o = 20cm$) and hammered all around the ring to finally excavate it with a knife. We covered the samples to transport them into the lab where we prepared the samples by digging several smaller rings to perform the desired analyses (Ksat, pF curve and bulk density) and proceed with their respective protocol.

2.2.1.2. Kampong Thom - Site 2

2.2.1.2.1. Experimental design

The second experimental site is a farm, owned by a local farmer, close to Site 1. He works in collaboration with ITC and half of his land is used for the experiments. The figure below shows the experimental design of this experiment.

Figure 20 - Picture of the second experimental site in Kampong Thom (02/03/22)

In this experiment, we also tested three irrigation regimes on the cultivars CAR15, in the 25m² plots.

The ranks were separated by a plastic tarpaulin (here represented by the black lines between the ranks on figure 21) so that the different irrigation regimes were really isolated, and to be sure that the water wouldn't flow from one rank to another.

Two doses of fertilizer were applied as well as shown on the schedule in figure 22. Both doses were 1,2 kg/plot of NPK 46:00:00, mixed with natural manure.

Concerning the pesticides, one product was applied against the golden apple snail on three occasions: 1 day, 7 days and 14 days after the transplant. Another product was applied against brown plant hopper 35 days and 45 days after the transplant.

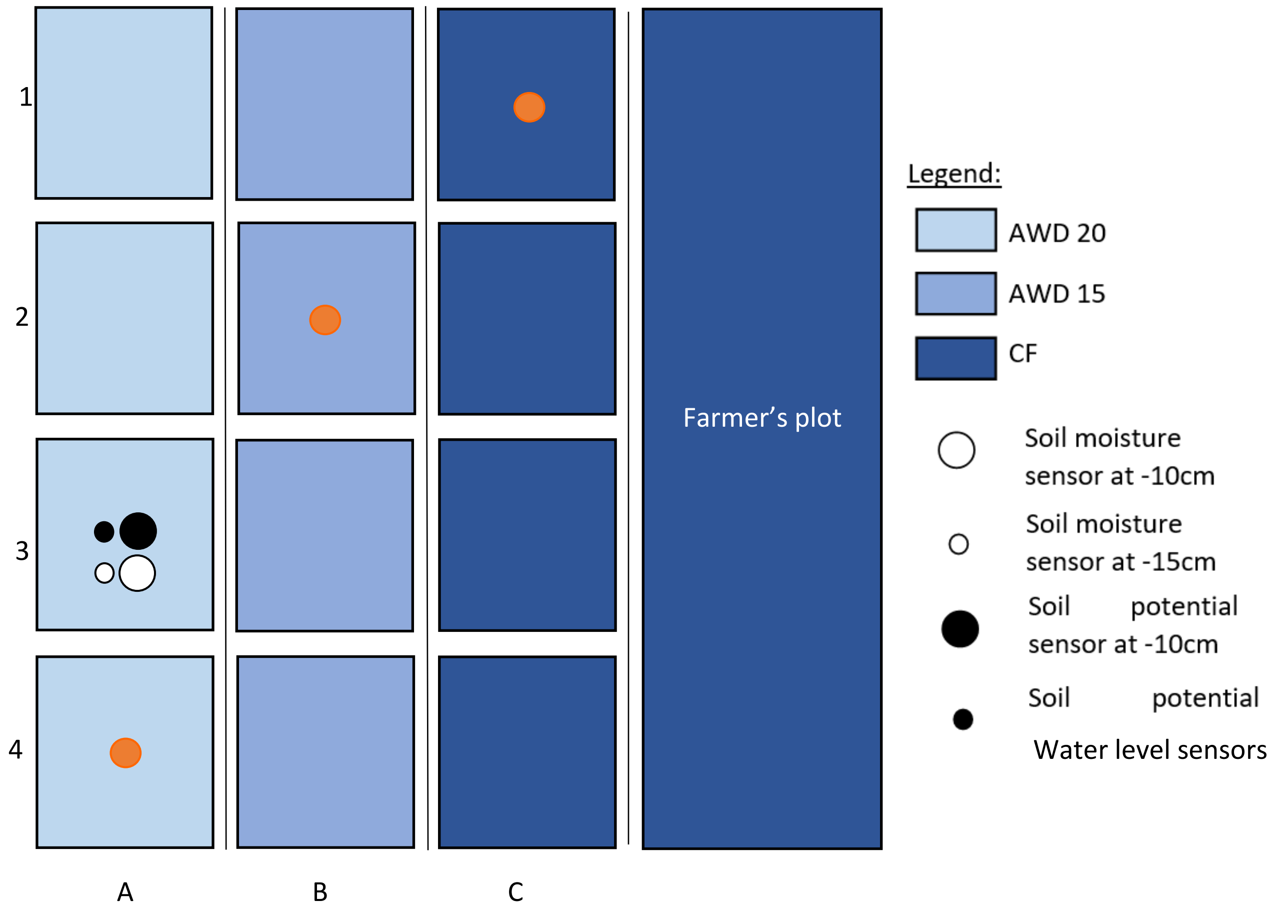

Figure 21 - Layout of the experiment in Kampong Thom, Site 2

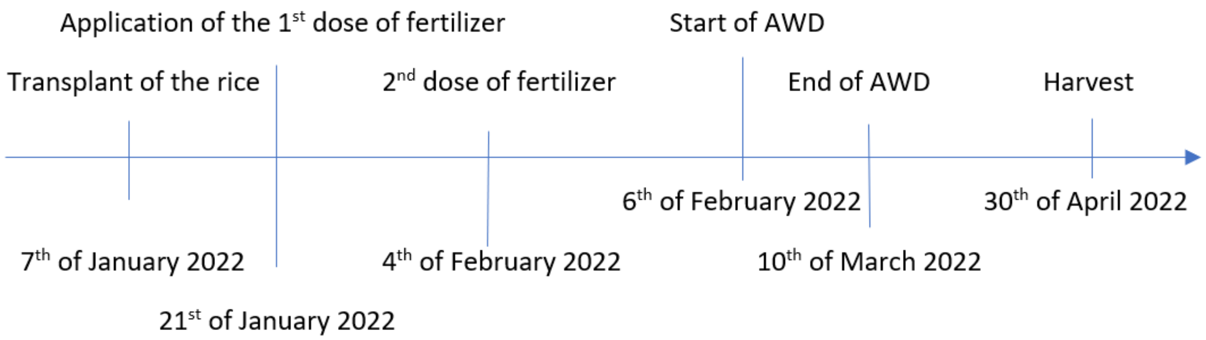

Figure 22 - Timeline of the experiment in Site 1 in the Kampong Thom province

2.2.1.2.2. Soil properties

The soil of this site is composed of three horizons, as shown in figure 23.

Figure 23 - Soil profile of the second experimental site in the Kampong Thom province (31/03/22)

The weather data of both sites was collected thanks to a weather station close by. This station collected data of sun radiation, relative humidity, precipitation and air temperature (minimum and maximum). With this data, the ETo was calculated thanks to the ETo calculator (FAO).

2.2.1.3. The experiment in CARDI

The experiment in CARDI was conducted two years in a row, both times with the same experimental layout.

2.2.1.3.1. Experimental design - 2021

In CARDI, the experiment contained 12 AWD15 plots and 12 CF plots of 25m² each. Four rice cultivars (OM5451, Sen Kro Ob, Sen Pidor and CAR15) were introduced, with a random repartition, duplicated in the CF and AWD plots. The plots were separated by bunds deep of 30-40 cm. The CF and AWD plots were separated by 4 meters so that the AWD plots are not influenced by the CF ones.

In both experiments, three doses of fertilizer were applied. The first dose was applied one day before the transplant. This dose contained 0,5kg per plot of NPK 46:00:00, 0,8 kg per plot of NPK 18:46:00 and 1,1 kg per plot of NPK 00:00:60. After this, one dose was applied 14 days and 28 days after the transplant. Both doses were 1,2 kg/plot of NPK 46:00:00.

This fertilizer application fits CARDI very well, as in this site, the available N and P are very low, but the available K is very high.

Concerning the pesticides, one product was applied against the golden apple snail on the first day, the 7th day and the 14th days after the transplant. Another product was applied against brown plant hopper 35 days and 45 days after the transplant.

On figures 24 to 28 are the experimental layouts and the timelines of the 2021 and the 2022 experiments in CARDI.

Figure 24 - Picture of the experimental plots in CARDI (16/03/22)

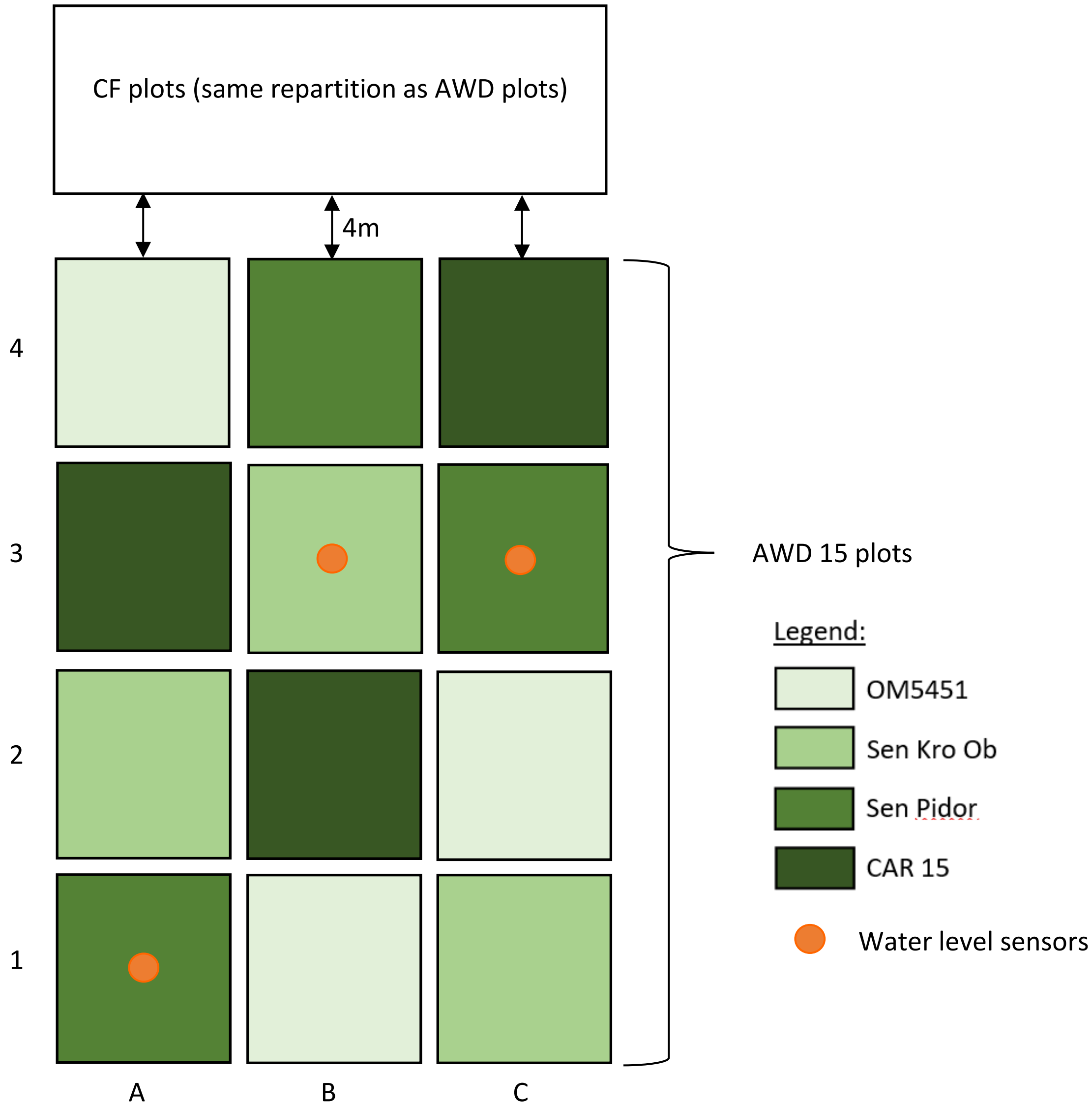

Figure 25 - Layout of the CARDI experiment conducted in 2021

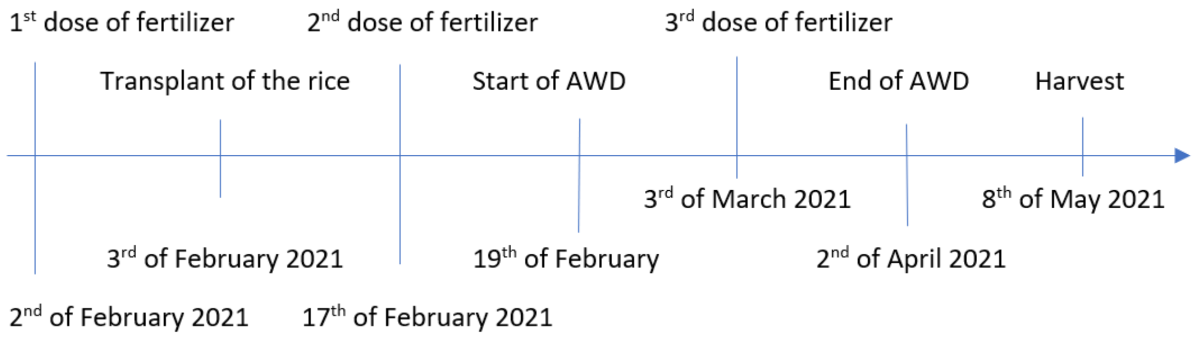

Figure 26 - Timeline of the experiment in CARDI in 2021

2.2.1.3.2. Experimental design - 2022

The CARDI experiment of 2022 is similar to the 2021 experiment. It has the objective to get a bigger and more accurate set of data.

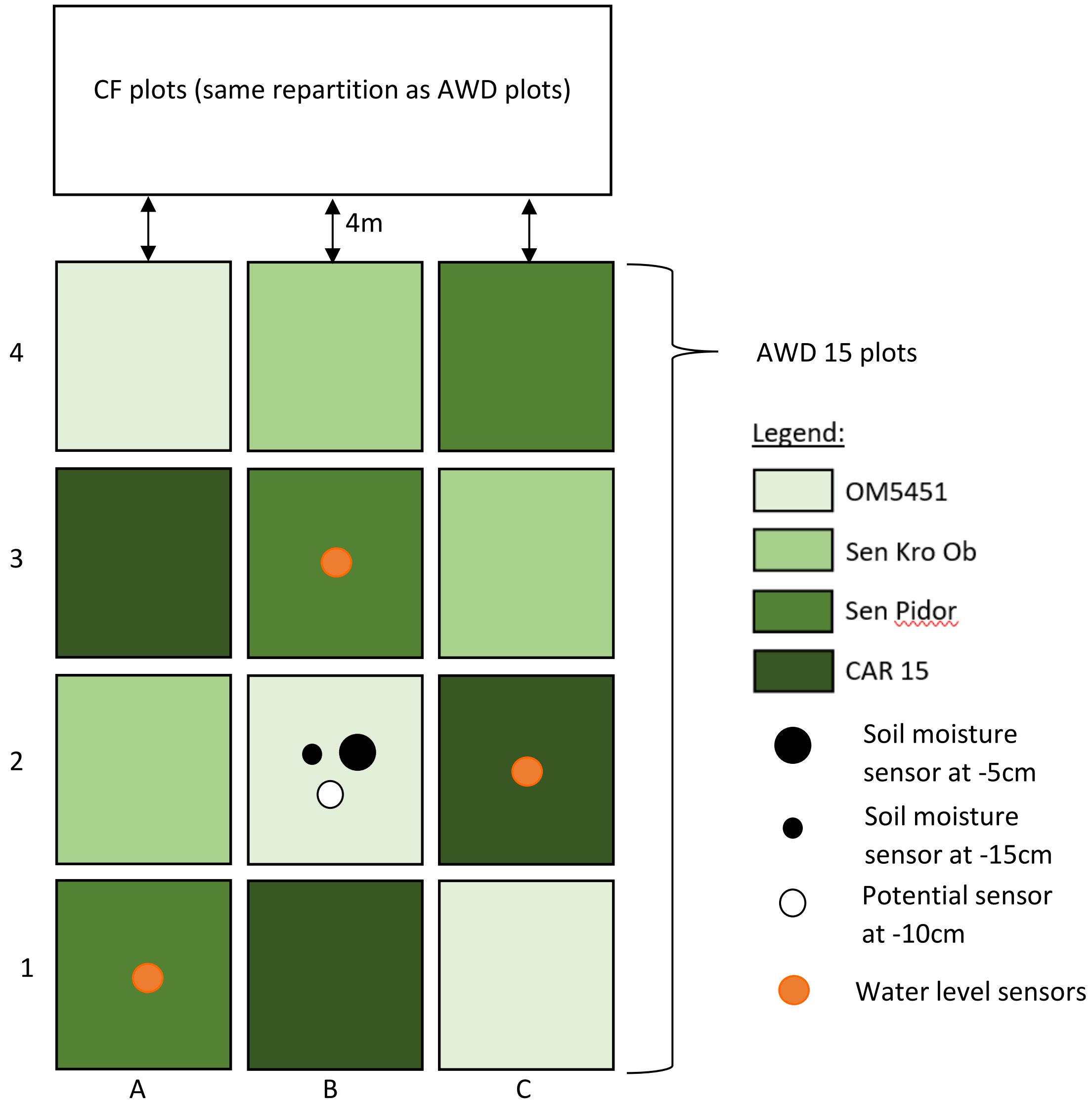

Figure 27 - Layout of the CARDI experiment conducted in 2022

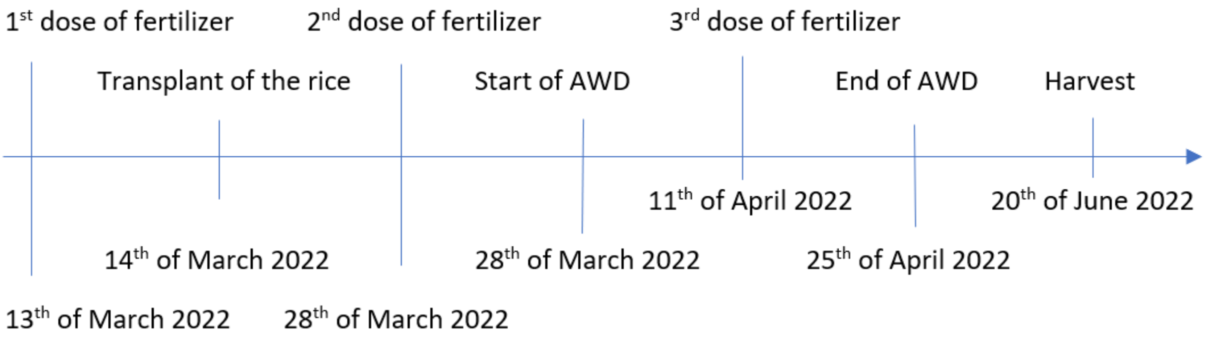

Figure 28 – Timeline of the experiment in CARDI in 2022

2.2.1.3.3. Soil properties

The soil in CARDI has three observable horizons, as shown on figure 29.

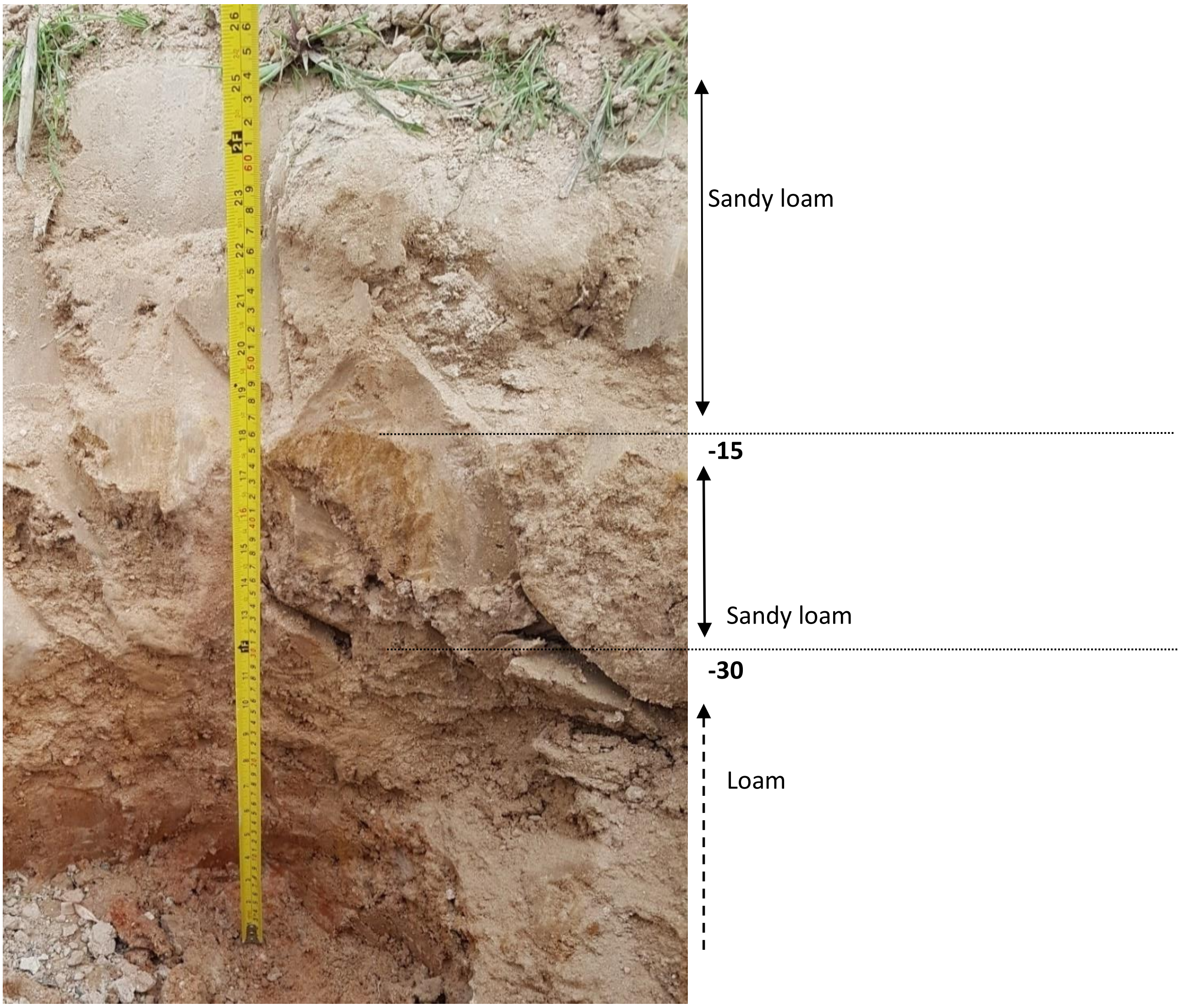

Figure 29 - Soil profile of CARDI (16/03/22)

In the CARDI center, there was an automated weather station that collected data about air temperature (minimum, average and maximum), the dew point, solar radiation, relative humidity, precipitation and wind speed, and the station software directly calculated the ETo.

The table below recaps all the parameters of the different scenarios that we will compare.

Table 1 - Recap of the parameters of the scenarios among the experiments

Parameter	**Kampong Thom S1**			**Kampong Thom S2**			**CARDI**							
Soil types	Sandy loam and sandy clay			Sandy clay loam, clay loam, clay			Sandy loam, loam							
Cultivars tested	CAR15			CAR15			CAR15		Sen Pidor		Sen Kro Ob		OM5451	
Irrigation regimes tested	CF	AWD 15	AWD 20	CF	AWD15	AWD20	CF	AWD 15	CF	AWD 15	CF	AWD 15	CF	AWD 15
Presence of sensors	None			2 moisture sensors + 2 potential sensors			2 moisture sensors + 2 potential sensors							
Fertilization	2 doses of NPK 46:00:00			2 doses of NPK 46:00:00 mixed with natural manure			1 dose before the transplant and 2 doses of NPK 46:00:00							

2.2.2. Monitoring of the experiments

In all sites, the water level was regularly monitored manually, in addition of the water level sensors. Unfortunately, during the AWD period, some pipes ended up getting blocked with the solidification of the soil. This reduced the accuracy of the measurements, but it didn't happen in all of the pipes and when it was noticed, we unplugged the pipes.

When a plot had a water level under -5cm, we took soil samples at the depths of -5cm and -10cm to monitor the evolution of soil moisture. When the water level was higher, the soil was saturated so we didn't take samples.

When the water dropped to the critic AWD level, irrigation took place. The plots were irrigated up to 50mm (in average) above the surface thanks to pumps. The bunds between the plots were open during the irrigation so that the water could flow from one plot to another, and the bunds were closed once the irrigation was done.

The canopy cover was monitored weekly thanks to pictures. Three pictures were taken vertically for each plot at a height of approximately 1.5m above the crop. The covered area is about 1.5mx2m. The pictures were analyzed on PhotoShop to determine the canopy cover area (Aide et al., 2007). The pictures can be cropped to limit the area, and the supervised classification of pixels can be performed with the magic wand tool.

The biomass was collected every two weeks on 1m² in the outer border of the plot as shown in figure 30. The collected biomass was then dried 48h at 70°C in the oven, to finally be weighted in the lab.

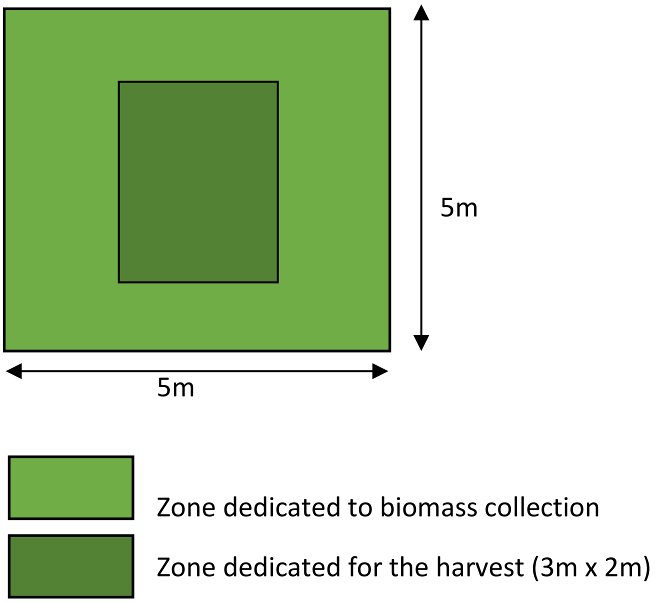

Figure 30 – Sketch of the zones dedicated to biomass collection

In CARDI, the pan evaporation was manually measured in addition to the automatic measures of the weather station. Also, the CARDI experiment of 2022 took place at the end of the dry season, so we faced many raining episodes. In order for the rain to disturb the experiment as little as possible, the water was drained from the AWD plots after it rained.

2.2.3. Harvest

All the harvests in the experimental fields happened the same way, the same parameters were collected. Here is the harvest protocol of the Site 1 in Kampong Thom that took place on the 31st of March of 2022 as an illustration.

We randomly harvested 10 hills (in CARDI, 5 hills) per plot in a 6 m² intact area in the center of the plots (to avoid border effect). These 10 hills (5 hills in CARDI) were cut at the base of the plant and the plant height was measured from the base to the tip of the highest panicle.

Among the hills harvested for each plot, we randomly took a sub-sample of 3 panicles to count the number of spikelets per panicle. Among this total number of spikelets, we counted the number of filled and unfilled spikelets by squeezing them.

We counted the number of panicles in each hill for all the plots and then hand-threshed the 10 hills (resp. 5 hills in CARDI) as shown in figure 31 to obtain the grain yield.

We then harvested the whole 6m² areas and hand-threshed the plants to obtain the biological yield.

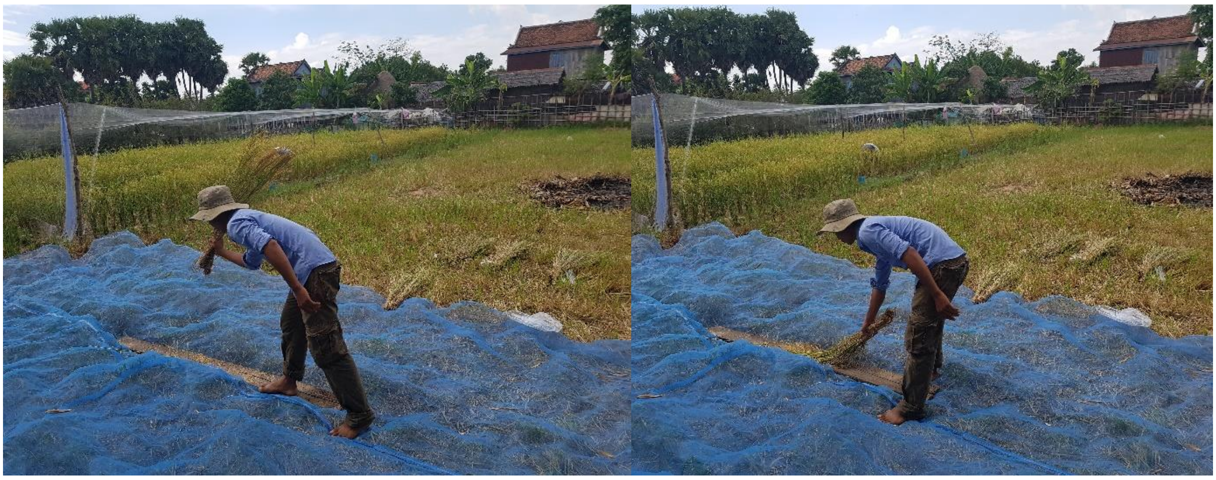

Figure 31 - Hand-threshing of the 10 hills per plot (31/03/22)

With this data, we approximated the total number of spikelets (ø) as:

$$TS = SP \times PM$$

With TS being the total number of spikelets (ø), SP the number of spikelets per panicle (ø) and PM the number of panicles per m^3 (ø).

We also calculated the harvest index (%) with the following formula:

$$HI = \frac{P}{b} \times 100$$

With P being the weight of filled spikelets (g) and b the aboveground total biomass (g).

Dry weight of straw, rachis, filled and unfilled spikelets were determined after drying in the oven at 70°C until the samples reached a constant weight (this took 2 days).

Aboveground total biomass was the total dry matter of straw, rachis, and filled and unfilled spikelets.

The grain yield was determined with the harvest of 6 m² area in each plot and was adjusted to the standard moisture content of 0.14 g H2O g-1 fresh weight.

We also measured other parameters, such as root depth, by digging into the soil in one plant per plot, so we have 4 root depths per cultivar (3 in CARDI). We determined the depth of the effective root zone by observing the zones of high concentration of roots (see fig. 32).

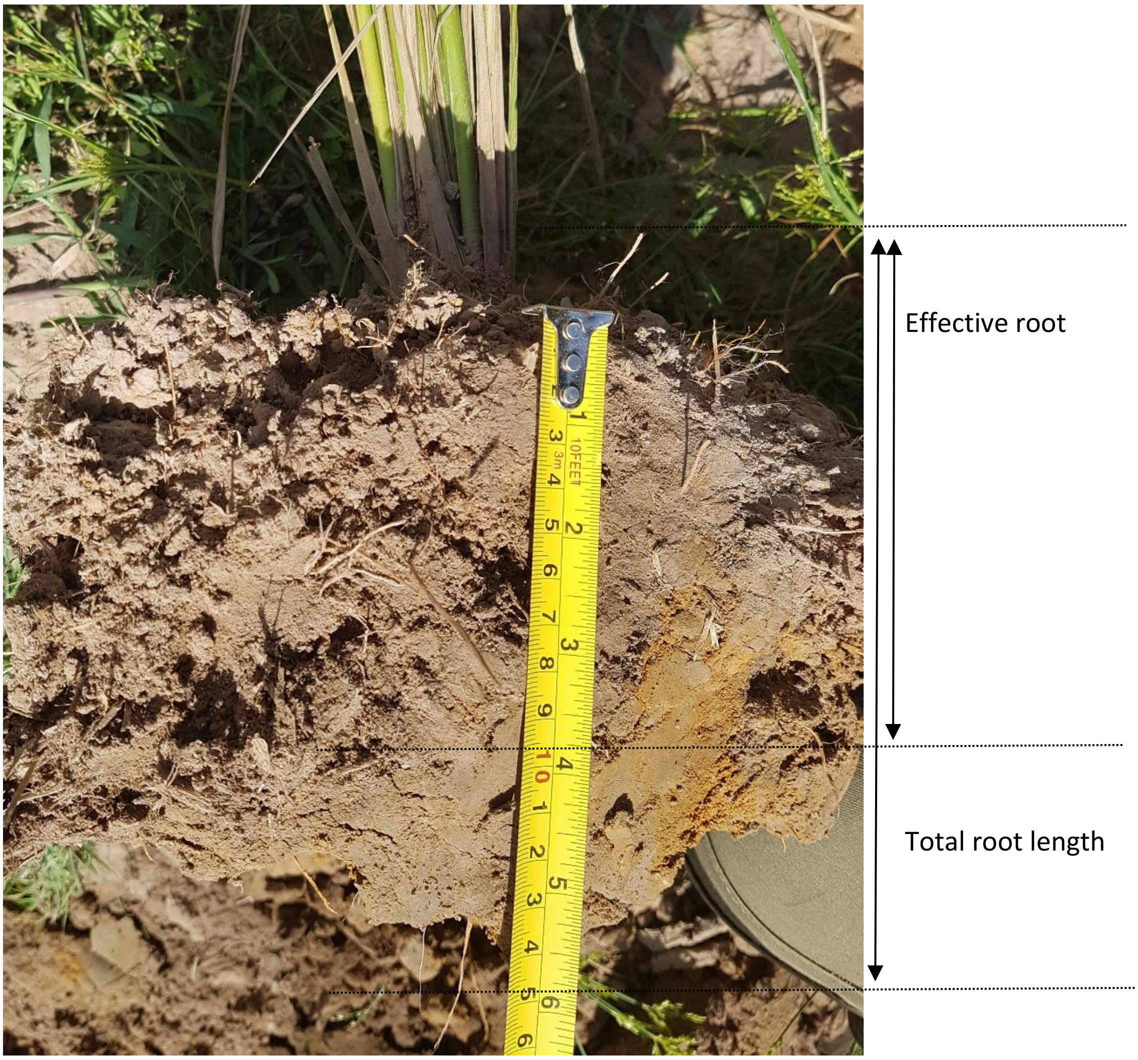

Figure 32 - Measurement of the root depth (31/03/22)

The water-use efficiency is the criteria that we used to compare different scenarios. The WUE is a good indicator in this case because it takes into account the necessity to optimize the production that is achievable with every m^3 of water in a context of climate change and water scarcity. Thanks to this equation, we can determine which scenarios allows the highest yield per m^3 of water received in the field.

$$WUE = \frac{Y}{IR + P}$$

Where *Y* is the economical yield in kg, *IR* the depth of irrigation applied and *P* the precipitation, both in m^3 (Kambou et al., 2014).

2.2.4. Statistical analysis

The results were processed with the R (version 4.0.3) software.

The objective of this analysis was to observe the effect of the main parameters (soil and fertilization, irrigation, cultivar) and determine if they were significant or not. To do this, we used several ANOVAs.

Firstly, to assess the effect of the irrigation, we compared data from different sites. In order to have a complete experiment, we used data in all sites, concerning the CAR15 cultivar (which is present in all the sites) with the regimes CF and AWD15. As we performed this analysis in all the sites, we had to consider the effect of the soil and fertilization, so a two-way ANOVA was realized.

To go deeper in the analysis of the effect of irrigation, we used both Kampong Thom experiments to compare the 3 regimes of irrigation that were tested in these experiments. As the soil types are different in Site 1 and 2, we performed a two-way ANOVA.

Finally, to compare the effect of the cultivars, we used data only from the CARDI experiment, so we didn't consider the effect of the soil. However, we still performed a two-way ANOVA with the following parameters: irrigation and cultivar.

2.2.5. Model

We used AquaCrop with the objective to compare the results of the model and the experiment, and especially figure out how to add more precision in the modeling of hydric stress.

One model was made for each configuration, with the cultivars CAR15 and Sen Pidor, the three soil types and the three irrigation regimes.

The parameters of climatic and soil data cited earlier were entered in the model.

The detailed parameters entered in the model are featured in the annex.

The calibration was realized with the trial-and-error process, as recommended by Steduto et al. (2012). In CARDI, the calibration of the model was made with the data of the year 2022, and the validation with the data of the 2021 experiment. In Kampong Thom, all the data is from 2022, so two third of the data set was used for calibration, and the other third for validation.

We started by adjusting the water content in the soil for it to be as close as possible to the reality (this is crucial for the model to correctly estimate the hydric stress). We did this by changing the soil (adjustment of K_{sat}) and management parameters. For example, in the AWD side of CARDI22, we modified the bunds depth to reflect the drainage of the plots after the rain. This parameter became 0.02m instead of 0.2m.

Then we adjusted the CC until it fitted the actual data in a satisfactory way. We modified some crop parameters such as CC_x, but always took care of respecting the phenological stages as a priority (they are in the annex). The modified parameters are all recapped in the annex.

Lastly, we adjusted the biomass, as it is calculated following the equation below and the transpiration depends on the CC.

$$B = K_S \times WP \times \sum \frac{Tr}{ETo}$$

Where WP is the water productivity, that is to say the weight of biomass produced per m² and per mm of transpired water in [ton/m²] and Tr the crop transpiration in [mm/day] (Steduto et al., 2012).

To have the best calibration as possible, we first calibrated the models on the plots that were constantly irrigated and had theoretically no water stress, and then on the AWD plots to refine the calibration and consider the effect of the stress, as done in Wellens et. al (2022).

There was a theoretical irrigation schedule, and one actual schedule was recreated for each plot (they were not all irrigated at the same time) from the irrigation records. However, except in the CARDI 2021 experiment, there was no data concerning the volume of irrigation, nor the discharge of the pump. The volume of irrigation was estimated from the record of the water level, which was sometimes incomplete (for example, in Kampong Thom, there is no data between the 8th of January and the 17th of January, and then again between the 21st of January and the 30th of January).

Concerning the calibration and validation, we used 3 indicators to evaluate the fitting between the observed and simulated data.

The root mean square error (RMSE), is defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{n}}$$

The RMSE is an indicator of the absolute uncertainty of the model, it shows the mean deviation between the simulated and observed values. It adopts the unit of the analyzed value, and the closer it is to 0, the better is the fitting.

The Nash-Sutcliffe efficiency (E) is calculated as follow:

$$E = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

It is a normalized indicator showing how the deviation between the simulated and observed values is different from the deviation between the observed values and their mean. E completes well the RMSE because the latter does not distinguish several small deviations from a huge deviation. Thus, E traduces the fitting of the simulated and observed data on a 1:1 line. The smaller the departure from the line, the higher is the performance of the model (Heng et al., 2009). E is unitless and ranges from –∞ to +1, with a better efficiency closer to 1.

Lastly, Willmott's index of agreement (d) is calculated as:

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(|S_i - \bar{O}| + |O_i - \bar{O}|)^2}$$

It displays the ratio of the mean square error on the potential error. It varies between 0 and 1, the better agreement being close to 1.

We used these indicators to validate the model on the evolution of the biomass and canopy cover.

Chapter 3

***

Results and discussion

In this chapter, the results from the different experiments are presented and discussed. From now on, we will call CARDI21 and CARDI22 the experiments led in CARDI in 2021 and 2022. The experiments in Kampong Thom will be written KT1 and KT2 for Site 1 and Site 2 respectively. The tables containing the raw data are available in the annex.

3.1. Soil data

3.1.1. Saturated hydraulic conductivity

Thanks to our measurements with the Ksat machine and our manual set-up, we were able to measure the saturated hydraulic conductivity in all the experimental sites.

Table 2 - Ksat values in all the experimental sites (in cm/day)

	CARDI	Kampong Thom S1	Kampong Thom S2
Layer 1	0,69	0,58	3,08
Layer 2	1,42	7,94	34,16
Layer 3	0,43	29,2	16,78

We can see a lot of different values. Even on one site, we observed a very important heterogeneity among the different samples taken on the field.

3.1.2. Water retention parameters

Table 3 - Values of water retention in all the experimental sites

	% volume	CARDI	Kampong Thom S1	Kampong Thom S2
Layer 1	**FC**	22.112	29.567	23.584
	PWP	12.379	12.720	17.312
	SAT	28.208	46.251	30.196
Layer 2	**FC**	29.115	44.988	25.519
	PWP	16.933	29.905	18.031
	SAT	35.173	0.600	29.019
Layer 3	**FC**	64.621	33.958	30.313
	PWP	35.628	18.090	19.248
	SAT	85.344	50.170	39.307

Thanks to the pressure plates experiment, we were able to determine the Van Genuchten parameters, that are relative to the water retention proprieties of the soil. The associated curves are featured in the annex.

3.1.3. Bulk density

Table 4 - Values of bulk density in all the experimental sites in (g/cm^3)

	CARDI	Kampong Thom S1	Kampong Thom S2
Layer 1	1,763	1,713	1,706
Layer 2	2,069	1,875	1,707
Layer 3	2,032	1,730	1,709

The bulk density traduces the compaction of the soil and gives an indication on soil aeration. Hence, this is important for water movement, and root growth. We can note that in CARDI the bulk density is particularly high, and this can have an impact on the roots (see paragraph 3.1.5.).

3.2. Soil dynamics

In this paragraph we are going to analyze the evolution of soil dynamics during the cultivation season thanks to the sensors that were placed in the fields and manual measurements. On the field we had some doubts concerning the ability of the soil to actually take in the water inputs from irrigation and precipitation. The data that we collected will help answer this question.

3.2.1. Soil moisture

3.2.1.1. Kampong Thom

The daily weather in Kampong Thom province during the experimental period is in the annex.

In KT1, there were no sensors except the water level sensors. However, no reference sensor was set-up so the results are not interpretable as a water level.

In KT2, two soil moisture sensors and two potential sensors were placed. There were also water level sensors with the same problem as in Site 1. The sensors were set to capture only one value per day, and on some sensors, the contact with the soil was not good so at the -15cm depth we don’t have any data.

On the figure 33, we can see the evolution of Θ in KT2. The sensors’ measures are represented on the left by triangles, and the manual measures are represented by dots.

We can see that the sensors’ measurements do not vary very much during the month of measurements and stay between 0.4 m^3/m^3 and 0.48 m^3/m^3. They don’t show any noticeable reaction to the irrigation events.

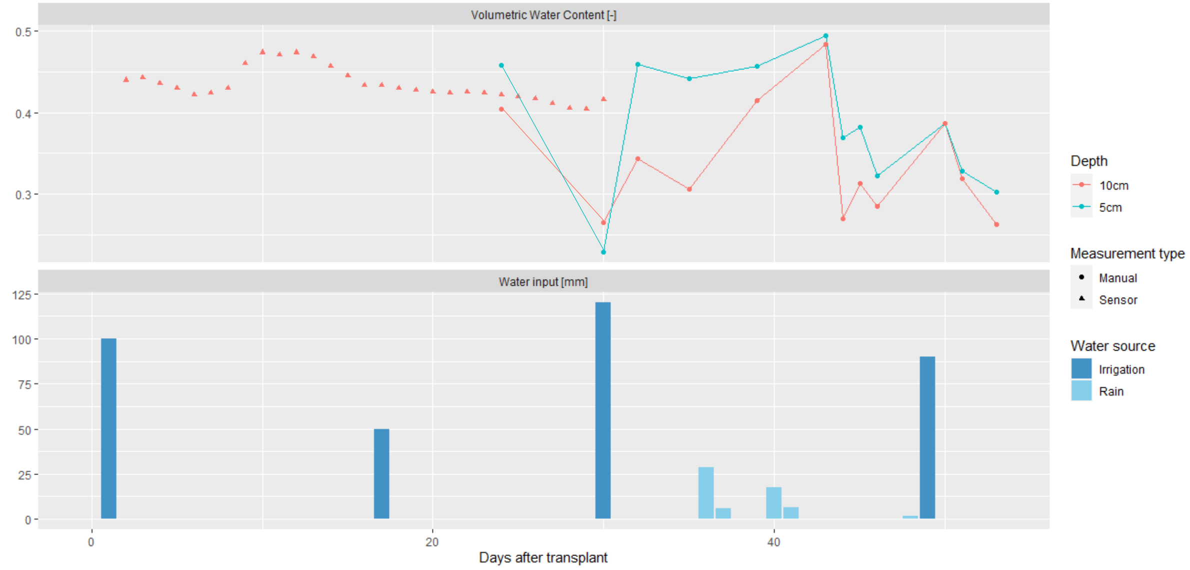

Figure 33 - Measures of the soil moisture in KT2

On the other hand, the manual measures undergo more drastic variations and show quick reactions to the irrigation and precipitation events. They must be interpreted with precaution because here there was only one measurement per day and per depth. The manual samples can also appear to have a superior Θ that in reality because when the field is flooded, it is very complicated to take a sample manually without some water perturbating the protocol. However, there is no reason for the samples to appear drier than they actually are.

In the present case, it seems like the sensors were set-up in a way that prevented their data from evolving very much even on occasions of irrigation. This could be caused by a bad contact between the soil and the sensor. Also, we have to note that the moisture sensors are supposed to be installed horizontally to get more precise data but in KT2 they were set-up vertically.

We tend to trust the manual measurements because they show more variations, a reaction to the water inputs, and as measurements were usually made a few days after water inputs, the biases of manual sample collection are reduced.

We don’t have any exploitable data for the water potential. The data concerning the bulk electrical conductivity is in the annex because it does not seem to bring a lot of knowledge concerning the water dynamics in the soil.

With the information brought by the soil moisture, we can say that in KT2, the soil reacts to the water intake.

3.2.1.2. CARDI, 2021

The weather data of CARDI is placed in the annex.

In CARDI21, there were three water level sensors placed but there was no reference sensor so we can’t exploit the data.

3.2.1.3. CARDI, 2022

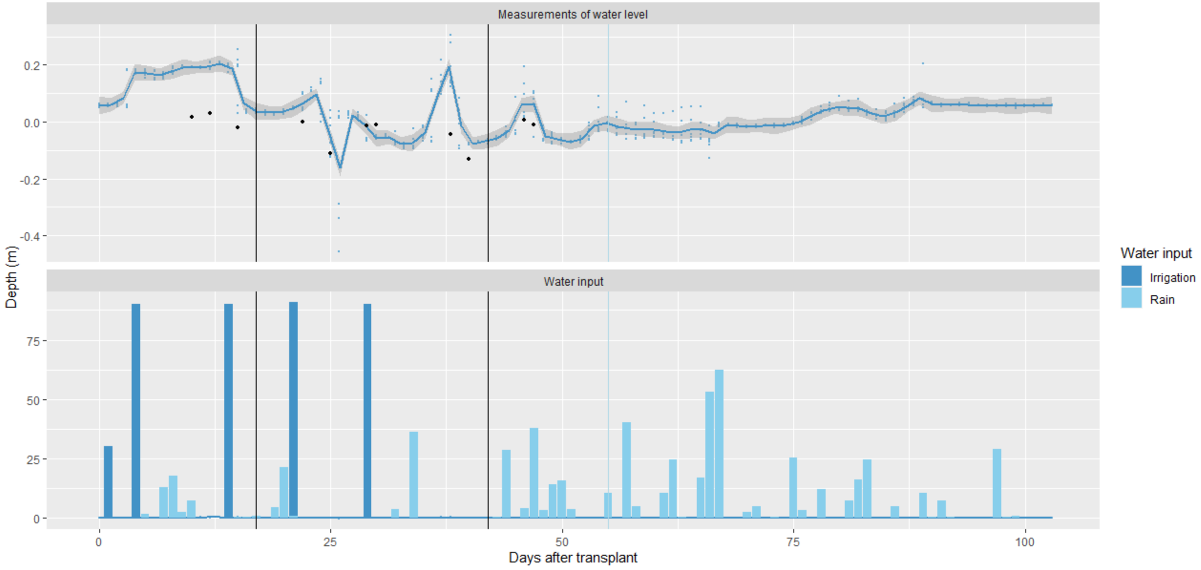

Figure 34 – Water level variations in CARDI22 – Plot B3

In CARDI22, we have a lot of data to analyze the soil dynamics. In the first place, we have data about the water level variations thanks to senors and manual measures.

On the figure 34, we can see the water level variations in an AWD plot according to the sensor, and the manual measures as black dots. We can see that the positive values of the sensor seem to be overestimated, but the manual measures' dynamic globally fits well the measures of the sensor.

The water level is negative during most of the experiment, but it rarely reaches -15cm. After a while we can see that there is a lot of rain, and the irrigation stops. When the rain was intense, the fields were drained but the water level stayed stable and could not go very low because of the frequency of the precipitation.

We added the theoretic dates of AWD as black lines, and the blue line is what we estimate would be a more accurate date as the end of AWD.

The moisture and potential sensor were set to take one measure per hour, so we have a lot more data. In figure 35 we can see the evolution of the soil moisture.

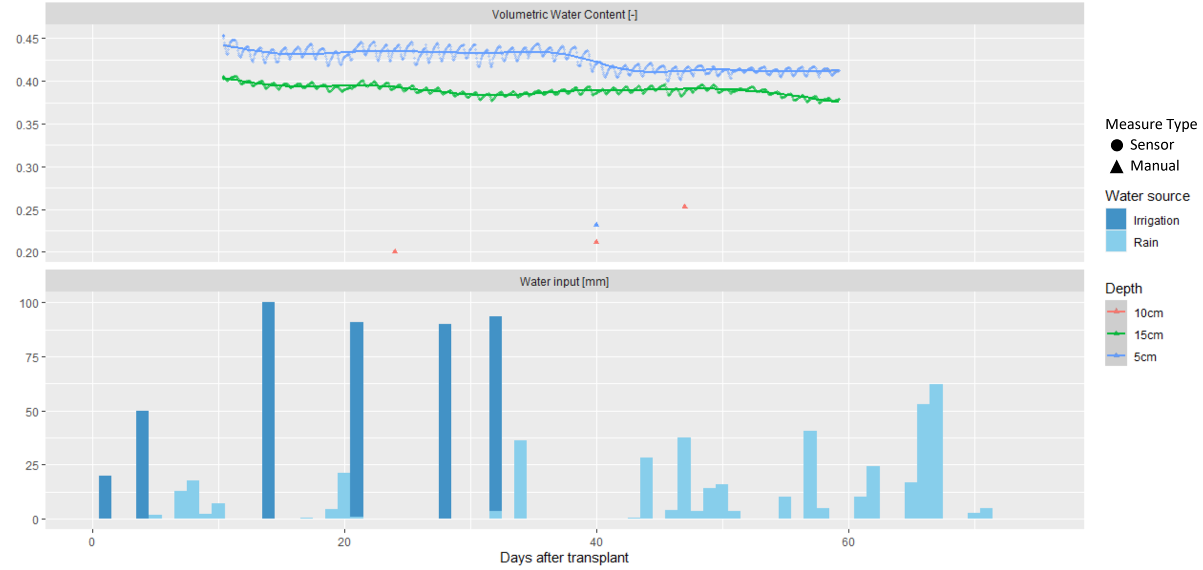

Figure 35 – Measures of the soil moisture sensor in CARDI22

We can see daily variations in the sensors' measurements, that can be attributed to the temperature variations. Indeed, the soil moisture decreases during the day because of the evaporation, and increases during the night because of the capillarity rise (Verhoef et al., 2005). We also can note that these variations are more intense the more the sensors are close to the surface, which seems logic, as the temperature variations lessen with the depth.

The sensors' values are quite high, and stay stable during all the measurement period, with a slight decrease at the end. The irrigation does not have a huge impact. This could traduce that the soil is saturated so Θ cannot go higher.

However, the manual measures are very different. Even if we do not have many manual measures for the plot where the sensor was installed, they are similar and as we said earlier, it is unprobeable to underestimate Θ in manual measurements.

We don't have enough manual measures to observe a dynamic so it is hard to interpret but we can suppose that the values of the sensors may not be reflecting the true volumetric water content. It could be either because of a bad contact with the soil, or a bad calibration. The soil may then not take in the water but it is hard to affirm.

3.2.2. Soil potential

The potential provides additional information to better understand the water dynamics in the soil, and the impacts on the plants.

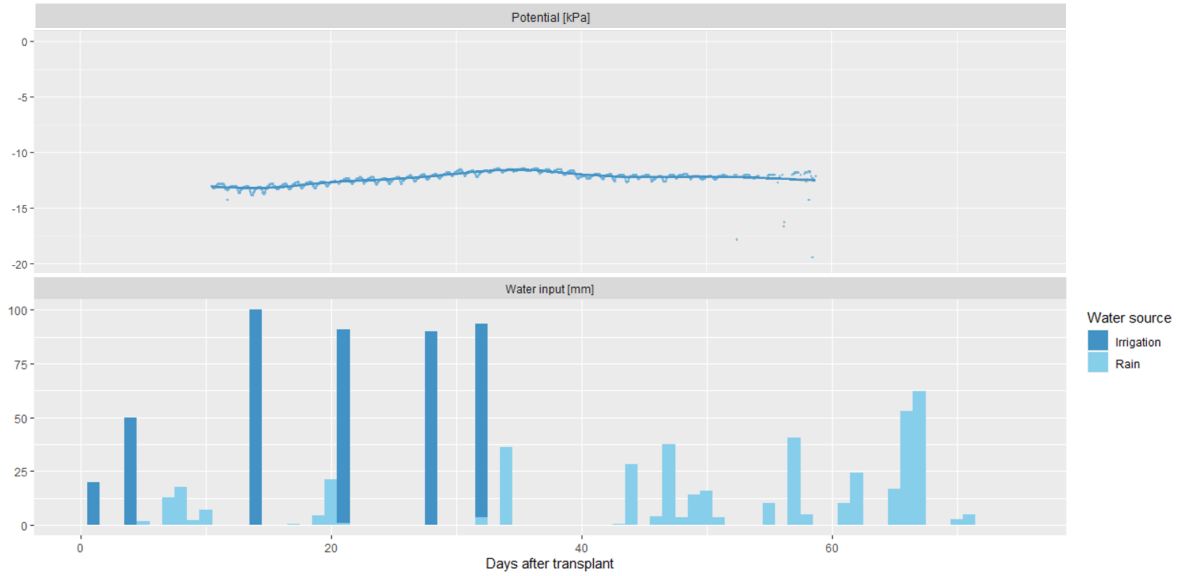

Figure 36 – Measures of the potential sensor in CARDI (depth of 10cm)

On figure 36, we can see daily variations due to the temperature (these are raw data, we could not have access to equations that correct the effect of temperature, but we can see here that this influence is limited and we can observe the dynamic of the potential). The potential is stable throughout the measurement period. It stays between -10kPa and -15kPa during the whole experiment. We can't see any clear impact of the precipitations, but this means the availability of the water to the plants does not change even if Θ decreases at the same time.

Unfortunately, it is hard to come to a conclusion because there was a huge difference between the manual measures and the sensors' measures, and then it is hard to trust the sensors, even though the moisture sensors were calibrated in the lab.

3.3. Harvest data

We are now going to present the harvest data and compare the different yield components of rice between the different sites and cultivars. The yield components are the structures of the rice that directly translate into yield. They are the panicle number per area, the number of spikelets and the percentage of filled ones among them, and finally the weight of each grain (Espino, 2014). These data are presented as barplots with the mean and standard deviation.

3.3.1. Panicle number per area

The panicle number per area depends mainly on the number of seedlings and the tillers production. Other factors that can reduce tillers production are nitrogen deficiency, weed competition and pests. The number of seedlings per area is called stand. A stand of 5 to 7 plants per ft^2 (= 54 to 75 plants per m^2) is usually considered as a poor stand. The planting density in all our experiments is 25 feet per m^2 so it is a very poor stand. However, the poorer a stand is, the more tillers are produced to compensate (within a biological limit), but when a lot of tillers are produced, maturity can be uneven, and this can be negative for the grain quality at harvest (California Rice Production Workshop, 2018).

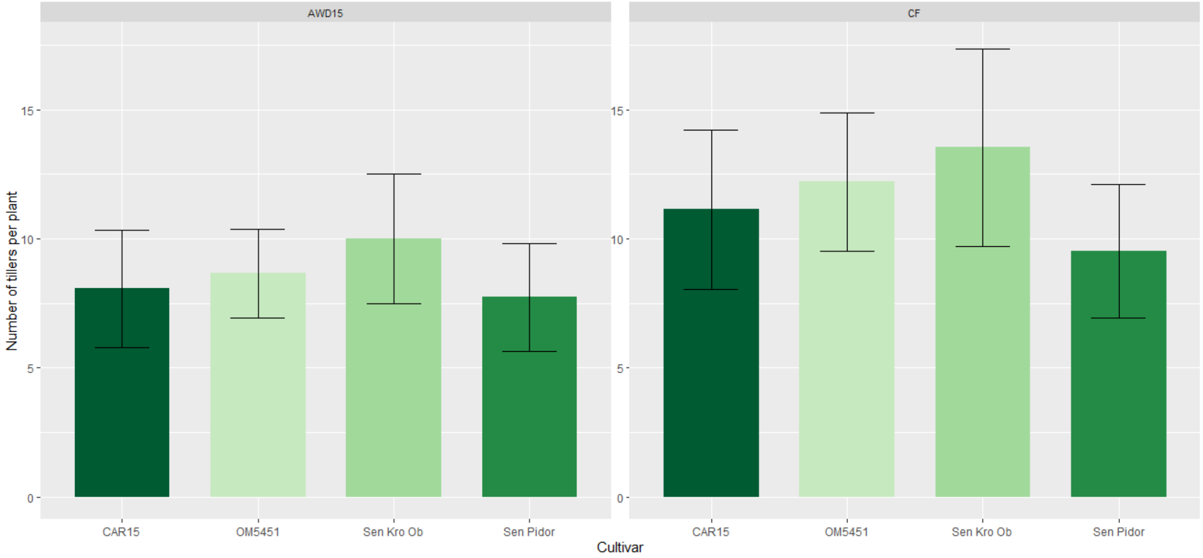

Figure 37 - Number of tillers per plant at harvest in CARDI, 2021

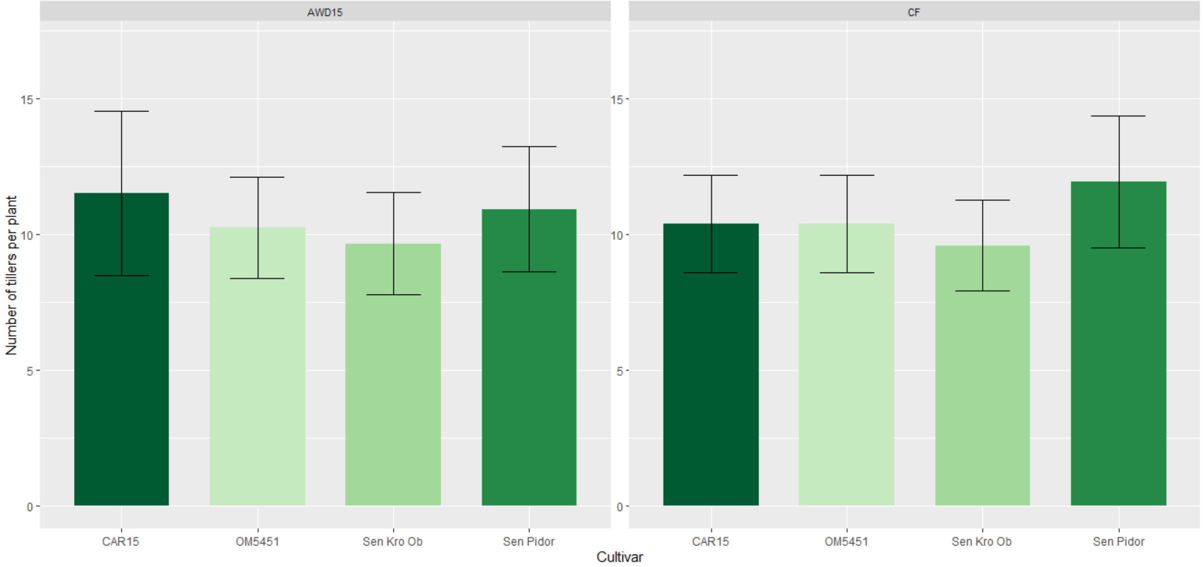

Figure 39 - Number of tillers per plant at harvest in CARDI, 2022

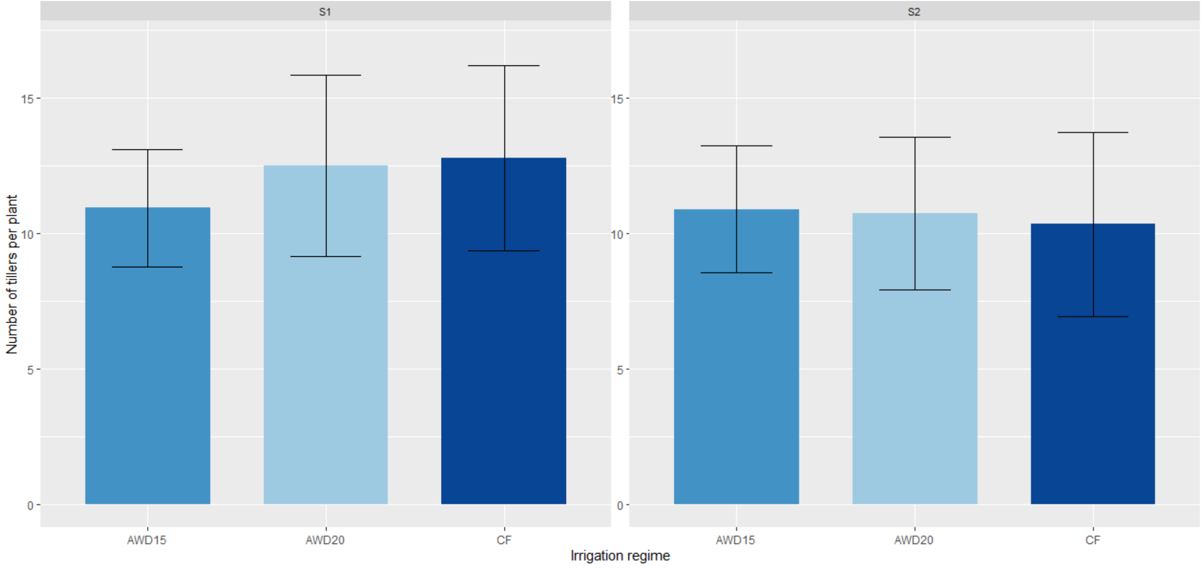

Figure 38 - Number of tillers per plant at harvest in Kampong Thom

Plants in good stands usually produce one to three tillers. In our case, the plants have produced up to 24 tillers, and in average more than 10 tillers.

In CARDI21 (see fig.37), we can clearly see that the CF side of the experiment produces a lot more tillers than on the AWD side, for all the cultivars. The difference is less noticeable in the CARDI22 (see fig.38) experiment. There is no difference for the cultivars Sen Kro Ob and OM5451, but we can see an inferior number of tillers for the cultivar CAR15 on the CF side, and a superior number of tillers for the Sen Pidor cultivar.

In KT1 (see fig.39), CF is the regime producing the most tillers and AWD15 the one producing the smallest number of tillers. In KT2, there is no significant difference between the three regimes.

3.3.2. Number of spikelets per tillers, and percentage of filled ones

The number of spikelets per panicle depends mainly on the variety. In our experiments, we just averaged the total number of spikelets in the 5 hills harvested in CARDI, and in the 10 hills harvested in Kampong Thom. The lower the seedling density, the higher the grain number per panicle, though there is a limit to this compensation. The percentage of filled spikelets can be affected by the temperature. Temperatures superior to 40°C during flowering can cause the germinating pollen tube to dry, and ultimately an empty grain. Other factors leading to empty grains can be excess nitrogen or pests. The figures 40 to 42 presents the number of spikelets in the different experimental sites. The colored bars are the total number of spikelets per tiller, the grey bars are the filled spikelets and on them is the percentage of filled spikelets.

As we saw for the tillers, there is an increase in the number of grains in the CARDI21 experiment in the CF regime, but not necessarily of filled grains. In CARDI22 the difference is less important, there is a small increase in the total number of spikelets for the cultivars OM5451 and Sen Pidor, but for all the cultivars the percentage of filled spikelets decreases.

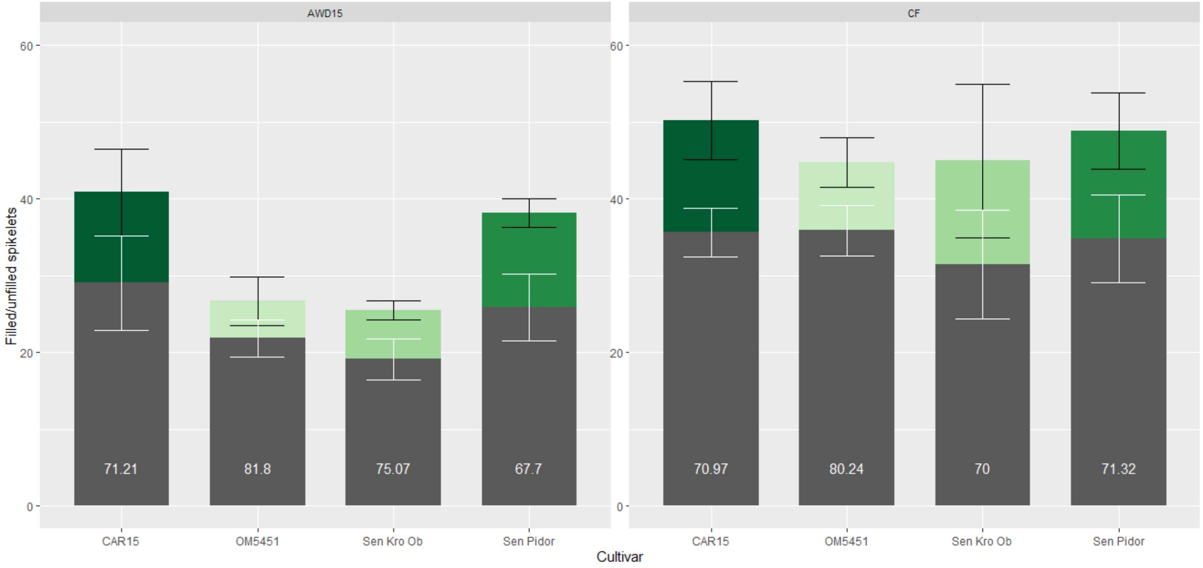

Figure 41 - Filled/unfilled spikelets per tiller at harvest in CARDI, 2021

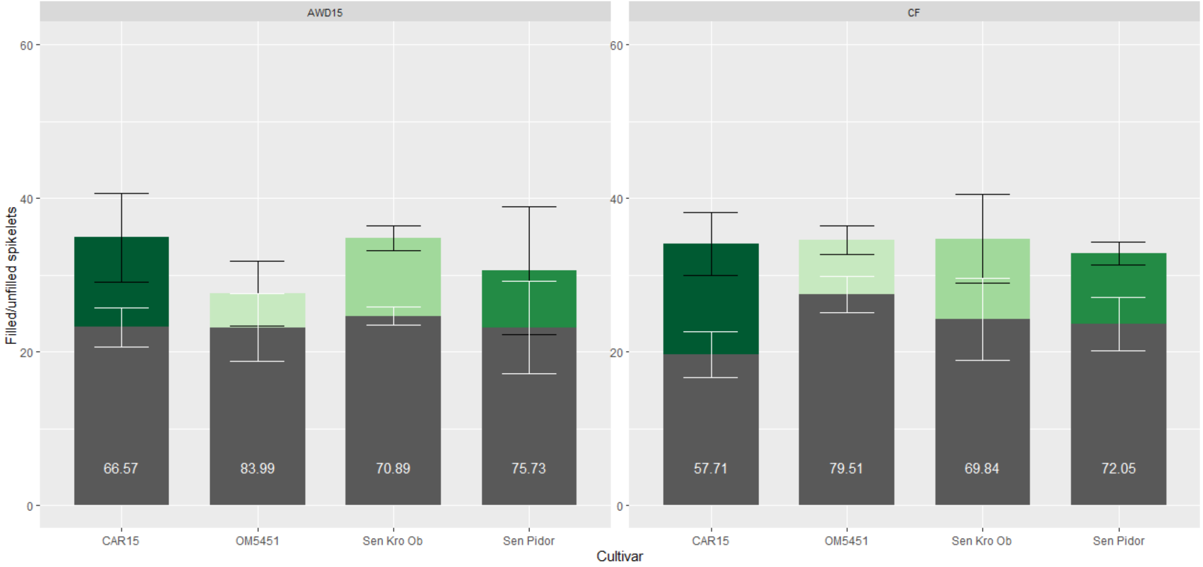

Figure 40 – Filled/unfilled spikelets per tiller at harvest in CARDI, 2022

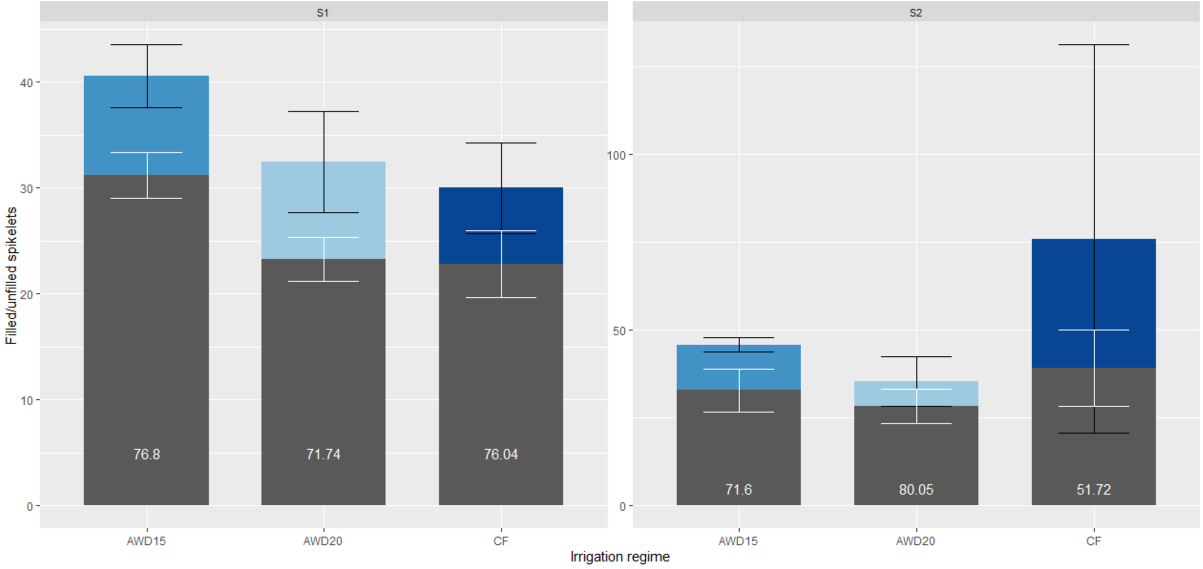

Figure 42 – Filled/unfilled spikelets per tiller at harvest in Kampong Thom

3.3.3. Grain weight

During the harvests and the processing of the samples, only the grain yield was measured, but we don't have data concerning the grain weight precisely. However we can assume that it did not vary much between the different irrigation regimes as it is mostly determined by genetic factors.

3.3.4. Plant height

The plant height is mostly related to genetic factors. In the literature there is no mention of management parameters that have an influence of the plant height. Indeed, in all the experiments the irrigation regime seems to have a negligeable impact on the plant height. It only varies between the cultivars. The barplots showing the plant height are featured in the annex.

3.3.5. Root depth

According to Yang et al. (2012), the roots have a very important role concerning the yield. Indeed, higher root biomass is mandatory to reach a higher number of panicles, a higher number of grains and a higher percentage of filled grains. Moderate irrigation practices are said to improve the root structure by stimulating its growth by adaptation.

In CARDI21, there is no data for the root depth at harvest.

We can see on figure 43 that in CARDI22 the root depth is really low, in both regimes it is below 10cm which is a very shallow root. However, the roots in the AWD15 regime are in average a little deeper than the roots in the CF regime (except for the Sen Kro Ob cultivar).

In both sides of Kampong Thom, the deepest roots are under the AWD15 regime, as we can see on figure 44.

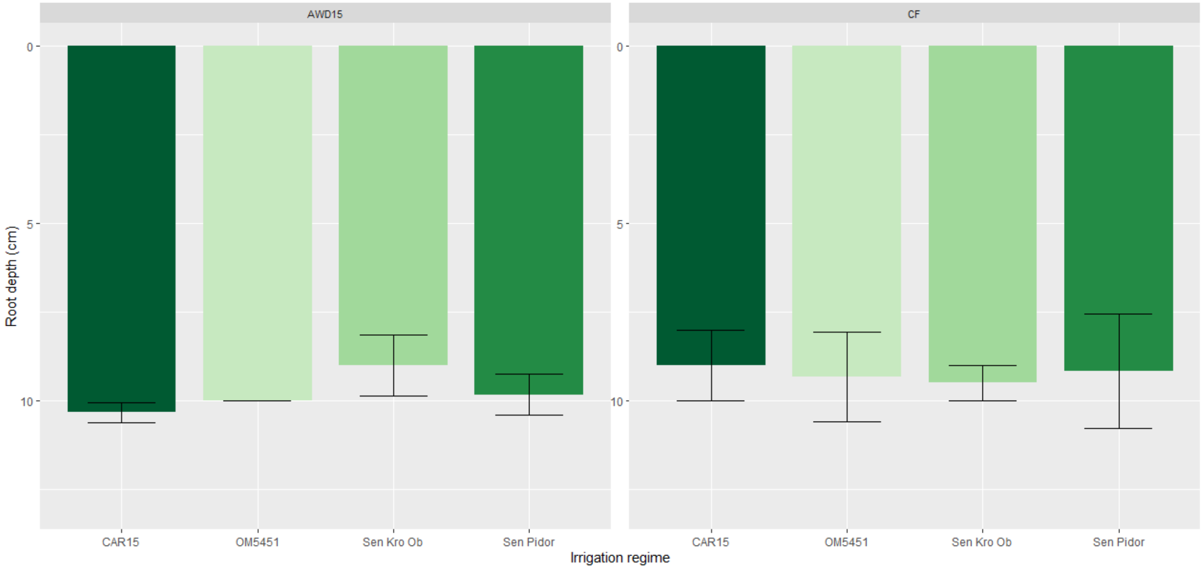

Figure 43 – Effective root depth at harvest in CARDI, 2022

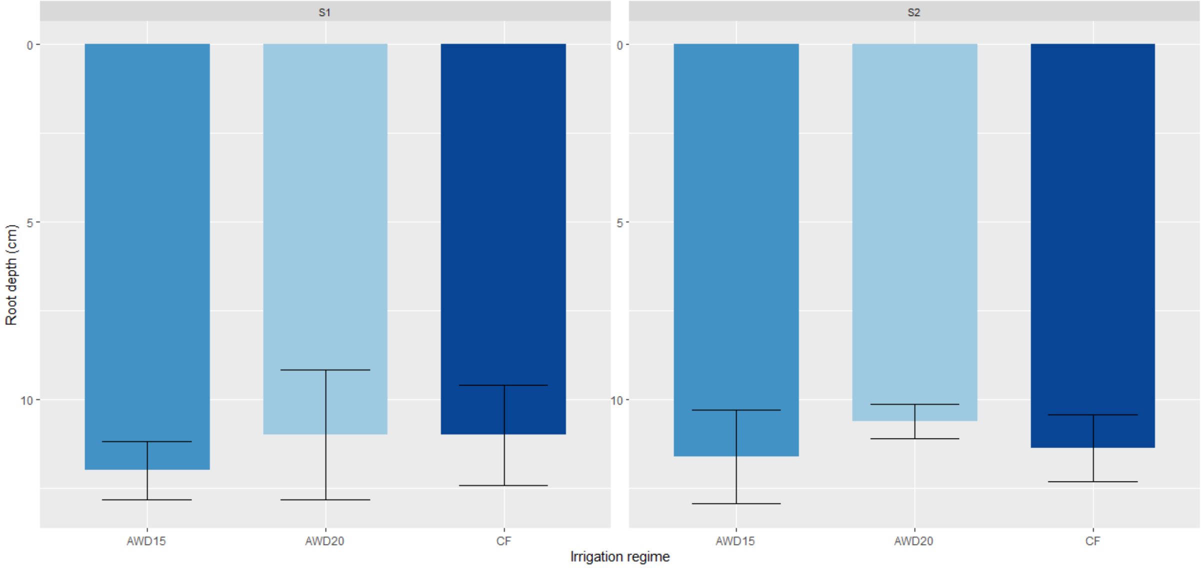

Figure 44 – Effective root depth at harvest in Kampong Thom

As many parameters change between the set-up and the management of the three experimental sites, we will compare them as systems.

If we observe similar reactions as a consequence of a parameter changing, then it is likely that this parameter is causing this reaction. If we observe different reactions because of one parameter change (for example irrigation), then there can be interference with another parameter (for example soil type). There are other phenomena like pests, weed competition, etc. that can have an impact but that we cannot really quantify.

The different sites seem to react differently to the changes. Indeed, concerning the tillers number, CF increases it in CARDI21 and KT1, does not really increase it in CARDI22 and it slightly decreases it in KT2. We observe the same pattern of differences between CARDI21 and CARDI22 for the number of spikelets.

There are also differences between CARDI and Kampong Thom. Indeed, the CAR15 cultivar's number of spikelets increases with CF in CARDI21, stays the same in CARDI22, and decreases in KT1. In KT2, the number of CF number of spikelets seems abnormally high because of one extreme value.

The hypothesis that we propose to explain the differences between the experiments CARDI21 and CARDI22 is the weather. Indeed, it is the same soil and same cultivars, but as the two experiments took place at different moments of the year, the heavy rains in CARDI22 prevented the AWD plots to dry, so the results from AWD and CF are not very different.

The root depth shows a homogenous reaction, as it is the deepest in AWD15 in all sites. The rice usually already has shallow roots, but a high bulk density can restrict root growth (USDA). All the bulk densities of the sites that we are studying are very high and either affect or restrict root growth. The roots are the shallower in CARDI, where the bulk density is the highest. This of course has an impact on the access of the plants to the water.

3.3.6. Yield

The figures 45 to 47 present the economic yield (i.e., grain yield) in all the scenarios. They are all inferior to the yield potentials presented in paragraph 2.1.1., and in CARDI the yields are inferior to the average national yield which is 3.41 t/ha of rice.

In CARDI21, the yield of CAR15 and Sen Pidor, the cultivars that are resistant to irrigation deficiency, stays stable or slightly decreases with the CF regime. CF increases the yield for the OM5451 and Sen Kro Ob cultivar. The harvest index of OM5451 and Sen Pidor does not change with the irrigation regime, but for Sen Kro Ob and CAR15 it increases significantly with CF.

In CARDI22, the yields are superior to the ones in CARDI21. This can also probably can be explained by the intense precipitations in 2022. The yields of all the cultivars increase with CF, except for OM5451. In AWD the cultivars OM5451 and Sen Pidor produce the highest yields, and in CF, it is the cultivars Sen Pidor and CAR15. The irrigation regime does not seem to have an impact on the harvest index.

In both Kampong Thom sites, AWD15 has a high yield (in KT1 it is the highest), and AWD20 has consistently the lowest yield. The harvest index of the AWD15 and AWD20 are similar, but in CF it is smaller.

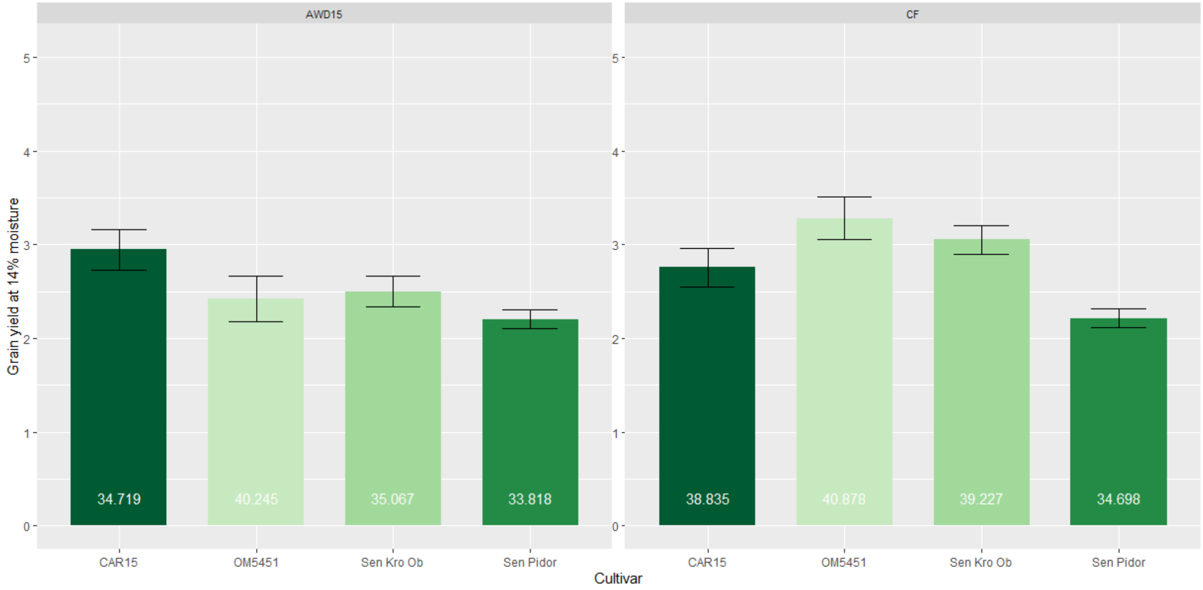

Figure 45 – Grain yield and harvest index in CARDI, 2021

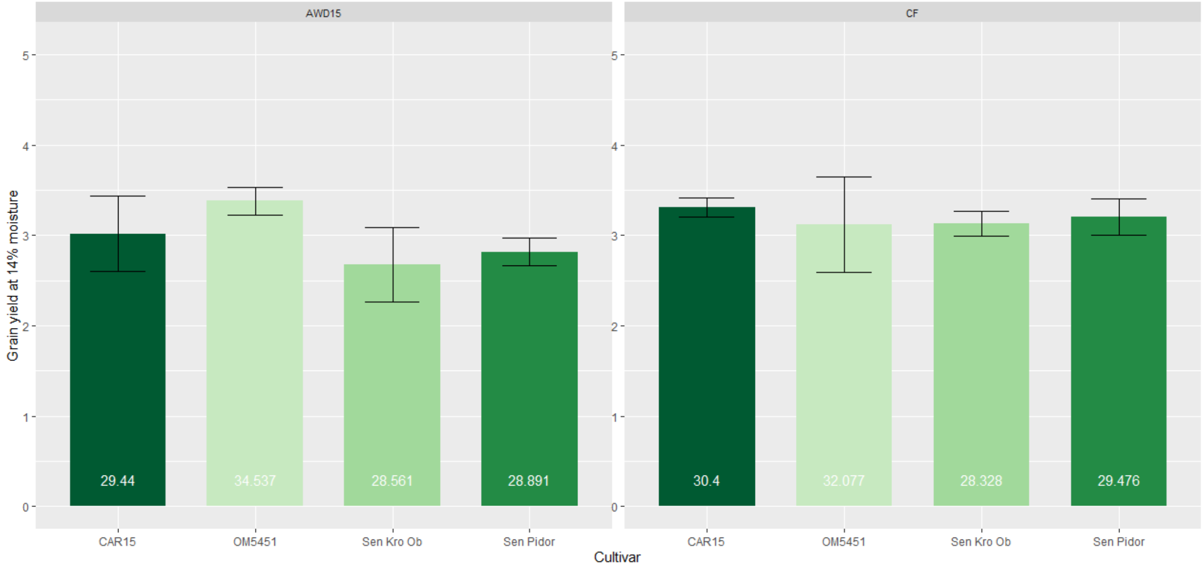

Figure 46 - Grain yield and harvest index in CARDI, 2022

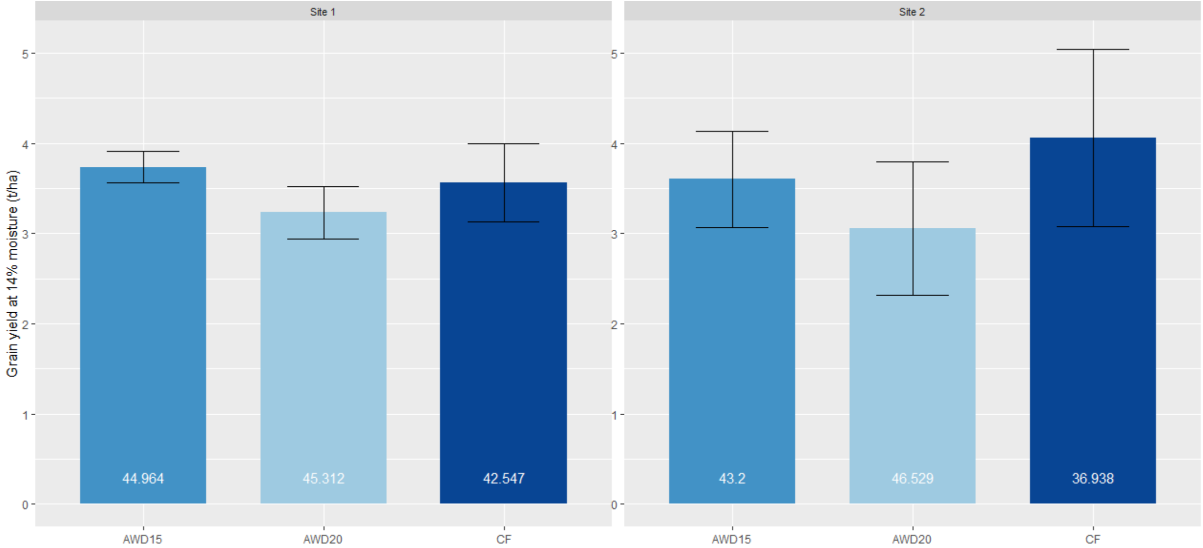

Figure 47 - Grain yield and harvest index in Kampong Thom

3.3.7. Water-Use Efficiency

The Water-Use Efficiency is the indicator that we use to determine which of rice production is the best. It is presented in the figures 48 and 49 below. There is a monetary translation of the WUE in the annex.

In the AWD plots in CARDI22, the water was drained after precipitation episodes. Thus, we made the calculation without taking into account the rain because even if the drainage was not perfect, the rain was removed as soon as possible and as a consequence had a minimal role in the growth of the rice.

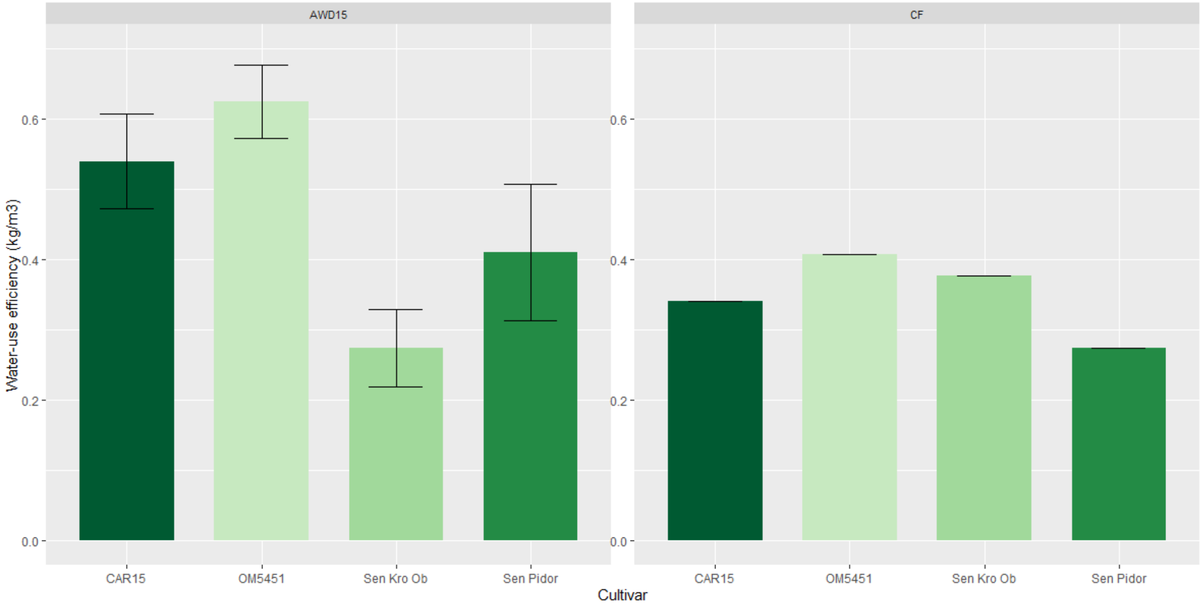

Figure 48a - Water-Use Efficiency in CARDI, 2021

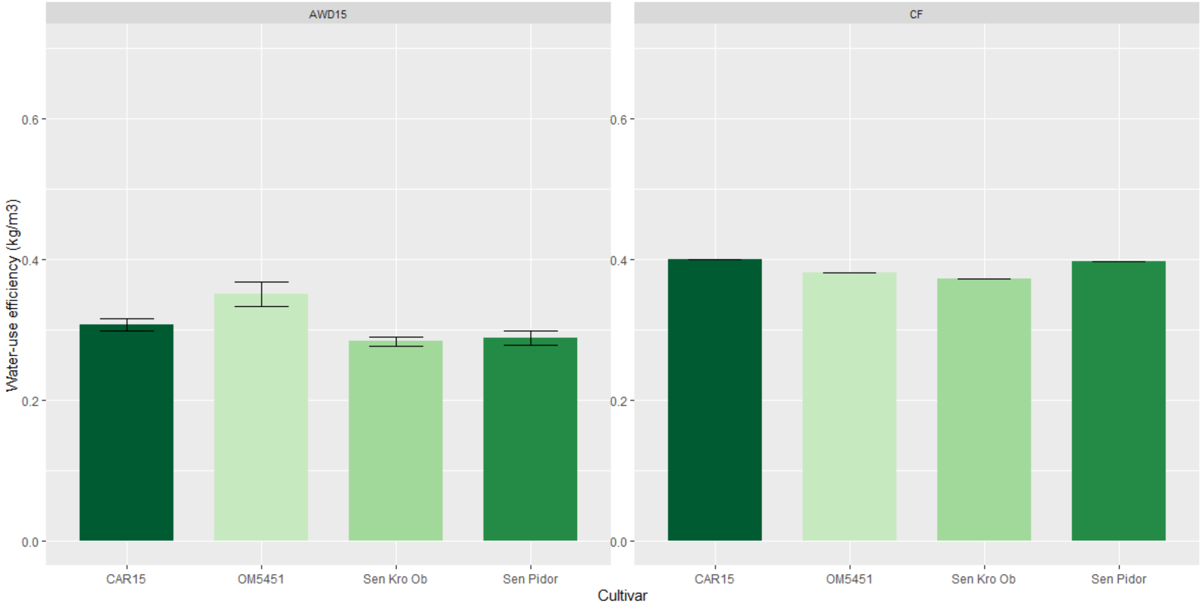

Figure 45b - Water-Use Efficiency in CARDI, 2022

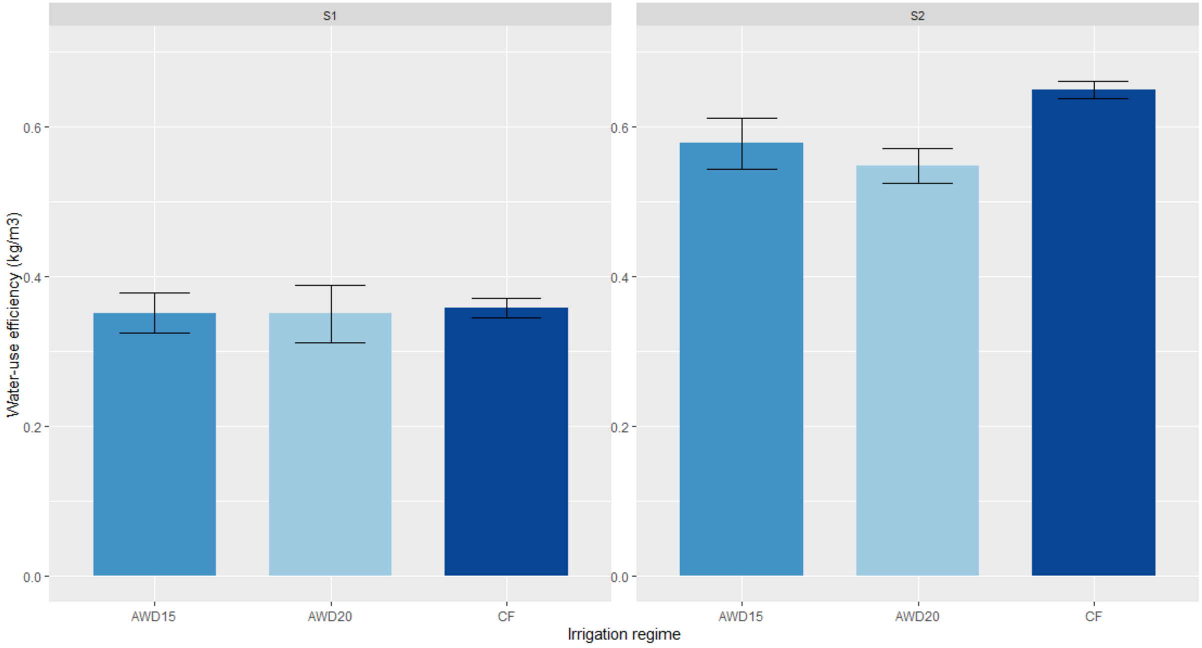

Figure 49 - Water-Use Efficiency in Kampong Thom

The scenarios that had the best WUE in this experiment are CF in the KT2 (the AWD scenarios of the same site are also very high), and OM5451 and CAR15 in AWD15 in CARDI21. The high WUE of OM5451 is surprising as it is not supposed to be resistant to irrigation deficit.

In KT1 and KT2, the yield was similar but the WUE is visibly different, so the difference comes from the amount of water applied. Some characteristics of KT2 like the application of manure could explain it.

We need to take a lot of precaution interpreting the WUE because it is based on measures of water level that may not be accurate. We did not have any data of volume or discharge so the quantity of irrigation applied may not be exact.

3.3.8. Qualitative observations

Some qualitative observations that happened on the field are listed in the annex.

3.4. Statistical analysis with ANOVAs

We are now going to analyze the results at a statistical level to see if the parameters of the scenarios have a significant impact on the yield. To do so we are going to perform Analyses of Variance. All the detailed conditions of application of the analyzes are featured in the annex.

3.4.1. Effect of irrigation

3.4.1.1. In all sites

For this first analysis, we will consider all the experimental sites in a two-way ANOVA with irrigation and soil as parameters. Only two regimes are present in all experiments: AWD15 and CF, so these are the ones that will be compared in this analysis. To have a complete experiment, we will use the data of the cultivar that is present in all sites: CAR15.

In the table below are presented the hypotheses that we had for this test.

Table 5 - Hypotheses for a two-way ANOVA

Null hypotheses (H_0)	Alternative hypotheses (H_i)
• There is no interaction between the soil and the irrigation • The irrigation regimes changes do not cause any significant differences in the results • The soil and fertilization changes do not cause any significant differences in the results	• There is a significant interaction between the soil and the irrigation • The irrigation regimes have a significant impact on the yield • The soil and fertilization have a significant impact on the yield

The ANOVA can be performed if certain application conditions are respected. This statistical test is only applicable on random and independent samples, and if the variances are homogenous. After the analysis, it is also necessary to verify the normal distribution of the residue of the test.

In our case, the experimental design of all experiments and data collection protocol ensure that the samples are random and independent. We also checked the homogeneity of the variances thanks to Levene's test where $p > 0.05$, so we can assume the homogeneity of the variances.

We performed several ANOVA tests, to see which model was the best fitted to the data.

We first wanted to assess if there was any significant interaction between the soil type and the irrigation. Indeed, the soil type could influence how the soil takes up the water. The results of the test indicated that there was not a lot of variation that could be explained by the interaction between the irrigation and soil type, so we cannot reject the null hypothesis.

We then performed a two-way ANOVA and the results indicate that the regime does not have a significant influence, so we cannot reject the null hypothesis. However, the site seems to have an influence, so we reject the null hypothesis.

To include more accuracy to the model, we tried to add a block variable, to take into account the variability. We separated the data from CARDI in two groups: the data from 2021 and 2022 so that the variability in the experimental conditions (weather, …) are considered. In Kampong Thom, we grouped some plots depending on the experimental design to consider some effects like shade, border effect, etc. The block variable has a low p-value and accentuates the effect of the site. This model seems to one that fits the data the best.

To be sure that the ANOVA is applicable, we checked the normal distribution of the residue with the Shapiro-Wilk test and obtained a p-value > 0.05. We also plotted the residuals and fitted values, as well as the QQplot of the residue (in the annex), and thanks to this, we can assume the normal distribution of the residue.

We then performed a post-hoc test for pairwise comparisons: the Tukey test. Indeed, the ANOVA is useful to tell if the differences between groups and treatments are significant, but it does show which ones. A pairwise test allows to determine which groups are significantly different from each other.

The figure 51 shows that in all three sites, there are significant differences in yield due to the difference in soil and fertilization, the irrigation regime does not cause significant differences. The highest yields are achieved in Kampong Thom, and there is no significant difference of yield between these two sites, but CARDI is significantly different from both KT1 and KT2.

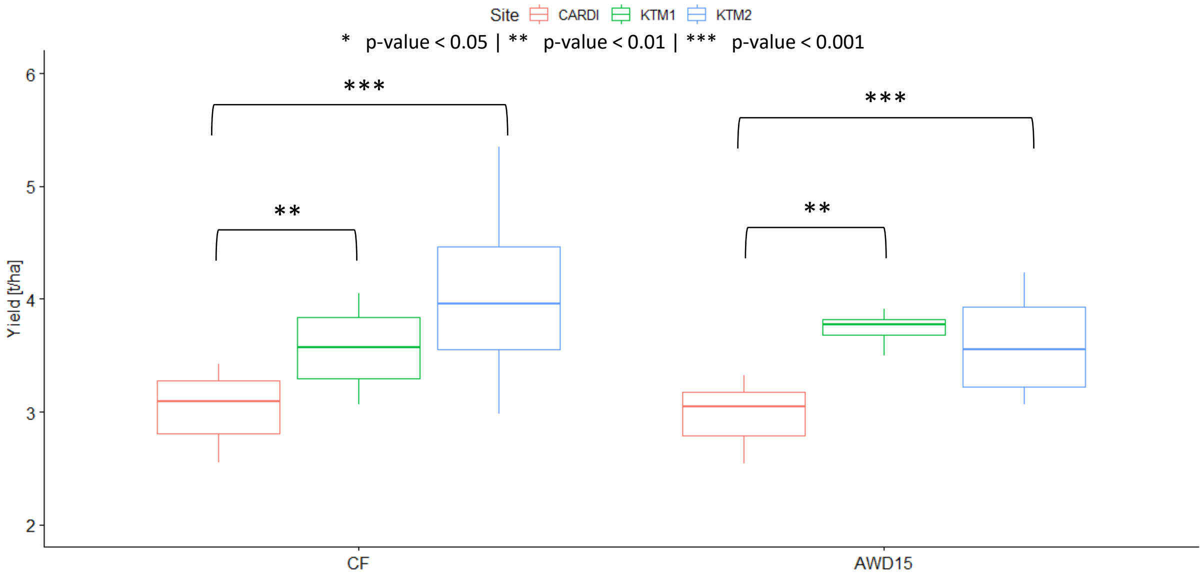

Figure 46 - Representation of the two-way ANOVA in the three experimental sites

The three experimental sites all received a different fertilization (see table 1) so we could think that the fertilization is causing the differences between them. However, KT1 is the site that received the smallest dose of fertilization, and its yield is significantly superior to CARDI. KT2 received one less dose than is CARDI as well, but it received manure and Ozlu et al. say that manure can have benefit that inorganic fertilizers don’t have. These benefits are relative to a better stability and texture of the soil in the long term, and this is also important concerning the infiltration of water. It also increased total nitrogen and soil organic carbon. Another parameter that could play a role here is the bulk density. Indeed, CARDI has the highest bulk density of all sites, which can restrict root growth, and as a consequence the access to water and the yield. As the soil and the fertilization are not the only parameters defining an experimental site, the microclimate could be responsible for the differences between CARDI and the Kampong Thom sites.

3.4.1.2. In Kampong Thom

In order to go deeper in the analysis of irrigation, we wanted to compare all the irrigation regimes. We used all the data from the Kampong Thom sites, where all three irrigation regimes were tested. In the two sites of this province, the soil and fertilization are different, so we performed a two-way ANOVA with irrigation and soil as parameters. The hypotheses of the test are presented in the table 6.

The conditions of application of the test were verified and the results of the two-way ANOVA with a blocking variable (to consider border effect and shade) is presented in figure 52.

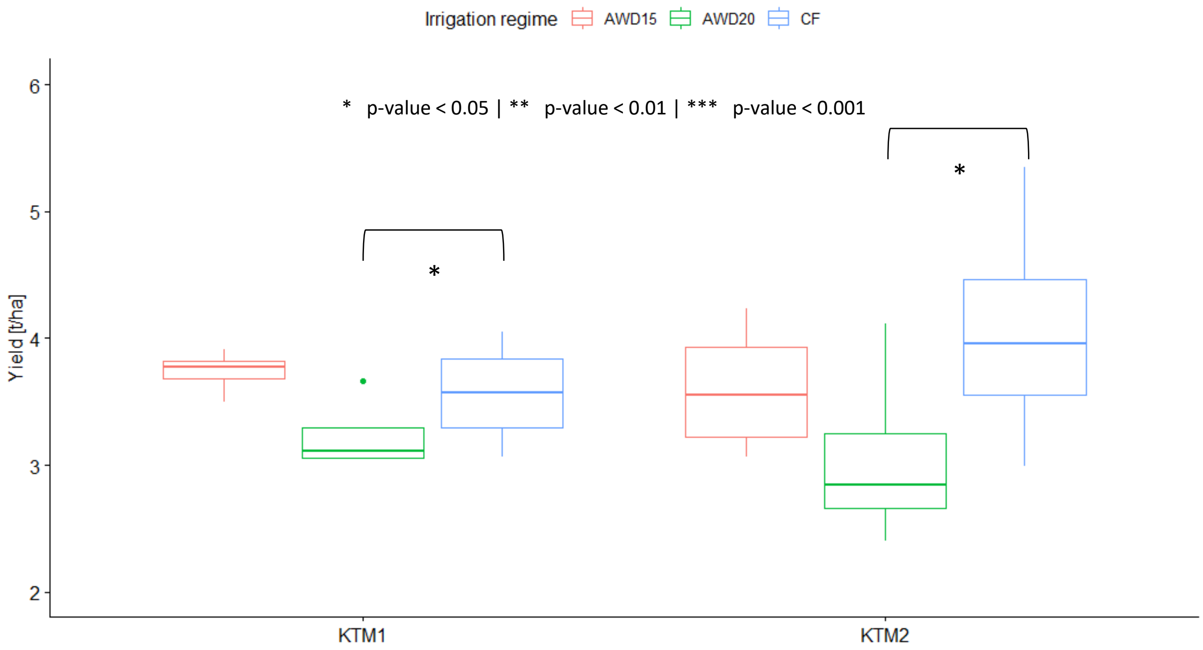

Figure 47 - Representation of the two-way ANOVA in Kampong Thom

The test indicates that we cannot reject the null hypothesis concerning interaction between soil and irrigation. The pairwise comparisons indicate that there are no significant differences between the two sites of Kampong Thom. In addition, the only significant difference between the irrigation regimes is that CF produces a higher yield than AWD20 (so the null hypothesis is rejected).

This means that CAR15's yield is not significantly impacted by the AWD15 regime. Its yield starts to be significantly impacted with AWD20. CAR15 is then very resistant to irrigation deficiency but for an optimization of the production it may be better to draw the limit of AWD at -15cm.

3.4.1.3. Effect of cultivar

In a second part, we wanted to assess the effect that the different cultivars of rice can have on the final yield. To process this information, we used the CARDI experiment only. As there are two irrigation regimes in this experiment, we performed a two-way ANOVA with the two parameters being irrigation and cultivar.

The hypotheses of the test are featured in the table 7.

Table 6 - Hypotheses for a two-way ANOVA

Null hypotheses (H_0)	**Alternative hypotheses (H_i)**
• There is no interaction between the cultivars and the irrigation • The irrigation regimes changes do not cause any significant differences in the results • The cultivars changes do not cause any significant differences in the results	• There is a significant interaction between the cultivars and the irrigation • The irrigation regimes have a significant impact on the yield • The cultivars have a significant impact on the yield

After having verified the application conditions of the test, we performed the two-way ANOVA with a blocking variable that was indicating the experimental year, to consider the variations in weather.

There is no interaction between the two parameters of the ANOVA (so the null hypothesis is not rejected), but there are significant differences between the different cultivars and between the two irrigation regimes (so both null hypotheses are rejected).

The result of the Tukey test is represented in the figures 53 and 54. We see that the cultivars CAR15 and OM5451 are both significantly different and consistently higher than Sen Pidor (which has consistently the lowest yield). This is surprising as Sen Pidor is supposed to be a high-yielding cultivar resistant to hydric stress.

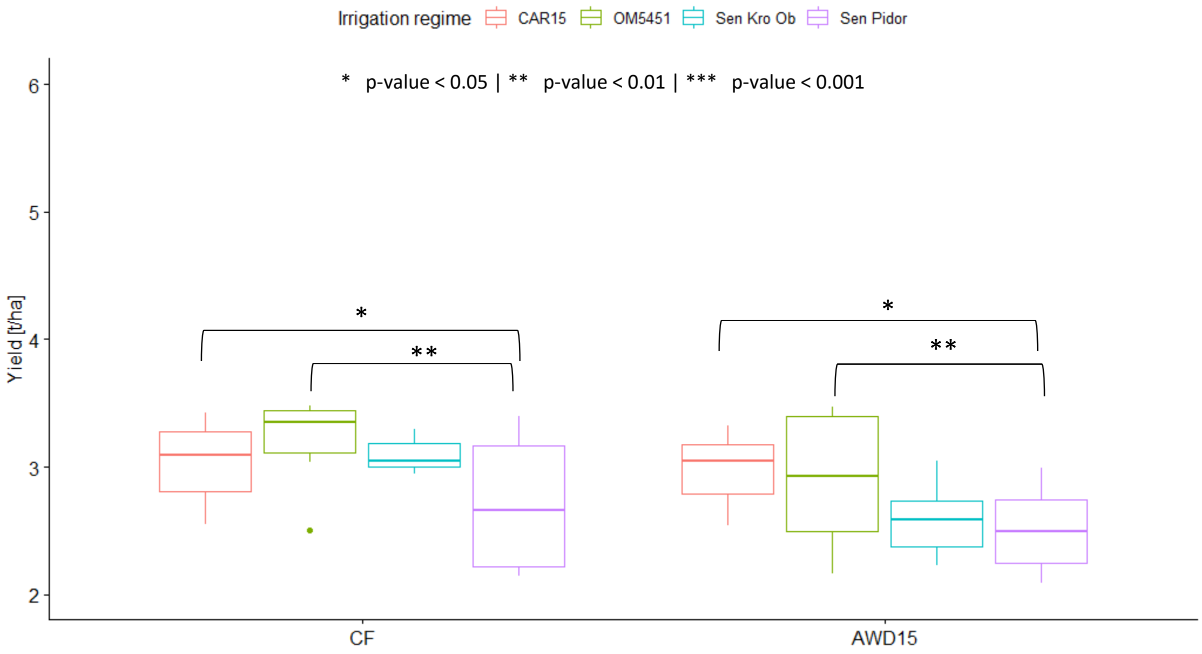

Figure 48 - Representation of the two-way ANOVA in CARDI

The test also showed that there were significant differences between AWD15 and CF in CARDI: a higher yield is produced in CF for all the cultivars. We could not see this in the first ANOVA because this the difference between AWD15 and CF is not significant in Kampong Thom so when the three sites were compared together, the differences in CARDI were blurred.

The difference in yield due to irrigation is visibly depending on the cultivar. Indeed, we observe a difference in yield between AWD and CF on the non-resistant cultivars. The yield of CAR15 does not change (so the observations from Kampong Thom are confirmed) and the yield of Sen Pidor decreases a little bit but less than the other cultivars.

We can then say that the parameters determining the yield are mainly the site. A site is made up of several factors, so the difference could actually be explained by the fertilization, or the microclimate, and probably a combination of these.

Then, the second parameter having the most impact is the cultivar, as it conditions the impact of irrigation. Indeed, the cultivars that are resistant to hydric stress will not be impacted by AWD, but other cultivars will.

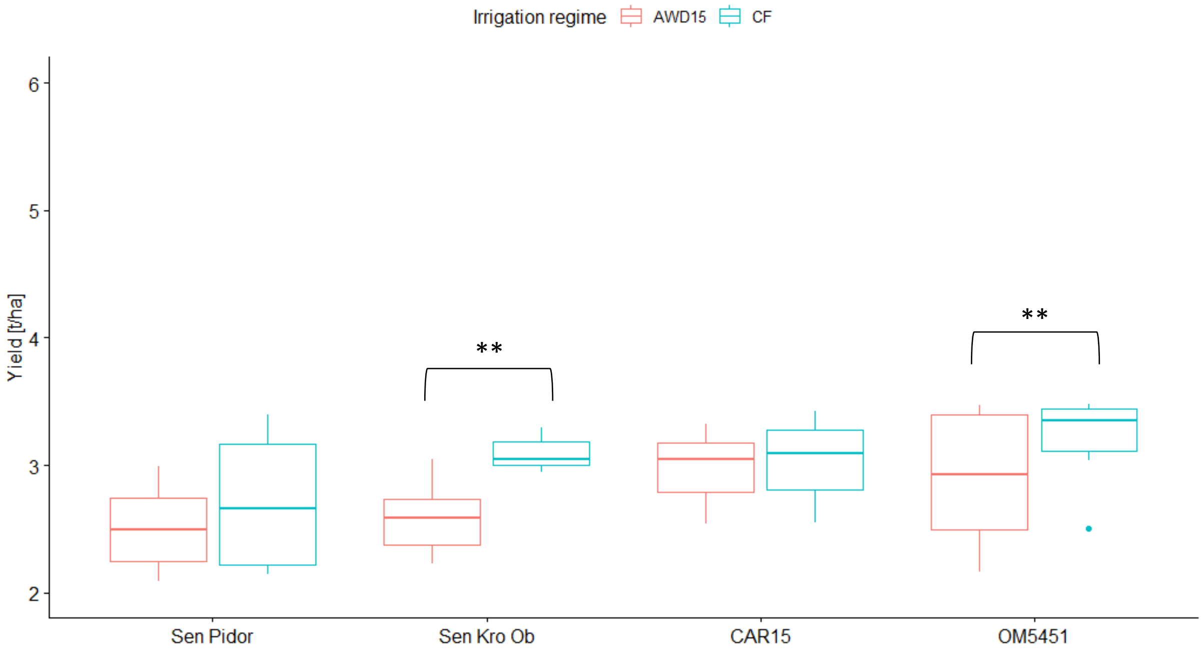

Figure 49 - Representation of the two-way ANOVA in CARDI

3.5. Modeling

It is interesting to note that when we first used the parameters presented in table 2, the canopy cover was underestimated, and the biomass was overestimated in all the scenarios of all sites.

3.5.1. CARDI

We started by using the data collected during the experiments (HI, phenological stages, etc. and adjust them). After a few tries, we found a good fitting for the CC and the dry yield.

However, the biomass was always overestimated a lot and to make it fit there was no other way than giving the parameters absurd values. Indeed, if we wanted to fit the biomass data, we had to reduce drastically the WP*, way under the usual range for C3 plants, and we also had to reduce drastically the $K_{c, Tr}$ term. To compensate this on the yield, we then had to increase the harvest index dramatically, to a value that makes no sense for rice.

We then decided to stick with the modeling with parameters that have realistic values.

Concerning the reason why the biomass is always overestimated in the model, it is possible that the CO_2 concentration has an impact in the calculation of biomass (Vanuytrecht et al., 2011). But this is probably not the only factor causing this phenomenon. We also realized that the CC was overestimated during the ripening stage. Indeed, the presence of the grain perturbated the analysis of the CC and resulted in an overestimation. This also has an impact as the biomass depends on the canopy cover. Finally, the fields can undergo a stress (fertility, salinity stress) that is not documented.

3.5.1.1. Sen Pidor

3.5.1.1.1. Calibration

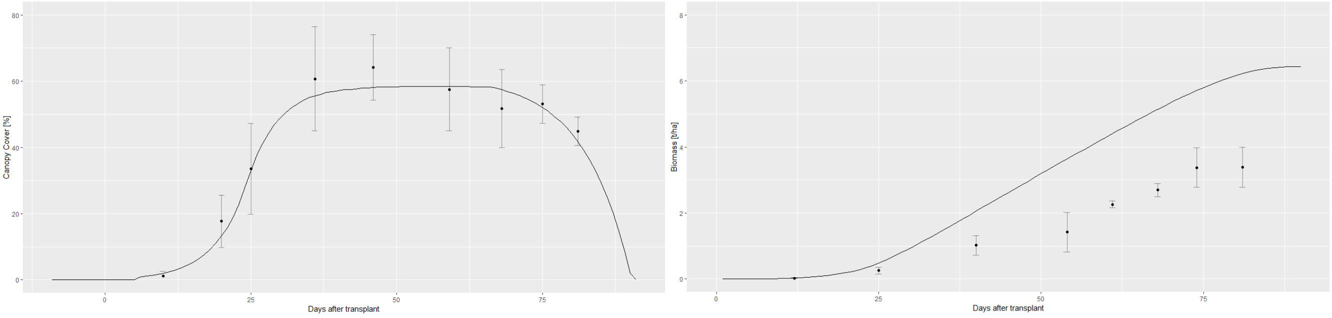

Figure 50 – Calibration of Sen Pidor (CF)

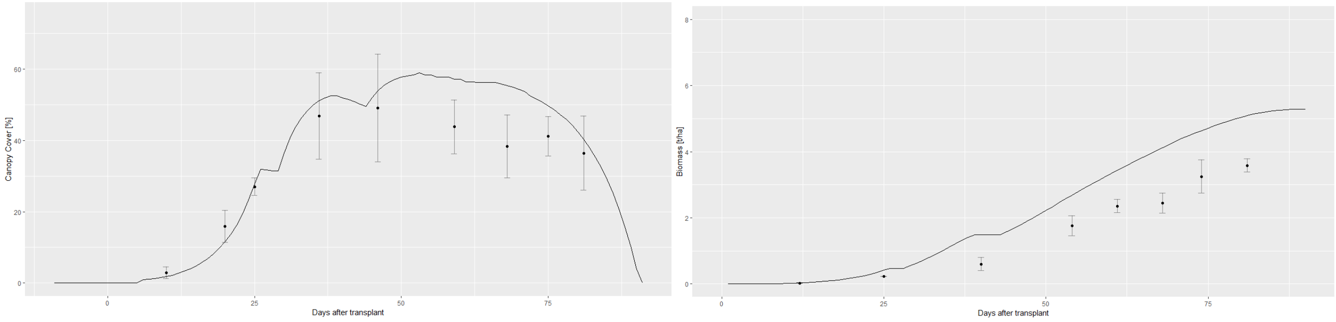

Figure 51 - Calibration of Sen Pidor (AWD15)

Table 7 - Calibration indexes for CAR15 in CARDI

	RMSE [%]	E	d
Biomass - CF	1.9	-1.45	.75
CC - CF	3.7	0.97	0.99
Biomass – AWD15	1.2	0.16	0.87
CC – AWD15	7.8	0.72	0.95

3.5.1.1.2. Validation

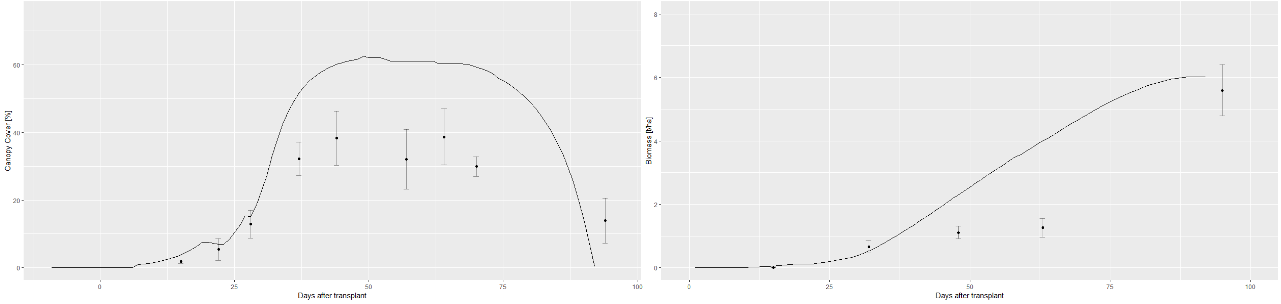

Figure 52 – Validation of Sen Pidor (CF)

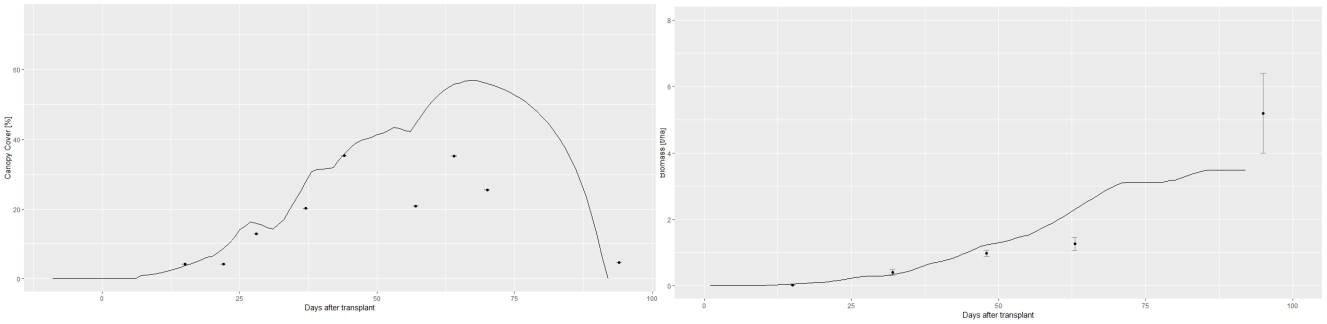

Figure 53 - Validation of Sen Pidor (AWD15)

Table 8 – Validation indexes for Sen Pidor

	RMSE [%]	E	d
Biomass - CF	1.4	0.53	0.9
CC - CF	19.9	-0.97	0.79
Biomass – AWD15	1.4	0.51	0.81
CC – AWD15	17.5	-0.72	0.76

For this cultivar, we can see that during the calibration, it was not possible to reach a good fitting for the biomass, unless we gave unrealistic values to some parameters. During the validation, we can see that the canopy cover is overestimated, and we suppose that it is a lack of irrigation that was not considered. The biomass does not have a great validation either.

During the calibration, the modeled yield comes close to the reality (CF : 2.711 ton/ha and AWD: 2,375 ton/ha) but during the validation, the CF yield is correct (2,645 ton/ha) but the AWD yield is very low (0,279 ton/ha)

3.5.1.2. CAR15

3.5.1.2.1. Calibration

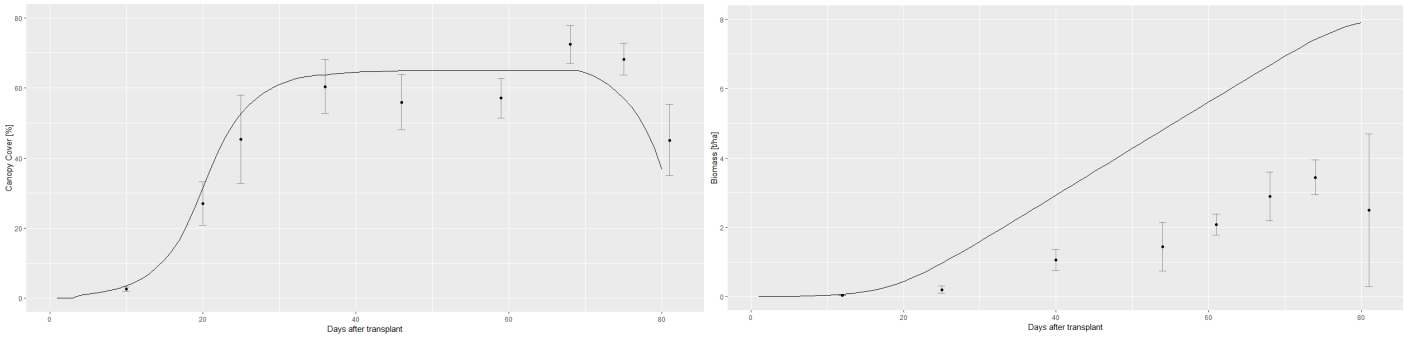

Figure 54 - Fitting of CAR15 in CARDI (CF)

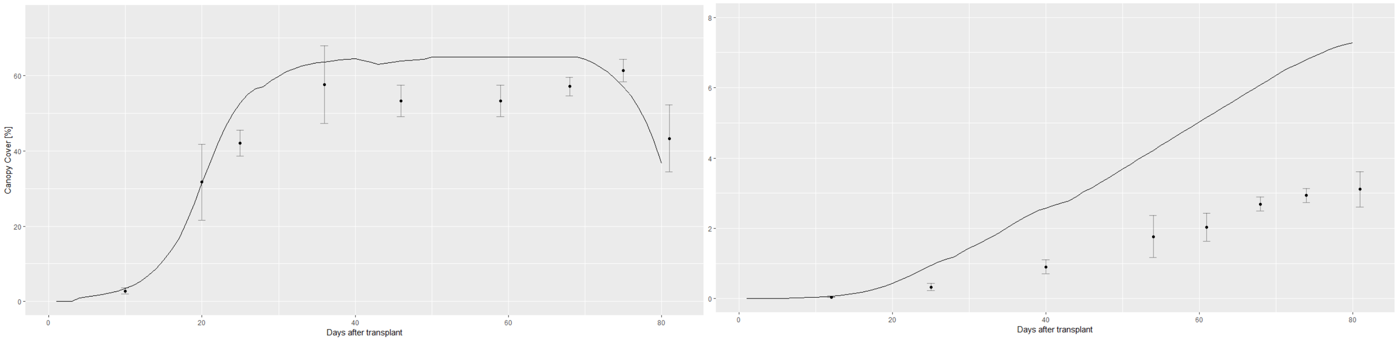

Figure 55 - Fitting of CAR15 in CARDI (AWD15)

Table 9 - Calibration indexes for CAR15 in CARDI

	RMSE [%]	E	d
Biomass - CF	3.1	-5.69	0.59
CC - CF	7.4	0.88	0.97
Biomass – AWD15	2.5	-4.37	0.63
CC – AWD15	5.9	0.9	0.98

The calibration of the biomass is rather good, and the obtained dry yield (2.631 ton/ha for CF and 2.428 ton/ha for AWD15) is close to the actual values.

3.5.1.2.2. Validation

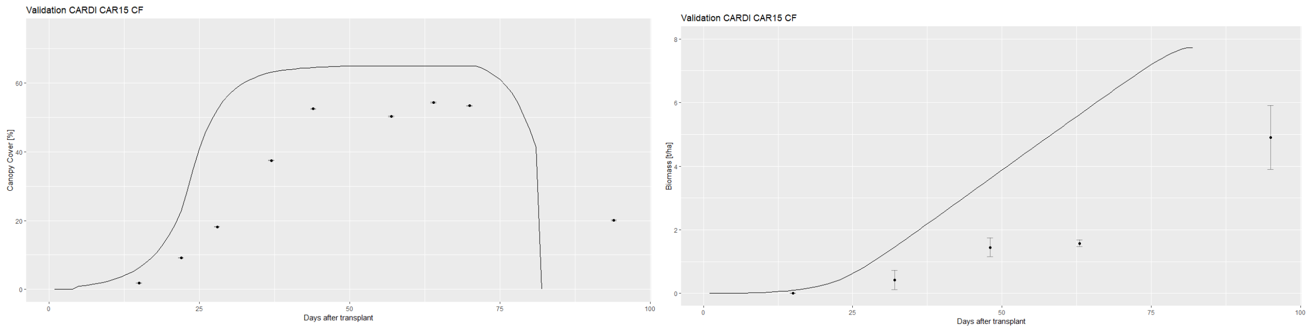

Figure 56 – Validation of CAR15 in CARDI (CF)

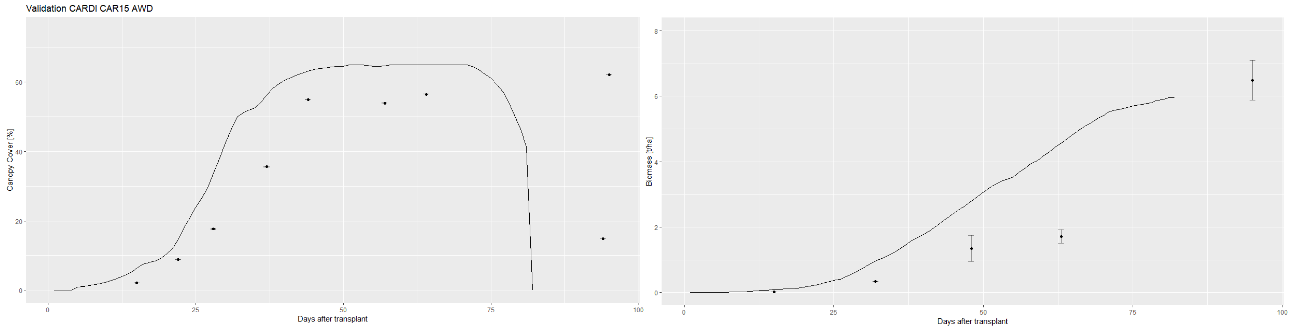

Figure 57 – Validation of CAR15 in CARDI

Table 10 - Validation indexes for CAR15 in CARDI

	RMSE [%]	E	d
Biomass - CF	3.0	-19.17	0.43
CC - CF	20.5	-0.02	0.76
Biomass – AWD15	1.53	-2.59	0.65
CC – AWD15	12.73	0.60	0.89

The validation of this model is not very good. We can see that the CC is also overestimated in the model, and the maturity also seems to happen later in 2021. This difference may be due to the management of the experiment as well. Indeed, the 2022 experiment took place to get a more accurate set of data, as the 2021 experiment was not so well managed.

We can see an important difference between the simulated yield for CF (1.819 ton/ha) and AWD (0.780 ton/ha), and they are both underestimated compared to the reality.

3.5.2. Kampong Thom – Site 1

3.5.2.1. Calibration

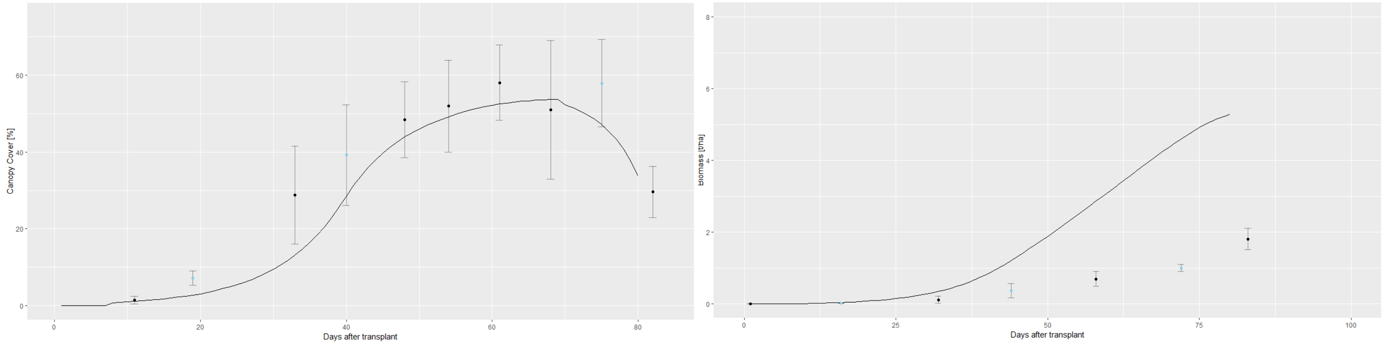

Figure 58 – Calibration and validation of CAR15 in Kampong Thom, site 1 (CF)

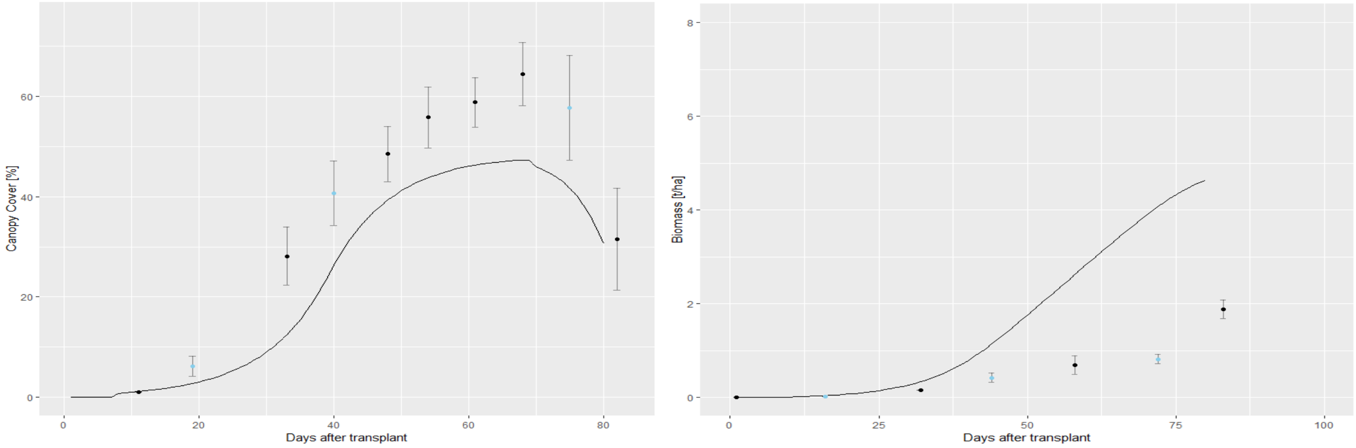

Figure 59 – Calibration and validation of CAR15 in Kampong Thom, site 1 (AWD15)

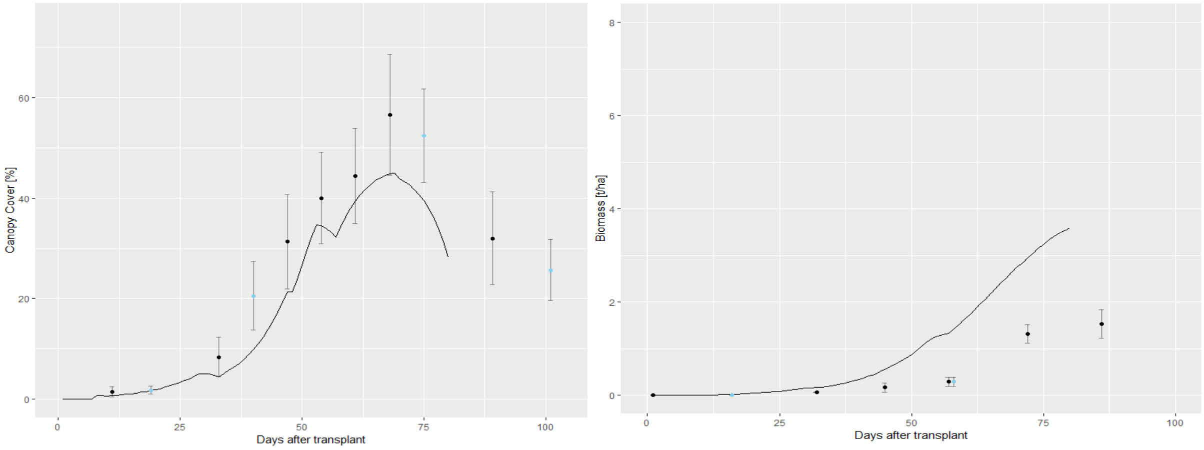

Figure 60 - Calibration and validation of CAR15 in Kampong Thom, site 1 (AWD20)

On figures 58 to 63 are the representations of the calibration and validation of CAR15 in Kampong Thom. The black dots are the measurements used for calibration and the black dots are the ones used for validation.

Here in Kampong Thom, we can see that the CC is underestimated in the AWD regimes. Indeed, it was complex to find an equilibrium between the values of CAR15 already established in CARDI, and the values of CAR15 in Kampong Thom. The higher yield in CF (3.385 ton/ha) can be explained by the longer roots in Kampong Thom.

Table 11 – Calibration indexes for CAR15 in Kampong Thom, site1

	RMSE [%]	E	d
Biomass - CF	1.8	-10.49	0.52
CC - CF	5.9	0.91	0.98
Biomass – AWD15	1.7	-12.05	0.5
CC – AWD15	6.5	0.91	0.97
Biomass – AWD20	0.9	-2.31	0.73
CC – AWD20	7.1	0.87	0.96

3.5.2.2. Validation

Table 12 – Validation indexes for CAR15 in Kampong Thom, site1

	RMSE [%]	E	d
Biomass - CF	1.8	-108.16	0.23
CC - CF	8.9	0.87	0.96
Biomass – AWD15	1.6	-58.15	0.3
CC – AWD15	11.4	0.78	0.92
Biomass – AWD20	0.8	-29.37	0.39
CC – AWD20	9.6	0.79	0.94

3.5.3. Kampong Thom – Site 2

3.5.3.1. Calibration

All the irrigation schedules show a huge irrigation deficit, even in CF, there is not a lot of difference from AWD15 and AWD20. Indeed, the irrigation schedules were recreated from a data sheet that featured the water level but there were long periods (up to two weeks) with no data. Thus, to recreate at least a real CF irrigation schedule, we artificially added irrigation events so that there is always a positive water level in CF.

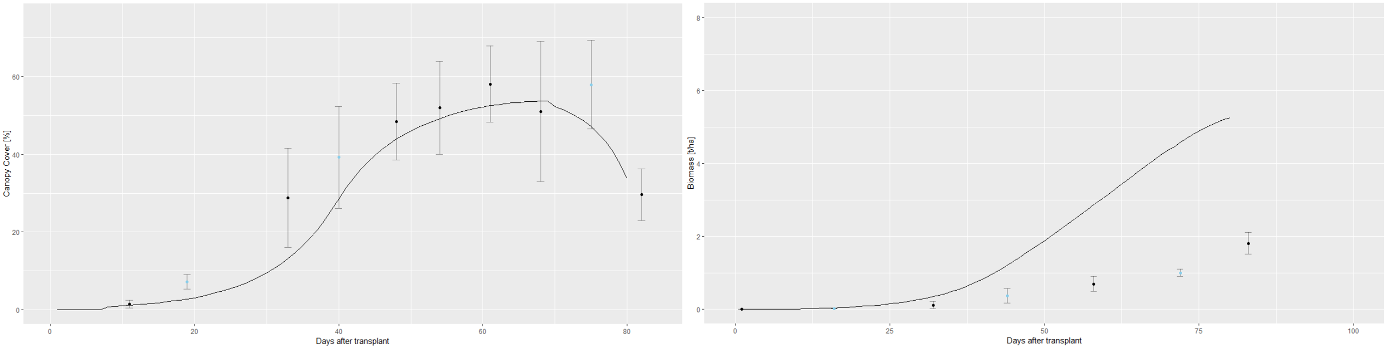

Figure 61 - Calibration and validation of CAR15 in Kampong Thom, site 2 (CF)

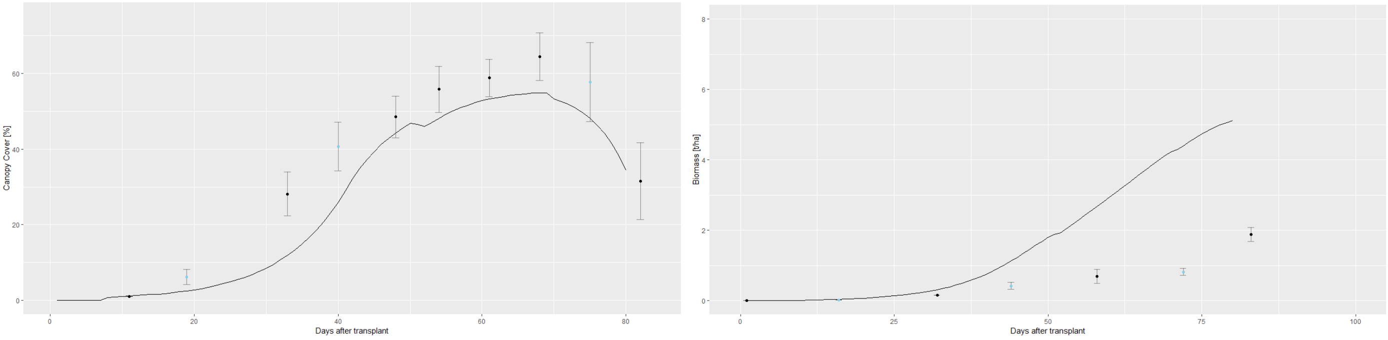

Figure 63 - Calibration and validation of CAR15 in Kampong Thom, site 2 (AWD15)

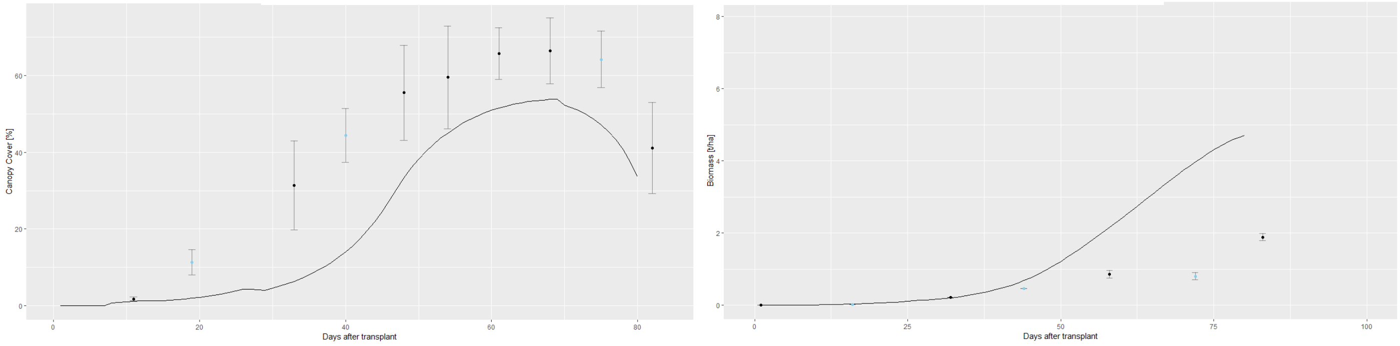

Figure 62 - Calibration and validation of CAR15 in Kampong Thom, site 2 (AWD20)

Table 13 – Calibration indexes for CAR15 in Kampong Thom, site2

	RMSE [%]	E	d
Biomass - CF	1.3	-15.99	0.5
CC - CF	7.2	0.86	0.97
Biomass – AWD15	1.2	-14.07	0.52
CC – AWD15	8.8	0.84	0.96
Biomass – AWD20	0.8	-3.29	0.71
CC – AWD20	16.8	-48	0.87

In the AWD data, we can see that the CC growth has suffered a water stress. It was perturbed at the beginning and didn't grow as fast as usually. It was also underestimated by the model.

3.5.3.2. Validation

Table 14 – Validation indexes for CAR15 in Kampong Thom, site2

	RMSE [%]	E	d
Biomass - CF	2.1	-26.33	0.42
CC - CF	9.1	0.81	0.95
Biomass – AWD15	2.1	-40,79	0.34
CC – AWD15	10.4	0.77	0.94
Biomass – AWD20	1.8	-32.24	0.37
CC – AWD20	20.9	0.08	0.79

In both sites of Kampong Thom, we did not have a lot of data especially for the validation so we can wonder if these indicators are relevant for such small datasets.

3.5.4. Model discussion

In the annex are the values of the cultivars after calibration. Sometimes, to get closer to our measurements, we needed to go further from some parameters that we had measured. For example, to get closer to the yield, we had to adjust the HI at a higher value than the observed one.

In Kampong Thom, we can model higher yields, like in reality, and this is partly thanks to the deeper roots, that can have access to more water.

We can say that overall, we did not reach the level of precision that we hoped for. This is due to several facts, including the lack of much information. Indeed, we did not have the data we needed concerning the irrigation, which is very restricting as we work with a water-based model. We had to recreate and extrapolate the irrigation events, and this had an impact on the precision of the modeling.

The gradient of water stressed was not always respected either. As explained in paragraph 3.4.1.3., the limit between AWD15 and AWD20 in Kampong Thom was blurred to say the least.

To describe the cultivars, we used data determined experimentally on one year and we tried to refine it with more experiments. However, we did not have a lot of data, (the problem was not the experimental set-up, but rather the fact that the data was not collected very often), so the calibration and especially the validation often happened with a very limited set of data. A larger set of data could be very useful for calibration and validation because the indexes would be a lot more significant with a wider dataset.

There is not a lot of data available on the cultivars that we studied, and they were created relatively recently. The data concerning the cultivars will thus be refined year by year as the dataset gets wider. This process of recalibration needs to continue in order to reach a good accuracy in the modeling of the water stress on these cultivars.

Conclusion and perspectives

4.1. What we learned

On a personal note, I learned a lot thanks to this thesis. I got the amazing opportunity to go abroad and discover a totally different culture, which was incredibly enriching. I also learned a lot about rice cultivation, field work, and data analysis, so I am very grateful for this experience.

In this study, we conducted and monitored an experiment to test the effect of three irrigation regimes on rice on three different soils, and with four different cultivars. This work was conducted with the objective to answer several questions.

We wanted to assess which cultivar was the most resistant to irrigation deficiency among the cultivars tested, and how far in the AWD it was possible to go before a loss in yield happened. In this experiment, the cultivar that was the most resistant was CAR15. Indeed, in all the sites, its yield was not significantly impacted by AWD15. However, in Kampong Thom, its yield started to be impacted by AWD20, so it would be best for an optimized production to set the limit of AWD at -15cm.

We also wanted to determine which scenario allowed the best Water-Use Efficiency. We saw that in the site 2 of Kampong Thom, all scenarios had a very high WUE. This could be due to a combination of the microclimate and fertilizer mixed with manure. In the AWD side of the CARDI experiment of 2021, we also observe a very good WUE for CAR15 and OM5451 (despite having a relatively small yield). These observations have to be interpreted carefully as the irrigation records are inconsistent.

Finally, we identified that the parameter influencing the most the yield is the experimental site (that is to say a combination of soil texture and density, fertilizer and microclimate). Then, the cultivar has an impact, especially it determines the impact of the irrigation depending on its resistance to irrigation deficiency.

Our experiment confirms the yield difference between resistant and non-resistant cultivars to irrigation deficiency. We can recommend AWD15 as standard irrigation regime for resistant cultivars for a more resilient rice cultivation.

We also dedicated our work to the modeling of the experiments. We overall did not reach a great accuracy in the modeling. We observed a recurring overestimation of the biomass and struggled to reach a good fitting. This can be caused by several factors, including stresses that were not considered like salinity stress, or fertility stress. We also realized that the CC was overestimated during the ripening stage so this also had an impact. The validation in the AWD scenarios is not necessarily worse than the validation of the CF regimes, but we observed that the water stress is often underestimated.

In some ways, this experiment showed us some flaws and it allows us to propose some adaptations for a better experimental management in the future.

4.2. Recommendations

For a better accuracy of the model, we can suggest in a first part to get a wider and more accurate set of data. Indeed, this is a water-based model and the irrigation records were inconsistent. The first step for a better calibration and a correct estimation of the water stress would thus be a better data collection. Having a wider set of data to be able to calibrate all the stresses and attribute their impact on the yield would help understand better the dynamic of the model as well.

Generally, a better monitoring of the experiments and more precision in the collection of data would make a huge difference, if this experiment had to be reproduced.

It may seem like a detail but the homogenization of the data collection would make it a lot easier and faster to analyze. Indeed, during this experiment, it was hard not to notice that the data was collected on different media (several notebooks, several laptops) without any sort of central gathering of information. This situation makes it hard to centralize data, and easy to lose some pieces of information (this was an issue that we faced, as well as mislabeling). Also, a standardization of the data supports (charts to fill, etc.) would make the data treatment easier, and avoid missing data (like the volume of irrigation). This requires a little more planification of the field work but it could improve the quality of the work significantly.

The data that needed to be collected regularly (water level, biomass, canopy cover) was missing for several periods of time, often quite long. This impacted the reliability of some datasets (like WUE), and made it especially hard to use the model, as the calibration and validation were realized with a very limited set of data. This seems very important to correct in the future, maybe by increasing the personnel dedicated to the monitoring, in order to have more complete and accurate datasets.

Also, we did not have any information concerning the composition of the water used to irrigate, even though it is a very central element in our experiments. We only could estimate its conductivity thanks to the bulk electrical conductivity sensors in the soil. We can recommend a water analysis for a similar experiment, because the composition of the water can have an impact on the growth of the plants and their toxicity in the short term, as well as the fertility of the soil in the long term.

4.3. Perspectives

Our study was yield-oriented. Indeed, we compared the scenarios based on the quantity of rice produces by a m^3 of water. However, there are other criteria that can define quality and efficiency, like nutritional potential, and quality of the grains. Moreover, according to the IRRI household survey of 2010, the grain and eating quality is the trait that most farmers look for in Cambodia, the high yield coming second in desirable varietal traits. It could be interesting to realize a similar study focusing on the nutritional potential of rice (Pandey S. et al., 2012).

Our study was especially focused on the CAR15 cultivar, and it allowed us to analyze how far it can go in the AWD process. It could be interesting to conduct a similar experience for the Sen Pidor cultivar as our experiment did not allow us to really test its limits towards irrigation deficiency. It would also be interesting to test which exact parameter inside one site influenced the yield the most in order to optimize the production even more.

Finally, for a better yield and a better productivity of rice, some changes need to be done. Indeed, as we saw, some experiments reached the average national yield and some did not, but not one scenario had reached the potential yield of its cultivar, in any irrigation regime. We can then recommend a better stand, which will make the plants produce less tillers, but a better quality of grain. Some other fertilizing practices can be recommended like an increased use of natural manure that has long term benefits, as well as the use of biochar for example, that changes the porosity of the soil (which can be very important for soils not taking up the water like may have observed in our experiment), increases the nutrient supply in the soil, and acts as a carbon sink (El-Naggar et al., 2019).

AWD is a practice with a growing recognition, with trials in many countries. It is a technique that does not necessitate a lot more work to implement. Indeed, it just needs a regular monitoring of the water level (in the AWD method based on a water level). In addition to its advantages concerning the water savings and the methane emissions, it also allows the farmers to save on pumping costs. It can even be beneficial during years without droughts (Vaiknoras et al., 2020). However, it is still rare compared to CF and there still is a need for sensibilization for it to become the new standard practice of rice irrigation. This would have a great impact in the agriculture sector and help it to face the challenges to come.

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