Rice Genotypic Variation on Phenological Development and Yield Performance in Cold Prone High Altitude Cropping Systems

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Dedication

This work is dedicated to my father Belay Abera and my mother Enguday Dubale.

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List of Abbreviations

ANOVA	Analysis of variance
APSIM	**A**gricultural **P**roduction **S**ystems s**IM**ulator
BMZ	German Federal Ministry of Economic Cooperation and Development
BVP	Basic vegetative phase
C	Carbon
CARD	Coalition for African Rice Development
CE	Crop establishment methods
CEC	Cation exchange capacity
CV	Coefficient of variation and
d	days
DAP	Diammonium Phosphate
DAS	Days after sowing
DS	Direct seeding
DSSAT	Decision Support System for Agrotechnology Transfer
EIAR	Ethiopian Institute of Agricultural Research
EM	Emergence
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Statistical Databases
FL	Flowering
FOFIFA	National Center for Applied Research and Rural Development Madagascar
G	Genotype
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GRiSP	Global Rice Science Partnership
HA	High altitude
HYDROMET	Hydrological and meteorological
Ind	*indica*;
Jap	*japonica*

LA	Low altitude
MoARD	Ministry of Agriculture and Rural Development
N	Nitrogen
NRRTC	Fogera National Rice Research and Training Center
NS	Non-significant
P	Phosphorus
PFS	Percent of filled spikelet
PI	Panicle initiation
PPT	percentage of productive tillers
Pr	probability
R	Ratio
R^2	Coefficient of determination
RAB	Rwanda Agriculture Board
RHmin	Minimum relative humidity
RSSP	Rural Sector Support Project
SAS	Statistical analysis system
SPP	spikelets per panicle
SSA	sub-Saharan Africa
TGW	Thousand grain weight
Tmax	Maximum temperature
Tmean	Mean temperature
Tmin	Minimum temperature
TP	Transplanting
TPH	Number of tillers per hill
UV-B	Ultraviolet-B Radiation
VPD	Vapor pressure deficite
WA	West Africa

Summary

Despite a huge potential for rice intensification, several constraints have been reported as bottlenecks for rice production in the East African high-altitude cropping system. In this system, yield reductions are mainly caused by moisture deficit, which dictates the sowing date of the crops, and cold stress, which can occur either during specific crop growth phases or during the entire cropping period. In order to minimize yield losses, cultivation of suitable genotypes and timely implementation of proved crop management options are implicitly needed. Therefore, the objectives of this study were to investigate the effects of weather during specific development stages on yield and yield components of a large number of rice genotypes contrasting in crop duration; to explore the effects of crop establishment method on the performance of a set of rice genotypes in high altitude; and to identify key data sets required for the adaptation of agricultural decision support tools to new environments: the case of RiceAdvice being introduced to the highlands of East Africa. Field trials were conducted during the cropping seasons of 2016 and 2017 at the Fogera rice research station in Ethiopia. Further, to generate data to be used for the advancement of RiceAdvice, trials were implemented in Madagascar (Ambohibary and Ivory) and Rwanda (Bugarama and Rwasave) at different altitudes. Thirty contrasting genotypes were included in the study to investigate the effects early and late sowing and the related weather variation experienced by the crop. The crop establishment methods (direct seeding and transplanting) were evaluated using nine contrasting genotypes. Daily mean, minimum, and maximum temperature, rainfall, radiation, and relative air humidity were recorded during the experimental period; and the phenological development of each genotype was closely monitored in all trials. Data on grain yield and yield components were recorded and finally subjected to analysis of variance. Results showed that yield was positively correlated with the percentage of filled spikelets and the number of productive tillers, and negatively correlated with the number of tillers per hill. Genotypes differed in duration, yield, and yield components between the two years, which was related to both, differences in sowing date as well as differences in weather conditions. Early sowing in 2017 led to an extended duration until maturity of short-duration genotypes, which was related to low radiation levels as the vegetative phase of short duration genotypes entirely took place during the cloudy rainy season. Contrastingly, the duration to maturity of medium- and long-duration genotypes was shortened after early sowing in 2017, probably related to higher relative air humidity. In 2016, late sowing in combination with the early onset of the

cool period led to high spikelet sterility in medium- and long-duration genotypes, as the cold-sensitive booting phase took place during the cold spell. Therefore, effects of sowing date on yield differed between genotype groups with short-duration genotypes suffering and medium- and long-duration genotypes profiting from early sowing and vice versa for late sowing. Similar results were obtained in the experiment conducted in Madagascar and Rwanda. At high altitude in Madagascar, short-duration genotypes performed well after late sowing, whereas medium-duration genotypes performed better after sowing one to two months earlier. Also, in Rwanda, delayed sowing compromised yield because of spikelet sterility related to low-temperature during the reproductive stage. Therefore, it was concluded that the choice of variety should depend on the sowing date, which is dictated by the onset of rains. Further, decisions on management intervention have to consider season-specific constraints. Comparison of transplanted and direct seeded rice showed that, in general, transplanting had a strong advantage over direct seeding. While at high-altitudes, growing medium- and long-duration genotypes with a high yield potential bears the strong risk of yield loss due to cold sterility, transplanting, which resulted in significantly higher yields than direct seeding, can mitigate this risk. As after transplanting, physiological maturity was observed earlier in the season than after direct seeding, rice plants, including medium- and long-duration genotypes, escaped the low temperature stress at the critical reproductive stage, and thus, low spikelet fertility. Thus, with a relatively cold tolerant genotype such as Yun-Keng, sowing a few weeks earlier within an irrigated nursery can make use of the full potential and increase yields. Comparison of the experimental sites in Ethiopia, Madagascar and Rwanda, showed that the mean temperature between sowing and flowering of the four tested genotypes was negatively correlated with altitude. In general, precise knowledge of the duration of the potentially suitable genotypes is required and a crop model that is well-calibrated for the genotypes as well as for the environment, in combination with a smartphone application such as RiceAdvice, would be of great help to support farmers' decision-making. The data recorded from the three countries' field trials can be used as data source to validate RiceAdvice, and thus, increase its applicability.

Zusammenfassung

Trotz eines großen Potenzials für die Intensivierung des Reisanbaus wurde von mehreren Einschränkungen als Engpässe für die Reisproduktion im ostafrikanischen Hochgebirgsanbausystem berichtet. In diesem System werden Ertragsminderungen hauptsächlich durch Feuchtigkeitsdefizite verursacht, die den Aussaattermin der Pflanzen bestimmen, sowie durch Kältestress, der entweder während bestimmter Wachstumsphasen der Pflanzen oder während der gesamten Anbauperiode auftreten kann. Um die Ertragsverluste zu minimieren, sind der Anbau geeigneter Genotypen und die rechtzeitige Umsetzung bewährter Anbaumethoden unabdingbar. Daher waren die Ziele dieser Studie, die Auswirkungen des Wetters während bestimmter Entwicklungsstadien auf den Ertrag und die Ertragskomponenten einer großen Anzahl von Reisgenotypen zu untersuchen, die sich in der Anbaudauer unterscheiden, die Auswirkungen der Anbaumethode auf die Leistung einer Reihe von Reisgenotypen in großer Höhe zu erforschen und Schlüsseldatensätze zu identifizieren, die für die Anpassung von landwirtschaftlichen Entscheidungshilfen an neue Umgebungen erforderlich sind: der Fall von RiceAdvice, das im Hochland von Ostafrika eingeführt wird. Die Feldversuche wurden während der Anbausaison 2016 und 2017 an der Reisforschungsstation Fogera in Äthiopien durchgeführt. Um Daten für die Weiterentwicklung von RiceAdvice zu generieren, wurden außerdem Versuche in Madagaskar (Ambohibary und Ivory) und Ruanda (Bugarama und Rwasave) in unterschiedlichen Höhenlagen durchgeführt. Dreißig kontrastierende Genotypen wurden in die Studie einbezogen, um die Auswirkungen von früher und später Aussaat und die damit verbundenen Witterungsschwankungen auf die Kultur zu untersuchen. Die Methoden zur Etablierung der Kultur (Direktsaat und Verpflanzung) wurden anhand von neun kontrastierenden Genotypen bewertet. Tägliche Mittel-, Minimal- und Maximaltemperaturen, Niederschlag, Strahlung und relative Luftfeuchtigkeit wurden während des Versuchszeitraums aufgezeichnet, und die phänologische Entwicklung jeden Genotyps wurde in allen Versuchen protokolliert. Die Daten zum Kornertrag und den Ertragskomponenten wurden erhoben und anschließend einer Varianzanalyse unterzogen. Die Ergebnisse zeigten, dass der Ertrag positiv mit dem Prozentsatz der gefüllten Ährchen und der Anzahl der produktiven Triebe und negativ mit der Anzahl der Triebe pro Pflanze korreliert war. Die Genotypen unterschieden sich in Dauer, Ertrag und Ertragskomponenten zwischen den beiden Jahren, was sowohl mit Unterschieden im Aussaattermin als auch mit Unterschieden in den Wetterbedingungen zusammenhing. Eine frühe Aussaat im Jahr 2017 führte zu einer

verlängerten Dauer bis zur Reife der Genotypen mit kurzem Zyklus, was mit der geringen Strahlungsintensität zusammenhing, da die vegetative Phase der Genotypen mit kurzem Zyklus vollständig während der bewölkten Regenzeit stattfand. Im Gegensatz dazu war die Dauer bis zur Reife von Genotypen mit mittlerem und langem Zyklus nach früher Aussaat im Jahr 2017 verkürzt, was wahrscheinlich mit der höheren relativen Luftfeuchtigkeit in Zusammenhang stand. Im Jahr 2016 führte eine späte Aussaat in Kombination mit dem frühen Einsetzen der Kälteperiode zu einer hohen Sterilität bei Genotypen mit mittlerem und langem Zyklus, da die kälteempfindliche Phase des Rispenschiebens während der Kälteperiode stattfand. Daher unterschieden sich die Auswirkungen des Aussaatdatums auf den Ertrag zwischen den Genotypgruppen, wobei die Genotypen mit kurzem Zyklus von einer frühen Aussaat benachteiligt waren und die Genotypen mit mittlerem und langem Zyklus von einer frühen Aussaat profitierten. Ähnliche Ergebnisse wurden in den in Madagaskar und Ruanda durchgeführten Experimenten erzielt. In den Höhenlagen von Madagaskar schnitten die Genotypen mit kurzem Zyklus nach später Aussaat gut ab, während die Genotypen mit mittlerem Zyklus nach ein bis zwei Monaten früherer Aussaat besser abschnitten. Auch in Ruanda beeinträchtigte eine verspätete Aussaat den Ertrag aufgrund der Sterilität der Ährchen, die mit den niedrigen Temperaturen während der Reproduktionsphase zusammenhängt. Daraus wurde gefolgert, dass die Wahl der Sorte vom Aussaattermin abhängen sollte, der wiederum vom Einsetzen der Regenfälle bestimmt wird. Darüber hinaus müssen Entscheidungen über Managementeingriffe die saisonalen Einschränkungen berücksichtigen. Der Vergleich von verpflanztem und direkt gesätem Reis zeigte, dass im Allgemeinen die Verpflanzung einen starken Vorteil gegenüber der Direktsaat hatte. Während in hohen Lagen der Anbau von Genotypen mit mittlerem und langem Zyklus und hohem Ertragspotenzial das starke Risiko von Ertragseinbußen aufgrund von Kältesterilität birgt, kann die Verpflanzung, die zu deutlich höheren Erträgen als die Direktsaat führte, dieses Risiko abmildern. Da nach dem Verpflanzen die physiologische Reife früher in der Saison beobachtet wurde als nach der Direktsaat, entgingen die Reispflanzen, einschließlich der Genotypen mit mittlerem und langem Zyklus, dem Stress durch niedrige Temperaturen in der kritischen Reproduktionsphase und damit der geringen Fertilität der Ährchen. Somit kann bei einem relativ kältetoleranten Genotyp wie Yun-Keng eine einige Wochen frühere Aussaat in einem bewässerten Saatbeet das volle Potenzial ausschöpfen und die Erträge steigern. Ein Vergleich der Versuchsstandorte in Äthiopien, Madagaskar und Ruanda zeigte, dass die mittlere Temperatur zwischen Aussaat und Blüte bei den vier getesteten Genotypen negativ mit der Höhenlage korreliert war. Generell ist eine genaue Kenntnis der Zyklusdauer der potenziell geeigneten Genotypen erforderlich und ein sowohl auf die Genotypen als auch auf die Umwelt gut kalibriertes Modell wäre in Kombination mit einer Smartphone-Anwendung wie RiceAdvice eine große Hilfe, um die Anbauentscheidungen der Landwirte zu unterstützen. Die in den Feldversuchen in den drei Länder erhobenen Daten können als Datenquelle für die Validierung von RiceAdvice verwendet werden und somit die Anwendbarkeit der Anwendung erhöhen.

Overview of publications

Based on the cumulative thesis regulation, this doctoral thesis consists of three articles (1st and 3rd articles published and 2nd article submitted).

Article I

Abera, B. B., Stuerz, S., Senthilkumar, K., Cotter, M., Rajaona, A., & Asch, F. (2020). Season-specific varietal management as an option to increase rainfed lowland rice production in East African high altitude cropping systems. *Journal of Agronomy and Crop Science, 206*, 433–443. https://doi.org/10.1111/jac.12418

Outline and overview

An overview of the research topic's importance and relevance is highlighted. Literature sources are reviewed and referred to discuss the rice importance, production, and limiting factors in sub-Saharan countries in general and in high altitude East Africa rice farming systems in particular. The two bottlenecks for rice production both at the beginning and later at the end of the season are clearly explained. Then, multiple genotypes with contrasting growth duration (short-, medium- and long-duration) were evaluated and comparison of genotypes' performances was made. The main objective was investigating the weather parameters' effects on the performance of genotypes at a specific development stages, thus the yield and yield components.

Article II

Abera, B. B., Senthilkumar, K., Cotter, M., & Asch, F. (Expected 2021). Transplanting as an option to cope with abiotic stress in high-altitude lowland rice production systems in East-Africa. Submitted to *Journal of Agronomy and Crop Science* on 05.01.2021. Current status: in review

Outline and overview

As an introduction, the prevailing environmental condition of the testing site and similar cropping systems were described. An overview of advantages and disadvantages of transplanting and direct seeding was reviewed from several literature sources. Therefore, the relevance of the topic is clearly stated. Within the framework of RiceAdvice project, we have evaluated the crop establishment methods in order to find the "best fit" method in the high altitude rice farming systems. In the methodology, two crop establishment methods were evaluated in combination with different contrasting rice genotypes: short-, medium-, and long-duration. The advantage of transplanting based on the findings is discussed towards solving the two critical challenges in the rice farming systems: Moisture deficit at early in the season and low temperature late at the reproductive stage of the crop.

Article III

Cotter, M., Asch, F., Abera, B. B., Chuma, A. B., Senthilkumar, K., Rajaona, A., Razafindrazaka, A., Saito, K., & Stuerz, S. (2020). Creating the data basis to adapt agricultural decision support tools to new environments, land management and climate change—A case study of the RiceAdvice App. *Journal of Agronomy and Crop Science, 206*, 423–432. https://doi.org/10.1111/jac.12421

Outline and overview

In order to highlight the importance and relevance of the research topic, the overview of the use and benefit of models and mobile apps are presented. Specifically the calibration and usage of RiceAdvice is elaborated. Previous findings were reviewed and the crucial data to be incorporated in the app in order to introduce to the new environment was summarized. Then the methodology of the field activities are described corresponding to selected site in East Africa: Ethiopia, Madagascar, and Rwanda. The result from Ethiopia is discussed that variety choice is important to escape the cold spell late in the reproductive stage. From Madagascar, sowing date and variety choice is noted. And from Rwanda, the effect of temperature due to altitude difference of nutrient uptake is clearly described.

1 General Introduction

1.1 Rice growth and development

Rice is among the three most cultivated cereal crops worldwide, and more than half of the world's population depends on it as their main source of calories (Chauhan et al., 2017; Seck et al., 2012). Asian rice (*Oryza sativa* L.) and African rice (*Oryza glaberrima* Steud.) are the two cultivated species. Besides, the genus *Oryza* comprises 22 wild species (Singh et al., 2018). Rice is adapted to very diverse environments, as it is growing in temperate, subtropical, and tropical areas under various edaphic and climatic conditions (Mackill & Lei, 1997; Yoshida, 1981). As one of the most intensely studied crops, information about rice growth and development, which is one of the critical aspects of this study, is available in various literature sources. The biological growth and phenological development are not distinct process in the crop cycle (Vergara, 1991). They instead are concurrent events running alongside each other.

Rice growth starts with seed germination, which depends on the availability of sufficient moisture and oxygen, and a favorable temperature regime. However, seed germination has been reported even under submerged conditions (Ghosal et al., 2019) and at low concentrations or even in the absence of oxygen (Magneschi & Perata, 2009). On the other hand, low temperatures have a considerable effect on germination (Li & Yang, 2020), with a sensitivity depending on the genotype. In the crop's life cycle, development passes three main stages: vegetative, reproductive, and ripening stage (Fig. 1.1) (GRiSP, 2013; Yoshida, 1981). The vegetative stage is characterized by leaf emergence, tillering, and the increase in plant height and biomass. Variations in crop duration until maturity are mainly attributed to variations in the duration of the growth stage from germination to Panicle initiation (PI) (Moldenhauer and Slaton, 2001; Moldenhauer et al., 2018; Yoshida, 1981). The reproductive stage starts at PI, which is followed by stem elongation, flag leaf development, booting, heading, and flowering. The ripening stage, which further divided in to milky, dough, and maturity stages, follows fertilization (GRiSP, 2013). At ripening, the grains size and weight increase due to the starch and sugar translocation mainly from leaf sheaths (Yoshida and Ahn, 1968). The duration of the ripening stage has been reported to be relatively constant, with minor differences among cultivars and growing environments (Razafindrazaka et al., 2020).

In general, variation in the duration of phenological phases is dependent on both genetic and environmental factors (Fukui et al., 2015). Photoperiod (for sensitive cultivars) and temperature determine the rate of the phenological development of a given cultivar. At suboptimal temperature regimes, rice may suffer from an extended duration of phenological phases and significant spikelet sterility e.g. in high altitude environments (Chuma et al., 2020; Dingkuhn et al., 2015; Razafindrazaka et al., 2020; Shrestha et al., 2013).

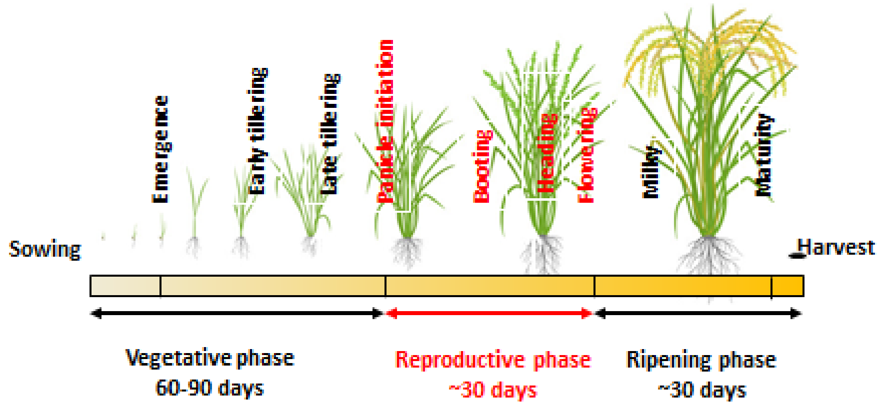

Figure 1.1 Rice growth and phenological development, based on the definitions in GRiSP, (2013). Modified from VectorStock.com.

1.2 Rainfed rice farming systems

Rice production ecosystems can be classified according to the source of water supplied for rice cultivation (Diagne et al., 2013). Rainfed systems receive the water from precipitation and include both terraced ("lowland") and non-terraced ("upland") systems. In irrigated rice systems, quite elaborate man-made interventions into the water cycle, such as reservoirs, irrigation canals, weirs, and embankments to control water tables are often found. "Paddy rice" systems are the most prominent example. Other categories encompass mangrove-swamp and deep-water environments, in which the primary water source can be either a natural water body or flood water. Three rice growing ecosystems are prevalent in Africa: I) rainfed upland, which is found in mountainous areas and entirely dependent on rainfall; II) rainfed lowland, which is characterized by bunded fields, keeping the rain as standing water for some days depending on the soil characteristics and the magnitude of the rain; and III) irrigated systems, in which the rice crop is grown with irrigation water from, e.g., reservoirs. About 70% of the area devoted to rice production in sub-Saharan Africa (SSA) is rainfed, of which lowland (meaning terraced) rice production has the highest share compared to upland rice (Diagne et al., 2013). In literature, high altitude rice farming systems form a separate category because of its distinct environmental features, particularly low temperature stress (Ahmad, 2004; Zena et al., 2010). In East Africa, where the largest mountain ranges of the continent are found (Fig. 1.2), crop production has traditionally been located mainly in the high altitude plateaus (Amede & Lemenih, 2020). Along with a range of other cropping systems, rice cultivation has expanded in East Africa, mainly in high altitudes under rainfed conditions (Cotter & Asch, 2020; Dusserre et al., 2012; Raboin et al., 2014).

In Africa, a large gap exists between the attainable yield and the actual yield of rice obtained in farmers' fields. Adapted and targeted crop management practices are the main strategy to diminish the yield gap (Diagne et al., 2013; Tanaka et al., 2017). In general, sustainable intensification and area expansion are crucial for crop production in SSA to subordinate its dependency on imports (van Ittersum et al., 2016). Addressing biophysical constraints of rice production in African countries largely increases the production and therefore, lifted millions of people above the poverty line. Rice is subject to various biotic and abiotic stresses (Zenna et al., 2017). The biotic constraints include weeds, diseases and pests, birds, and rodents. Despite biotic constraints being perceived as more severe by rice farmers in SSA countries (Diagne et al., 2013), abiotic constraints play a significant role in rice production worldwide (Fahad et al., 2019). In high altitudes, a limitation of photosynthesis, thereby reduced plant growth and yield due to abiotic stress has been reported from different research findings (Dingkuhn et al., 2015; Fu et al., 2016; Shrestha et al., 2013).

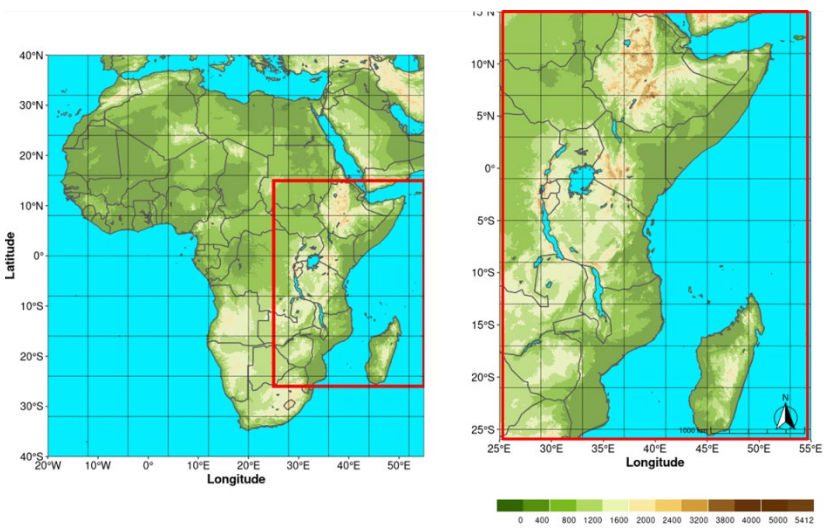

Figure 1.2 Altitude gradient map of Africa and East Africa.

1.3 Abiotic stresses in rice production

Various factors are considered as abiotic stresses, e.g. excessive or insufficient soil moisture, low soil fertility, salinity / alkalinity, high concentrations of toxic minerals, limited or excessive light and extreme temperatures, which are all limiting the plant growth and development (Chen, 2012). The production and productivity of rice are profoundly influenced by the above mentioned stresses all over the world (Balasubramanian et al., 2007; Shyamsunder, 2015). Insufficient soil moisture causes drought stress, consequently different genotypes response varied in terms of physiological activities, thus compromise the final yield (Zu et al., 2017). Erratic rainfall and its poor distribution heavily affect rainfed rice production in Africa (Alou et al., 2018). Regarding development, drought stress extends the duration of the vegetative phase. During heading stage, it prevents peduncle elongation and consequently, affects panicle exertion (Muthurajan et al., 2011). Moreover, this effect delays heading and can trap spikelets inside the flag-leaf sheath, leading to increased spikelet sterility and, thus, significantly reduced the ultimate grain yield.

On the other hand, in river deltas, where drought is usually of no or little concern, rice is vulnerable to salt stress. Reduced rate of photosynthesis is reported to be the main effects of salt stress at different growth and development stages (Radanielson et al., 2018). Salinity tolerance in rice depends on the interaction of both environmental and genetic factors. Asch and Wopereis (2001) observed the strongest negative effects of salinity at the beginning of the reproductive stage, rather than during seedling stage. Salinity strongly affects yield components and reduces spikelet number per panicle, 1000 grain weight, and increases sterility, leading to reduced grain yield. While salinity is a constraint to 2% of rice area of Africa, extreme temperatures, particularly cold, is the most important constraint in East Africa's high altitude rice farming systems (van Oort, 2018).

Increases in rice production can be achieved through area expansion and / or increased productivity, which are both constrained by extreme temperatures. Most plants cannot tolerate a heat above 40°C, while many plants of tropical origin are damaged at 10℃ temperatures and below (Dingkhun et al., 1995; Smirnoff, 2014). Rice is highly sensitive to temperature stress (cold and heat) (Arshad et al., 2017), but its sensitivity depends on the development stage and genotypes (Drame et al., 2013). Both, chilling and freezing have been considered as low temperature stress or cold stress. Chilling stress (0-15°C) effects from temperatures low enough to produce injury without forming ice crystals in plant tissues, whereas freezing stress (<0°C) is due to ice formation within plant tissues (Hasanuzzaman et al., 2013). Temperature varies considerably with altitude and local topography (Kai and Iba, 2014) and thus, challenges resulting from low temperatures are often observed in high altitude production systems. A considerable proportion of East Africa can be classified as low temperature prone area (for rice cultivation) due to its high elevation (Dingkuhn et al., 2015; Drame et al., 2013; Dussere et al., 2012; Shrestha et al., 2013; Zenna et al., 2017).

Cold stress impedes various growth and reproductive processes in rice (Arshad et al., 2017; Jia et al., 2015) including poor germination, seedling mortality, reduced tillering, delayed heading, and spikelet sterility (Zhang et al., 2014). It affects panicle initiation and thus, delays flowering, and affects the physiological activities like anther respiration (Arshad et al., 2017). Plants maintain various molecular mechanisms involving proteins, antioxidants, metabolites, regulatory factors, other protectants, and membrane lipids to survive the temperature stress (Kai and Iba, 2014). Reduction in rice growth due to low temperature could be associated with a decline in uptake of nutrients from the soil as well (Chuma et al., 2020; Setter & Greenway, 1988; Vu et al., 2020; Zia et al., 1994) since it affects metabolic activities (Jia et al., 2015).

1.4 Cold tolerance variability and variation of rice genotypes

The plant's response to cold stress is a dynamic process and a variety of genotypes differ in their tolerance level (Hasanuzzaman et al., 2013). Temperature stress may depend on the duration of the exposure and severity of the stress, the plant growth and developmental stage at which the stress occurs, and whether ice formation takes place in the intercellular spaces (Janmohammedi et al., 2015; Kai and Iba, 2014). Environment and genotype effects cause variability in speed of phenological development resulting in different thermal conditions come upon at sensitive phases (Dingkuhn et al., 2015). There are several management strategies to reduce or avoiding the effects of cold stress on rice yield. The first and most important one is growing cultivars of appropriate duration according to an adapted cropping calendar and thus, avoiding stress (Shimono, 2011). Further, growing resistant genotypes can minimize the problem even during the cold spells (Farrell et al., 2006).

The strategies and mechanisms for cold tolerance vary with genotype (Bonnecarrère et al., 2011), and tolerance level differ at various stages, and many genes are associated with this variation (Saito et al., 2010). Cold stress tolerance is associated with a noticeable alteration of biochemical and physiological processes, e.g. changes in the expression pattern of genes and their protein products (Janmohammedi et al., 2015). Temperature stress tolerance is often related to enhanced activities of enzymes involved in the plant's antioxidant systems (Arshad et al., 2017). *Japonica* subspecies are generally considered as more cold-tolerant than *indica* subspecies (Saito et al., 2010). So far, many tolerant varieties have been developed in different parts of the world and remain significantly contribute to the maintenance of rice yields under cold stress in temperate and high altitude production systems (Cruz et al., 2013).

1.5 Crop management in rice cultivation

The genetic potential of a variety can be realized only when a proper crop management practices are optimized in a favorable biophysical environment. The target of using improved varieties and crop management practices is to improve the productivity of high potential lands and exploit the potential of underutilized lands through improved land preparation, crop establishment, integrated nutrient management, and weed management (Senthilkumar et al., 2018). Direct seeding and transplanting are the most common crop establishment methods in rice farming. The choice of the crop establishment method depends on the availability of manpower and other related inputs, such as herbicides (Farooq et al., 2011; Kumar et al., 2018; Parameswari et al., 2014).

Rahman et al. (2019) reported that the method of crop establishment significantly influenced rice performance with regard to yield and yield components. Higher grain yield and a higher water productivity were reported for direct dry-seeded (Soriano et al., 2018; Ullah et al., 2018) and pre-germinated direct seeded (Rana et al., 2014) versus transplanted rice. However, is not necessarily the case in areas where biotic and abiotic stresses are the main constraints (Kaur & Singh, 2017), or areas with narrow sowing windows. In direct dry seeding, many factors, such as low germination percentage, poor field conditions, cold weather damage, and poor weed competition (Chhokar et al., 2014; Wang et al., 2016) can result in stand loss and low yield performance. A well-leveled field is essential for dry seeding to facilitate uniform seeding depth, thereby establishing a consistent stand (Kumar & Ladha, 2011). Practically, uniformity of seeding depth is difficult to obtain in dry broadcasting. Furthermore, weed infestation can cause immense yield loss in direct dry seeding (Kamoshita et al., 2016). On the other hand, uniform establishment of the rice crop and better weed competition were reported in transplanted rice (Chhokar et al., 2014). The high number of tillers (from 10 to 30) may be emerged in transplanted rice, whereas less (up to five tillers) may be produced in direct-seeded rice (Yoshida, 1981). As the rice farmers look for a solution for the challenges due to climate change and weather pattern shifts, transplanting offers a good alternative. Further, it may also allow for crop intensification as the transplanted crop needs less time in the main field and therefore, eventually another crop can be grown in the same field.

1.6 Digitalization and modeling as a potential tool to strengthen and support farmers' decision making

The agroecological and agronomic suitability of rice genotypes is significantly determined by growth duration and phenology. Proper prediction of the duration and phenology of a rice cultivar improves the decision of farmers' field activities, thus improving productivity. Many crop growth models could be applied as supportive tools to obtain the maximum yield. Crop growth model provides time- and cost-effective means to extrapolate findings from an experimental fields and laboratory studies to larger scales to develop adaptation technology (Chapter four; Li et al., 2017). Well calibrated and validated growth models can help to predict the future crop performance (Dias et al., 2016). Several models, online and smartphone apps have been developed and introduced to rice farmers to improve their decision-making for the application of the appropriate crop management. Validation of several apps and models has been reported for utilization in new environments other than their original development areas. As reported by Larijani et al. (2011), ORYZA2000 model can be applied as a supportive tool for selecting a suitable rice yield improvement approaches before field activities are conducted. On the other hand, ORYZA2000 was modified into ORYZA v3, which has a more robust capability to simulate rice growth and development dynamics and has a wider applicability domain concerning rice production environments (Li et al., 2017). RiceAdvice, which has been developed by AfricaRice, is currently in use in Nigeria, Benin, and Senegal, where it has initially been parameterized (Saito et al., 2015). Its utilization could be easily expanded to new areas, e.g. East Africa, after proper calibration and validation. Therefore, creating a data base is the first step to develop and/or validate the app for its wider use.

1.7 Objectives

This study's objective was to investigate alternative solutions to improve rice production in the rainfed lowland rice farming systems in the high-altitudes of East Africa, where rice production is highly vulnerable to cold. To strengthen and improve farmers' decision-making for sustainable rice intensification, it is crucial to identify appropriate genotypes and crop management options that are adapted to the specific environmental conditions. Fogera Plain was selected as a case study site representing high altitude rainfed lowland rice production systems to meet the first two specific objectives and representative sites from Madagascar and Rwanda were added to meet the third specific objectve:

i. To investigate the effects of weather during specific development stages on phenology, yield, and yield components for a large number of rice genotypes contrasting in crop duration, in order to identify customized sowing windows for the different genotypes depending on their growth duration.
ii. To investigate the effects of the crop establishment methods (transplanting vs. direct seeding) on the performance of rice genotypes with contrasting phenology in high altitude farming systems.
iii. To identify key data sets required for the adaptation of agricultural decision support tools to new environments: the case of RiceAdvice being introduced to the highlands of East Africa.

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2 Season-specific varietal management as an option to increase rainfed lowland rice production in East African high altitude cropping systems.

Abstract

Due to land expansion and an increase in productivity, rice production in sub-Saharan Africa has been growing at a rate of 6% in the past decade. Rainfed rice production systems have accounted for a large share of this expansion. In these systems, the potential growing period not only depends on the length of the rainy season and thus water availability, but is often, especially in the highlands of East Africa, bordered by the onset of the cool period of the year, when low minimum temperatures compromise rice yields. The objective of this study was to investigate the yield potential of 30 rice varieties contrasting in crop duration and cold tolerance in the highlands of East Africa, with its limited length of growing period. A field trial was conducted in the cropping seasons in 2016 and 2017 at the Fogera rice research station, Ethiopia. As a function of the onset of rains, rice was sown mid-July in 2016 and early July in 2017. Early sowing in 2017 led to an extended crop duration and significantly lower yields of the short-duration varieties, and to a shortened duration and significantly higher yields of the medium- and long-duration varieties, when compared to late sowing in 2016. Late sowing compromised yield of the medium- and long-duration varieties because of low temperatures during booting stage, which led to high spikelet sterility. Early sowing resulted in low yields of the short-duration varieties, probably due to low solar radiation during the cloudy rainy season, which coincided with the vegetative stage. Therefore, choice of variety should be a function of the variable onset of the rainy season and related sowing date. However, crop models precisely calibrated for potential varieties and the respective environmental conditions could fully support the selection of a suitable variety, depending on the date of sowing, for example with the help of online tools or smartphone applications.

Keywords

abiotic stress, genotypes, phenology, spikelet sterility, yield components

2.1 Introduction

Rice production in sub-Saharan Africa has been growing at a rate of about 6% over the last decade (FAO, 2019; Seck et al., 2013). The production increase has been due to land expansion (70%) as well as an increase in productivity (30%). A large share of this expansion has happened in rainfed lowland systems (Africa Rice Center, 2014). The major determinant for the expansion of rainfed systems is the length of time available for crop growth (Garitty et al., 1986). However, in systems with strong differences in seasonal water availability, the length of the cropping season is constrained by the onset and length of the rainy period as well as the level of water management employed in the system. Thus, crop exposure to drought or water deficits strongly depends on the sowing date (van Oort, 2018). In addition, rice is a thermophilic crop that in general does not grow well at temperatures below 20 °C (Dingkuhn et al., 1995). Rice yields are significantly reduced due to spikelet sterility when the crop experiences temperatures below 18 °C during the early reproductive stage (Shrestha et al., 2012). In East Africa, in contrast to West Africa, rainfed rice systems are not only constrained by water availability due to seasonal rainfall patterns, but also by low temperatures due to altitude late in the season. This type of cold stress threatens rice production in the central highlands of East Africa (Uganda, Rwanda, Tanzania, and Kenya) and the highlands of Ethiopia (van Oort, 2018). The Fogera Plain is one of the most important rainfed lowland rice producing areas in Ethiopia, contributing about 30% to national rice production (Astewel, 2017). As in all rainfed systems, the onset of the rainy season dictates the actual sowing dates on the Fogera Plain, and the resulting soil moisture reaches levels sufficient for the germination and establishment of the crop. In the northern hemisphere, sowing normally occurs in summer (e.g. mid-June) resulting in harvest in October or November. Low temperatures coinciding with critical reproductive development e.g. for a few days during booting stage, strongly affect seed set and consequently, the yield (Arshad et al., 2017; Dingkuhn et al., 1995; Shrestha et al., 2012).

In general, the yield potential of rice cultivars is determined by their phenological characteristics, particularly crop duration (Dingkuhn and Asch, 1999), since a shortened crop duration has been associated with reduced grain yield via a shorter period of biomass accumulation (Wheeler et al., 2000). Therefore, to fully exploit the yield potential in a rainfed system, genotypes are needed that maximize yield and minimize the risk of crop failure (Dingkuhn, 1995; Shrestha et al., 2011). There are potential options for the selection of rice varieties that fit the system and minimize the risk of sterility due to low temperatures towards the end of the season. One option would be simply using a short-duration variety that will reach physiological maturity before temperatures drop. In case of early onset of the rainy season, a part of the potential cropping period would be lost. Another option would be to use medium-duration rice varieties that have a relatively high level of cold tolerance that allows them to make full use of the cropping period while minimizing the risk of cold sterility in case temperatures drop early. Using a crop model, such as RIDEV or ORYZA, simulating duration and development using varietal photo-thermal constants would allow choosing a variety targeted for the system even as a function of the onset of rains. However, the simulation of genotypic duration would have to be quite accurate.

The objective of this study was to investigate the effects of weather during specific development stages on yield and yield components of a large number of rice genotypes contrasting in crop duration with the aim of widening the management options for varietal selection to intensify rice cropping in rainfed and temperature limited systems. Ethiopias' Fogera Plain is used as a case study site representing high altitude rainfed lowland rice production systems.

2.2 Materials and Methods

2.2.1 Site description and experimental design

A field trial was conducted during the 2016 and 2017 cropping seasons at the Fogera rice research station in Ethiopia, located at 11° 58′ N and 37° 41′ E and at an altitude of 1811 m above sea level. Fogera attains unimodal rainfall pattern from June to mid-September, with a mean annual precipitation of 1200 mm and mean annual minimum and maximum temperatures of 13°C and 25°C, respectively. The soil is a vertisol with a clay content of 71.25%. It is slightly acidic (pH 5.90) and the 20 cm soil horizon contains 0.22% total N, 12.64 ppm available P (Olsen), 0.93 cmol (+) exchangeable K·kg·soil^{-1}, 3% organic carbon, and 52.9 cmol (+) kg^{-1} CEC (Tadesse et al., 2013).

The experiment was laid out in a randomized complete block design with three replications. Plot size was 3 x 4 m and three to four seeds were dibbled with a 0.25 m by 0.15 m spacing between and within rows, respectively. Sowing depended on the available soil moisture and was done on 15.07.2016 and on 05.07.2017. After two weeks, germinated seeds were thinned to one seedling per hill. As per the recommendation, Urea (46% N) and Diammonium Phosphate (DAP) (46% P_2O_5; 18% N) at the rate of 69 kg N and 23 kg P per ha were applied.

One third of N along with the entirety of the P fertilizer was applied as basal application before sowing. The remaining thirds of N was applied as top-dressing at tillering and at panicle initiation (PI) respectively. Weeding was done three times, at tillering, PI, and late booting stage.

2.2.2 Genotypes

Thirty genotypes were included in the study. Three genotypes (X-Jigna, Ediget, and Hibir) were obtained from the Fogera National Rice Research and Training Center (NRRTC). X-Jigna is a popular genotype in the area for more than 30 years (Gebey et al., 2012). Ediget and Hibir are recently released varieties by the national rice research system (MoARD, 2011 & 2013). The remaining 27 genotypes, both *indica* and *japonica* types, have contrasting durations to maturity and varying levels of tolerance for cold, and were obtained from AfricaRice. Table 2.1 shows all genotypes grouped by duration: short 120 to 140 days, medium 141 to 160 days, and long > 160 days.

Table 2.1 Rice genotypes included in the study.

No	Genotype	Type	Source	No	Genotype	Type	Source	No	Genotype	Type	Source
Short (120 to 140 days)				Medium (141 to 160 days)				Long (>160 days)			
1	Machapuchre	Jap	ARC	15	Soameva (Soa)	Ind	ARC	27	FARO-35	Ind	ARC
2	Chhomrong	Jap	ARC	16	Yun-Keng (YK)	Jap	ARC	28	WITA 4	Ind	ARC
3	HS 379	Ind	ARC	17	Zong-Eng (ZE)	Jap	ARC	29	SIM 2 Sumadel	Ind	ARC
4	Duragan	Jap	ARC	18	NERICA L-19 (NL19)	Ind	ARC	30	Partao	Ind	ARC
5	Merig	Jap	ARC	19	Mailaka (Mai)	Jap	ARC				
6	Osmanlik-97	Jap	ARC	20	Kelimamokatra (Kel)	Jap	ARC				
7	Kirkpinar	Ind	ARC	21	IR64	Ind	ARC				
8	Demir	Jap	ARC	22	FOFIFA 160 (F160)	Ind	ARC				
9	Ediget	Jap	NRRTC	23	B6144F (B61)	Jap	ARC				
10	Diamante	Ind	ARC	24	Silewah (Sil)	Jap	ARC				
11	Hibir	Jap	NRRTC	25	Padisashal (Pad)	Ind	ARC				
12	Manjamena	Ind	ARC	26	Makalioka 34 (MK34)	Ind	ARC				
13	X-Jigna	Jap	NRRTC								
14	SCRID	Ind	ARC								

Abbreviations: ARC = Africa Rice Center; Ind = *indica*; Jap = *japonica*; NRRTC = Fogera National Rice Research and Training Center.

2.2.3 Data collection and analysis

Daily mean, minimum, and maximum temperature, rainfall, radiation, and relative air humidity were recorded at 2 m height during the experimental period with a Delta-T WP-GP1 weather station installed next to the experimental fields (Fig. 2.1).

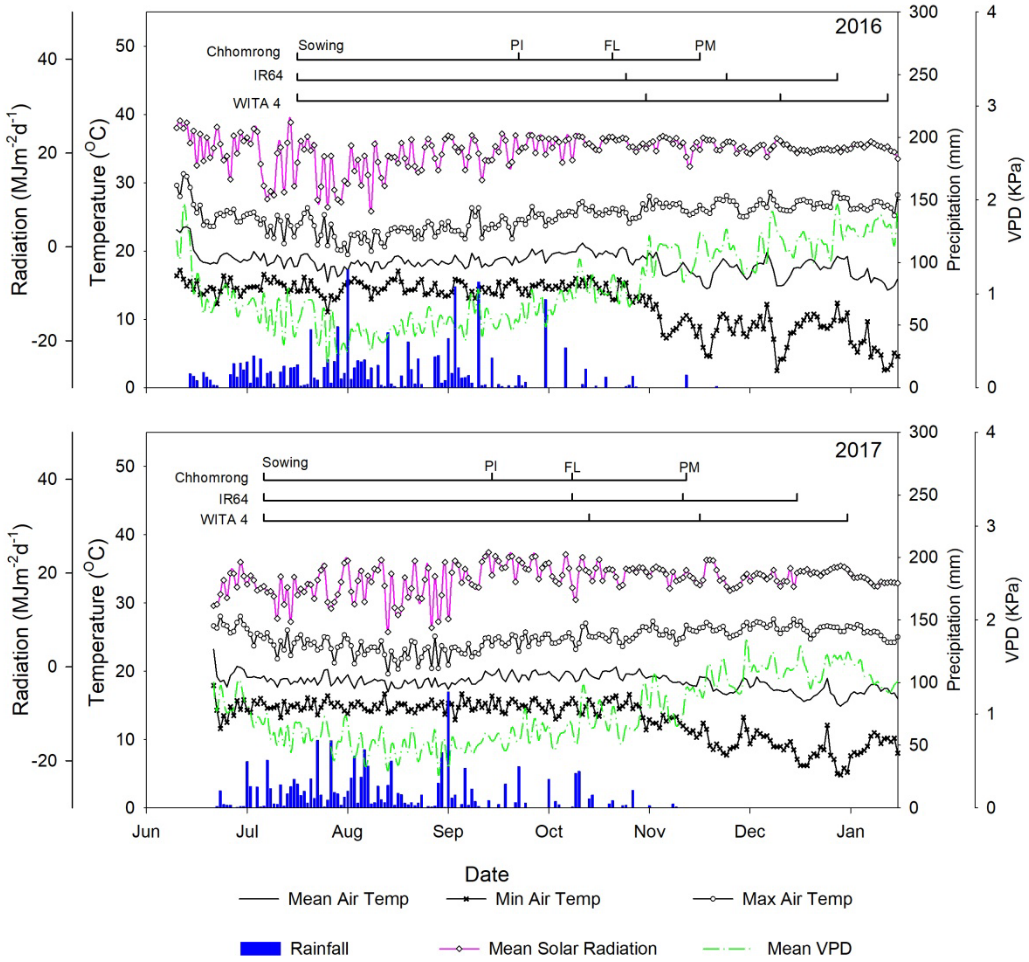

Figure 2.1 Daily weather data from June to December 2016 and 2017 in Fogera, Ethiopia. PI = panicle initiation, FL = flowering and PM = physiological maturity of three representative genotypes.

The phenological development of each genotype was closely monitored in both seasons. Grain yield was taken from a central 3.15 m^2 area of each plot. Number of tillers per hill (TPH), percentage of productive tillers (PPT), spikelets per panicle (SPP), percentage of fertile spikelets (PFS), and thousand grain weight (TGW) were determined from the central nine hills of the yield area. Data on yield and yield components were subjected to analysis of variance (ANOVA) using the statistical analysis system version 9.4 (SAS Institute Inc.). Means were compared using Tukey's test.

2.3 Results

2.3.1 Genotypic phenological responses

Tested genotypes showed variable phenological development and differed in their duration to maturity from 120 up to 176 days (d) (Tab. 2.2). Following duration to physiological maturity, genotypes were categorized into three groups: fourteen were short-duration (120 to 140 d), twelve were medium-duration (140 to 170 d) and four were long-duration (170 to 180 d) (Tab. 2.2). The earlier rains in 2017 allowed for sowing ten days earlier than in 2016. Depending on the duration group, genotypes responded contrastingly to the shift in planting dates. This difference in phenological development between the duration groups became evident at PI. For the short-duration genotypes, earlier sowing increased the duration from emergence to PI and all following phenophases by up to 7 days (maturity), but for the medium- and long-duration genotypes it shortened the duration from emergence to PI and all following phenophases by up to 11 days (Fig. 2.2).

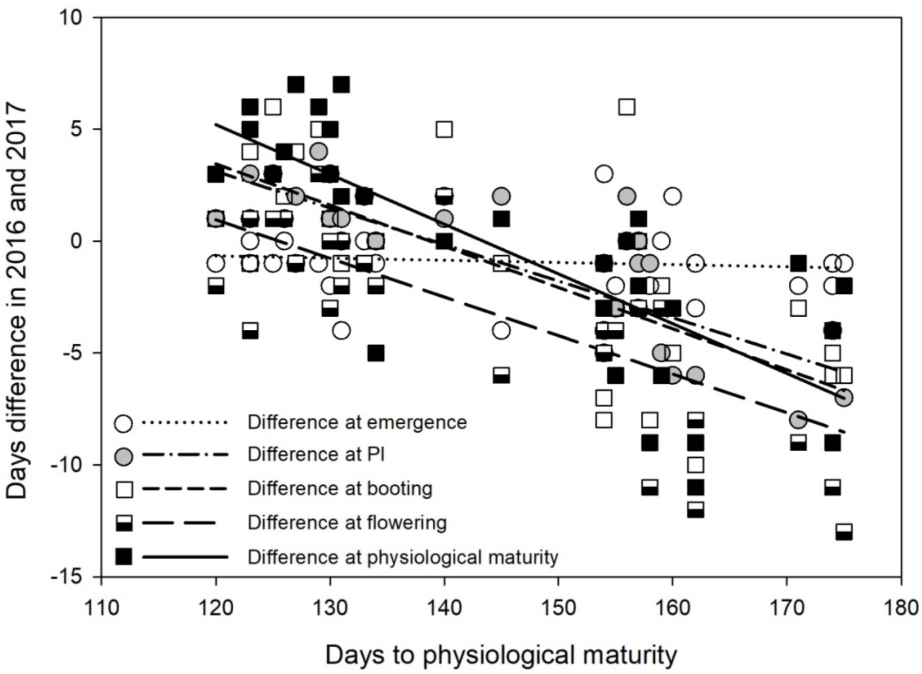

Figure 2.2 Difference in duration from sowing to emergence, sowing to panicle initiation (PI), sowing to booting, sowing to flowering and sowing to physiological maturity between 2016 and 2017 for 30 varieties depending on their duration sowing to physiological maturity.

Table 2.2 Number of days from sowing to the respective development stage of thirty genotypes in Fogera Plain in 2016 and 2017.

Genotypes	**Emergence (50%)**		**Panicle initiation**		**Booting (50%)**		**Heading (50%)**		**Flowering (85%)**		**Physiological Maturity**	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
Machapuchre	12	11	65	66	78	79	90	89	94	92	119	122
Chhomrong	10	10	67	68	81	80	92	88	95	91	120	126
HS 379	11	11	66	67	78	80	91	91	95	96	124	128
Duragan	11	10	65	68	78	82	92	93	96	97	121	126
Merig	11	10	67	70	79	85	92	93	96	97	124	127
Osmanlik-97	12	11	68	70	80	84	94	93	98	97	124	131
Kirkpinar	14	10	66	66	81	80	95	93	97	97	130	132
Ediget	11	10	67	71	81	86	93	96	97	100	126	132
Demir	11	12	68	69	82	83	96	93	100	97	128	133
Diamante	11	11	70	71	84	86	97	95	101	99	128	135
Hibir	14	12	70	73	85	88	98	97	102	102	129	132
Manjamena	13	12	72	72	85	85	96	96	101	99	137	132
X-Jigna	12	14	74	75	87	92	100	103	104	106	140	140
SCRID	14	14	73	75	91	90	104	103	108	107	132	134
Soameva	14	10	81	83	97	96	110	107	116	110	145	146
Yun-Keng	12	15	85	81	102	95	116	112	121	116	156	153
Zong-Eng	15	14	87	82	104	96	118	113	121	117	155	154
NERICA L-19	13	13	89	84	105	103	116	114	122	119	162	156
Mailaka	15	14	91	91	105	105	120	117	124	122	158	156
Kelimamokatra	14	14	88	90	101	107	119	119	123	123	156	156
IR64	14	16	98	92	107	102	120	121	128	125	162	159
FOFIFA 160	15	13	97	94	109	106	122	117	125	121	158	152
B6144F	14	12	89	88	108	100	124	114	128	117	163	154
Silewah	16	13	91	90	109	107	122	121	128	125	157	158
Padisashal	15	12	99	93	114	104	127	118	133	121	167	158
Makalioka 34	15	14	102	96	116	107	127	121	132	124	168	157
FARO-35	14	12	103	95	117	114	133	124	137	128	172	171
WITA 4	14	13	104	97	120	114	140	127	144	131	176	174
SIM 2 Sumadel	16	15	107	103	121	116	139	133	143	139	176	172
Partao	14	12	103	99	118	112	140	129	145	134	179	170

To analyze if the differences in duration between the two years resulted from annual differences in weather or from the shift in sowing date, monthly weather data for both years was statistically compared (Tab. 2.3). In both years, the period between emergence and PI was between July and October for all three groups of genotypes. During this period, mean temperature slightly increased, resulting from a constant minimum and an increasing maximum temperature. Radiation sharply increased in September at the end of the rainy season, while a clear drop in air humidity became evident in October. Between July and October, mean monthly weather hardly differed between the two years. Only in July, Tmax was higher in 2017, and in October, VPD was significantly lower in 2017. The largest difference between years was recorded in November, when it was relatively cool and dry, and Tmin dropped quickly in 2016 (also see Fig. 2.1). Over the entire cropping period, 2017 was slightly warmer, cloudier, and more humid.

Depending on the crop duration, varieties were exposed to different climatic conditions. Further, early or late sowing led to changes in weather conditions for the crop, in addition to the naturally occurring differences in weather parameters between 2016 and 2017. Due to seasonality, between emergence and PI, short-duration varieties were exposed to lower mean and maximum temperatures, lower radiation, and higher air humidity than medium- and, to an even greater extent, than long-duration varieties (Fig. 2.3). After early sowing in 2017, short-duration varieties were subjected to a higher mean temperature during vegetative stage, while long-duration varieties were subjected to a lower maximum temperature and higher air humidity than after late sowing in 2016. Independent of genotypic crop duration, in 2017, plants were subjected to a higher minimum temperature and lower radiation during the vegetative stage than in 2016.

Table 2.3 Mean monthly weather parameters between July and December in 2016 and 2017. Small letters indicate significance between months, capital letters indicate significance between years, both at $p<0.05$.

	Tmean [°C]		Tmin [°C]		Tmax [°C]		Radiation [W m^{-2}]		RHmin [%]		VPD [kPa]	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
Jul	18.2 b	18.8 ab	14.7 a	14.9 a	23.1 dB	24.1 cA	196 c	193 b	55.7 ab	51.3 b	0.70 de	0.80 d
Aug	18.3 b	18.2 b	14.7 a	14.8 a	22.7 d	22.6 d	215 bc	194 b	58.5 a	59.0 a	0.63 e	0.63 e
Sep	18.8 b	19.2 ab	14.6 a	15.0 a	24.2 c	24.1 c	241 ab	243 a	52.4 b	55.0 ab	0.77 d	0.74 de
Oct	19.6 a	19.5 ab	14.1 a	14.5 a	25.9 b	25.2 b	254 a	232 a	37.5 c	43.5 c	1.10 cA	0.97 cB
Nov	17.0 cB	18.1 bA	8.6 bB	10.8 bA	26.4 ab	26.0 ab	249 a	229 a	21.7 dB	28.5 dA	1.42 bA	1.28 bB
Dec	17.5 cA	16.7 cB	8.4 b	8.0 c	26.9 a	26.3 a	243 ab	230 a	17.6 d	18.5 e	1.59 a	1.51 a
Mean	18.2 B	18.4 A	12.5 B	13.0 A	24.9	24.7	233 A	220 B	40.6 B	42.6 A	1.04 A	0.99 B

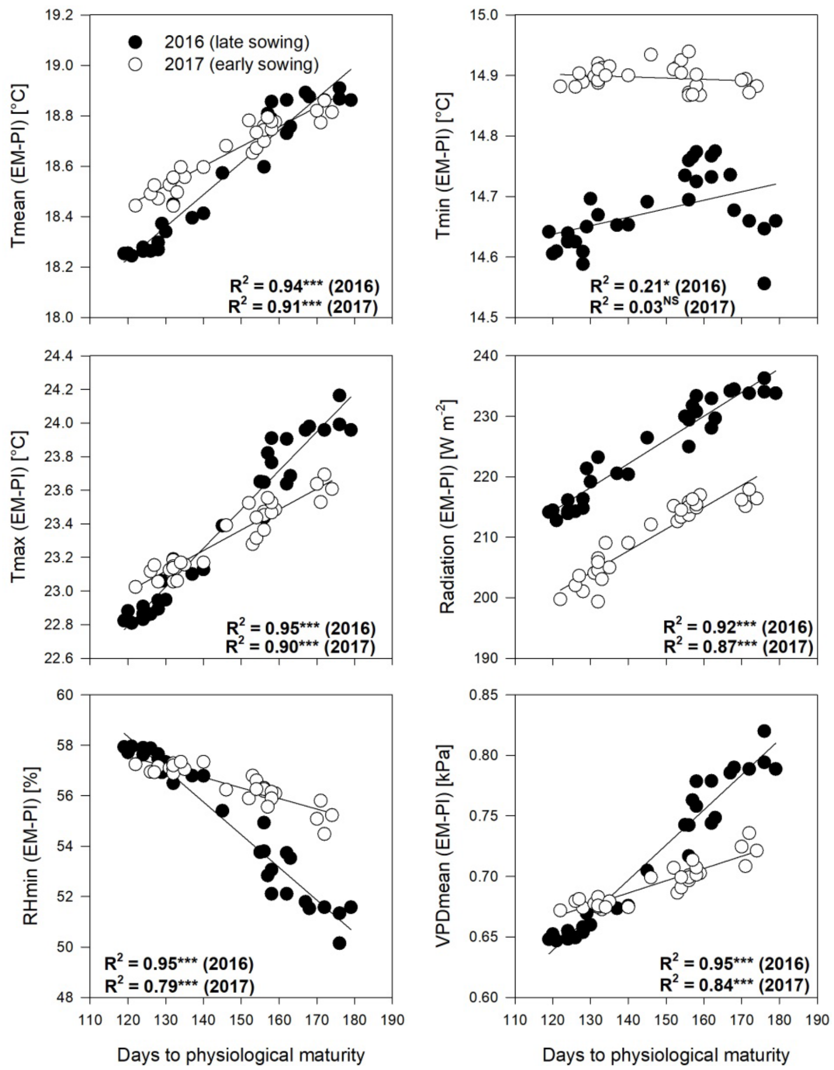

Figure 2.3 Average weather conditions in 2016 and 2017 between emergence (EM) and panicle initiation (PI) for 30 varieties as related to their duration to physiological maturity. ***, *, ^{NS}: significant at P-value ≤0.001, ≤0.05, non-significant, respectively.

2.3.2 Yield and yield components

After late sowing in 2016, grain yield was highest for Yun-Keng (7.2 t ha^{-1}) and lowest for SIM 2 Sumadel and Partao (both 0.2 t ha^{-1}) (Tab. 2.4). Average yield of the short-duration varieties in 2016 was 5.8 t ha^{-1} and thus significantly higher than yield of the medium- and long-duration varieties with 3.6 and 0.5 t ha, respectively. After early sowing in 2017, the yield was highest for Zong-Eng and Mailaka (both 6.6 t ha^{-1}), and lowest for SIM 2 Sumadel (2.4 t ha^{-1}). Average yield of the medium-duration varieties in 2017 (5.2 t ha^{-1}) was significantly higher than of the short- and long-duration varieties with 4.2 and 2.9 t ha^{-1}, respectively. Early sowing in 2017 led to a significantly lower average yield of the short-duration varieties and a significantly higher average yield of the medium-and long-duration varieties. The difference in grain yield between 2016 and 2017 for the different varieties was positively correlated with their respective duration from sowing to maturity (Fig. 2.4).

Number of tillers per hill was highest in IR64 with 18.2 and 14.8, while it was lowest in Silewah with 9.4 and 6.6 in 2016 and 2017, respectively (Tab. 2.4). Late sowing in 2016 resulted with 12.4 in a significantly higher tiller number than in 2017 with 10.8 tillers. The percentage of productive tiller (PPT) varied from 97.3% in Ediget to 83.1% in IR64. While in the short-duration group PPT did not differ between years, with an average of 92.9%, PPT was significantly higher in 2017 for the medium- and long-duration group, with 97.5% and 95.4% respectively, than in 2016, with 83.8% and 81.9% respectively. The number of spikelets per panicle (SPP) ranged from 59.7 in Chhomrong to 144.6 in Yun-Keng. Early sowing in 2017 led to a severely reduced number of SPP for the short-duration group with 100.1 SPP in 2016 vs. 65.1 SPP in 2017. Less pronounced, but still significant was the reduction of SPP for the medium-duration group with 123.7 SPP in 2016 vs. 107.8 SPP in 2017. Average SPP did not differ between years in the long-duration group, with 112.6 and 111.9 SPP in 2016 and 2017 respectively. The percentage of fertile spikelet (PFS) ranged from 27.8% in WITA 4 to 96.3% in Chhomrong. Whereas in the short-duration group, average PFS did not differ between years, with 93.8% and 89.1% in 2016 and 2017 respectively, it was significantly higher in 2017 for the other groups (Fig. 2.5). In the medium-duration group, PFS increased from 65.7% in 2016 to 88.7% in 2017, and from 4.7% in 2016 to 62.8% in 2017 in the long-duration group. In 2016, two varieties from the medium-duration group, FOFIFA 160 and Silewah, displayed a high tolerance to low temperatures (Fig. 2.5). Thousand grain weight (TGW – Tab. 2.4) ranged from 22.5 g in SIM 2 Sumadel to 34.0 g in Ediget. TGW was highest in the short-duration group with 30.9 g in 2016 and 30.0 g in 2017, followed by the medium-duration group with 25.7 g in 2016 and 27.7 g in 2017 and finally, by the long-duration group with 24.8 g in 2016 and 25.1 g in 2017. Average TGW by group only differed significantly between years in the medium-duration group.

Table 2.4 Yield and yield components of studied genotypes in Fogera Plain in 2016 and 2017. Abbreviations: TPH=tillers per hill, PPT=percentage of productive tillers, SPP=spikelet per panicle, PFS=percentage of fertile spikelet, TGW=1000 grain weight, CV=coefficient of variation and Pr= probability.

	Yield (t ha^{-1})		TPH		PPT (%)		SPP		PFS (%)		TGW (g)	
Genotypes	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**
Short duration												
Machapuchre	5.9^{bcd}	5.3^{ab}	13.0^{abcd}	15.1^{a}	96.6^{a}	94.0^{abc}	95.5^{cd}	54.0^{cde}	96.7^{a}	94.4^{abc}	33.2^{a}	30.0^{abcd}
Chhomrong	6.2^{abc}	4.1^{de}	15.2^{a}	13.3^{abc}	97.7^{a}	93.5^{abc}	64.6^{e}	54.8^{cde}	99.4^{a}	93.1^{abc}	32.3^{ab}	31.8^{abc}
HS 379	5.0^{ef}	3.3^{fgh}	10.5^{cdf}	12.9^{bc}	95.3^{a}	87.5^{e}	94.6^{cd}	43.9^{e}	93.7^{abc}	79.9^{h}	31.8^{abc}	29.3^{bcd}
Duragan	5.6^{cde}	4.2^{de}	8.5^{f}	10.2^{def}	95.4^{a}	91.7^{cde}	102.2^{bcd}	62.6^{bcd}	95.1^{abc}	88.2^{def}	32.7^{ab}	30.5^{abcd}
Merig	5.5^{cdef}	4.4^{cd}	9.1^{f}	8.8^{fg}	88.4^{c}	97.7^{a}	100.6^{bcd}	71.6^{bc}	91.4^{abc}	91.5^{bcde}	30.3^{bcd}	33.2^{ab}
Osmanlik-97	6.1^{abc}	3.7^{efg}	10.9^{cdf}	11.2^{cde}	89.5^{bc}	89.6^{cde}	99.4^{bcd}	55.7^{cde}	96.1^{ab}	87.7^{ef}	31.8^{ab}	31.3^{abcd}
Kirkpinar	4.8^{f}	3.0^{h}	8.7^{f}	9.9^{defg}	95.4^{a}	90.2^{cde}	88.5^{cd}	48.7^{de}	92.6^{abc}	79.3^{h}	33.1^{a}	29.7^{bcd}
Demir	6.7^{a}	5.2^{abc}	15.1^{a}	13.8^{ab}	98.2^{a}	88.1^{de}	104^{bc}	55.4^{cde}	94.4^{abc}	91.7^{bcd}	28.1^{d}	27.6^{de}
Ediget	5.7^{cde}	4.8^{bc}	9.2^{f}	8.0^{g}	98.2^{a}	96.4^{ab}	96.2^{bcd}	75.4^{b}	96.6^{a}	95.1^{ab}	34.2^{a}	33.7^{a}
Diamante	5.8^{bcd}	3.9^{def}	13.0^{abc}	13.8^{ab}	94.9^{ab}	96.8^{a}	97.9^{bcd}	55.7^{cde}	93.2^{abc}	91.0^{cde}	29.3^{cd}	28.9^{cd}
Hibir	6.5^{ab}	4.4^{cd}	14.0^{ab}	9.4^{efg}	88.7^{c}	92.0^{bcd}	81.9^{de}	62.3^{bcd}	94.8^{abc}	82.5^{gh}	32.0^{ab}	31.4^{abcd}
Manjamena	5.7^{cde}	5.6^{a}	15.0^{a}	9.6^{efg}	80.9^{d}	96.8^{a}	160.0^{a}	108.8^{a}	87.6^{c}	91.6^{bcde}	24.4^{e}	24.9^{e}
X-Jigna	5.9^{bcd}	3.3^{gh}	11.9^{bcd}	12.0^{bcd}	88.4^{c}	90.5^{cde}	99.5^{bcd}	51.7^{de}	88.4^{bc}	85.1^{fg}	30.3^{bcd}	27.6^{de}
SCRID	5.4^{def}	4.0^{de}	10.4^{df}	8.5^{fg}	95.8^{a}	92.2^{bcd}	117.5^{b}	110.7^{a}	93.8^{abc}	96.7^{a}	28.7^{d}	30.1^{abcd}
Medium duration												
Soameva	5.9^{b}	6.1^{ab}	14.4^{b}	11.5^{b}	72.7^{g}	98.0^{a}	116.9^{d}	92.7^{de}	91.7^{a}	93.5^{bcd}	26.0^{c}	31.5^{a}
Yun-Keng	7.2^{a}	6.4^{a}	9.4^{c}	8.7^{cde}	94.1^{a}	100^{a}	168.5^{a}	120.6^{bc}	91.1^{a}	97.4^{ab}	31.2^{a}	30.9^{ab}
Zong-Eng	6.8^{a}	6.6^{a}	11.9^{bc}	8.1^{de}	89.4^{abc}	99.4^{a}	161.2^{ab}	122.5^{bc}	92.6^{a}	97.8^{a}	28.8^{ab}	28.9^{abcd}
NERICA L-19	2.9^{e}	5.5^{bc}	10.2^{c}	9.7^{bcd}	81.5^{ef}	98.9^{a}	124.5^{cd}	144.9^{a}	90.6^{a}	94.0^{abc}	21.2^{e}	25.4^{de}
Mailaka	3.9^{cd}	6.6^{a}	13.9^{b}	10.8^{bc}	91.0^{ab}	100^{a}	117.7^{d}	105.9^{cd}	79.1^{bc}	87.4^{ef}	24.4^{cd}	25.4^{de}
Kelimamokatra	4.6^{c}	6.3^{a}	12.9^{b}	11.4^{b}	93.8^{ab}	100^{a}	123.0^{cd}	124.3^{b}	84.7^{ab}	90.0^{de}	25.0^{cd}	26.7^{cde}
IR64	1.7^{f}	4.4^{e}	18.2^{a}	14.8^{a}	73.0^{g}	93.1^{b}	110.6^{d}	80.1^{e}	49.4^{d}	86.0^{f}	23.4^{de}	28.2^{abcde}
FOFIFA 160	3.7^{d}	4.5^{e}	13.5^{b}	11.6^{b}	77.2^{fg}	99.1^{a}	106.7^{d}	91.7^{de}	72.8^{c}	91.0^{cde}	24.7^{cd}	27.4^{bcde}
B6144F	0.9^{g}	5.1^{cd}	11.9^{bc}	10.6^{bc}	84.6^{cde}	90.3^{b}	125.3^{cd}	90.2^{de}	7.4^{f}	76.2^{g}	21.5^{e}	25.4^{de}
Silewah	4.1^{cd}	3.3^{f}	9.4^{c}	6.6^{e}	88.2^{bcd}	100^{a}	142.1^{bc}	125.7^{b}	92.7^{a}	93.0^{cd}	28.6^{b}	29.5^{abc}
Padisashal	0.5^{g}	2.8^{f}	10.1^{c}	8.8^{cd}	76.7^{fg}	91.5^{b}	82.1^{e}	97.0^{de}	7.8^{f}	72.7^{g}	30.3^{ab}	28.7^{abcde}
Makalioka 34	1.6^{f}	4.7^{de}	17.4^{a}	11.8^{b}	83.3^{de}	99.3^{a}	105.8^{d}	98.3^{d}	29.1^{e}	85.5^{f}	23.3^{de}	24.9^{e}
Long duration												
FARO-35	1.0^{a}	3.2^{a}	14.8^{a}	11.2^{ab}	79.4^{a}	98.0^{a}	111.0^{ab}	127.8^{a}	11.5^{a}	68.7^{a}	24.6^{b}	27.9^{a}
WITA 4	0.4^{ab}	2.8^{ab}	12.0^{b}	11.4^{ab}	81.9^{a}	85.5^{b}	123.7^{a}	98.6^{b}	2.2^{b}	53.3^{c}	24.7^{ab}	24.1^{ab}
SIM 2 Sumadel	0.2^{b}	2.4^{b}	15.2^{a}	11.9^{a}	81.7^{a}	99.0^{a}	94.9^{b}	109.1^{b}	4.2^{ab}	66.5^{ab}	22.7^{b}	22.2^{b}
Partao	0.2^{b}	3.1^{a}	11.1^{b}	9.7^{b}	84.7^{a}	98.9^{a}	120.9^{a}	112.0^{ab}	0.9^{b}	62.7^{bc}	27.1^{a}	26.2^{a}
CV(%)	10.5	8.3	12.9	12.1	4.0	2.9	11.8	12.4	7.0	2.8	5.5	8.4
Pr	**	**	**	**	**	**	**	**	**	**	**	**

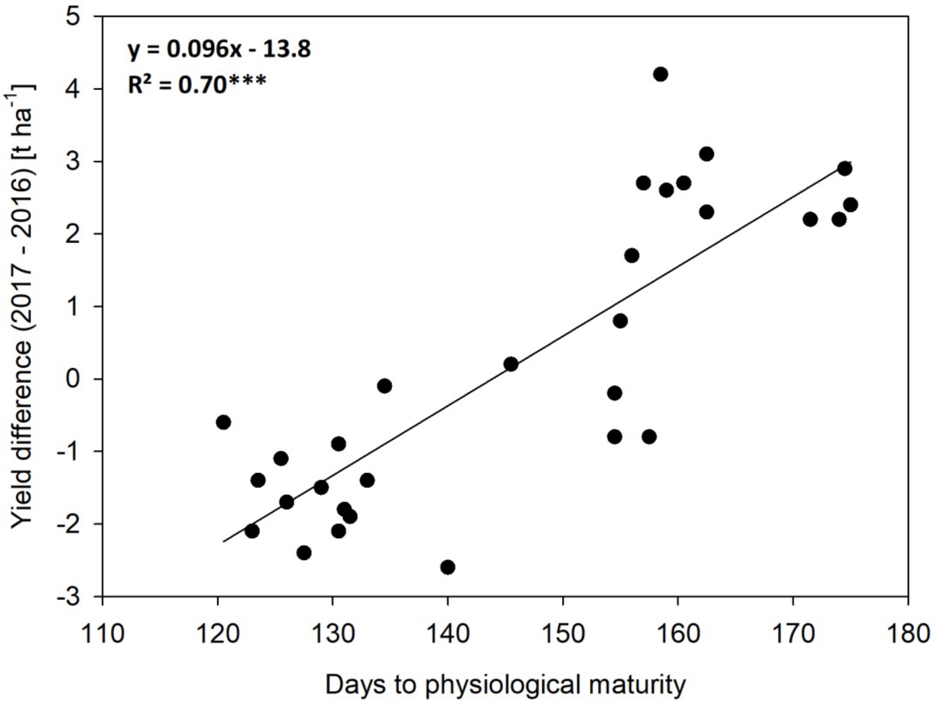

Figure 2.4 Difference in grain yield [t ha^{-1}] between 2016 and 2017 for 30 varieties shown against their duration to physiological maturity.

To evaluate cold tolerance of the 30 genotypes in the two seasons, spikelet sterility was regressed versus minimum temperature during the critical cold-sensitive phase one week before and after booting (Fig. 2.5). Sterility levels in 2017 (early planting) remained low and minimum temperatures during booting never decreased below 14°C. In 2016, only short-duration genotypes escaped low temperatures, and most medium- and long-duration genotypes suffered from more than 80% spikelet sterility. Varieties FOFIFA 160 and Silewah maintained the control level spikelet sterility at temperatures below 12°C during booting, while for cold-sensitive varieties, the threshold for spikelet sterility appeared to be around 13°C during booting.

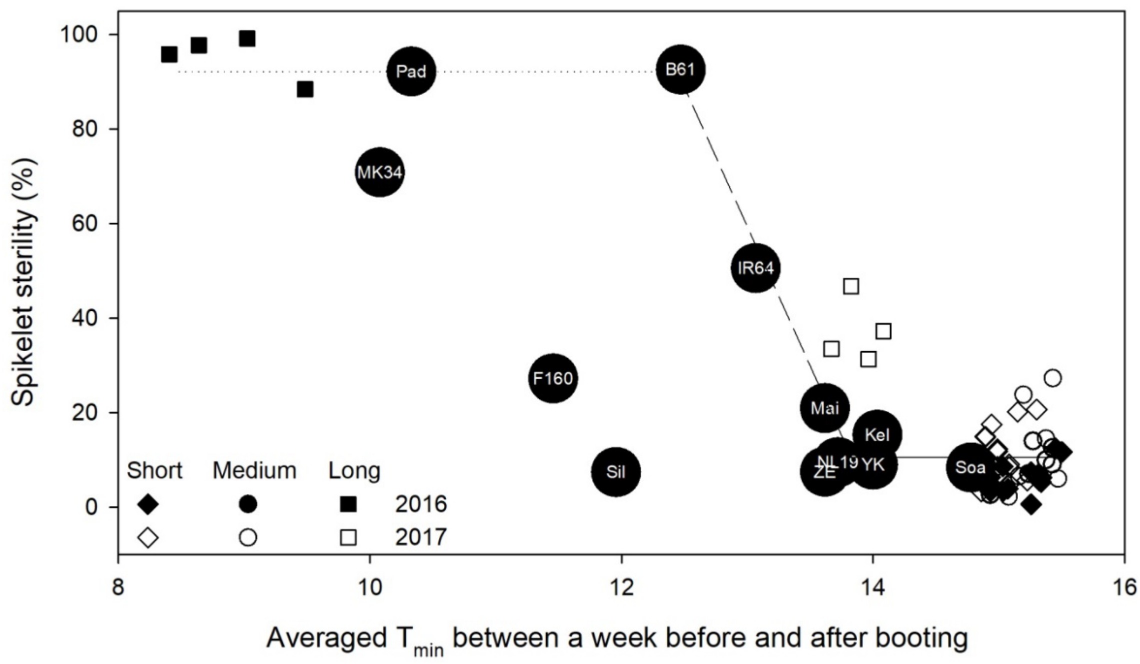

Figure 2.5 Relationship between spikelet sterility and the averaged T_{min} observed between a week before and after booting ($\pm$7 days), individually determined for each genotype and year. The correlation is eye-fitted. For abbreviations of variety names see Table 2.1

2.4 Discussion

2.4.1 Crop duration

As in all rainfed systems, the sowing date of the rice crop on the Fogera Plain depends on the onset of the rainy season and as a result is variable. Early sowing in 2017, due to an early onset of the rainy season, had different effects on the varieties regarding their development in comparison to sowing two weeks later in 2016. While short-duration varieties increased their duration from emergence to PI, most of the medium and all long-duration varieties decreased their duration after early sowing in 2017. These differences could be either due to different weather conditions experienced by the plants resulting from seasonality or explained by different weather conditions between the two years. To definitively answer this question, a phenological model, precisely calibrated for all the varieties used in this study, is needed. However, prevailing weather conditions during the cropping season were compared and it was found that due to seasonality, short-duration varieties received lower mean and maximum temperatures, while minimum temperatures received depended little on crop duration and seasonality, respectively. The increased cycle length of short-duration varieties in 2017 could not be explained with temperature, which was slightly higher between emergence and PI than in 2016. For the short-duration genotypes, the only difference in weather between the two years was the lower radiation in 2017, which was a result of both early sowing and differences between years. Stuerz et al. (2020) showed that low radiation can have a prolonging effect on rice development, but they did not find this effect under field conditions. Since early sowing resulted in a longer photoperiod, photoperiodism can also not be excluded in explaining the increased cycle length. However, late sowing will result in a larger amount of radiation received by the crop during the vegetative phase, and short-duration varieties seem to profit most of this with regard to crop duration.

Larger differences between years were observed for the medium- and long-duration varieties. In 2017, they grew at a higher Tmin and higher air humidity than in 2016, which could also explain the shortened vegetative phase. However, Tmin never dropped below 13°C during the vegetative phase, which is above the estimated general base temperature of rice, roughly 10°C (Dingkuhn, 1995). Also lower minimum temperatures were compensated by higher maximum temperatures in 2017. Consequently, for medium- and long-duration varieties, temperature does not explain the observed differences in duration between years very well. Since low air humidity can extend crop duration (Stuerz et al., 2020), the difference in air humidity between the two years is the most likely weather parameter explaining the shortened duration in 2017. Since air humidity declined slowly after the end of the rainy season, early sowing could enhance rate of development of medium- and long-duration varieties during the vegetative stage.

2.4.2 Yield and yield components

Similar to crop duration, time of sowing had different effects on short- and medium- / long-duration varieties in terms of yield. While early sowing in 2017 led to lower yields for the short-duration varieties, medium- and long-duration varieties showed higher yields, compared to 2016. Thus, the difference in duration and the difference in yield between the two years were negatively correlated (Fig. 2.4). In contrast, in literature a longer vegetative phase and thus a higher biomass production, has a positive correlation with crop duration and yield (Chen et al., 2019; Nguyen-Sy et al., 2019; Vergara et al., 1966). Therefore, a direct link between the shortened duration and higher yields can be excluded.

Yield was positively correlated with the percentage of filled spikelets and the number of productive tillers, and negatively correlated with the number of tillers per hill (Tab. 2.3). However, early sowing in 2017 led to less TPH, higher PPT for the medium- and long-duration varieties, less SPP, which was more pronounced in the short-duration group, a higher PFS in the medium- and long-duration group, and a high TGW in the medium-duration varieties (Fig. 2.6). Lower tiller number could be a result of the lower radiation levels received by the crop in 2017, as shading leads to lower tiller emergence rates (Lafarge et al., 2010). While medium- and long-duration varieties compensated the lower tiller number in 2017 by a higher PPT, short-duration varieties rather showed lower PPT than TPH, leading to a relatively constant panicle number per hill between the two years for all duration groups. However, SPP was lower after early sowing in 2017, with the largest effect seen in short-duration varieties. Unfortunately, leaf area and biomass were not measured in this experiment, but as low radiation levels primarily affect the carbon gains by the plant (Hoang et al., 2016), and TPH of the short-duration varieties was little affected in 2017, we hypothesize that leaf area per tiller and dry weight per tiller were lower in 2017 than in 2016, especially of the short-duration varieties. Since leaf area per tiller is positively correlated with SPP (Stuerz et al., 2014), the lower radiation levels in 2017 could explain the lower SPP.

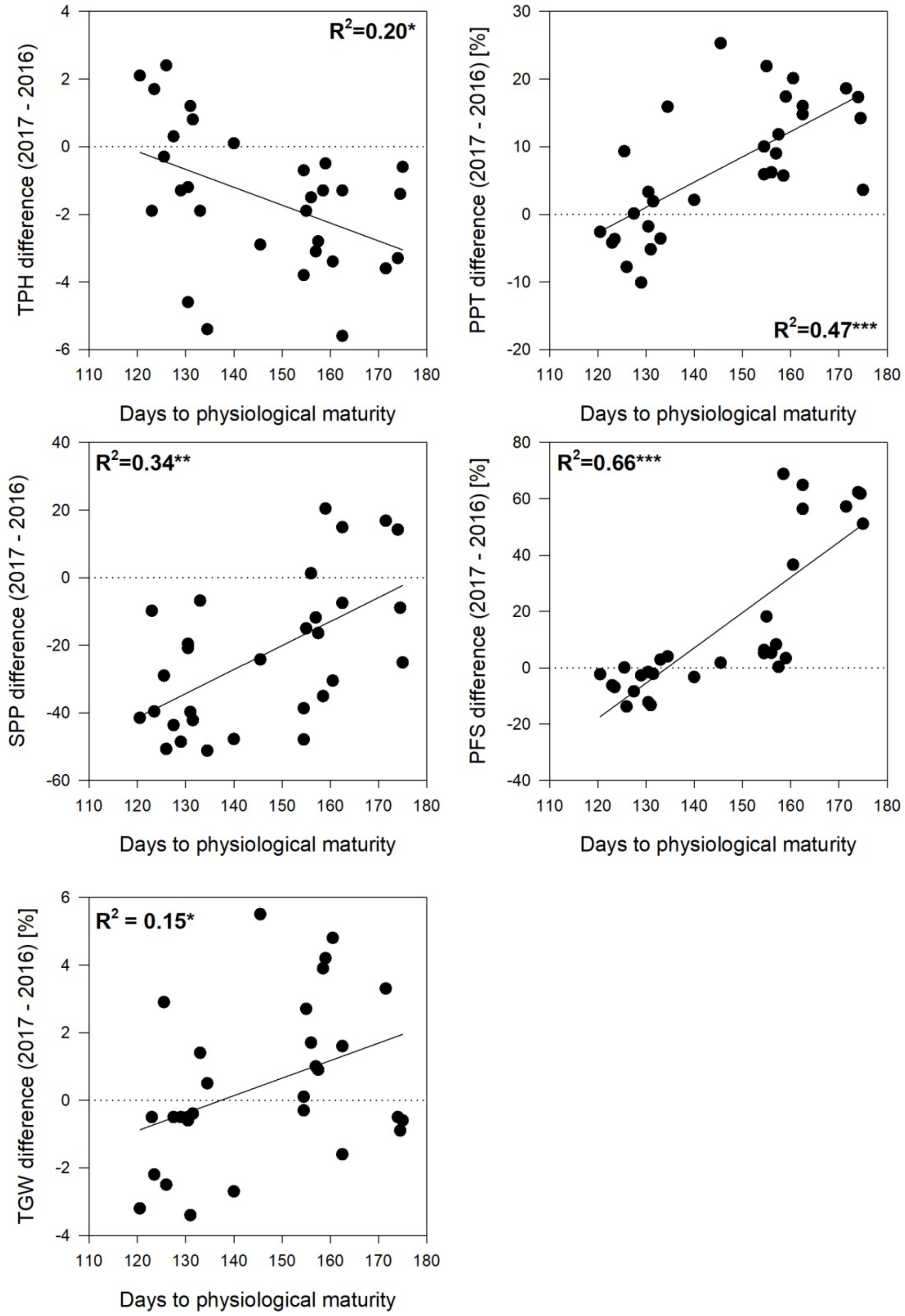

Figure 2.6 Correlations between the duration to physiological maturity and the difference in the respective yield components between the two years (2017 – 2016). TPH=tillers per hill, PPT=percentage of productive tillers, SPP=spikelet per panicle, PFS=percentage of fertile spikelet, TGW=1000 grain weight. ***, **, *: significant at P-value ≤0.001, ≤0.01, ≤0.05, respectively.

The most important yield component explaining the differences in yield between the two years is PFS. Since late sowing in combination with the earlier drop of Tmin in 2016 led to temperatures below 14°C around booting stage for the medium- and long-duration varieties, many of them strongly suffered from cold sterility, in accordance with Shrestha et al. (2013). However, varieties Silewah and FOFIFA 160 showed superior tolerance to low temperature (Fig. 2.5). Sterility of both varieties in contrasting thermal environments was assessed by Razafindrazaka et al. (2020), who found a relatively high tolerance to low temperature for Silewah, but not for FOFIFA 160. Here, further research is needed to elucidate the difference in performance of FOFIFA 160 in both studies.

Differences in duration, yield, and yield components between the 2 years were caused by differences in sowing date as well as differences in weather between 2016 and 2017. However, short-duration varieties experienced lower radiation in 2017, and early sowing aggravated this, leading to vegetative phase entirely taking place during the cloudy rainy season. Medium-duration varieties suffered from the early onset of the cool period in 2016, and late sowing led to the cold-sensitive booting phase of these varieties took place during the period when low minimum temperatures were most likely to happen. Since the date of sowing depends on the unpredictable onset of the rainy season, either the potential of an irrigated seedbed and transplanting should be investigated to extend the season, or the choice of variety should depend on the sowing date. To avoid the risk of cold sterility two rules should be followed, the selected variety should arrive at booting stage latest at the end of October, but to make use of the higher radiation levels in September, it should have the longest cycle length possible without compromising the first rule. Therefore, precise knowledge of the duration of the potentially suitable varieties is required and a crop model that is well-calibrated for the varieties as well as for the environment in combination with a smartphone application such as RiceAdvice (chapter four), would be of great help to support farmers' decision-making.

2.5 Acknowledgements

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3 Transplanting as an option to cope with abiotic stress in high-altitude lowland rice production systems in East-Africa

Abstract

The current practice of direct seeding in East-African high-altitude rice farming systems is constrained by water availability early in the season and low temperatures later in the season at the crop's critical reproductive stage. Thus, productivity is restricted as only short-duration varieties can be grown due to the risk of crop failure. To fully exploit the yield potential of such rainfed systems, the best combination of crop establishment methods and climatic "best fit"-genotypes is required. In this study, nine rice genotypes were evaluated under direct seeding and transplanting in the 2016 and 2017 cropping seasons with the aim of identifying genotype by environment by management combinations best fitting the high altitude, rainfed rice production systems. On average across all genotypes, transplanting had a positive yield effect of 18% and 23% in 2016 and 2017, respectively. Regarding the phenological development, individual phenophases were not significantly affected by transplanting relative to direct seeding; however, vegetative development stages in transplanted rice tended to be about 15% longer than when direct seeded. Even though the transplanting showed extended some more days for vegetative growth, it has compensated through early preparation of the nursery, thereby escaped the cold spell late in the season. The results from the current study provide options to adapt cropping calendars by combining genetic resources with targeted crop management, thus improving and stabilizing yields of rainfed lowland rice farming systems in the high altitudes.

Keywords: *Oryza sativa*, rainfed, crop establishment, phenology, cold stress, yield

3.1 Introduction

Rice, *Oryza sativa* L., is one of the most important staple food commodities and constitutes the source of calories for more than half of the world's population. For sub-Saharan Africa (SSA), rice has become a highly strategic and priority commodity (Abera et al., 2019). Beyond its current contribution to food security, demand has been rapidly growing for the past couple of decades due to high population growth, increased urbanization, and associated dietary preferences (Seck et al., 2013), and production has also been growing annually at 6% in the last decade (FAOSTAT, 2020). However, in spite of the recent increase in production and productivity, rice is still far behind to satisfy the demand as only about 60% of the consumption is met by domestic production (Saito et al., 2019). In many African countries, rice has been growing mainly by smallholder farmers under rainfed conditions (Gebey et al., 2012; Tanaka et al., 2017). Rainfed farming comprises about 70% of the rice area with unreliable water resources and a prevalence of several abiotic stresses (Drame et al., 2013; Ismail, 2020). In Ethiopia, for example, the rainfed rice production in the Fogera Plain, the major rice producing area, exceeds 30 percent of the national production (Astewel, 2017).

In general, rainfed lowland rice in high-altitude cropping systems of East Africa is constrained by two major abiotic factors: (1) available precipitation during the cropping period and (2) low temperatures causing spikelet sterility towards the end of the cropping season (chapter two; Chuma et al., 2020). The onset of rains determines the actual sowing dates when the resulting soil moisture reaches levels sufficient for the germination and establishment of the crop. With direct seeding, farmers' currently preferred practice, unreliable rainfall early in the season constrains crop establishment due to variable and often insufficient water availability. For this reason, rice is often sown late and only short-duration varieties are grown due to the additional risk of spikelet sterility caused by cold stress during the early reproductive stages. Low temperatures coinciding with critical reproductive development stages e.g. for a few days during booting stage, strongly affect seed set and, thus, yield (Arshad et al., 2017; Dingkuhn et al., 1995; Shrestha et al., 2012). To fully exploit the yield potential of such rainfed systems, the best combination of the method of crop establishment and "best fit"-genotypes is required to maximize yield while minimizing the risk of crop failure (Dingkuhn, 1995; Saito et al., 2013; Saito et al., 2017; Shrestha et al., 2011). Changing from direct seeding to transplanting would minimize the risk of early season drought, since a small nursery surface can easily be irrigated as well as the risk of cold sterility towards the end of the season by selecting a variety that reaches critical stages before temperatures drop. Phenological properties of rice cultivars, particularly crop duration, to a large extend determine their yield potential (Dingkuhn and Asch, 1999; Stuerz et al., 2020). Medium-duration rice genotypes with a relatively high level of cold tolerance would allow making full use of the cropping period while minimizing the risk. For transplanting, rice is sown in nurseries, which require much less space and water and, thus, allow for more variability in the sowing date. Seedbed duration can act as a buffer period in case the onset of the rainy season is delayed.

In this study, we evaluated nine rice genotypes with contrasting phenology for their performance under direct seeding and transplanting with the aim of identifying genotype by environment by management combinations best fitting the high altitude, rainfed East African rice production systems.

3.2 Material and methods

3.2.1 Site description and experimental design

The Fogera Plain in Ethiopia was selected as a case site for East African high-altitude systems. A field trial was conducted in 2016 and 2017 cropping seasons at Fogera rice research station, Ethiopia, located at 11° 58′ N and 37° 41′ E at an altitude of 1811 m above sea level. Fogera attains a unimodal rainfall pattern from June to mid-September, mean annual precipitation of 1200mm and mean annual minimum and maximum temperatures of 13°C and 25°C, respectively. The soil is a vertisol with a clay content of 71%. It is slightly acidic (pH 5.90) and the top 20 cm soil horizon contains 0.22% total N, 12.64 ppm available P (Olsen), 0.93 cmol (+) exchangeable $K \cdot kg \cdot soil^{-1}$, 3% organic carbon, and 52.9 cmol (+) kg^{-1} CEC (Tadesse et al., 2013a).

The experiment was laid out in a split plot design with three replications. Crop establishment methods namely direct seeding (DS) and transplanting (TP), were assigned to the main plots and nine genotypes were randomized and used in sub-plots. Plot size was 3 x 4 m and 0.25 m by 0.15 m spacing between and within rows, respectively. Sowing and transplanting depended on the available soil moisture. For direct dry seeding, land preparation followed the onset of rains for easy plowing. Three to four seeds were dibbled on 15.07.2016 and on 05.07.2017. After two weeks, emerged seedlings were thinned to one seedling per hill. For transplanting, nurseries were established on 26.06.2016 and 16.06.2017 with a seed rate of 25 kg ha^{-1} and provided with supplemental irrigation as required based on the soil moisture conditions. Three-week old seedlings were transplanted on 18.07.2016 and 8.07.2017 in to plowed and puddled soil. As per the recommendation, Urea (46% N) and Diammonium Phosphate (DAP) (46% P_2O_5; 18% N) at the rate of 69 kg N and 23 kg P ha^{-1} were applied. One third of N and all of P were applied as basal application before sowing for direct dry seeding and one week after transplanting for transplanting. The remaining two thirds of N were top-dressed in equal splits at tillering and at panicle initiation (PI) respectively. Weeding was done three times at tillering, PI, and late booting stage.

3.2.2 Genotypes

Nine genotypes were included in the study. 'X-Jigna' has been a popular genotype in the study area for more than 30 years (Gebey et al., 2012). Ediget was released as a variety by the national rice research system (MoARD, 2011) and seeds of the two genotypes were obtained from Fogera National Rice Research and Training Center (NRRTC). The remaining seven genotypes, both *indica* and *japonica* types with contrasting duration to maturity and varying levels of cold tolerance, were obtained from AfricaRice. Table 3.1 shows all genotypes grouped by duration.

Table 3.1 Rice genotypes included in the study grouped by days to maturity (d).

Short (120 to 140 d)		**Medium (141 to 160 d)**		**Long (>160 d)**	
Genotype	**Type**	**Genotype**	**Type**	**Genotype**	**Type**
Ediget	Jap	Yun-Keng	Jap	WITA 4	Ind
X-Jigna	Jap	Makalioka 34	Ind	SIM 2 Sumadel	Ind
Manjamena	Ind	IR 64	Ind		
SCRID	Ind				

Abbreviation: d= days; Ind = *indica*; Jap= *japonica*;.

3.2.3 Data collection and analysis

Daily mean, minimum and maximum temperature, rainfall, radiation, and relative air humidity were recorded at 2 m height during the experimental period with a Delta-T WP-GP1 meteo-station installed next to the experimental fields (Fig. 3.1). The phenological development of each genotype was closely monitored in both seasons and the data were recorded according to Razafidrazaka et al. (2020). Data on grain yield was taken from a central 3.15 m^2 area of each plot. Number of tillers (TPH), percentage of productive tillers (PPT), spikelet per panicle (SPP), percent of filled spikelet (PFS), and thousand grain weight (TGW) were determined from the central nine hills of the yield area. Data on yield and yield components were subjected to analysis of variance (ANOVA) using statistical analysis system version 9.4 (SAS Institute Inc.). Means were separated using Tukey's test.

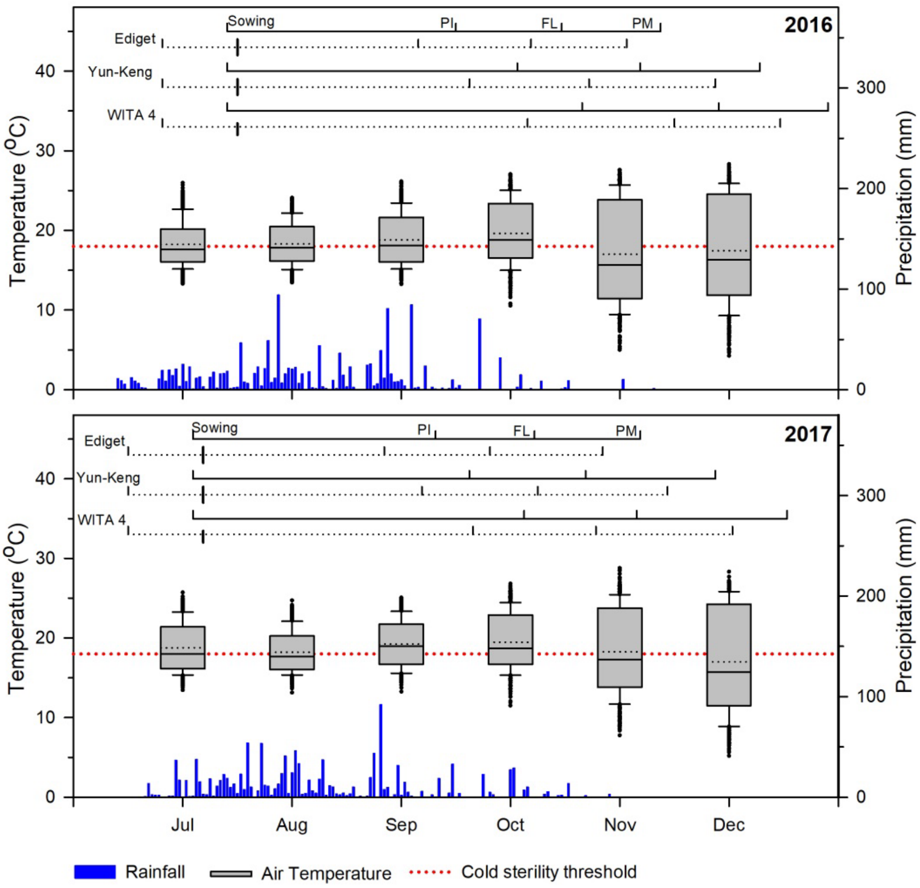

Figure 3.1 Daily weather data and phenology of three contrasting rice varieties in 2016 and 2017 in Fogera, Ethiopia. PI = panicle initiation, FL = flowering and PM = physiological maturity of three representative genotypes. Solid line = direct seeding; Dotted line = transplanting.

3.3 Results

3.3.1 Effects of transplanting vs. direct seeding on yield and yield components

Figure 3.2 shows the yield and yield components of the nine tested genotypes for the rainy seasons in 2016 and 2017 for directly seeded and transplanted crops, respectively. Transplanting resulted in higher or similar values for yield and yield components regardless of genotype or season. Genotypes differed strongly in yield (Tab. 3.2). In 2016, on average, the long duration genotypes produced the lowest yields of < 1 t ha^{-1} but transplanting increased the yield three-fold compared to direct seeding. Short duration genotypes showed stable high yields at 5.7 and 6.2 tha^{-1} for direct seeding and transplanting, respectively. For the medium duration genotypes transplanting increased yields by factor 1.8 and 1.28 for 'IR64' and 'Makalioka 34', respectively, whereas 'Yun-Keng' out-yielded all genotypes with about 7.5 tha^{-1} and only a small positive effect of transplanting. In 2017, with transplanting, medium and long duration genotypes yielded on a level similar to the short duration genotypes and performed significantly better under direct seeding than in 2016. Again, 'Yun-Keng' showed the highest yields, with transplanting inducing a 16% yield increase. On average across all genotypes, transplanting increased the yield by 18% and 23% in 2016 and 2017 compared to direct seeding, respectively.

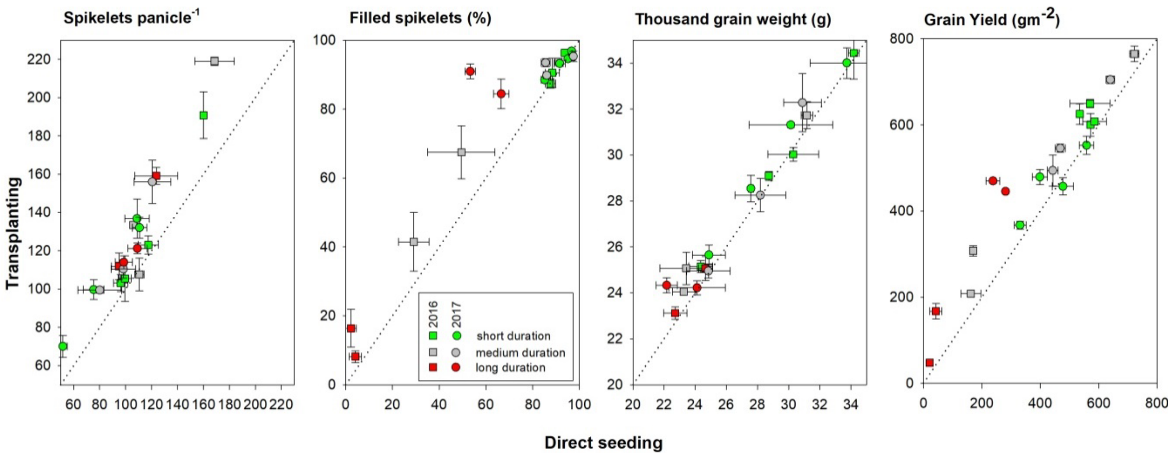

Figure 3.2 Direct comparison of selected yield components of varieties differing in duration to maturity for direct seeding and transplanting. Error bars = standard error of means, n= 3. Dotted line indicates 1:1 relationship.

Analyzing the yield components shows that in 2016 transplanting produced a constant but small positive effect across most yield components for the short duration varieties (Tab. 3.2 and Fig. 3.2). In the medium and long duration genotypes, with the exception of 'IR64', transplanting increased the number of spikelets by about 20-40% as compared to direct seeding which explains the positive effect of transplanting on yield. Most of those medium and long duration genotypes, however, suffered from cold stress during panicle development, leaving 33% (IR64) to 92% (SIM 2 Sumadel) of the spikelets unfilled. The exception in 2016 was medium duration 'Yun-Keng' with a transplanting induced increase in spikelets per panicle of 30% and only about 4% of unfilled spikelets which enabled this variety to maintain its high yield. In 2017, yield of the short duration varieties was on average 23% lower for direct seeding and 21% lower for transplanting compared to 2016. This reduction in yield resulted from a reduction in tiller number (-18% for DS and -22% for TP) in combination with a reduction in spikelets per panicle (-27% for DS and -16% for TP). However, for the same genotypes, transplanting in 2017 increased spikelets per panicle by more than 20%. In contrast, not regarding 'Yun-Keng', yield of the medium and long duration varieties increased on average by factor 3.8 (DS) and 2.8 (TP) compared to 2016. The main reason for this increase is an escape from cold stress during panicle formation indicated by the high number of filled spikelets. These varieties also benefited strongly from transplanting in 2017 with yield increases relative to direct seeding of 20 to 100%. These differences were mainly due to a 10% increase in productive tiller number, about 15% increase in spikelets per panicle and a strong increase in the number of filled spikelets relative to direct seeding. 'Yun-Keng' maintained yield levels similar to those from 2016 and transplanting induced a 16% increase in yield in 2017 mainly due to 30% increase in spikelets per panicle and a small increase in 1000 grain weight.

Table 3.2 Yield and yield components of genotypes differing in duration to maturity either directly sown (DS) or transplanted (TP) in 2016 and 2017

	Yield (tha^{-1})			Tiller no. hill^{-1}			Panicles tiller^{-1} (%)			Spikelets panicle^{-1}			Filled spikelets (%)			1000 grain weight (g)		
Genotype	**DS**	**TP**	**R**	**DS**	**TP**	**R**	**DS**	**TP**	**R**	**DS**	**TP**	**R**	**DS**	**TP**	**R**	**DS**	**TP**	**R**
2016																		
Ediget	5.73^{b}	6.01^{b}	1.05	9.2^{f}	9.3^{d}	1.01	98.2^{a}	98.0^{a}	1.00	96.2^{d}	103.1^{f}	1.07	96.7^{a}	95.2^{a}	0.98	34.2^{a}	34.5^{a}	1.00
Manjamena	5.71^{b}	6.50^{b}	1.14	15.0^{c}	15.2^{c}	1.01	80.9^{c}	86.1^{cd}	1.06	160.0^{a}	190.8^{b}	1.19	87.6^{a}	87.4^{a}	1.00	24.4^{de}	25.2^{d}	1.03
X-Jigna	5.86^{b}	6.09^{b}	1.04	11.9^{de}	14.7^{c}	1.24	88.4^{b}	95.6^{ab}	1.08	99.5^{cd}	105.5^{ef}	1.06	88.4^{a}	90.5^{a}	1.02	30.3^{bc}	30.0^{c}	1.00
SCRID	5.36^{b}	6.26^{b}	1.17	10.4^{def}	10.6^{d}	1.02	95.8^{a}	96.9^{a}	1.02	117.5^{bc}	123.0^{de}	1.05	93.8^{a}	96.3^{a}	1.03	28.7^{c}	29.1^{c}	1.01
Yun-Keng	7.23^{a}	7.65^{a}	1.06	9.4^{ef}	10.3^{d}	1.10	94.1^{a}	96.7^{a}	1.03	168.5^{a}	219.0^{a}	1.30	91.1^{a}	93.8^{a}	1.03	31.2^{b}	31.7^{b}	1.02
IR64	1.71^{c}	3.08^{c}	1.80	18.2^{a}	20.3^{a}	1.12	73.0^{d}	83.5^{d}	1.14	110.6^{bcd}	107.6^{ef}	0.97	49.4^{b}	67.5^{b}	1.36	23.4^{de}	25.1^{d}	1.07
Makaloika 34	1.63^{c}	2.09^{d}	1.28	17.5^{bc}	18.5^{ab}	1.06	83.3^{bc}	90.7^{bc}	1.09	105.8^{bcd}	133.4^{d}	1.26	29.1^{b}	41.5^{b}	1.43	23.3^{de}	24.1^{de}	1.03
WITA 4	0.43^{d}	1.68^{d}	3.91	12.0^{d}	15.3^{c}	1.28	81.9^{c}	83.3^{d}	1.02	123.7^{b}	159.2^{c}	1.29	2.2^{c}	16.4^{c}	7.45	24.7^{d}	25.1^{d}	1.02
SIM 2 Sumadel	0.22^{d}	0.48^{e}	2.18	15.2^{c}	17.3^{bc}	1.14	81.7^{c}	83.2^{d}	1.02	94.9^{d}	111.9^{ef}	1.18	4.2^{c}	8.1^{c}	1.93	22.7^{e}	23.1^{e}	1.02
Mean	*3.76*	*4.43*	*1.18*	*13.2*	*14.6*	*1.11*	*86.4*	*90.4*	*1.05*	*119.6*	*139.3*	*1.17*	*60.3*	*66.3*	*1.10*	*27.0*	*27.5*	*1.02*
p-value CE		***			**			***			***			**			NS	
p-value G		***			***			***			***			***			***	
*p-value CE*G*		*			NS			NS			*			NS			NS	
2017																		
Ediget	4.78^{c}	4.82^{cd}	1.01	8.0^{d}	8.7^{c}	1.09	96.4^{ab}	99.1^{a}	1.03	75.4^{d}	99.7^{e}	1.32	95.1^{ab}	94.6^{ab}	0.99	33.7^{a}	34.0^{a}	1.01
Manjamena	5.59^{b}	5.78^{b}	1.03	9.6^{cd}	9.7^{c}	1.01	96.8^{ab}	96.8^{ab}	1.00	108.8^{ab}	136.8^{ab}	1.26	91.6^{b}	93.2^{ab}	1.02	24.9^{de}	25.7^{de}	1.03
X-Jigna	3.31^{e}	3.89^{e}	1.18	12.0^{b}	12.2^{b}	1.02	90.5^{c}	95.7^{ab}	1.06	51.7^{e}	70.0^{f}	1.35	85.2^{c}	88.5^{de}	1.04	27.6^{cd}	28.5^{bc}	1.03
SCRID	3.99^{d}	5.05^{cd}	1.27	8.5^{d}	8.5^{c}	1.00	92.2^{c}	96.1^{ab}	1.04	110.7^{ab}	132.0^{bc}	1.19	96.7^{a}	96.9^{a}	1.00	30.1^{bc}	31.3^{ab}	1.04
Yun-Keng	6.41^{a}	7.42^{a}	1.16	8.7^{d}	8.9^{c}	1.02	100^{a}	99.3^{a}	0.99	120.6^{a}	156.0^{a}	1.29	97.4^{a}	95.3^{a}	0.98	30.9^{ab}	32.3^{a}	1.04
IR64	4.43^{cd}	5.16^{c}	1.17	14.8^{a}	16.1^{a}	1.09	93.1^{bc}	94.2^{b}	1.01	80.1^{cd}	99.4^{e}	1.24	86.0^{c}	89.8^{cd}	1.15	28.2^{bc}	28.3^{cd}	1.00
Makaloika 34	4.69^{c}	5.68^{b}	1.21	11.8^{b}	13.1^{b}	1.11	99.3^{a}	98.7^{a}	0.99	98.3^{bc}	110.5^{de}	1.12	85.5^{c}	93.5^{ab}	1.09	24.9^{de}	25.0^{e}	1.00
WITA 4	2.82^{f}	4.64^{d}	1.64	11.4^{bc}	12.4^{b}	1.09	85.5^{d}	95.2^{ab}	1.11	98.6^{bc}	114.0^{cde}	1.16	53.3^{e}	90.9^{cd}	1.71	24.1^{e}	24.2^{e}	1.00
SIM 2 Sumadel	2.39^{f}	4.87^{cd}	2.04	11.9^{b}	12.8^{b}	1.08	99.0^{a}	99.0^{a}	1.00	109.1^{ab}	121.2^{bcd}	1.11	66.5^{d}	84.4^{e}	1.27	22.2^{e}	24.3^{e}	1.09
Mean	*4.27*	*5.26*	*1.23*	*10.7*	*11.4*	*1.07*	*94.8*	*97.1*	*1.02*	*94.8*	*115.5*	*1.22*	*84.1*	*91.9*	*1.09*	*27.4*	*28.2*	*1.03*
p-value CE		***			NS			**			***			***			NS	
p-value G		***			***			***			***			***			***	
*p-value CE*G*		***			NS			*			NS			***			NS	

R = TP/DS; G = genotype; CE = crop establishment method; NS = $p \geq 0.05$; * = $p \leq 0.05$; ** = $p \leq 0.01$; *** = $p \leq 0.001$. Values sharing the same letters are not significantly different for $p \leq 0.05$ according to a Duncan Multiple Range Test from a two factorial ANOVA (n=3)

3.3.2 Effects of transplanting vs. direct seeding on phenology

In all cases, transplanting delayed duration to maturity by 10 (long duration) to 14 (short duration) days (Fig. 3.3). Individual phenophases were not significantly affected by transplanting relative to direct seeding, however, vegetative development stages in transplanted rice tended to be about 15% longer than when direct seeded. No difference was found for the reproductive stages (Appendix – Table I & II). The general duration of the different varieties was maintained as given in Table 3.1 as indicated by the off-set of the regressions relative to the 1:1 line.

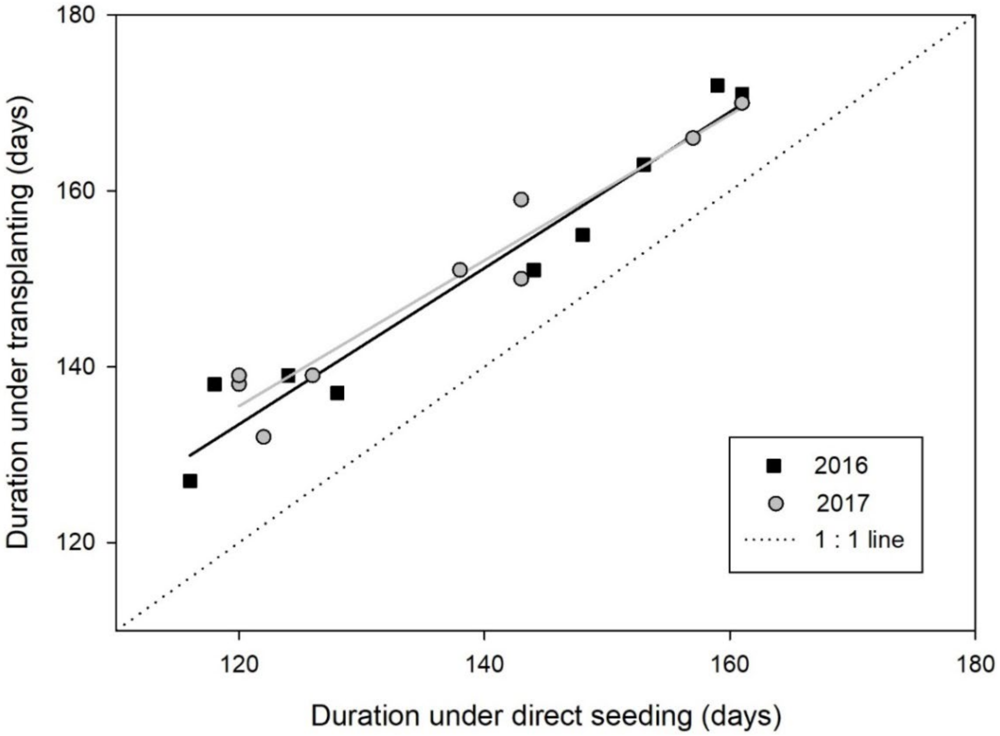

Figure 3.3 Comparison of the durations to maturity for direct seeding and transplanting for both experimental years. Both regressions resulted in highly significant ($p<0.01$) R^2 values (gray, 2017 = 0.94 and black, 2016 = 0.95.

The succession and duration of the different phenophases (Appendix – Table I & II) resulted in strongly contrasting thermal environments for the different varieties. Figure 4 shows this exemplarily for minimum temperature during booting stage for direct seeding and transplanting for the two years and all varieties. With increasing duration to maturity, temperature during booting stage decreased but the effect of the year was much stronger than the effect of crop establishment on this relationship. Temperature during booting was generally higher in 2017 and was across all duration types at around 15°C for transplanting in 2017. In 2016 temperature during booting for the same duration types was about 5°C higher for the transplanted crop than for direct seeding, but generally too low for proper seed development for all medium and long duration varieties as reflected in the percentage of filled spikelet (Fig. 3.2).

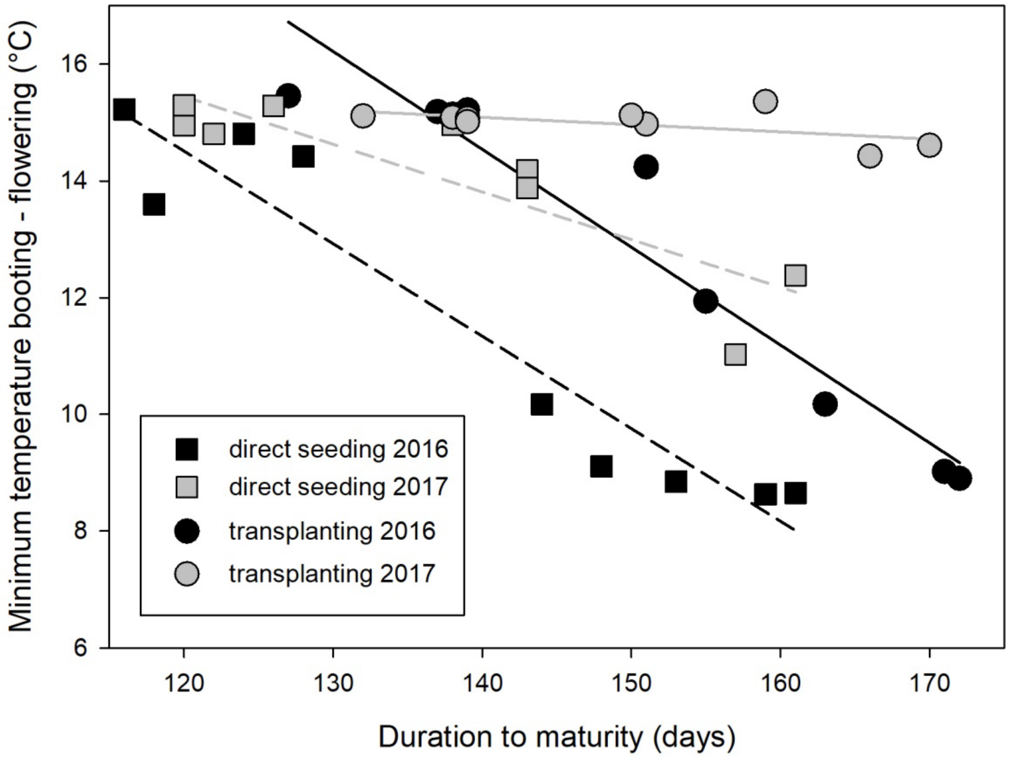

Figure 4. Relationship between minimum temperature during booting stage and duration to maturity for all varieties for direct seeded and transplanted rice in 2016 and 2017. The regressions show slopes varying with year and crop establishment method (2016, direct seeding, black dashed = -0.16; 2016, transplanting, black solid = -0.17; 2017, direct seeding, gray dashed = -0.08; 2017, transplanting, gray solid = -0.01)

3.4 Discussion

3.4.1 Transplanting vs. direct seeding

Transplanting as a crop establishment method has been widely discussed. The disadvantage of the method clearly is labor intensity if not mechanized (Haefele et al., 2016). In rainfed systems, direct seeding, on the other hand, is prone to poor stand count and losses from early droughts due to unpredictable rainfall patterns which increase the weed pressure in the ongoing season (Ohno et al., 2018). Although initially debated (Sharma, 1995), it has been shown that transplanting has the potential to increase yields, nutrient efficiency and water productivity in irrigated systems (Chen et al., 2017; Tadesse et al., 2013b; Ullah et al., 2020; Zhang et al., 2018). Rice nurseries allow for selection of uniform seedlings and some flexibility on transplanting dates. In the high-altitude systems for rice production in East Africa such flexibility is needed to cope with unreliable starts of the rainy season and sub-optimal thermal environments towards the end of the growing season (chapter two; Razafindrazaka et al., 2020). This effect was clearly demonstrated by the results of the second year, where sowing was about 10 days earlier than in the year before, and for the transplanted rice plants temperatures during booting were the same for all varieties independent of their duration to maturity (Fig. 3.4). In the direct seeded trial of 2017 medium and long duration varieties experienced temperatures below critical for cold sterility (Fig. 3. 4). This indicates that a critical part of the thermal time of the basic vegetative phase (Dingkuhn and Asch, 1999) was accumulated already in the seedbed prior to transplanting reducing the risk of running into cold sterility towards the end of the season (Shrestha et al., 2011) when temperatures drop in October (Fig. 3.1)

3.4.2 Crop growth and development

The nurseries in the field trials reported here, were initiated to be transplanted alongside with the direct seeded crop for which the sowing date was decided by the onset of the rains. Nurseries were established about three weeks prior to the anticipated sowing date and thus rice in the nurseries emerged on average about 22 (2016) to 25 (2017) days earlier in the year than the direct seeded rice (Appendix – Table I and II). When transplanted, seedlings were about 3 to 3.5 weeks old, which resulted in a transplanting shock of about 10-12 days, which is in line with findings by Dingkuhn et al. (1995), leading to a physiological maturity of the transplanted rice about 10 to 13 days earlier in the season than the direct seeded rice. This difference was mainly due to longer vegetative development stages in the transplanted rice (Appendix Table I and II). Earlier sowing would have resulted in a longer seedbed duration, which may have offset the advantage of spending part of the basic vegetative phase (Dingkuhn and Miezan, 1995) in the nursery by a longer transplanting shock, since the older the seedlings at transplanting, the more intense the transplanting shock which can delay development up to one month (Salam et al. 2001). Nonetheless, for the African high-altitude cropping systems, sowing early, up to eight weeks prior to the rainy season, may allow increasing the potential yield of the system by choice of variety if the delay of development from late transplanting is not too severe, as was the case with IR 64 and Yun-Keng in the trials reported here (Appendix Table I and II).

3.4.3 Yield and yield components

When irrigation facilities are lacking or limited, the start of the rice growing season entirely depends on the onset of rains with strong interannual variability (Senthilkumar et al., 2020; Tanaka et al., 2017). Rice cultivation systems with limited water availability have incentivized breeders to breed for short duration genotypes (Rehman et al., 2016; Zhang et al., 2013), despite of short duration rice varieties having a lower yield potential than medium or long duration rice varieties (Suriyagoda et al., 2020). For East-Africa, Chuma et al. (2020) has shown that even with the temperature limitations at the end of the growing season, most medium duration genotypes out-yielded short duration varieties.

It has been shown that genotypic yield strongly depends on the micro-climate the genotype experiences in specific phenophases during which specific yield components are being formed (Dingkuhn and Miezan, 1995; Razafindrazaka et al., 2020; Shrestha et al., 2012). In this way a positive effect of temperature on yield potential via a larger number of tillers per hill may be off-set by a negative influence of low temperatures during panicle formation leading to non-fertile spikelets.

In the present study, varieties of varying duration and different crop establishment methods were combined to find a combination of sowing date, crop management, and genotype allowing to fully exploit the yield potential of the East African high-altitude rice production systems. In the two years of trials all genotypes performed better and had higher yields when transplanted independent of the environmental conditions the genotype was subjected to due to its duration to maturity (Tab. 3.2, Fig. 3.2). However, the low temperatures towards the end of the season hit the medium and particularly the long duration varieties during the critical booting stage (Fig. 3.1 and Fig. 3.4). The low temperatures encountered during these few days, resulted in very high cold sterility rates particularly in the long duration varieties with direct seeding and particularly when sown late (Tab. 3.2, Fig. 3.2). This phenomenon was also observed for late sowing in West-Africa (Dingkuhn et al., 1995). Despite the fact that yields under transplanting were still higher than under direct seeding, the effect of cold sterility reduced the yields in theses varieties by 60-90% in 2016 (Tab. 3.2).

In contrast, the slower vegetative development of the transplanted rice plants (Appendix – Table I and II) resulted in a longer source build-up phase, which is reflected in the 10- 28% higher number of tillers in the medium and long duration varieties under transplanting compared to the direct seeded counterparts (Tab. 3.2). A longer source build-up and more tillers result in a larger leaf area and in more leaf area per tiller. Stuerz et al. (2014) have shown that a larger leaf area per tiller induces a larger number of spikelets per panicle. Figure 2 shows that independent of duration all genotypes have a higher number of spikelets per panicle under transplanting. With the exception of 'Yun-Keng', the effect ranges from 0 to 30% with a strong interannual variation (Tab. 3.2). 'Yun-Keng' produced consistently 30% more spikelets per panicle under transplanting independent of the thermal environment the variety was growing in. This was also reflected in a generally larger leaf area index under transplanting (data not shown).

3.5 Conclusions

We have shown that in the high-altitude cropping systems in East Africa represented by the Fogera Plain in this study, in general, transplanting has a strong advantage over direct seeding. Our study has also shown that growing medium and long duration varieties that may have a high yield potential at high altitudes bears a strong risk of yield loss due to cold sterility because of the temperature limitations towards the end of the cropping season. On the other hand, growing a relatively cold tolerant variety such as 'Yun-Keng', sowing a few weeks earlier within an irrigated nursery can make use of the full potential and increase yields by about one third or about 2 tons ha^{-1}.

Irrigating a small nursery prior to the actual season does not constrain water resources and allows much more flexibility in both choice of variety and planting dates. With increasing uncertainty in rainfall patterns due to climate change and the increasing demand for rice in the near future, flexibility would greatly reduce risks. Thus, the next steps for high-altitude rice cropping systems constraint by such abiotic stresses need to be: 1) breeding cold tolerant medium and long duration varieties, 2) investigate the effect of seedling age on transplanting shock and on yield components, 3) testing of multiple varieties nursery with staggered planting dates to maximize water productivity, decrease the risk of crop failure, allow for opportunities in yield potential and increase area productivity for increased food security.

Finally, an economic and ecological assessment is needed for this kind of adaptive technology.

3.6 Acknowledgements

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Appendix – Table I. Days after sowing for phenological development of genotypes under transplanting (TP) and direct seeding (DS) in 2016 and 2017

Genotypes	**Emergence**			**PI**			**Booting**			**Heading**			**Flowering**			**PM**		
	DS	TP	Diff	DS	TP	Diff	DS	TP	Diff	DS	TP	Diff	DS	TP	Diff	DS	TP	Diff
2016																		
Ediget	208	187	21	264	253	11	279	272	7	291	284	7	295	287	8	324	314	10
Manjamena	210	188	22	269	259	10	282	275	7	293	287	6	298	292	6	334	327	7
X-Jigna	209	188	21	271	258	13	284	273	11	297	286	11	301	291	10	337	325	12
SCRID	211	188	23	270	260	10	288	279	9	301	292	9	305	296	9	329	326	3
Yun-Keng	209	189	20	282	268	14	299	285	14	313	299	14	318	303	15	353	340	13
IR64	211	189	22	295	278	17	304	292	12	317	308	9	325	314	11	359	344	15
Makaloika 34	212	188	24	299	284	15	313	299	14	325	315	10	330	319	11	365	351	14
WITA 4	211	189	22	301	286	15	317	304	13	337	324	13	341	328	13	372	360	12
SIM 2 Sumadel	213	189	24	303	291	12	318	308	10	336	324	12	341	329	12	372	361	11
2017																		
Ediget	196	174	22	257	243	14	272	259	13	282	269	13	286	274	12	318	306	12
Manjamena	198	174	24	258	244	14	271	259	12	282	271	11	285	275	10	318	312	6
X-Jigna	200	174	26	261	247	14	278	264	14	289	276	13	293	280	13	326	313	13
SCRID	200	174	26	261	249	12	276	263	13	289	277	12	293	281	12	320	313	7
Yun-Keng	201	174	27	267	253	14	281	265	16	298	283	15	302	287	15	339	325	14
IR64	202	176	26	278	258	20	288	273	15	307	290	17	311	293	18	345	326	19
Makaloika 34	200	174	26	282	265	17	293	278	15	307	292	15	310	297	13	343	333	10
WITA 4	199	175	24	283	268	15	300	286	14	313	301	12	317	304	13	360	345	15
SIM 2 Sumadel	201	176	25	288	271	17	301	285	16	319	303	16	325	308	17	358	342	16

Diff = Calendar difference from DS to TP using days of the year (DOY); PI = panicle initiation; PM = physiological maturity

Appendix – Table II. Duration differences and advantage of corresponding phenological developments of genotypes under transplanting (TP) and direct seeding (DS) in 2016 and 2017.

Genotypes	Emergence - PI			PI - Booting			Booting - Heading			Heading - Flowering			Flowering - PM			Emergence - PM		
	DS	TP	R	DS	TP	R	DS	TP	R	DS	TP	R	DS	TP	R	DS	TP	R
2016																		
Ediget	56	66	1.18	15	19	1.27	12	12	1.00	4	3	0.75	29	27	0.93	116	127	1.09
Manjamena	59	71	1.20	13	16	1.23	11	12	1.09	5	5	1.00	36	35	0.97	124	139	1.12
X-Jigna	62	70	1.13	13	15	1.15	13	13	1.00	4	5	1.25	36	34	0.94	128	137	1.07
SCRID	59	72	1.22	18	19	1.06	13	13	1.00	4	4	1.00	24	30	1.25	118	138	1.17
Yun-Keng	73	79	1.08	17	17	1.00	14	14	1.00	5	4	0.80	35	37	1.06	144	151	1.05
IR64	84	89	1.06	9	14	1.56	13	16	1.23	8	6	0.75	34	30	0.88	148	155	1.05
Makaloika 34	87	96	1.10	14	15	1.07	12	16	1.33	5	4	0.80	35	32	0.91	153	163	1.07
WITA 4	90	97	1.08	16	18	1.13	20	20	1.00	4	4	1.00	31	32	1.03	161	171	1.06
SIM 2 Sumadel	90	102	1.13	15	17	1.13	18	16	0.89	5	5	1.00	31	32	1.03	159	172	1.08
Mean	73	82	1.13	14	17	1.18	14	15	1.06	5	4	0.93	32	32	1.00	139	150	1.08
2017																		
Ediget	61	69	1.13	15	16	1.07	10	10	1.00	4	5	1.25	32	32	1.00	122	132	1.08
Manjamena	60	70	1.17	13	15	1.15	11	12	1.09	3	4	1.33	33	37	1.12	120	138	1.15
X-Jigna	61	73	1.20	17	17	1.00	11	12	1.09	4	4	1.00	33	33	1.00	126	139	1.10
SCRID	61	75	1.23	15	14	0.93	13	14	1.08	4	4	1.00	27	32	1.19	120	139	1.16
Yun-Keng	66	79	1.20	14	12	0.86	17	18	1.06	4	4	1.00	37	38	1.03	138	151	1.09
IR64	76	82	1.08	10	15	1.50	19	17	0.89	4	3	0.75	34	33	0.97	143	150	1.05
Makaloika 34	82	91	1.11	11	13	1.18	14	14	1.00	3	5	1.67	33	36	1.09	143	159	1.11
WITA 4	84	93	1.11	17	18	1.06	13	15	1.15	4	3	0.75	43	41	0.95	161	170	1.06
SIM 2 Sumadel	87	95	1.09	13	14	1.08	18	18	1.00	6	5	0.83	33	34	1.03	157	166	1.06
Mean	71	81	1.15	14	15	1.09	14	14	1.04	4	4	1.06	34	35	1.04	137	149	1.10

R=TP/DS; PI = panicle initiation; PM = physiological maturity

4 Creating the data basis to adapt agricultural decision support tools to new environments, land management and climate change—A case study of the RiceAdvice App

Abstract

Increasing demand for land to ensure human food security in the future has already impelled agricultural production into marginal areas. The environmental conditions found there have a more pronounced impact on agricultural productivity than in the systems used so far under favourable conditions. In addition to this challenge, climate change is expected to increase the unreliability of weather conditions (through increased variability and occurrence of extremes) for farmers considerably. This unreliability is even more serious in developing countries' farming system where food security is vulnerable. Current efforts in digitalization offer great possibilities to improve farmers` decision-making processes. A wide range of online tools and smartphone applications is available to support both agricultural extension services and smallholder farmers alike. These apps are often parameterized and validated to certain environments and are troubled when applied to new geographical locations and different environmental conditions. We have conducted field trials to demonstrate potential methods to close knowledge gaps in the data background for one of these apps, RiceAdvice, concerning three key aspects: shifting of cropping calendar, adjustment of fertilizer management and genotype selection. Sites in Ethiopia, Madagascar and Rwanda were selected to represent altitudinal gradients, with overlapping elevations reflecting differences in temperature to enable cross-country comparisons. Planting dates were distributed throughout three calendar years, with continuous iterative planting dates taking place in Madagascar, in- and off-season planting dates in Rwanda with different fertilizer applications, and one planting date during each rainy season in Ethiopia with different management options. With these trials, we have been able to identify key data sets needed for the adaptation of agricultural decision support tools to new environments. These include the assessment of climatic constraints on innovations to cropping calendars (e.g. double cropping), informed selection of alternative varieties able to complete crucial parts of their phenological development to avoid temperature-related stress inducing, for example spikelet sterility in rice in

late development stages and the effectivity of potential innovations in fertilizer management strategies.

Keywords

crop, environment interactions, management strategies, paddy rice in high elevation, temperature limitation, water limitation

4.1 Introduction

The need to satisfy a growing demand for food production, especially under changing climatic conditions (van Oort and Zwart, 2018), is posing new challenges and opportunities to smallholder farmers worldwide (Brown and Funk, 2008; Lobell et al., 2008; van Ittersum et al., 2016). On one hand, marginal lands are being increasingly brought into production (Young, 1999), on the other hand, better market opportunities promote diversification of production systems (Bindraban, 2012; Keyzer, 2010; Taddese, 2001; Tielkes, 2015; van Wart et al., 2013). Non-traditional crops and improved varieties are being introduced to existing agricultural systems, challenging farmers´ knowledge and experience in handling these new opportunities. Shifting or expanding agricultural activities into highland areas will lead to an increased impact of low temperatures due to the altitudinal gradient (Shrestha et al., 2013). Low temperatures, as an example, can reduce nitrogen uptake in a variety of crop plants (Dong et al., 2001; Lukas et al., 2011; Zia et al., 1994) leading to the necessity of exploring alternative fertilizer management schemes. Cold stress during the early reproductive stages of e.g. rice can cause serious yield losses due to a number of effects on phenological development and yield building components (Thakur et al., 2009; Pereira da Cruz et al., 2006; Dingkuhn et al., 1995). Cropping calendars have to be adapted or developed to include new management and crop selection options, and research is needed to understand how these options can be applied in new environmental conditions (Shrestha et al,. 2011). In addition, changing climatic conditions pose additional risks from both increasingly erratic rainfall patterns and rising temperatures (Ceccarelli et al., 2010; Lobell et al., 2008; Olesen et al., 2011) as well as from newly emerging biotic stressors (Hazell, 1985; Rodenburg and Johnson, 2009; Swaminathan, 2007). Droughts and heavy rains are seen as very likely to increase in frequency in large parts of the world, resulting in a need for extended scope of and improved access to state-of-the-art and just-in-time weather forecasts also for smallholder farmers, especially in the developing world. Efforts to improve this situation are ongoing and manifold, such as the Africa HYDROMET Program (World Bank, 2017), supporting multi-national long-term efforts on different spatial scales. Van Oort and Zwart (2018) have shown that climate change can be expected to have a strong impact on rice cultivation in Africa, and have highlighted that regional differences in these impacts require regional adaptations strategies such as improved nutrient management strategies or shifts in cropping calendars. Climate-change-related adaptation and mitigation measures do also offer new possibilities to intensify agricultural production particularly in temperature-limited environments such as high altitudes or seasonally hot regions (Jagadish et al., 2012; Shrestha et al., 2012).

One of the possibilities to improve farmers´ decision making in such challenging environments is the use of online or application (app) based tools, either directly by farmers or through the help of extension services. These apps assist farmers in many aspects ranging from weather forecasts and cropping calendars to more complex server-based crop growth models. One of these apps is RiceAdvice, developed by the Africa Rice Center. AfricaRice and partners have developed this decision-support tool to improve farmers' decision-making in irrigated rice production systems in West Africa (WA). This tool is based on detailed physiological field experiments and has been tested in Nigeria, Senegal, and Benin (RiceAdvice, 2019). RiceAdvice in WA provides farmers and extension staff with information on best bet cropping calendars for rice; with emphasis on good agricultural practices in general, and soil fertility management in particular. The app, and the underlying model, was successfully used to derive optimal cropping calendars and guide varietal choice as a function of sowing date and location along Senegal and Niger rivers. It can estimate threshold dates beyond which sowing of rice becomes too risky because of cold (wet season) and heat (dry season) stress at flowering. The model calculates growth duration and yield loss due to extreme temperatures as a function of daily air and water temperature and sunshine hours and a set of varietal-specific photo-thermal constants. The recommendations provided by the RiceAdvice app are a result of inputs from farmers such as preferred/available rice variety, availability of fertilizer inputs, ability of the farmer to invest into inputs, and market price of milled paddy rice to predict the return price (Saito and Sharma, 2018; Saito et al., 2015).

In order to support these kind of app-based extension approaches, the models behind have to be calibrated and validated using a wide range of input data. This is especially the case when even well-known varieties of staple crops like rice are being introduced to new environments, e.g. irrigated rice to the highlands of East Africa. In contrast to parts of Western Africa, where both heat and cold stress can become a limiting factor in rice production, cold stress is a major factor influencing the performance of rice genotypes in East African highlands. The magnitude to which this effect affects different rice genotypes is not sufficiently studied to further adapt crop growth models to East African conditions (van Oort, 2018; van Oort & Zwart, 2018).

The key aspects that have been identified as crucial for this adaptation are: a) the selection of genotypes based on their performance under rainfed conditions in systems limited by late-season cold spells (using Ethiopia as case study site), b) potential adaptations to existing cropping calendars by varying sowing windows to avoid cold stress in susceptible development stages (using Madagascar as study site), and c) the influence of low temperatures on the efficiency of fertilizer application strategies (using Rwanda as study site).

4.1.1 Challenges to rice production in the three East African study sites

Fogera plain is one of the major rice producing areas dominated by rainfed lowland in Ethiopia (MoARD, 2010). In terms of production, it contributed above 30% of rice production in the country (Astewel, 2017). However, productivity is decreasing (Lema et al., 2016) due to several constraints. In Fogera, rainfed rice is usually sown in the second half of June dependent on the onset of the rainy season and the availability of enough soil moisture. In general, rice cultivation in Fogera is limited by the availability of water for irrigation before the onset of the rains and by low temperatures towards the end of the rainy season (MoARD, 2010). In Madagascar, rice is the most important staple food and has an important place in the agricultural economy. Rice production is dominated by irrigated lowland systems and is grown from coastal plains to the highlands ecosystems in the center (GRISP, 2013). One of the major constraints in high altitude cropping system is cold injury, which occurs at different stages of crop growth (Arshad et al., 2017; Shrestha et al., 2012). Cropping calendars are organized according to the rainfall pattern (Sarremejean et al., 1961) as the irrigation systems are strongly depending on seasonal precipitation. The warm and wet season normally starts in October and ends in March or April. Therefore, any delay in crop establishment caused by the late onset of the rainy season will result in yield penalty.

In Rwanda, inefficient splitting of N applications, including the use of excess N during early vegetative growth stages of rice contributes to low nitrogen use efficiency (Thind et al., 2012). Current N fertilizer recommendations for irrigated rice generally consist of fixed rates and timings for large rice growing areas having similar climate and landforms. Such blanket fertilizer recommendations do not take into account the effects of temperature in estimating crop nutrient requirements and are unresponsive to temporal variation in crop N demand (Thind et al., 2012). Furthermore, effects of elevation on site specific climate are often not taken into consideration when estimating nutrient demands of crops grown in higher altitudes (Becker et al., 2007), and thus in different thermal environments.

Five study sites were set up in the three countries, and field studies were conducted for 2 years. The main objectives were to assess the impact of low temperature environments on the performance of contrasting rice genotypes planted either a) within a limited window for the growing period (due to water and temperature constraints) to select suitable varieties, b) under a wide range of temperature environments and planting dates to identify potential alternative cropping calendars or c) using variations in fertilizer management to assess the efficiency of fertilizer dose and split recommendations and alternatives. Here we focus on the links these studies provide for assessing the influence of temperature dynamics and genotypic performance on resource use, development, and productivity of lowland rice grown in high altitudes and discuss the next steps required to adapt the West-Africa-calibrated RiceAdvice tool to East-African conditions.

4.2 Materials and Methods

In order to gather the data required to adapt RiceAdvice to the environmental and agricultural conditions of Eastern Africa, we set up field trials in Madagascar, Rwanda, and Ethiopia. In all countries, local guidelines for crop management were used regarding crop establishment, fertilizer management, and pest control, if not stated otherwise. Within the countries, trial sites were selected to represent altitudinal gradients, with overlapping elevations between countries to enable cross-country comparisons. Planting dates were distributed throughout three calendar years (2015 to 2017), with continuous monthly planting dates in Madagascar (phenological responses), main- and off-season planting dates in Rwanda testing alternative fertilizer applications schemes (fertilizer use optimization), and one planting date during each rainy season in Ethiopia testing a large number of genotypes contrasting in duration (selection of suitable genotypes). Four rice genotypes, namely Chhomrhong, IR64, X-Jigna, and Yun-Keng, were included in all treatments at all sites: For all trials at all sites, data on phenological development, as well as yield and yield components were recorded. All sites were equipped with weather stations and sensors to record plot specific temperature data. More detailed information on crop and site-specific management and data collection is provided in chapter two, Boshuwenda et al. (2020), and Razafindrazaka et al. (2020).

4.2.1 Field trials sites and specific research questions

In Madagascar, two sites were selected in cooperation with the National Center for Applied Research and Rural Development (FOFIFA) to represent two altitudinal archetypes: Ambohibary (1674 masl) and Ivory (838 masl). The lower elevation site was selected as reference site to represent highly suitable environments for growing rice, whereas the high altitude site serves as a more challenging site, due to low temperatures limiting the options for planting dates, and thus adapting cropping calendars. At these sites, two years of field trials using monthly staggered planting dates for 20 varieties were conducted to assess the impact of low temperatures during different stages of the phenological development on yield and yield components. Following this approach, options for adapting the local cropping calendar based on planting dates, phenology and yield performance of different varieties can be developed (for more information, see Razafindrazaka et al. (2020).

In Rwanda, experiments were conducted at two Rwanda Agriculture Board research sites at (I) high altitude Rwasave marshland, Butare (2°36’S, 29°43’E; 1600 masl), Huye district, in the Southern province of Rwanda; (II) low altitude Bugarama marshland, Bugarama (41°50’S, 29°00’E; 900 masl), Rusizi District, Western Province. A randomized complete block design was used in farmers` fields. The current nitrogen recommendation in Rwanda considers applying a total N rate of 80 kg ha^{-1} with a basal application at transplanting. Standard fertilizer recommendations and alternative fertilizer management strategies (omission of basal N application, different doses, different splits) were tested and compared for their impact on crop performance under regular and temperature limited conditions at both altitudes. Details on the layout, methods, and data analysis used are provided in Boshuwenda et al. (2020).

In Ethiopia, field trials were set up at the Fogera rice research station of the Ethiopian Institute of Agricultural Research (EIAR, at 11° 58′ N, 37° 41′ E, 1811 masl). In a randomized complete block design with three replicates 30 different genotypes with contrasting phenology were screened over two years to allow selecting genotypes specifically fitting to the respective year as a function of their yield performance and phenological duration. In this way yield could be maximized while avoiding chilling injury towards the end of the season. More details on these trials are provided in chapter two.

4.3 Results

4.3.1 Rainfall dependent rice cultivation resulting in cold stress for varieties in Ethiopia

Duration from sowing to physiological maturity differed among the 30 tested genotypes between 120 and 178 days. Accordingly, genotypes were categorized into three groups: short duration, ≥120 to <140 days (14), medium duration, ≥140 to <160 days (12), long duration, ≥160 to 178 days (4). As can be seen in table 4.1, the short duration genotypes performed acceptably well during these trials, reaching yields between 5.7 and 6.5 t/ha. IR64, Makalioka 34, and all the long duration genotypes showed a high spikelet sterility and thus very low yields (0.2 -1.7 t/ha). The crucial factor here was that flowering started after the onset of the cold period at 100 DAS (see figure 1 for a weather diagram), resulting in a drastic increase in spikelet sterility. One notable exception in the medium duration group is Yun-Keng, a cold-tolerant japonica variety, being a potential candidate for genotype recommendations in these environments.

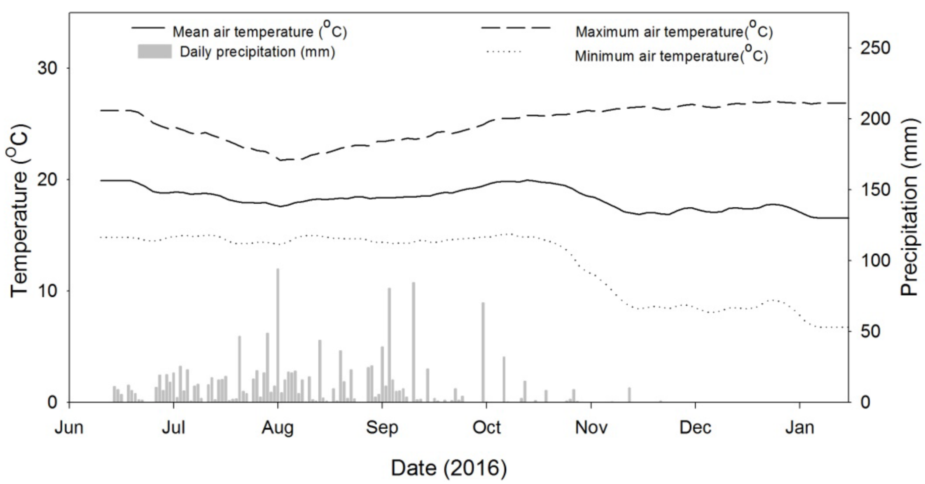

Figure 4.1 Weather chart for the year 2016 in Fogera, Ethiopia. Sowing was end of June 2016, after the first rainfall event in June. Note: A clear negative trend in minimum temperatures can be seen from the end of October onwards (Days after sowing: 100).

Table 4.1 A selection of nine of the 30 genotypes tested, grouped by duration (short < 140 and long ≥160 days to maturity). Days to mid-booting has been assessed in field observations in 2016, Fogera, Ethiopia. During these trials, the onset of the cold season began at day 100 after sowing. A cold day, for this purpose, is defined as the first day of a series of at least 3 consecutive days in the growing season with a minimum daily temperature below 13°C. (for more details, see chapter two)

Genotype	Duration	Days to booting	Spikelet sterility (%)	Yield (t/ha)
Chhomrong	Short	77	0.6	6.2
WAB 189	“	75	3.4	5.7
X-Jigna	“	84	12	5.9
Yun-Keng	Medium	99	8.9	7.2
IR64	“	103	51	1.7
Makalioka 34	“	112	71	1.6
FARO 35	Long	114	88	1.0
WITA 4	“	116	98	0.4
SIM2 Sumadel	“	117	96	0.2

4.3.2 Alternatives for adapting the cropping calendar in Madagascar

According to their duration from sowing to physiological maturity, the 20 genotypes were divided into three groups: short duration (days to flowering ≤ 90 days – 6 varieties), medium duration (days to flowering > 90 and ≤ 120 days -9 varieties), and long duration (≥ 120 days to flowering – 5 varieties). The November sowing date at mid altitude was selected as the reference for the classification (recommended practice). Across genotypes duration from flowering to physiological maturity was more or less constant. Thus, differences in crop duration reflected genotype x environment interactions in vegetative and/or reproductive development phases.

The environmental conditions coinciding with a certain development stage and therefore with a certain phase during which a certain yield component is formed depends on the duration to flowering of the respective genotype and the selected sowing date. Results show that in mid altitude, yields were highest after sowing between November and January and a complete yield failure was observed after sowing in March and April. In contrast, in high altitude, yield performance depended strongly on the combination of genotype group and planting date. Short duration varieties yielded best when sown in November. Medium duration varieties performed well when sown in September, October, and November whereas long duration varieties achieved good yields when sown in September and October but November sowing was not any more appropriate for long duration genotypes. In mid altitude, the group of early maturing genotypes consistently showed the lowest yields due to low number of panicles per m² and low spikelet number per panicle. (detailed results in Razafindrazaka et al., 2020). In high altitude, differences in genotypic yield as a function of the sowing date was mainly due to chilling injury during the booting stage and a resulting high spikelet sterility. Thus, selecting the most appropriate genotype for a given planting date in high altitudes proved to be vital for the crops success, whereas the mid altitude allows for greater flexibility in genotype-specific planting dates and thus offers more options for potential adaptations to the cropping calendar (Fig. 4.2).

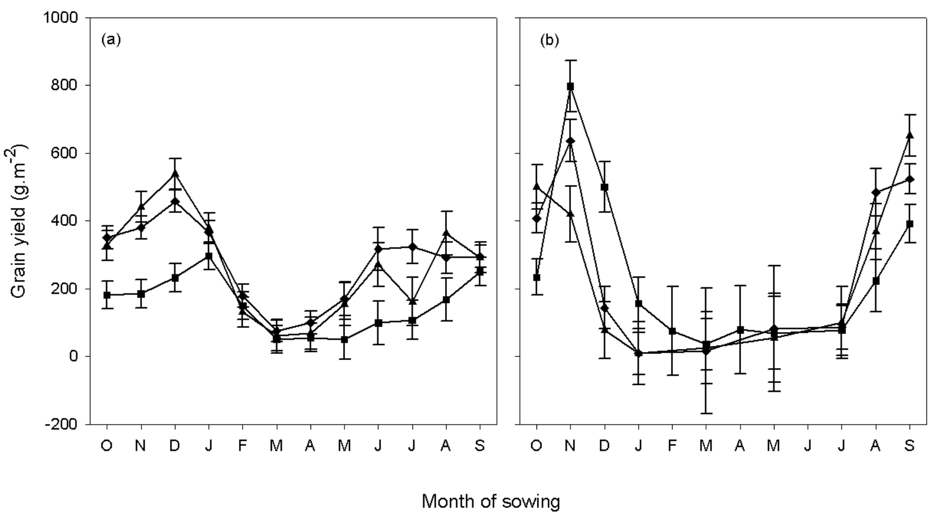

Figure 4.2 Mean grain yield in g.m-2 obtained from the three different groups of genotypes for the monthly sowing date from two (a) Mid altitude and (b) High altitude sites in Madagascar. Presented results are mean values of the two seasons 2015/16 and 2016/17. Symbols represent the different groups of genotype. Squares represent short duration genotypes (Chhomrong, Hibir, Kirkpinar, Machhapuchre, WAB 189-B-B-B-8-HB, X-Jigna), diamond medium (B6144F-MR-6-0-0, FOFIFA 160, IR64, Kelimamokatra, Mailaka, Manjamena, Nerica L19, Silewah, Soameva) and triangles long duration genotypes (FARO 35, Sim 2 sumadel, WITA 4, Yunkeng, Zhongeng). Error bars indicate standard deviation.

4.3.3 Effects of fertilizer management strategies in the highlands of Rwanda

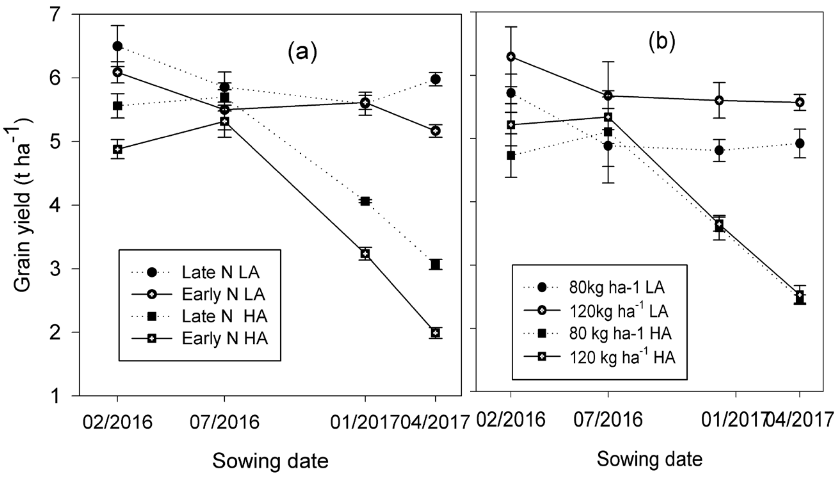

Figure 4.3 a (left) Mean grain yield (t ha^{-1}) obtained from early and late basal nitrogen application treatments at low and high altitudes in Rwanda. Presented results are mean values of four genotypes. b (right) Grain yield as affected by three N rates at low (LA) and high (HA) altitudes in Rwanda. Presented results are mean values of four genotypes. Error bars indicate standard deviation.

The effect of nitrogen rates and time of basal nitrogen application was investigated in mid and high altitudes. Early basal N application which is currently recommended, corresponds to the application of nitrogen at transplanting; late basal N application corresponds to the postponing of the basal N amount to tillering and PI stages. In high altitude, independent of the genotype grain yield increased by 0.5 to 0.8 t/ha when N was applied late, whereas at mid altitude no clear effect on grain yield increase was found when N application was postponed (Fig. 4.3a). On the other hand, increasing N rate from 80 to 120 kg/ha at mid altitude resulted in up to 20% higher yields with no additional effect with even higher rates. In high altitude, additional N had no significant effects on grain yield (Fig. 4.3b). Variations in grain yield were larger at high altitude due to spikelet sterility induced by low temperatures during sensitive reproductive stages at the April sowing date. For more details, see Boshuwenda et al. (2020).

4.3.4 Comparison of temperature and phenological development between study sites

The five experimental sites were selected to represent an altitudinal gradient with two sites at mid altitude (Ivory, Madagascar, 838 masl; Bugarama, Rwanda, 900 masl) and three sites at high altitude (Rwasave, Rwanda, 1600 masl; Ambohibary, Madagascar, 1668 masl; Fogera, Ethiopia, 1811 masl). Mean temperature for the time between sowing and flowering of the four commonly cultivated varieties Chhomrong, IR64, X-Jigna and Yun-Keng is presented in Figure 4.4.

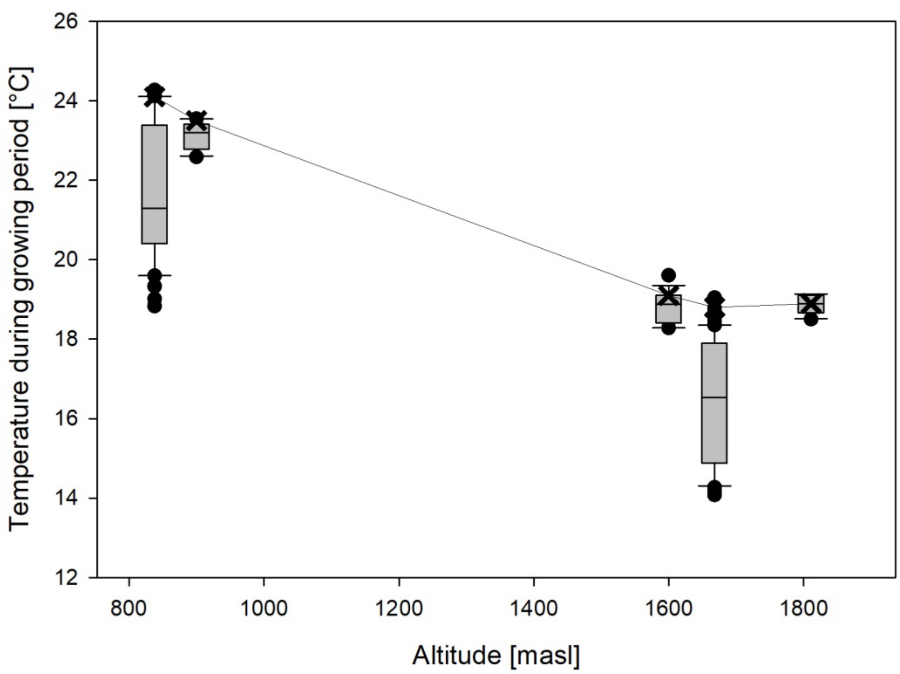

Figure 4.4 Mean temperature between sowing and flowering for 4 varieties (Chhomrong, IR64, X-Jigna, Yun-Keng) sown on different dates according to the altitude of the experimental site. In order of their altitude, experimental sites are Ivory, Bugarama, Rwasave, Ambihibry and Fogera. Error bars indicate standard deviation.

A large variation of mean temperature was observed in Ivory (18.8°C - 24.3°C) and Ambohibary (14.1°C - 19.0°C), because of the large number of sowing dates, which were distributed throughout the year. In Bugarama (22.6°C - 23.5°C) and Rwasave (18.3°C - 19.6°C) variation was smaller due to a smaller number of sowing dates and a much smaller intra-annual temperature amplitude due to the locations' proximity to the equator. In Fogera (18.5°C -

19.1°C), the small variation resulted from only two sowing dates, which were carried out during the same period of two successive years. In order to relate the results from the different sites to each other and to their altitude, mean temperature during the time between sowing and flowering of the four varieties sown at the recommended dates was calculated. Here, mean temperature was highest at 838 masl (Ivory) with 24.1°C, closely followed by 23.5°C at 900 masl (Bugarama). Mean temperatures at the high altitude sites were very similar with 19.1°C, 18.8°C and 18.9°C at 1600, 1668 and 1811 masl, respectively.

Likewise, average duration from sowing to flowering after the recommended sowings was similar at the two mid altitude sites with 86.3 days at 838 masl and 89.0 days at 900 masl and at the three high altitude sites with 114.0, 118.3 and 112.8 days at 1600, 1668 and 1811 masl, respectively (Fig. 4.5). Since a much larger temperature range was observed at the sites in Madagascar, duration to flowering showed the largest variation (67 – 165 and 115 – 293 days in Ivory and Ambohibary, respectively) as well.

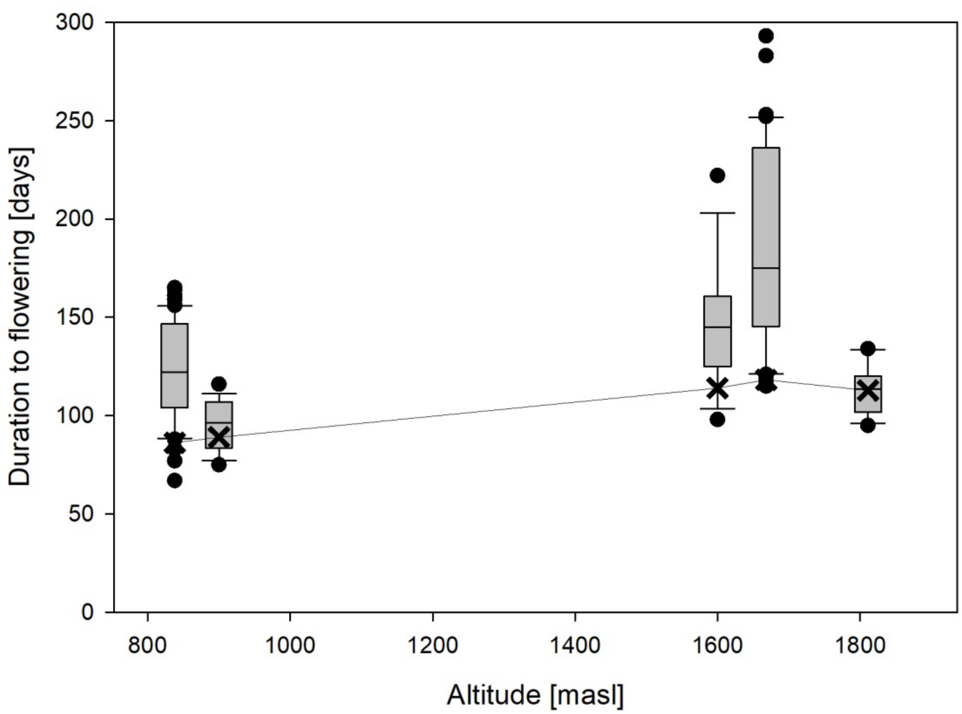

Figure 4.5 Duration from sowing to flowering for 4 varieties (Chhomrong, IR64, X-Jigna, Yun-Keng) sown on different dates according to the altitude of the experimental site. In order of their altitude, experimental sites are Ivory, Bugarama, Rwasave, Ambihibry and Fogera. Error bars indicate standard deviation.

4.4 Discussion

4.4.1 Closing the knowledge gap for digital extension tools

The RiceAdvice App, and the underlying model, have been developed and tested with a focus on providing cropping calendars and genotype selection guidelines to West African rice farmers. These recommendations are derived from expected growth duration and yield loss due to extreme temperatures as a function of daily air and water temperature, daily hours of sunshine and a set of genotype-specific photo-thermal cardinals. This allows for the identification of sowing windows for farmers to minimize risks of yield failures by extreme temperatures. In order to improve the quality and reliability of the recommendations by RiceAdvice, to enable an extension of its` scope into highland areas in other parts of Africa, and to prepare the app for the challenges of the expected effects of climate change, a number of issues will have to be researched, clarified, and implemented. In the introduction we have named the three pressing issues that we have aimed at investigating: a) variety selection within a limited window for the growing period, b) alternative cropping calendars under a wide range of temperature environments and planting dates and c) variations in fertilizer management to assess the impact of low temperatures on the efficiency of fertilizer dose and split (distribution over the planting season). Other issue that will need to be tackled in the future are d) the variability of crop nutrient demand along the stages of phenological development per se, and e) in relationship to the thermal environment in which it is grown. A study by He et al. (2016) points towards a strong sequential influence of temperature on soil organic C, total N, and fine root N content in high altitude agricultural systems. Low temperatures result in higher accumulation of organic C and N in the soil combined with a reduced uptake of N by the crops, potentially resulting in less efficient fertilizer use and higher losses from leakage. In light of the potential impacts of climate change, it will be necessary to implement more detailed functionalities on f) the expected ex-post impacts of weather anomalies (e.g. heat spikes during booting stage or flowering), and a functionality g) to alert and inform participating farmers of unexpected but necessary management interventions (e.g. shifts in fertilizer or pesticide application time).

The findings of the studies introduced in this paper can help to improve apps such as RiceAdvice with regard to cropping calendar planning, variety selection, and nutrient management. Due to temperature constraints, sowing windows are narrower in high altitudes, but still, where irrigation water is available, rice can be successfully cultivated during a relatively long period. The risk of yield failure after a late sowing or due to an early onset of the cold period can be minimized via a carefully considered choice of variety. Varietal characteristics, such as duration-type and cold tolerance, are essential criteria that can make the difference between a good yield and complete yield failure in a risky environment. Phenology was strongly influenced by altitude, since observed crop duration of the five varieties was similar at the two mid altitude sites as well as at the three high altitude sites. No influence of latitude on phenology in terms of crop duration was found, indicating that the test genotypes were day-neutral and not photoperiod-sensitive (Dingkuhn et al., 1995; Dingkuhn et al., 2017; Sommerfield et al., 1992).

The differences in nitrogen requirements of rice genotypes grown at different altitudes that were found in Rwanda, allow assumptions for the performance of these genotypes at other locations such as Madagascar or Ethiopia. While at high altitude late N application led to higher yields, the effect was not significant throughout the study period. Since N requirements depend on development stage, these findings relate to differences in development rates, which are mainly temperature dependent (Zia et al., 1994). Both, temperature during the growing season and development rates were similar at the high altitude sites in all three countries (Fig. 4.4) and therefore, fertilizer management recommendations for at least the three studied high altitude sites should integrate these findings and link it to the respective soil fertility information, but a much broader applicability to other high altitude sites can be presumed.

Modelling approaches similar to the engine running RiceAdvice are being followed by established, more complex crop growth models such as APSIM (**A**gricultural **P**roduction **S**ystems s**IM**ulator, a multi-module model focusing on plant, soil and management aspect, simulating biophysical processes and impacts of management decisions, www.apsim.info), DSSAT (Decision Support System for Agrotechnology Transfer, including dynamic crop growth simulation related to soil-plant-atmosphere dynamics, www.dssat.net) and Oryza2000/V3 (a rice growth and development centered cropping model family focusing on abiotic stresses, Boumann et al., 2001). There are different approaches implemented to model ecophysiological processes, some of which might need to be readjusted based on current findings (Stuerz et al., 2020). One possibility to improve RiceAdvice could be to implement a modelling engine similar to

Oryza2000, but adapted for the needs of a modern, mobile, app-based extension tool. This, more detailed model, could e.g. be adaptable in both its complexity and data demand based on local data availability, or be supported by a server- or cloud based computing approach, where supra-regional information is being stored and models are run centrally. This would allow for citizen science and big data approaches, feeding results back into the models to validate and improve the predictions.

4.4.2 Overcoming adverse environmental conditions through the selection of genotypes and management strategies

A relatively late recommended sowing date, due to water restrictions resulting from the rainfed conditions common in Fogera, led to the reproductive stages of the tested rice genotypes coinciding with the onset of low temperatures. Both long- and medium-duration genotypes were exposed to low temperatures in their reproductive stage. An effect that could be seen very clearly in long-duration genotypes exhibiting high spikelet sterility. The critical air temperature that induces cold damage depends on the cultivar (Dingkuhn et al., 1995). Some rice cultivars can grow and develop under low temperature conditions (Sanghera et al., 2011). Adaptations to the cropping calendar and appropriate selection of genotypes is reported as best strategy to escape the risk of cold damage and to ensure stable rice production (Shimono et al., 2011). In the study highlighted here, the onset of the season is strongly limited by water availability due to the absence of irrigation possibilities and thus allows much less flexibility in the cropping calendar. As the onset of cold stress is largely weather and climate dependent, adaptions to the cropping calendar would have to happen at the beginning of the season. A potential possibility to shift phenological stages away from the threshold of cold stress would depend on drought-tolerant varieties allowing farmers to plant earlier using improved furrow or ditch systems for improved rainwater harvesting during the earliest rain fall events, or on the establishment of pre-season, irrigated nurseries allowing to sow a wider range of duration types with limited amounts of irrigation water, giving the farmers a larger pool of varieties to choose from depending on the onset of the rainy season. This would offer an opportunity for farmers in Fogera to go for high yielding medium- (or even long-) duration varieties while avoiding the risk of high spikelet sterility. RiceAdvice could help in determining the varieties to sow and in selecting the one to plant.

4.4.3 Classifying crop duration in novel environments

The genotype classification used in this study was a new classification for East African highland environment, as, for example, crop duration deviates from the original environment in which the genotype was selected for its desired trait. This is the case for WITA 4 as an example, which was originally released in Nigeria to solve the problem of long duration and low yielding traditional varieties (Saito et al., 2010; Toungos, 2016). However, in this study, the same genotype showed much longer growing period and was thus classified among the late maturing varieties.

Sowing dates suitable for rice-growing yields at high altitudes were generally higher than at mid altitudes due to much higher number of tillers per hill. The number of tillers depends on the light and temperature conditions, the nutritional status of the plant and the supply of carbohydrates from photosynthesis (Yoshida & Hayakawa, 1970). Since the crop management at both altitudes was the same, the only factors that were not homogenized were the temperature and precipitation (and resulting humidity). Higher temperatures and drier conditions at mid altitude resulted in higher respiration losses and therefore lower biomass production (Crawford et al., 2012) which in turn translated into a lower number of tillers per hill.

4.4.4 Fertilizer management under highland conditions

Shifting basal N application to tillering and panicle initiation stages increased grain yields at high altitude. This yield increase could be attributed to a larger number of panicles per m^2 and more spikelets per panicle due to the increase of available N the crucial stages of panicle development (Sui et al., 2013). Slow root development and low nitrogen uptake induced by low temperatures at high altitude during the early growing stage most likely lead to losses of fertilizer bases N, though rice seedlings may rely on the indigenous soil N supply since N levels in Rwandan marshlands are adequate (Hayashi et al., 2008; RSSP, 2012). Both Huang et al. (2008) and Chen et al. (2014) reported an increased biomass accumulation after heading stage with high N rates at panicle initiation that led to higher grain yields. Increased carbon and N metabolism ability of rice grains, enhancement of enzyme activities and acceleration of the grain filling rate were reported by Jianga et al. (2016) and attributed to a moderate postponing of basal N application. Studies conducted by Sharma et al. (2007) and Qi et al. (2012) reported significant grain increase when the basal N was delayed by 20 and 10 days, respectively. Thus, RiceAdvice would have to take these effects under consideration when advising farmers in East African Highlands on fertilizer strategies, as has already been suggested by (Saito et al., 2019).

4.4.5 Digital extension as opportunity

Lack of infrastructure both for transport and knowledge transfer often hinder conventional extension services to supply farmers with up-to-date, site-related information instead of blanket recommendations. Extension services using app-based tools and solutions offer a tremendous opportunity to improve smallholder farmers´ decisionmaking in Africa. On one hand, more and more farmers have access to mobile and smart phones, while, on the other hand, computational power of these devices increases constantly. Providing extensions services and smallholder farmers with regionally adapted, validated, scale-able decision support tools that are able to tackle the challenges discussed in this paper offers the potential to improve crop yields, and thus rural livelihoods, profoundly.

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5 General Discussions

5.1 Seasonal variability and genotype performance

Due to the variability in the onset of rains, the sowing date can be sooner or later in the season in rainfed rice farming systems. Weather conditions differ between cropping seasons / years, an effect that is enhanced by climate change (Lar et al., 2018; van Oort and Zwart, 2018). Further, as a consequence of variable sowing dates and seasonality, weather experienced by the crop can vary (Acharjee et al., 2019), even stronger between years than the natural inter-annual variation of weather conditions. Therefore, these cumulative effects of variable weather conditions are responsible for deterred rice performance (Devkota et al., 2013; Kim et al., 2013). Until viable solutions are found, rice production at Fogera and in similar environments with a moisture deficit during the early season and cold stress during the late-season will remain a challenge. In our study (chapter two), crop performance was evaluated for thirty contrasting genotypes (short-, medium- and long-duration) for two cropping seasons differing in sowing dates. The effect of sowing date on crop duration and yield varied among genotypes. Prevailing weather conditions during the cropping seasons were compared, and it was found that due to seasonality short-duration as well as medium- and long- duration genotypes were exposed to different temperatures, and radiation and relative humidity levels during their different phenological phases. This result is in line with the findings of Ndour et al. (2016), Razafindrazaka et al. (2020) and Tu et al. (2020). According to Dingkuhn and Miezan (1995), short- and medium-duration rice genotypes showed different photothermal responses and agronomic performance in different seasons. For the short-duration genotypes, weather experienced during the two seasons only differed in radiation, which was lower in 2017 as a result of early sowing coupled with weather differences between the two years. The lower radiation levels explained the extended phenological development of short-duration genotypes compared to the performances in 2016. Lower development rates under low light intensities were demonstrated by Stuerz et al. (2020). On the other hand, since low air humidity can extend crop duration (Stuerz et al., 2020), the difference in air humidity between the two years is the most likely weather parameter explaining the shortened duration of medium- and long-duration genotypes in 2017.

Similarly, yield performances of the tested genotypes differed between both experimental years. Lower yield was recorded for short-duration genotypes after early sowing compared to late sowing. In contrast, higher yields were obtained after early sowing of long- and medium-duration genotypes. As a consequence of genotype-dependent experienced weather conditions, yield components were significantly different, resulting in significant effects on final grain yield (Hussain et al., 2014; Ndour et al., 2016). In our study, yield was positively correlated with the percentage of filled spikelets and the number of productive tillers, while it was negatively correlated with the number of tillers per hill. The early sowing in 2017 generally led to fewer tillers per hill (TPH). The lower tiller number was most likely related to the lower radiation levels received by the crop in 2017 during the vegetative stage. The negative effects of low radiation levels during vegetative stage on tiller number (biomass production) and thus final grain yield have been described by several authors (Gautam et al., 2019; Huang et al., 2020; Qi-hua et al., 2014; Restrepo and Garcés, 2013). Investigating the effect of UV-B on rice growth, Mohammed et al. (2007) showed reduced tillering under sub-ambient UV-B. However, in medium- and long-duration genotypes, the lower tiller number was compensated by a higher PPT in 2017. Higher Tmin during the early reproductive stage of medium- and long-duration genotypes due to early sowing resulted in an advantage compared to late sowing in 2016 in terms of higher PPT. Ndour et al. (2016) also reported improved PPT in less extent of cold stresses from early sowing dates. Higher PFS in the medium- and long-duration group and a high TGW in the medium-duration genotypes were found in our study in early sowing in 2017 compared to late sowing in 2016. PFS was the yield component that explained the largest share of the differences in yield between the two years. Since the late sowing came along with a temperature drop early in the season in 2016 causing Tmin below 14°C around the booting stage of the medium- and long-duration varieties, many of them enormously suffered from cold sterility. However, two varieties, i.e. Silewah and FOFIFA 160, showed superior tolerance to low temperature (Figure 2.5). The cold tolerance of Silewah has been demonstrated earlier by Ndour et al. (2016), while for FOFIFA 160, it has not been shown yet.

5.2 Genotype selection at high altitude cropping systems

In the highlands of East Africa, rice performance varies between years due to seasonal weather variation. Low temperature has been discussed as the major constraint affecting rice production and thus, compromising the goal to minimize the gap between rice production and demand (Africa Rice Center, 2011; Zena et al., 2010). As Africa's rice production can only satisfy 60% of its demand (Saito et al., 2019), the remaining 40% are imported from surplus producers, mainly from Asian countries. To minimize the large share of imports, new technologies need to be developed and implemented in the rice sector to achieve the farming systems' potential (GRiSP, 2013: Saito et al., 2017; Tanaka et al., 2017).

In countries where rice is mainly produced in temperate and mountainous areas, yield increases were realized with the cultivation of suitable genotypes (Biswas et al., 2019). In recent years, breeding efforts mainly focused on short duration genotypes, in order to fit the cropping system to the given environment (Lakew et al., 2016; Won et al., 2020). However, the untapped potential of medium- and long-duration and thus, potentially high yielding genotypes (Banumathy et al., 2016), should be considered for sustainable rice intensification. As a matter of course, this demands a proper crop management implementation and weather forecasting (Zhang et al., 2019). It is worth noting that the medium-duration genotypes had higher yields than the short-duration genotypes after early sowing in our study. This may be due to less exposure of the genotypes to low temperature stress at critical reproductive stage (Ndour et al., 2016), and due to the characteristics of the genotypes, which gained more biomass during their relatively long vegetative phase (Huan-he et al., 2016). Exemplarily, the medium-duration Yun-Keng showed the best yield performance among the tested genotypes. Additionally, the superior yield performance was a result of the cold-tolerance of this genotype. Further, early sowing can minimize the risk of exposure to cold stress during critical reproductive stages. Chuma et al. (2020) and Razafindrazaka et al. (2020) also reported Yun-Keng's high yielding result. Therefore, there are two options to include the medium-duration genotypes in high altitude cropping systems: i) sowing early in such a way that the effect of low temperature stress can be avoided or reduced during their critical reproductive stage, ii) growing cold tolerant genotypes.

5.3 Crop management for proper utilization of the cropping season

In our study (chapter three), transplanting resulted in considerable higher yield than direct seeding for medium and long duration genotypes. However, only minor differences between crop establishment methods were observed for short-duration genotypes. The yield advantage of medium- and long-duration genotypes after transplanting was more pronounced after early sowing in 2017. Rahman et al. (2019), who evaluated different crop establishment methods, found a significant yield advantage from transplanted, compared to direct seeded rice. In this study, higher yields were associated with higher PFS and TGW, which was improved due to transplanting, early sowing, and using medium-duration genotypes. Samejima et al. (2020) also reported that grain yield was correlated with PFS and TGW.

Although transplanting resulted in extended duration due to transplanting shock, early nursery preparation created an excellent opportunity for the genotypes to benefit during the vegetative stage from the beneficial thermal environment at Fogera. All genotypes underwent a higher minimum temperature after transplanting compared to direct seeding. Further, early nursery preparation can give a yield advantage due to lower risk of cold spells coinciding with critical reproductive stages. Transplanting shock can be a drawback in adapting transplanting technology (Dingkuhn et al., 1995). However, the nursery facilitates fast and good germination and emergence of seedlings; thus, vigorous seedlings can be picked. In our study, a short period of growth and development in the main field after transplanting was observed, since part of BVP took place in the nursery bed (Dingkuhn and Asch, 1999), compared to direct dry seeding. On the contrary, direct seeding pushed the reproductive stage to coincide with the cold spell in October and November (chapter two). The genotypes' response to different crop establishment methods is essential for focusing on and utilizing its potential, particularly for medium- and long-duration genotypes. Here, the results demonstrated the possible alternatives as a function of sowing date depending on the onset of rains. Raising seedlings in the nursery with an early sowing date and transplanting right after good conditions emerged is one way to get a greater chance to complete grain filling. Nevertheless, direct seeding and short-duration genotypes should not be disapproved at all; instead, they could be an opportunity when the onset of rains is delayed in the season.

5.4 Enabling RiceAdvice more applicable in Eastern Africa high altitude rice cropping system

Current advanced information technology, access to a smartphone and other apparatus create an opportunity to provide extension services improved in quality and area coverage, significantly strengthening farmers' decision making for proper agronomic practices: variety selection, sowing date, application of fertilizer rate and frequency (Dingkuhn, 1995; Saito et al., 2015). ORYZA, APSIM, CERES-Rice, RIDEV, and similar models have been reported as supportive tools adapted to the new environment other than they were parameterized, calibrated, and validated initially (Dingkuhn et al., 2015; Kim et al., 2013; Larijani et al., 2011; Lu et al., 2020; Zhang & Tao, 2013). Similarly, field trials were conducted in Ethiopia, Madagascar, and Rwanda to record the crucial data to adapt RiceAdvice to the Eastern Africa high-altitude rice farming systems. From this study (chapter four), the short duration genotypes performed acceptably well in late planting due to a delayed onset of rains at Fogera. The crucial factor here was that flowering started after the onset of the cold period at 100 DAS, resulting in a drastic increase in spikelet sterility. The genotypes were tested in Madagascar, and similar results were obtained. Their category of growth duration has slight differences, though. Differences in crop duration were observed in genotype × environment interactions in vegetative and reproductive development phases (Razafindarazaka et al., 2020). The coincidence of environmental conditions with a particular development stage or phenophases during which a specific yield component is formed depends on the duration of the respective genotype's flowering and the selected sowing date.

The results from this study, in high altitude, suggested that the choice of variety and sowing date should be synchronized at a given location to obtain the maximum yield. Medium- and long-duration genotype suffered more due to low temperature at the reproductive stage. At the same time, other weather parameters like radiation and relative humidity took their share of influences on the crop growth before the reproductive stage, thereby low productivity (Huang et al., 2020; Vijayalakshmi et al., 1991). From the investigation conducted in different altitudes in Rwanda, N use efficiency was reduced along the altitude gradient from mid to high altitudes (Chuma et al., 2020). Shimono et al. (2012) reported that rice exposure to low water temperature resulted in slow N uptake. Vu et al. (2020) also found that N uptake was affected by low night temperature, thereby reducing growth. Late N application showed a yield advantage at high altitude; instead, the rate didn't give a significant advantage. The result also showed that delayed sowing compromised the yield as a result of spikelet sterility due to the low-temperature effect during reproductive stages. Variety Yun-Keng performed well in all tested high altitude locations. This may be attributed due to the cold tolerance of the genotype (Ye et al., 2009).

Temperature and phenological development were compared between the experimental sites with their contrasting environmental conditions. It is observed that the mean temperature between sowing and flowering of the four tested genotypes corresponded with the altitudinal differences: relatively low in the high altitudes and warm to hot in the mid-altitudes. As also reported by Dingkuhn et al. (1995) and Shrestha et al. (2013), the crop duration was longer at high altitudes as a result of low-temperature and relatively short in mid-altitudes. The results recorded from the three countries' field trials, which had different experimental focuses, can be used as data source to validate RiceAdvice, which was initially developed for the West African rice farming system (Saito et al., 2015).

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6 Conclusion

In this study, the differences in sowing date as well as the variability in weather parameters between 2016 and 2017 showed differences in genotypes' duration, yield and yield components. In the cloudy rainy season of 2017, short-duration genotypes experienced lower radiation, thus extended vegetative stage period. Consequently, their yield was lower compared to the late sowing in 2016. On the other hand, medium- and long-duration genotypes suffered from the early onset of the cool period in 2016, and late sowing led to the cold-sensitive booting phase of these varieties took place during the period when low minimum temperatures were most likely to happen. However, in early sowing in 2017, the crop duration was shortened and a substantial yield was obtained. This result clearly indicated that in the process of variety choice and any management intervention, the season-specific constraints have to be considered that the variety choice should depend on the sowing date dictated by the onset of rains. The decision should also be matching with the technically how to avoid the risk of cold sterility in such a way that the variety should arrive at booting stage latest at the end of October. At the same time, to make use of the higher radiation levels in September, it should have the longest cycle length possible without pushing days to booting beyond October. On the other hand, growing a relatively cold tolerant variety such as Yun-Keng, can minimize low temperature risks towards the end of the cropping season, and can make use of the full potential of the season.

From a comparison study of direct seeding vs. transplanting, in general, transplanting has a positive advantage over direct seeding. Transplanting led to a physiological maturity happened earlier in the season than the direct seeded rice. Then the genotypes, particularly medium-duration, got thermal advantage and escaped the low temperature stress at the critical reproductive stage, thus low spikelet sterility. As a resort for dependence of sowing date on the unpredictable onset of the rainy season, the potential of an irrigated seedbed and transplanting opened the window to incorporate the medium high yielding genotypes in high-altitude cropping systems. Irrigating a small nursery prior to the actual season does not constrain water resources and allows much more flexibility in both choice of variety and planting dates, though it needs further an economic and ecological assessment. All the findings in this study indicated that precise knowledge of the duration of the potentially suitable varieties and management options with the appropriate time of activities are required to prove the yield increase in the high-altitude rice cropping systems. Therefore the data can be an input for a crop model calibration for the varieties and for the environment. Thus, next step will be validation of a smartphone application RiceAdvice to support farmers' decision-making.

Furthermore, other alternatives should be investigated and implemented to increase the productivity as well as the production to satisfy the demands. With increasing uncertainty in rainfall patterns due to climate change and the increasing demand for rice in the near future, integration of genotype development and management options would greatly reduce risks. Thus, the next steps for high-altitude rice cropping systems constraint by such abiotic stresses need to be: 1) breeding cold tolerant medium and long duration varieties, 2) investigate the effect of seedling age on transplanting shock and on yield components, 3) testing of multiple varieties nursery with staggered planting dates to maximize water productivity, decrease the risk of crop failure, allow for opportunities in yield potential and increase area productivity for increased food security.