Development of a decision support tool to optimize timing of maize planting

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Executive Summary

This study demonstrates the potential of providing planting date decision support to farmers, based on real-time forecasts of soil moisture, combined with climatological information on rainfall and temperature seasonality. The planting date decision support tool (DST) has been calibrated and validated for six countries. Kenya, Malawi, Zambia, Uganda, Rwanda and Nigeria. For Rwanda, the DST has been validated against observed data for two separate seasons (A and B). The dataset used for validation were >32,000 historical recordings of planting date and yield. Findings were as follows:

Kenya

- Overall, the planting date DST performed well for Kenya.
- Farmers who planted late had consistent and often statistically significantly lower yields than those who planted at the recommended time.
- The outcomes for farmers who planted early was variable. Where the rains in the early part of the season remained steady, as happened in 2017, yields were high. In other years, however, sporadic rainfall resulted in slightly lower yields for early planters. This reflects the riskiness of very early planting and indicates that, notwithstanding occasional good outcomes, the decision support tool is right not to advise planting before the rains are climatologically likely to be well-established

Rwanda

- Overall, the model performs well for Rwanda.
- The optimal planting date selected by the system seems robust. However, the level of 'compliance' is far lower than for Kenya. In other words, farmers do not plant near the optimal time. This is likely to reflect the fact that the farmers are aiming for two growing seasons, and so the timing of planting is constrained by the timing of the previous season's harvest.
- For the B season, the chances of germination failure are minimal and so there is little point in a planting date DST. Farmers should simply plant as soon as they can after the A season harvest.

Uganda

- It was difficult to draw firm conclusions from the Uganda case study, primarily because of the low quality of the validation data, especially for the 2017 and 2018 seasons.
- Although the evidence for the quality of the planting date DST is weaker for Uganda than it is for Kenya and Rwanda, it is relevant that the rainfall seasonality, farmer planting behaviour, and the degree of variation in recommended date is similar to that seen in Kenya.
- The daily precipitation, moreover, follows a similar pattern to Kenya. It is reasonable, therefore, to suppose that the DST is potentially useful and that the parameters used for Kenya can be applied to Uganda.

Malawi

- Overall, the planting date DST performs effectively for Malawi.
- It is clear that planting near the optimal time is of benefit to farmers.
- In some years, a substantial number of farmers plant far later than recommended (>2 months), and achieve very low yields. In 2018, this late planting occurred after a period of sporadic rain during January, perhaps suggesting re-planting.
- The need for replanting perhaps reflects the risky nature of planting in conditions of very low soil moisture and hence the need for the planting date DST.

Zambia

- The Zambia study provides some evidence that the planting DST identifies the optimum planting date, although the quality and quantity of the data means that it is not possible to be definitive.
- In both 2019 and 2020, farmers who planted late had lower yield than farmers who planted close to the recommended date. However, these results were not statistically significant for 2020 because of the low number of farmers in the sample.

Nigeria

- Overall, because of the lack of the data and the variable climate, it is not possible, at this stage to have confidence in the DST for Nigeria.
- The recommendation is that One Acre Fund continue to collect data on planting date and yield, with the aim of calibrating a DST for the region, once more data are available.

The planting date tool is ready to be piloted in Kenya, Zambia, Malawi and for the Rwanda A season, but more data are required to determine the decision-making criteria in Nigeria. There is no need or benefit to planting date decision support for the Rwanda B season – farmers should simply plant as soon as they can after the A season harvest. Piloting and scale-up of planting date recommendations delivered via SMS will be done across several countries of operation during 2021. The focus of the pilots should be on effective communication of recommendations to farmers. For example, farmers are to be encouraged to plant early, it is likely that the suitability for planting will vary over the weeks following the first advice to plant. There needs to be careful consideration as to how the planting advice is phrased.

Full Report

Introduction

Deciding when to plant is critical for smallholders. East Africa's variable climate renders farmers vulnerable both to germination failure because of lack of soil moisture, and insufficient rain to meet crop water requirement (also known as the water resource satisfaction index (WRSI)). If they plant too early, farmers risk seedling death if the rains are not established; if they plant too late, there will not be enough rain to sustain the crop through critical development periods. Our study demonstrates the potential of providing planting date decision support, based on real-time forecasts of soil moisture, combined with climatological information on rainfall and temperature seasonality.

Case studies

The validation was performed for the countries and seasons shown in *Table 1* for the localities shown in *Figure 1*. Although it is common in Africa to have more than one growing season, in this study, two seasons were considered only in Rwanda. The localities shown in *Figure 1* are superposed on a map of the maximum achievable climatological water resource satisfaction index (WRSI), averaged over 15 years (2003-2017). As a rule of thumb, a WRSI of less than 0.5 indicates severe water stress. Brown colours on *Figure 1* thus suggest regions that are not suitable for rainfed maize production. It can be seen that most, but not all, of the One Acre Fund sites are located in regions that are climatologically suitable for maize cultivation.

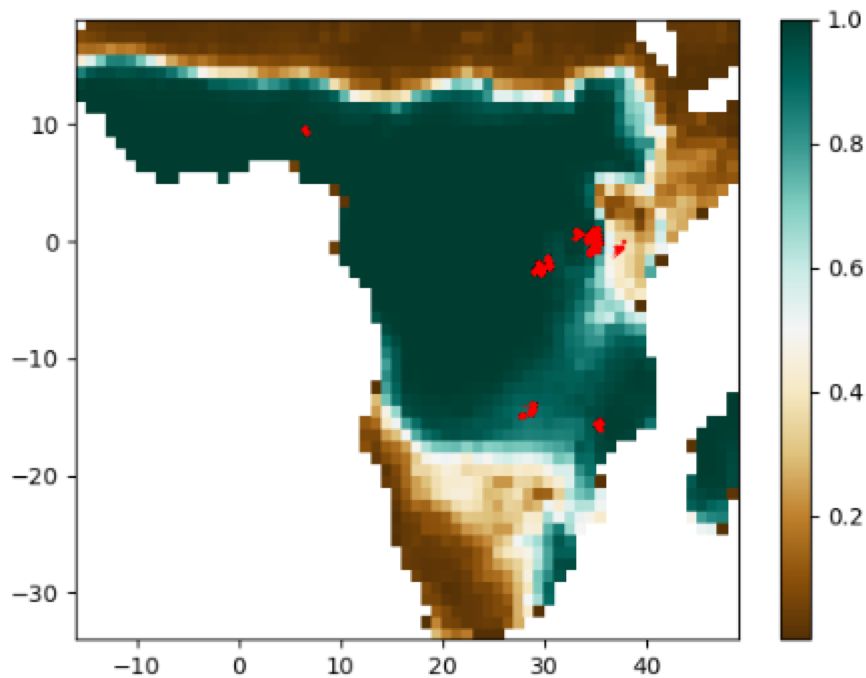


Figure 1. Climatological water requirement satisfaction index (WRSI) calculated for variable planting dates throughout Africa. On the figure, WRSI is calculated for the planting date that results in the highest climatological WRSI (averaged over 15 years). The red circles indicate localities for yield and planting date observations.

Table 1. Summary characteristics of the case study seasons.

Country	Season	Number of data points	Average planting date	Average yield (kg/acre)
Kenya	2016[1] LR[2]	3647	2nd April 2016	1159
Kenya	2017 LR	1577	8th March 2017	1655
Kenya	2018 LR	4219	12th March 2018	1308
Kenya	2019 LR	3319	1st April 2019	1199
Malawi	2017 LR	746	27th Nov 2016	1332
Malawi	2018 LR	1080	25th Nov 2017	817
Malawi	2019 LR	957	27th Nov 2018	818
Nigeria (north)	2015	155	23rd June 2015	773
Nigeria (north)	2016	148	21st June 2016	781
Nigeria (south)	2018	168	9th June 2018	1064
Nigeria (south)	2019	188	30th May 2019	780
Rwanda	2015B	853	23rd Feb 2015	1335
Rwanda	2016A	1090	10th Oct 2015	1325
Rwanda	2016B	929	6th March 2016	951
Rwanda	2017A	990	5th Oct 2016	1202
Rwanda	2017B	1847	24th Feb 2017	820
Rwanda	2018A	1181	29th Sept 2017	1692
Rwanda	2018B	1614	24th Feb 2018	1066
Rwanda	2019A	1553	30th Sept 2018	348
Rwanda	2019B	1227	20th Feb 2019	351
Rwanda	2020A	1449	28th Sept 2019	699
Uganda	2017 LR	221	14th March 2017	1353
Uganda	2018 LR	559	11th March 2018	1648
Uganda	2019 LR	693	20th March 2019	1253
Uganda	2020 LR	190	14th March 2020	1593
Zambia	2019 LR	795	11th Dec 2018	1041
Zambia	2020 LR	777	1st Dec 2019	1286

[1] The year given is the year of harvest, not necessarily planting

[2] LR is 'long rains'

Methodology

Data

Planting date and yield observations

One Acre Fund collected large datasets of geo-located yield and planting data observations for the seasons listed in Table 1 and for the locations displayed on Figure 1. The Nigeria data were sourced both from surveys of One Acre Fund farmers (Nigeria - south) and for trials conducted in the TAMASA programme (Bello et al. 2018).

A basic quality control was undertaken to check for repeated values, missing values and infeasible locations and planting dates. The data were generally found to be of good quality. However, the Nigeria dataset contained planting dates that were well outside the main planting season and a few data points were recorded without location information or with missing planting dates or yields. These points were removed.

Model driving data

The model is driven with TAMSAT v3.1 rainfall data and the NCEP reanalysis (Maidment et al. 2017, Kalnay et al. 1996). The following data were used from the NCEP reanalysis. 10m wind speed, daily 2m minimum and maximum temperature, specific humidity, sea-level pressure and skin temperature. All data were provided at the daily time scale and were re-gridded to a common 0.25^0 resolution. Both the TAMSAT and the NCEP data are complete and the only pre-processing carried out was the re-gridding of the datasets. The driving data are routinely processed within the TAMSAT system and are publicly available here.

Water resource satisfaction requirement was calculated for maize, based on FAO parameters for growing degree days, and based on the ratio of actual to potential evaporation inferred from the land-surface modelling results. The WRSI could be easily calculated for other crops. It would also be simple to adjust the WRSI parameters for different varieties of maize (for example a fast growing 90-day variety).

Soil moisture and WRSI prediction

General methodology for modelling soil moisture

The soil moisture modelling approach adopted in this study is based on that used in the Joint UK Land Environment Simulator (JULES), which is based on the Met Office Surface Exchange Scheme (MOSES). The JULES/MOSES methodology is fully described in Best et al, 2009, 2011, Clark et al, 2011 and Cox et al, 1999. In order to speed up computation, and hence to allow the system to be implemented in Python over large regions, several adaptations have been made to the JULES method. Unlike JULES, the model does not include full photosynthesis or radiation schemes, resulting in differences to the way that potential evapotranspiration and stomatal conductance are derived (see Asfaw, 2020).

As a result of the modifications listed above, the model requires different driving data to JULES. Specifically, rather than long and shortwave radiative fluxes, skin temperature is prescribed. The meteorological driving data required to run the model at the daily scale are thus. 2m daily mean air temperature, 2m maximum air temperature, 2m minimum air temperature, skin temperature, surface pressure, 10m wind speed, 2m surface humidity and precipitation. The model is run at an hourly time step, using the JULES methods for disaggregating the daily driving data to the hourly scale.

In the model, vegetation properties are prescribed in a similar way to JULES, except that there is no capability to tile vegetation or to vary plant function types over a grid. For the purposes of this study, a maize crop was assumed to be growing for the WRSI modelling and bare soil was assumed for the soil moisture forecasts. The treatment of crops is described in the next section.

Methodology for modelling soil moisture in regions of crop cultivation, and for deriving the Water Resource Satisfaction Index (WRSI)

The soil moisture model used in this study was adapted for crops by allowing the leaf area index (LAI), plant height (h) and rooting depth (r_d) to vary in both space and time. The variable LAI, h and r_d are based on a growing degree day (GDD) model, for which the plant development stage and hence the LAI, h and r_d depend on prescribed crop-specific GDD. Within a region, these stages will be reached on different dates, depending on the temperature and planting date.

The WRSI is defined as the seasonal mean percentage crop water requirement, calculated from planting to harvest, with the harvest date based on the GDD to maturity. The full method for calculating WRSI, and its relationship to soil moisture is described in Asfaw, 2020 (with the description included as an appendix to Boult et al, 2020).

Forecasting of seasonal mean soil moisture and WRSI

In this study, the TAMSAT-ALERT forecasting method described in Asfaw et al, 2018 is used to produce spatially variable probabilistic forecasts of soil moisture, which are then integrated into the DST. This method is summarized as follows.

The TAMSAT-ALERT system aggregates meteorological metrics (such as precipitation) over user defined periods, which can include both the past and future. Land surface metrics, such as soil moisture, and agricultural metrics, such as crop yield, can be derived by driving impact/land surface models with the aggregated meteorological time series. The conceptual framework of TAMSAT-ALERT is shown in *Figure 2*. Time series of meteorological variables are generated by splicing together historical data (satellite-based observations or reanalysis) with an ensemble of possible weather futures. The future weather ensemble is the weather that has occurred at the locality in question in the past.

In effect, TAMSAT-ALERT is an ensemble forecasting system, with ensemble members based on possible weather futures, derived from the climatology. Predictions of seasonal metrics are derived by statistically analyzing the ensemble. TAMSAT-ALERT can thus be used to monitor and predict any metric that can be derived from environmental time series data. It should be noted that TAMSAT-ALERT can be run without recourse to any proprietary data.

In its default state, TAMSAT-ALERT treats all possible weather futures as equally likely. Forecast information can be integrated by weighting the ensemble, using information from forecasts to judge the likelihood of each ensemble member. So, if it is predicted that there is a 20% chance of upper tercile June-August rainfall, ensemble members for which June-August rainfall is in the upper tercile, are down-weighted accordingly. This method of weighting implicitly accounts for the inevitable mismatch between the forecast variable (e.g. June-August precipitation) and the metric of risk (eg crop yield). If the metric and forecast variable are not closely aligned, the effect of the weighting is to randomly weight some ensemble members more strongly than others. The effect on the risk assessment will be minimal.

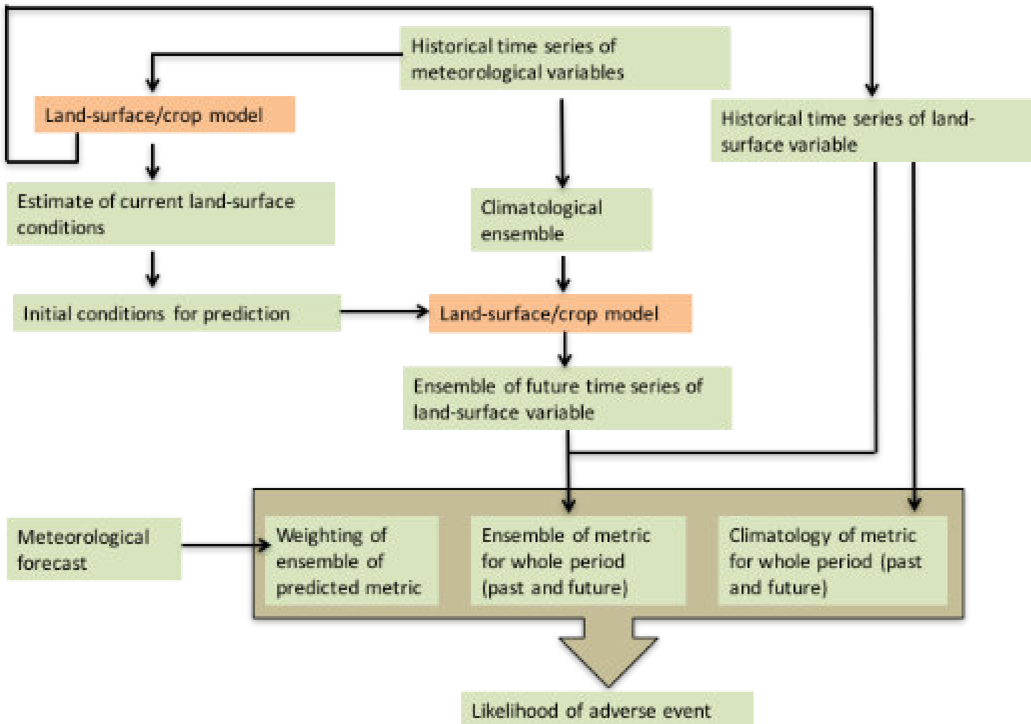


Figure 2. The conceptual design of TAMSAT-ALERT

In essence, TAMSAT-ALERT provides a quantitative answer to the question.
Given the climatology, the stage of the growing season, the state of the land-surface, the weather so far in the season of interest, and the meteorological forecast, what is the likelihood of some adverse event?

TAMSAT-ALERT is a general framework that can incorporate any impact or land-surface model, which is driven with meteorological data. In this application, TAMSAT-ALERT will be run using the soil moisture modelling approach described in the previous sections.

Planting date decision support tool

The decision of when to plant is a trade-off between the risk of soil moisture deficit during the germination period, resulting in seedling death and the risk of planting too late and risking water stress at later times during the season. To reflect this trade-off the planting date DST incorporates two criteria[3].

1. Probability of the predicted upper level soil moisture exceeding a predefined threshold is greater than a predefined value. The predefined threshold is determined through a sensitivity study (see next sections). In this study, upper level is the top level in the soil moisture model (top 10 cm) and soil moisture is expressed as percent field capacity (PFC), where PFC = $\frac{\theta}{\theta fc}$. Where θ is the soil moisture, θ_{fc} is the soil moisture at field capacity,

[3] During the sensitivity study process, an important test is that the planting criteria are met during historical years. However, it is theoretically possible that in some locations, during very dry years, the planting criteria are not met. The recommendation is that if the end of the WRSI window is approaching and the soil moisture criteria have not been met that farmers are advised to plant as soon as they can – but that there is a higher than usual risk of germination failure.

where field capacity is 80% of soil saturation. Following previous pilots of the planting date DST, the probability criteria for the soil moisture is set to 0.8.
2. Probability that the WRSI exceeds a predefined fraction of the climatological maximum achievable WRSI is greater than a predefined value. The WRSI probability criteria are fixed to 0.5 to ensure that the primary decision-making criteria is the temporally varying soil moisture, and to accommodate the considerable interannual variability in WRSI in some regions. The WRSI is calculated climatologically rather than predicted using the TAMSAT-ALERT approach because previous studies within the TAMSAT group indicate that the predictability of WRSI on seasonal time scales is far lower than the short time scale predictability of the upper level soil moisture (Boult et al. 2020, Brown et al. 2018).

In order to accommodate the possibility of two rainy seasons, the DST is constrained to run within pre-determined large time windows for each region and season.

- Kenya and Uganda long rains. December – May
- Nigeria rainy seasons. April – October
- Malawi and Zambia rainy seasons. September – April
- Rwanda A. August – February
- Rwanda B. February – May

Criteria for the decision support

The decision support criteria were based on a series of sensitivity studies, in which the WRSI and PFC criteria were varied. The sensitivity studies were carried out for forecasts of 5, 10 and 15 day accumulations of soil moisture. The model was judged, qualitatively, on the relationship between yield and compliance with the recommended planting date (see Appendix).

Based on these results, for Kenya, Rwanda, Uganda and Zambia, the criteria were set as follows:

- Climatological probability of a WRSI exceeding 0.75 of the maximum achievable WRSI is greater than 0.5
- Probability of the 15-day soil moisture exceeding 70PFC is greater than 0.8

For Malawi, it was found that these criteria resulted in advice that was far later than the observed planting practices, and that in some years, the joint criteria were not met. For these reasons, the criteria for Malawi were set to:

- Climatological probability of a WRSI exceeding 0.4 of the maximum achievable WRSI is greater than 0.5
- Probability of the 15-day soil moisture exceeding 25PFC is greater than 0.8

For Nigeria, it was not possible to draw conclusions because of the lack of data.

The fact that it was necessary to vary the decision support criteria is not surprising considering the variability in the climate and the fact that many farmers cultivate crops in sub-optimal conditions. Furthermore, experimental work suggests that the sensitivity of root growth during the early growing season varies according to temperature, with there being more benefit to high soil moisture when temperatures are highest (Cutforth et al. 1986).

Findings

Validation against observations

The yield achieved by farmers was compared with the difference between the recommended and observed planting dates. The yield data were gathered into bins, with each bin representing a 10 day relative difference compared to the recommended date. Yield was expressed as the median of the binned yield values. Negative differences indicate that planting occurred earlier than recommended, and positive values indicate that planting occurred later than recommended. Values near zero indicate 'compliant' farmers (i.e. those who planted close to the recommended date). *Table 2* provides the data used in the plots, along with the number of farmers, the standard deviation in yield, the level of statistical significance (P-value derived using Moody's test for the difference between medians). Note that only bins with more than 25 data points are included in the yield/compliance plots, but that all data are shown in *Table 2.*

Collated data for all countries and seasons

The 'All countries' plot collates the data from all the case study countries and seasons. To allow for regional and interannual variation in yield, the yield is expressed relative to the yield achieved by compliant farmers for each season and country. It can be seen that the farmers in general fare better when they plant close to the recommended date. Farmers who plant earlier than recommended have slightly reduced yields, and those planting later do markedly worse. *Table 2* shows that the improvements in yield achieved by planting close to the recommended date are significant at the 5% level for all bins. It should be noted, however that there is a lot of variability. Not all farmers who plant close to the recommended time do better than those who plant early or late. This is illustrated by box and whisker plots shown in *Figure 4,* which demonstrates that there is a wide range of outcomes for farmers, regardless of whether they plant early, are compliant or plant late.

Table 2 and subsequent tables shows yield data binned by the difference between actual and recommended planting date. The data are binned for 10-day periods from -45 to -35 to +35 to +45 where negative values indicate farmers planting before the DST recommendation and positive values indicate farmers planting after the recommended day. The top row is the median difference between the actual planting date and the recommended planting date for the farmers in a given bin. The second and third rows are the median and standard deviation in yield for the farmers in a given bin. The P value refers to Moody's test for difference between medians, carried out for a comparison between yields achieved by the farmers in each bin and the yield achieved by the farmers planting near the recommended date. The bottom row is the number of farmers in each bin.

Table 2. Comparison between yield achieved and the difference between the observed and recommended planting dates. All yield data is in kg/acre

Median difference from recommended planting date (days)	-39	-28	-19	-9	1	10	19	29	39
Median yield difference (kg/acre)	-45	-19	-21	-78	0	-348	-450	-558	-615
Standard deviation in yield (kg/acre)	766	839	807	955	894	1001	955	975	1074
P value	3%	0%	0%	0%		1%	0%	0%	0%
Number of farmers	352	773	1416	2245	5479	5648	4541	2758	1796

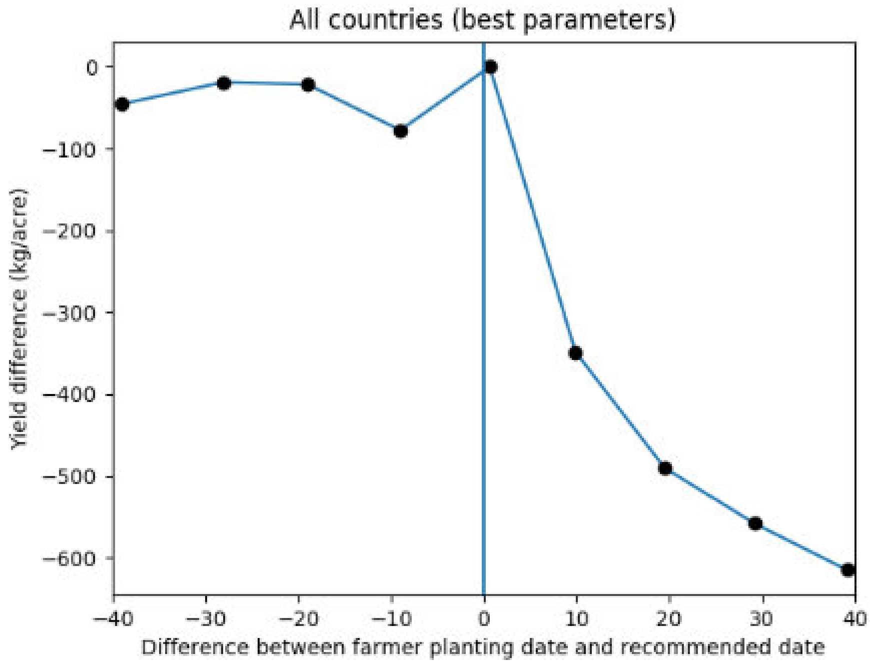


Figure 3. Yield plotted against the difference between the actual and recommended planting time for all countries and seasons. Yields in all bins were significantly different to the -5 to 5 day bin.

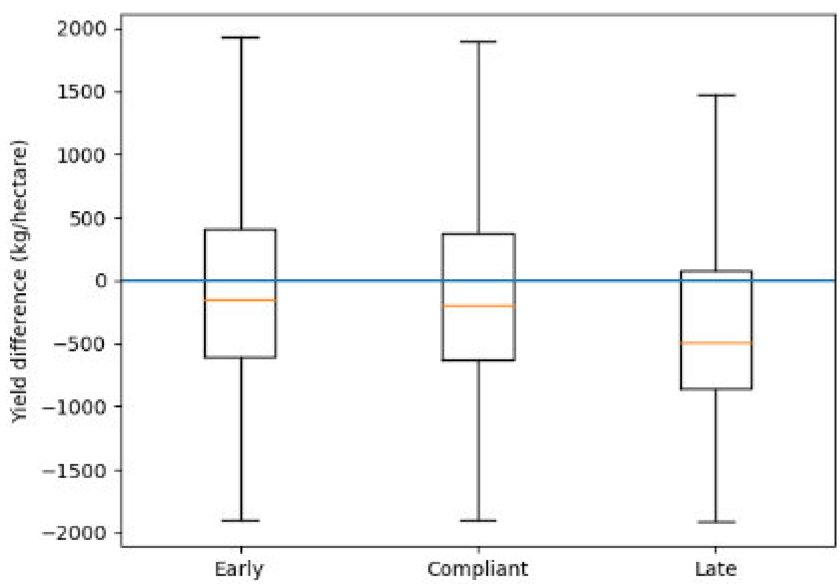


Figure 4. Box and whiskers plot for yield difference between the median for compliant farmers (in a given season and country) and the yield achieved. The categories are. early (>10 days before recommendation); compliant (within 10 days of recommendation) and late (>10 days after the recommendation).

Country validations

The results for all countries are summarised in *Figure 5*. It can be seen that for all of the countries, other than Nigeria yield is significantly lower in the late planting groups than the compliant group.

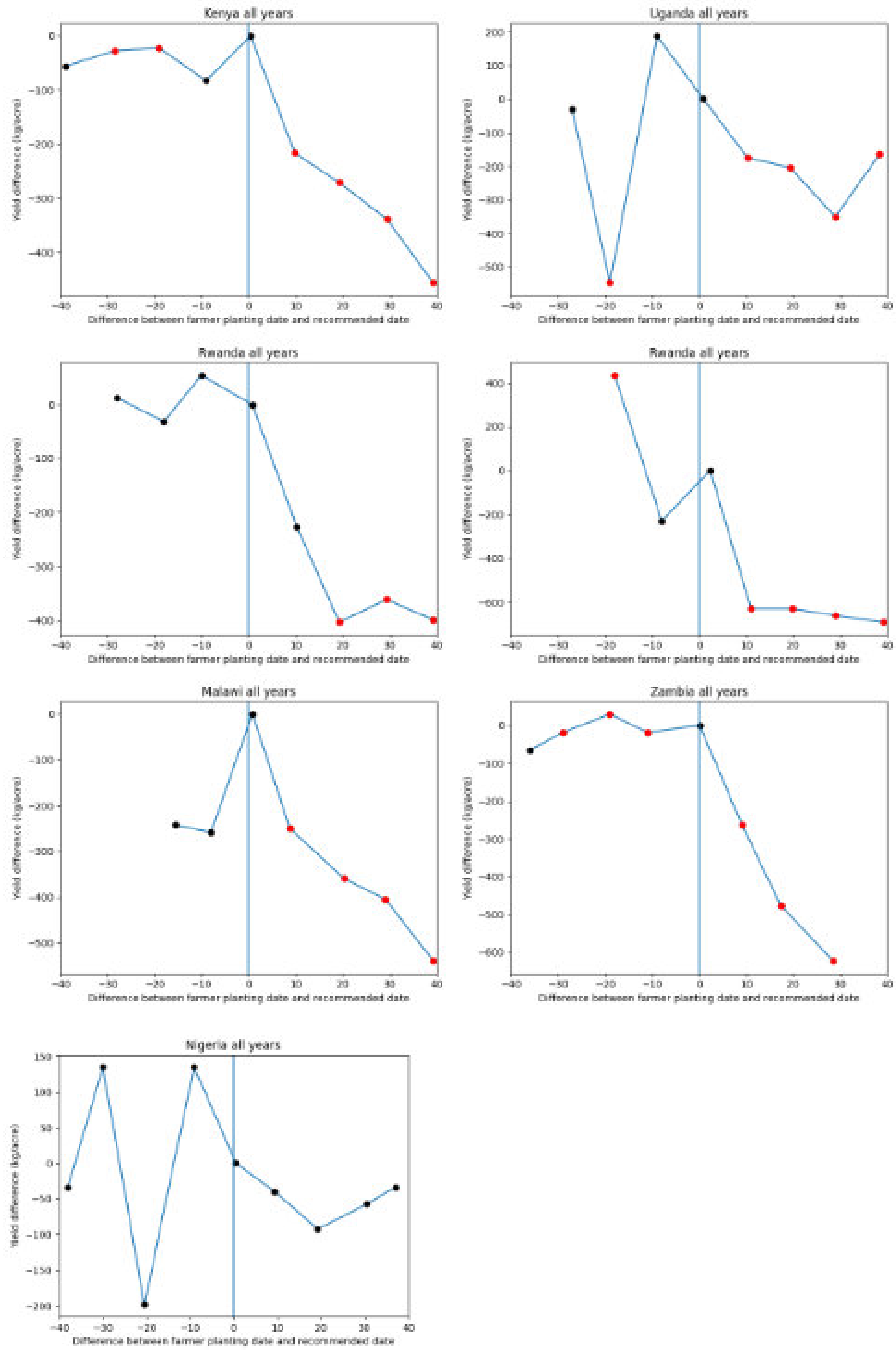


Figure 5. Yield plotted against the difference between the actual and recommended planting time for individual countries – data collated from all seasons for which we have data. Red dots denote yields that are significantly different to yields within the -5 to 5 day bin. Rwanda appears twice due to there being two seasons evaluated - A season is on the left, B season on the right.

Kenya

Kenya has two rainy seasons, although only the long rains were considered in this study. *Figure 6* shows the progression of the rains during each of the seasons analysed. The rains started early in 2016, followed by a break. The early start to the rains resulted in early recommended planting dates (*Figure 7*). Very few farmers planted in advance of the recommendations (*Figure 8* and *Table 3*), but those who did had lower yields than farmers who planted around the recommended date (*Figure 9*), probably because of the relatively weak rains during April and May and the sporadic rains during March (*Figure 6*). In 2017, the rains started later than in 2016 (*Figure 6*), and the planting recommendation was, therefore, later. The farmers who planted in advance of this date, mainly in the northeast of the region (*Figure 8*) had higher yield than those who planted around or after the recommended date *(Figure 9*), thanks to the steady rainfall during February and March. It is notable that in other years, the rainfall was far more sporadic in that part of the season *(Figure 6*). In 2018, the rainy season was strong (*Figure 6*), but the rains started late in most of the region. The majority of farmers (~70%) planted within 10 days of the recommendation (*Figure 8* and *Table 2*), but those who planted late had lower yields than those who planted early or around the recommended time (*Figure 9*). In 2019, there was a heavy rainy event in December *(Figure 6*), and some farmers planted significantly ahead of the recommended date, in response to this (*Figure 8*). It should be noted that the heavy rainfall event was not sufficient to lead to recommendation of early planting (*Figure 7*). Those farmers who planted early tended to have slightly lower yields than those who planted at around the recommended time (*Figure 9*).

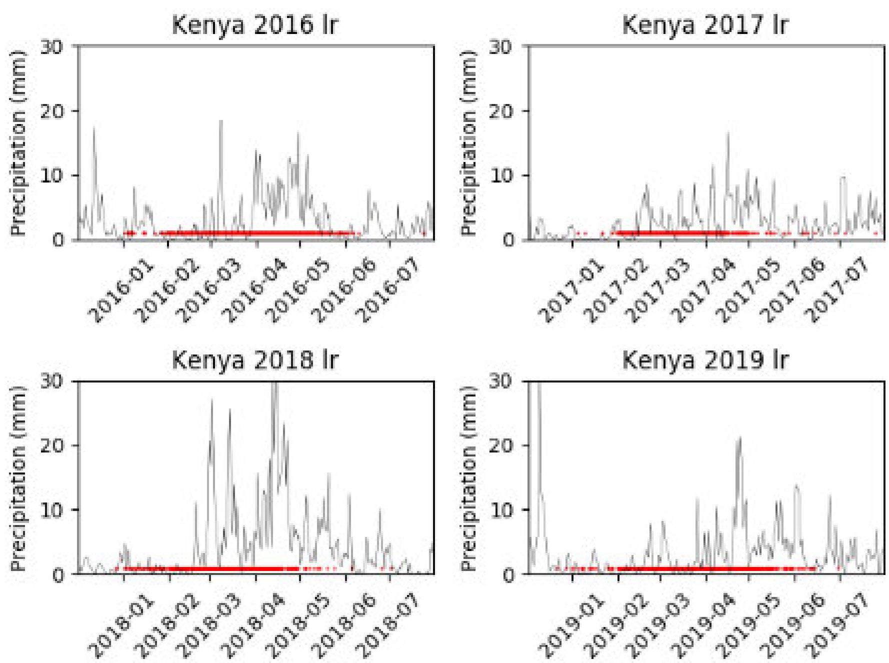


Figure 6. Precipitation time series for the Kenya case study seasons (grey line). The red marks indicate days on which planting occurred.

Overall, the planting date DST performed well for Kenya. *Table 3* shows that farmers who planted late had consistent and often statistically significantly lower yields than those who planted at the recommended time. The outcomes for farmers who planted early was variable. Where the rains in the early part of the season remained steady, as happened in 2017, yields were high. In other years, however, sporadic rainfall resulted in slightly lower yields for early planters. This reflects the riskiness of very early planting and indicates that, notwithstanding occasional good outcomes, the decision support tool is right not to advise planting before the rains are climatologically likely to be well-established.

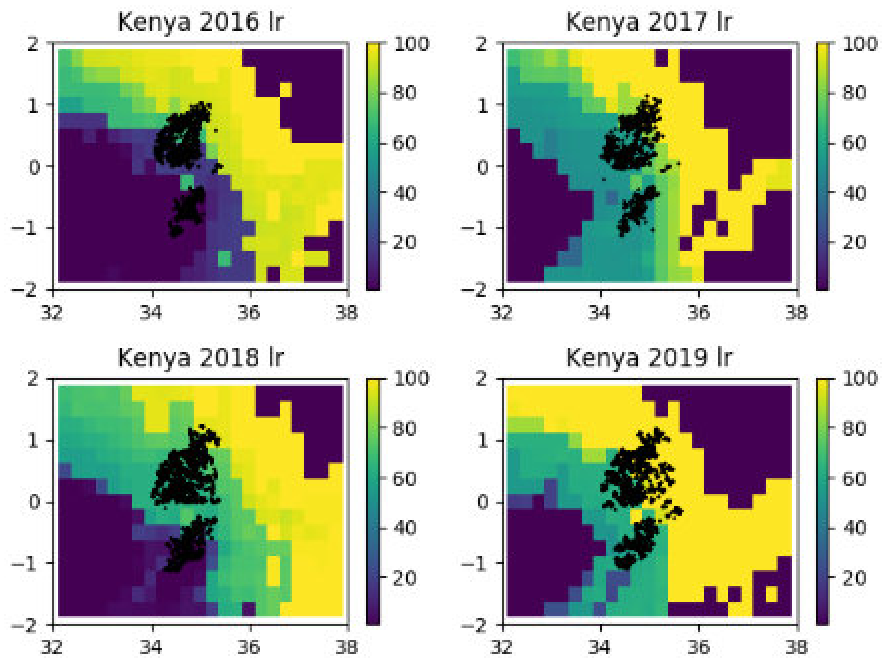


Figure 7. Recommended planting day of the year for the Kenya case study seasons

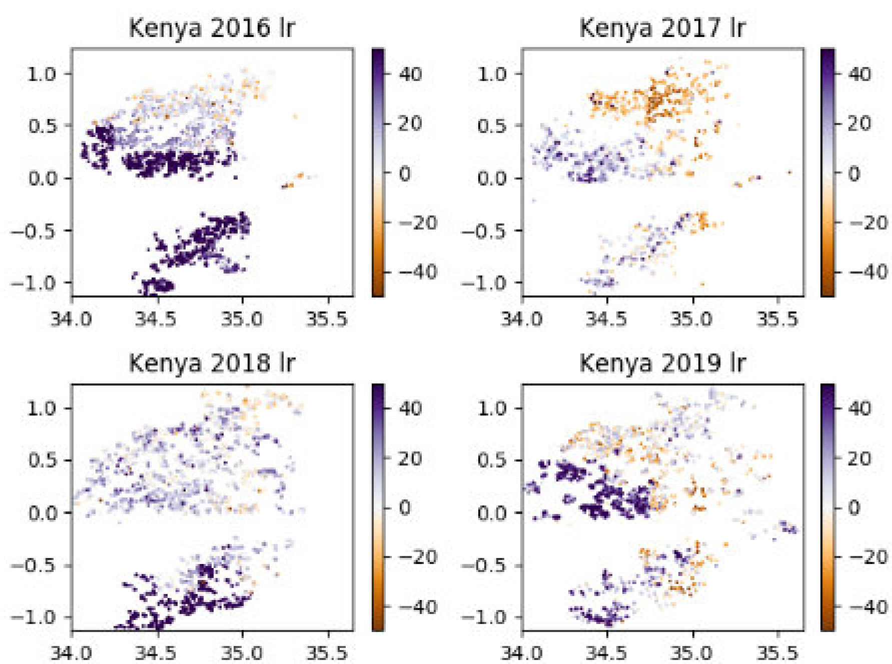


Figure 8. Difference between recommended and observed planting date for the Kenya case study seasons

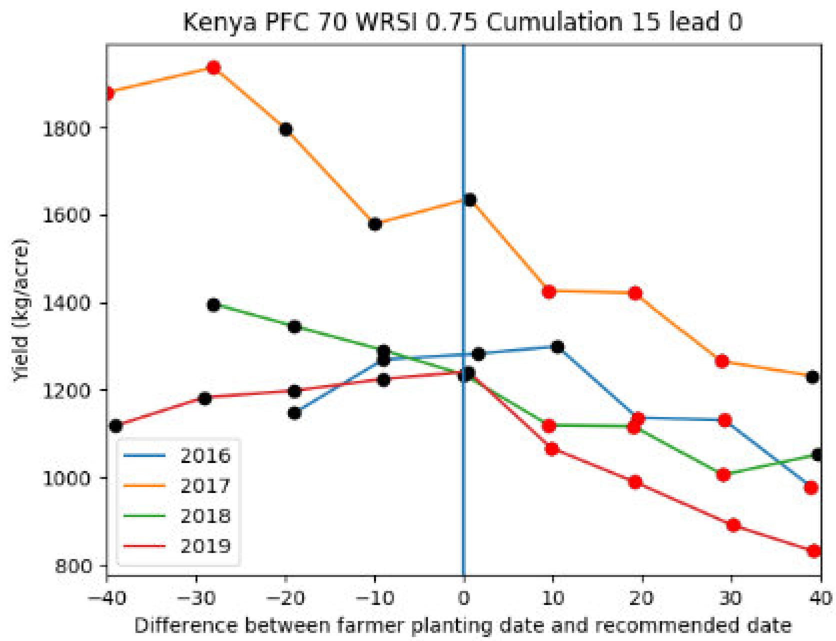


Figure 9. Yield plotted against the difference between actual and recommended planting time for Kenya. Red dots indicate that the yield is significantly different from the -5 to +5 day difference bin.

Table 3. Yield achieved by farmers categorised by difference between observed and recommended planting date (-5 to 5) *for each of the growing seasons for which we have data in Kenya*

Season	Metric	-45 to -35	-35 to -25	-25 to -15	-15 to -5	**-5 to 5**	5 to 15	15 to 25	25 to 35	35 to 45
2016 lr	Median difference from recommended date (days)	-42	-29	-19	-9	**2**	11	19	29	39
2016 lr	Median yield (kg/acre)	1305	976	1147	1270	**1282**	1300	1137	1132	979
2016 lr	Standard deviation in yield (kg/acre)	487	714	480	604	**685**	682	617	576	568
2016 lr	P value	0.99	0.99	0.75	1.00		0.89	0.01	0.00	0.00
2016 lr	Number of farmers	3	7	39	72	**270**	403	451	309	143
2017 lr	Median difference from recommended date (days)	-40	-28	-20	-10	**1**	10	19	29	39
2017 lr	Median yield (kg/acre)	1880	1937	1797	1579	**1636**	1426	1421	1266	1232
2017 lr	Standard deviation in yield (kg/acre)	789	697	688	707	**668**	672	592	476	576
2017 lr	P value	0.03	0.01	0.08	0.69		0.00	0.00	0.00	0.10
2017 lr	Number of farmers	88	145	251	169	**265**	315	171	64	32
2018 lr	Median difference from recommended date (days)	-40	-28	-19	-9	**0**	10	19	29	40
2018 lr	Median yield (kg/acre)	1467	1397	1346	1291	**1235**	1120	1117	1006	1052
2018 lr	Standard deviation in yield (kg/acre)	621	687	730	674	**676**	662	661	613	598
2018 lr	P value	0.53	0.05	0.12	0.12		0.03	0.04	0.00	0.15
2018 lr	Number of farmers	24	71	187	530	**1362**	774	412	180	118
2019 lr	Median difference from recommended date (days)	-39	-29	-19	-9	**1**	10	19	30	39
2019 lr	Median yield (kg/acre)	1118	1183	1199	1225	**1242**	1068	990	891	832
2019 lr	Standard deviation in yield (kg/acre)	692	743	722	712	**748**	698	611	677	535
2019 lr	P value	0.27	0.36	0.44	0.72		0.00	0.00	0.00	0.00
2019 lr	Number of farmers	143	231	234	396	**663**	482	282	231	290

Rwanda

There are two growing seasons in Rwanda. the A season and the B season (*Figure 10*). The A season is the main growing season, and starts in August/September, with a harvest early in the succeeding year. The B season is a secondary growing season, which starts as soon as the A season ends.

Figure 11 shows that planting tends to start at a similar time each year for the A season, but that in some years, planting continues for several months, whilst in other years, planting is concentrated in a shorter time frame. In 2016, for example, planting extends for several months (running into the 'B season'), whilst in 2018, almost all planting is complete by the end of November. *Figure 12* shows that the variation in recommended day is lower in both space and time than for Kenya (c.f. *Figure 7*), which is consistent with the general similarity in daily rainfall patterns between the three case study seasons (*Figure 11*). There is, however, some variation, with planting dates recommended to be slightly earlier at most localities in 2016 than in the other years. In general, farmers tend to plant later than the recommended date (*Figure 13* and *Table 2*). *Figure 14* shows that the few farmers who do plant near the recommended time had higher yields than those who planted after, and lower or similar yields to those who planted before.

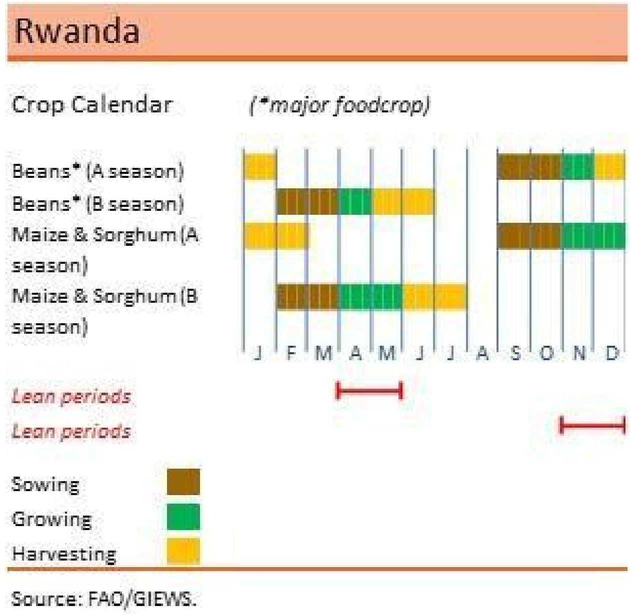


Figure 10. The cropping calendar in Rwanda (from http.//www.fao.org/giews/countrybrief/country.jsp?code=RWA)

The B season is quite different to the A season. Even in advance of the season, the soil moisture tends to be near to field capacity. This means that the planting advice will be to plant on the first day that the model is run – i.e. as soon as possible (*Figure 12*). In the B season, farmers universally plant after the recommended date (*Figure 13*, *Figure 14* and *Table 4*). In general, the greater the delay between the recommended and actual planting date, the lower the yield.

Overall, the model performs well for Rwanda. The optimal planting date selected by the system seems robust. However, the level of 'compliance' is far lower than for Kenya (*Table 4*). In other words, farmers do not plant near the optimal time. This is likely to reflect the fact that the farmers are aiming for two growing seasons, and so the timing of planting is constrained by the timing of the previous season's harvest. This is especially the case for the B season. Indeed, for the B season, the chances of germination failure are minimal and so there is little point in a planting date DST. Farmers should simply plant as soon as they can after the A season harvest.

Table 4. Yield achieved by farmers categorised by difference between observed and recommended planting date (-5 to 5) for each of the growing seasons for which we have data in Rwanda

Season	Metric	-45 to -35	-35 to -25	-25 to -15	-15 to -5	**-5 to 5**	5 to 15	15 to 25	25 to 35	35 to 45
2016a	Median difference from recommended planting date (days)		-29	-18	-10	**1**	10	19	29	39
2016a	Median yield (kg/acre)		1753	2137	2705	**1861**	1567	1254	1384	1384
2016a	Standard deviation in yield (kg/acre)		803	860	1430	**1000**	971	865	670	792
2016a	P value		0.67	0.33	0.07		0.08	0	0.01	0
2016a	Number of farmers		6	27	20	**66**	102	86	39	54
2017a	Median difference from recommended planting date (days)	-41	-26	-18	-10		10	20	28	38
2017a	Median yield (kg/acre)	1522	3094	1636	2258	**2108**	2184	1226	1524	1781
2017a	Standard deviation in yield (kg/acre)	1522	1486	1243	1550	**1628**	1580	1580	1789	1727
2017a	P value	0.48	1.00	0.79	1.00		0.83	0.00	0.05	0.47
2017a	Number of farmers	2	3	12	35	**95**	80	101	70	45
2018a	Difference between obs and rec			-22	-9	**2**	10	19	29	39
2018a	Median yield			1907	1314	**1347**	1374	1282	1170	981
2018a	Standard deviation in yield			481	430	**582**	643	827	648	765
2018a	P value			0.96	0.93		1.00	0.76	0.82	0.76
2018a	Number of farmers			3	9	**32**	60	57	52	16
2019a	Difference between obs and rec	-39	-31	-20	-10	**0**	10	19	29	40
2019a	Median yield	1637	1575	1805	1521	**1695**	1462	1345	1553	1342
2019a	Standard deviation in yield	542	524	578	778	**784**	758	751	917	742
2019a	P value	0.67	0.71	0.97	0.35		0.21	0.2	0.5	0.13
2019a	Number of farmers	6	8	9	21	**68**	58	71	49	32
2020a	Difference between obs and rec	-35	-26	-18	-10	**1**	11	20	31	40
2020a	Median yield	1182	2073	1341	1651	**1520**	1373	1416	1219	1357
2020a	Standard deviation in yield	0	505	818	901	**700**	760	810	833	631
2020a	P value	1.00	0.52	0.86	0.76		0.45	0.78	0.06	0.73
2020a	Number of farmers	1	11	26	73	**95**	191	119	75	55

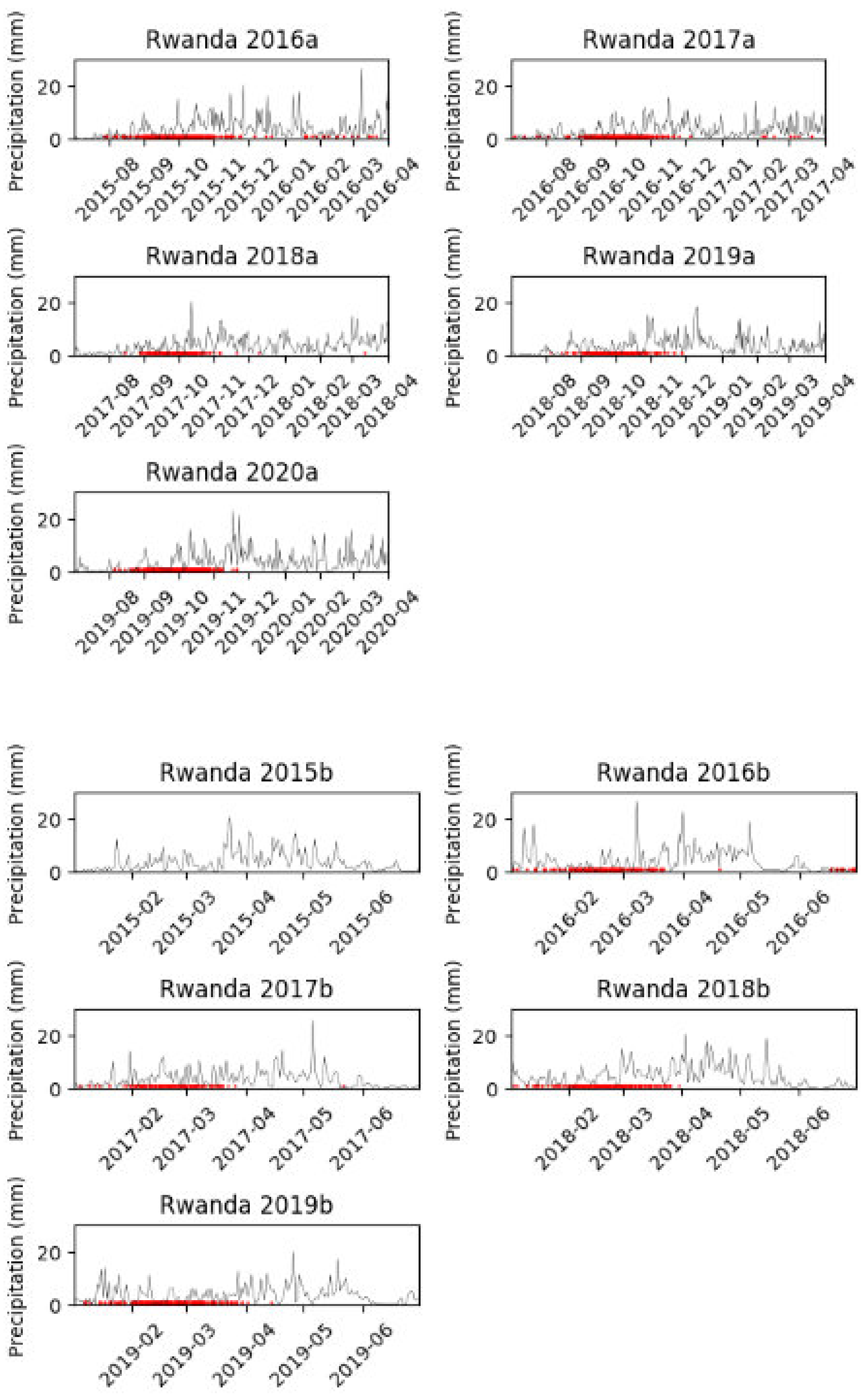


Figure 11. Precipitation time series for the Rwanda case study seasons (grey lines). The red marks indicate days on which planting occurred.

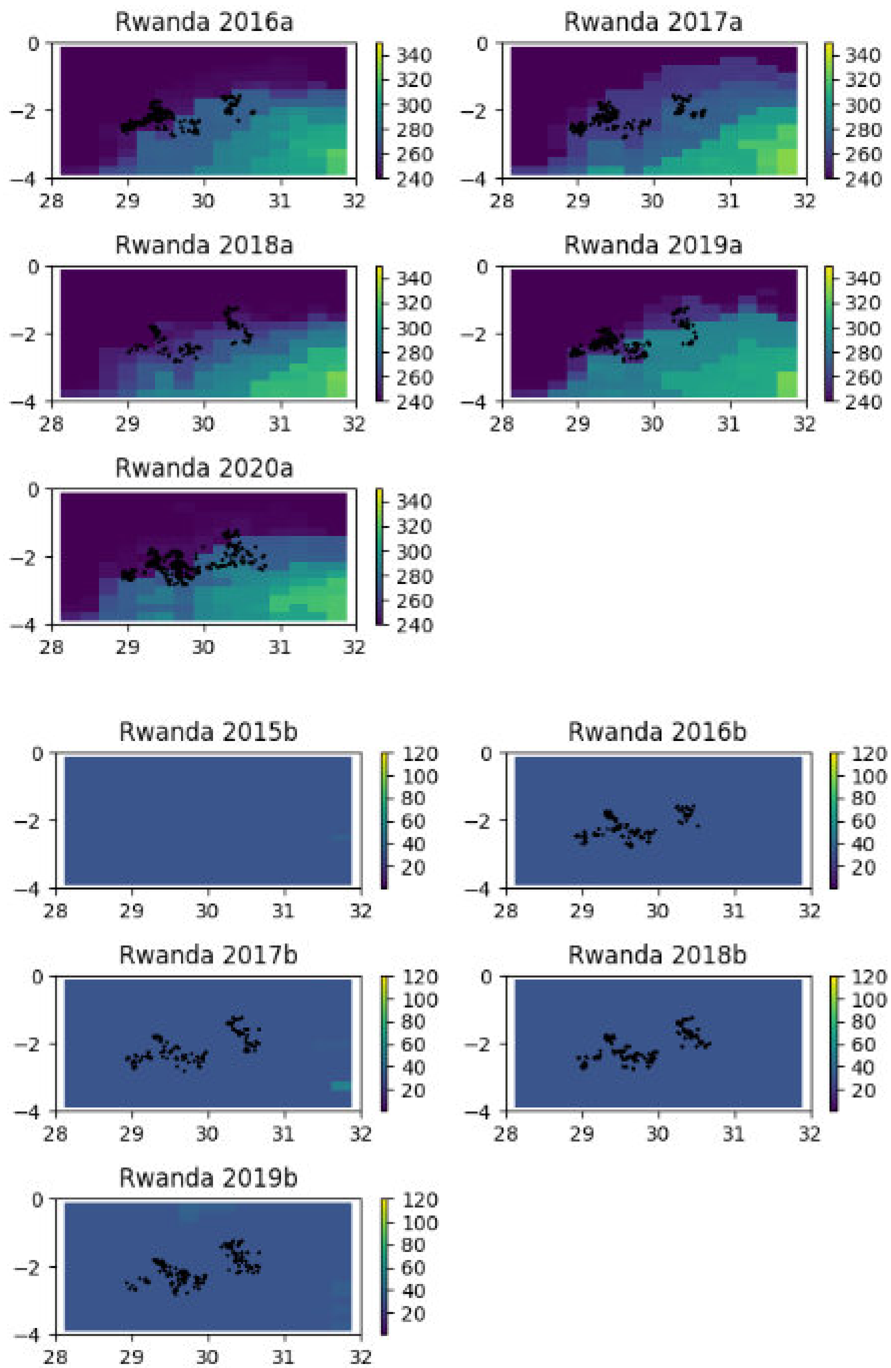


Figure 12. Recommended planting day of the year for the Rwanda case study seasons

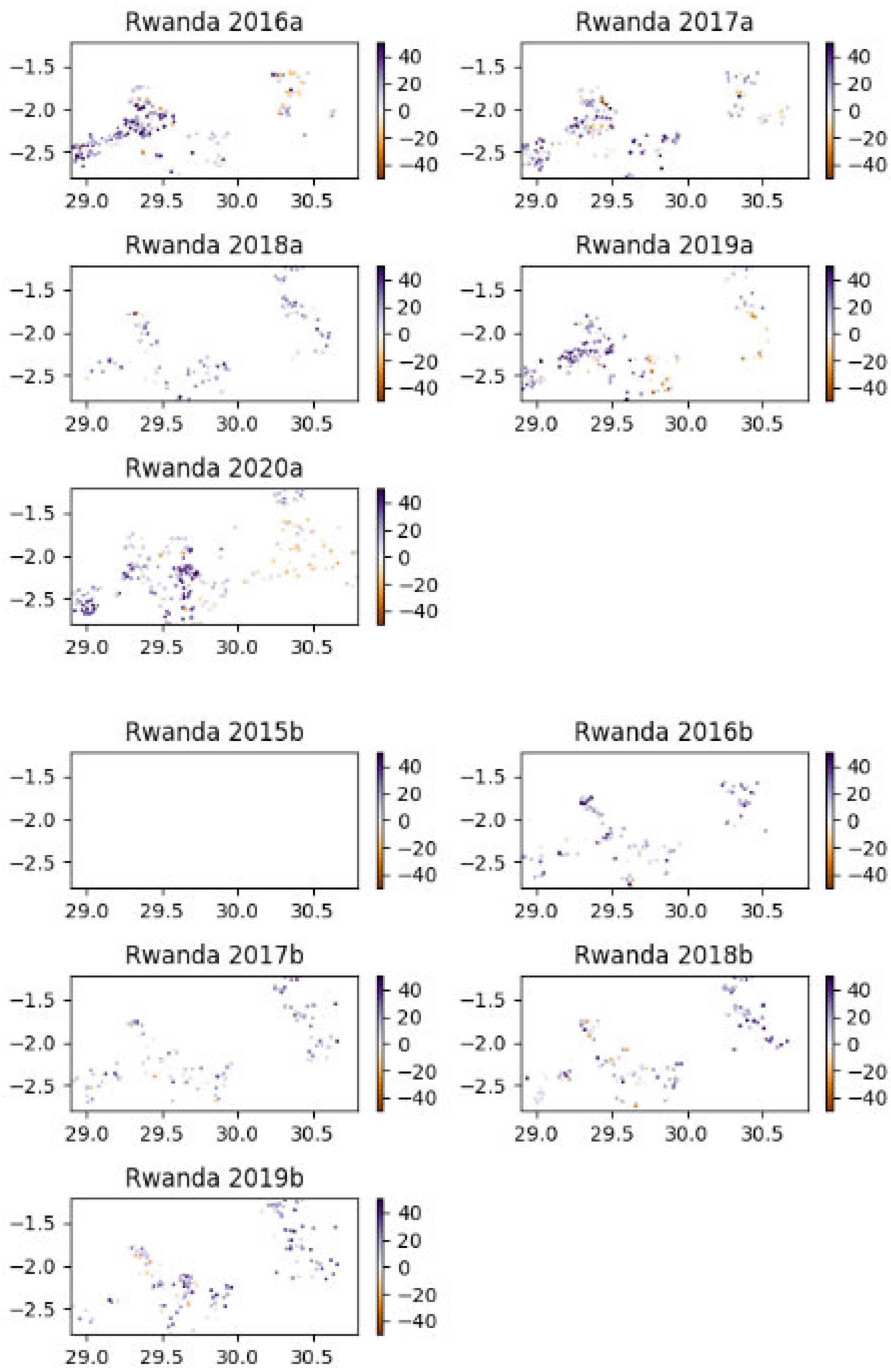
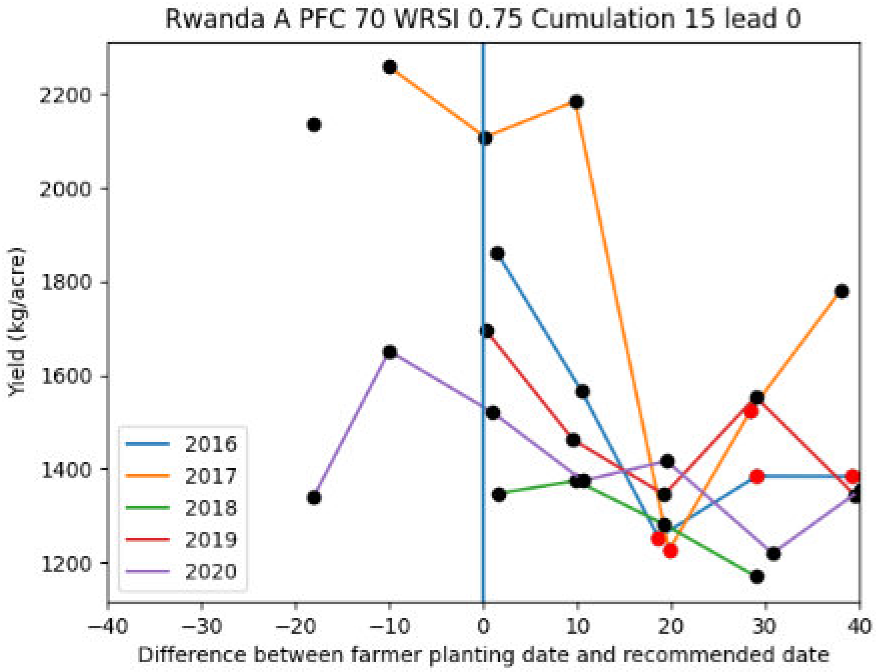


Figure 13. Difference between recommended and observed planting date for the Rwanda case study seasons



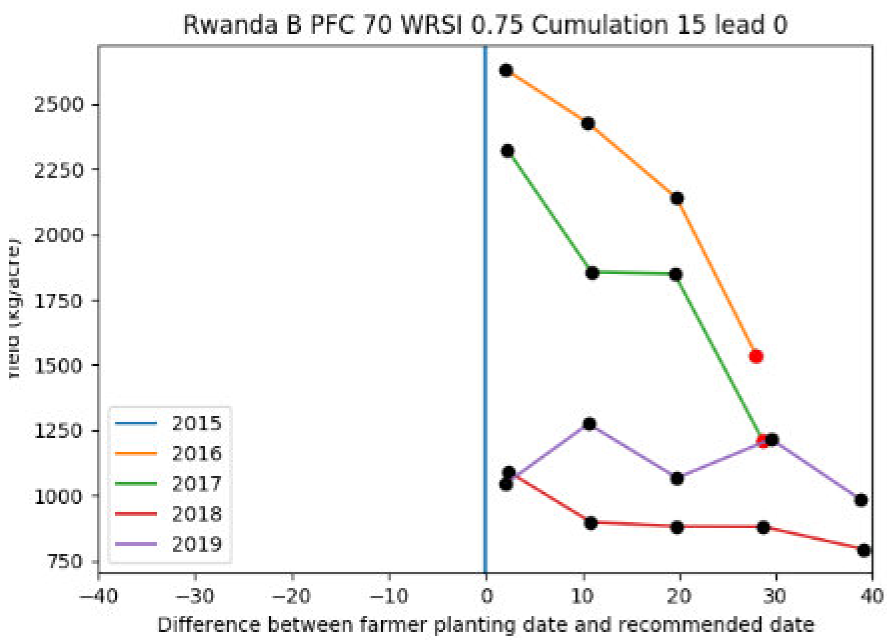


Figure 14. Yield plotted against the difference between actual and recommended planting time for Rwanda. Red dots indicate that the yield is significantly different from the -5 to +5 day difference bin.

Uganda
It is difficult to draw firm conclusions from the Uganda case study, primarily because of the low quality of the data, especially for the 2017 and 2018 seasons. It was not possible to analyse 2017 in any detail. It is, however, notable in 2018 that most farmers planted within 10 days of the recommended date (*Figure 18* and *Table 5*). In 2019, a significant proportion of farmers planted late, and achieved slightly lower yields than those who planted close to the recommendation. The results are, however, not statistically significant.

Although the evidence for the quality of the planting date DST is weaker for Uganda than it is for Kenya and Rwanda, it is relevant that the rainfall seasonality, farmer planting behaviour, and the degree of variation in recommended date is similar to that seen in Kenya (c.f. *Figure 7* and *Figure 16*). Unlike Rwanda, there is only one major maize growing season, meaning that farmers have more freedom to decide when to plant. Farmers, furthermore, seem to plant once the rains are well-established. The daily precipitation, moreover, follows a similar pattern to Kenya (c.f. *Figure 6* and *Figure 15*). It is reasonable, therefore, to suppose that the DST is potentially useful and that the parameters used for Kenya can be applied to Uganda.

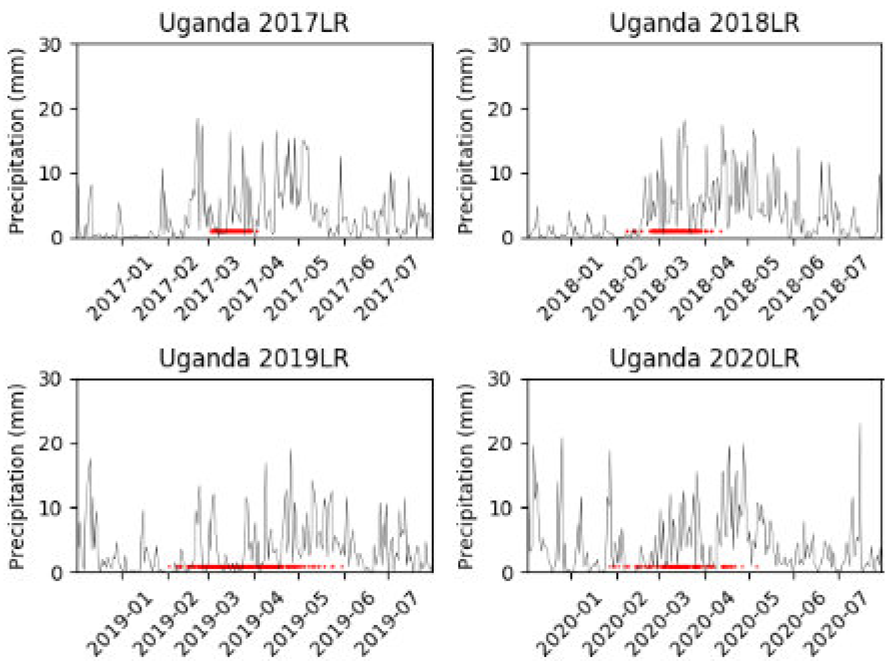


Figure 15. Precipitation time series for the Uganda case study seasons (grey line). The red marks indicate days on which planting occurred.

Table 5. Yield achieved by farmers categorised by difference between observed and recommended planting date (-5 to 5) for each of the growing seasons for which we have data in Uganda

Season	Metric	-45 to -35	-35 to -25	-25 to -15	-15 to -5	**-5 to 5**	5 to 15	15 to 25	25 to 35	35 to 45
2017LR	Median difference from recommended planting date (days)						11	20	28	38
2017LR	Median yield (kg/acre)						1251	1124	1208	1883
2017LR	Standard deviation in yield (kg/acre)						614	690	633	1252
2017LR	P value									
2017LR	Number of farmers					**0**	80	83	53	5
2018LR	Median difference from recommended planting date (days)		-29	-16	-8	**1**	10	18	29	38
2018LR	Median yield (kg/acre)		1613	2945	2071	**1613**	1681	1478	939	1565
2018LR	Standard deviation in yield (kg/acre)		0	549	751	**718**	732	479	1090	172
2018LR	P value		0.99	0.25	0.01		0.41	0.20	0.38	0.62
2018LR	Number of farmers		1	3	72	**275**	139	45	12	4
2019LR	Median difference from recommended planting date (days)	-37	-27	-20	-10	**1**	10	20	30	39
2019LR	Median yield (kg/acre)	320	1194	714	967	**781**	787	1012	1259	1093
2019LR	Standard deviation in yield (kg/acre)	928	778	880	885	**1215**	1046	977	1006	1117
2019LR	P value	1.00	0.52	0.41	0.30		0.95	0.29	0.49	0.34
2019LR	Number of farmers	5	30	63	86	**125**	130	107	45	56
2020LR	Median difference from recommended planting date (days)	-41	-29	-22	-10	**0**	9	17	29	39
2020LR	Median yield (kg/acre)	388	287	320	635	**719**	736	587	438	677
2020LR	Standard deviation in yield (kg/acre)	157	0	486	379	**419**	502	447	324	314
2020LR	P value	0.49	0.49	1.00	1.00		1.00	0.56	1.00	0.81
2020LR	Number of farmers	2	2	7	9	**63**	41	20	11	14

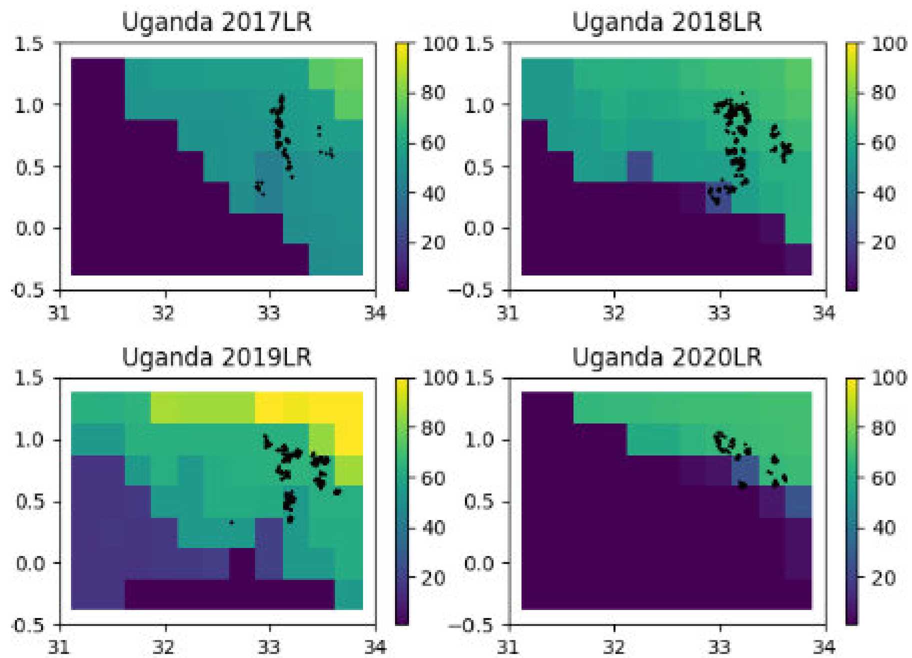


Figure 16. Recommended planting day of the year for the Uganda case study seasons

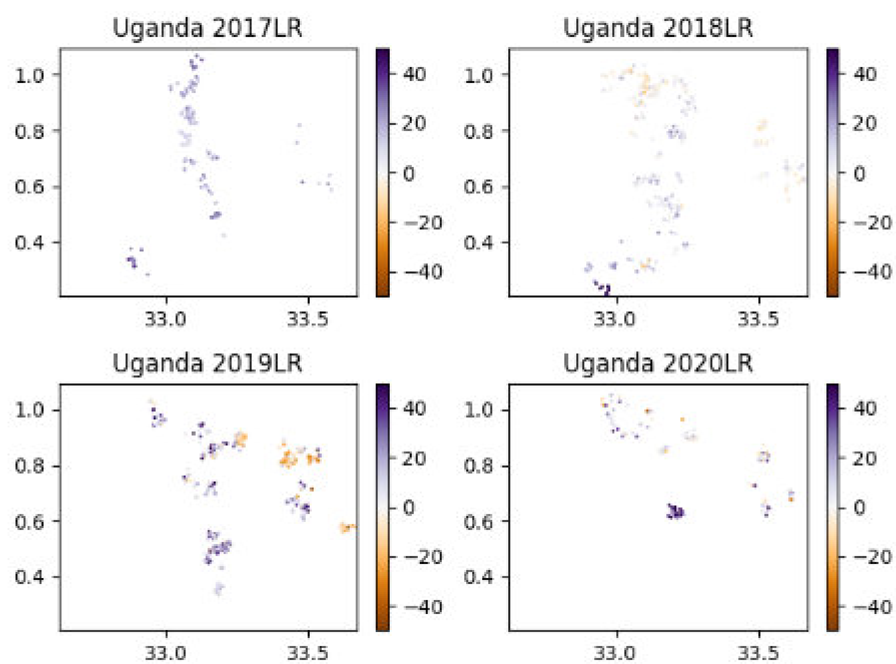


Figure 17. Difference between recommended and observed planting date for the Uganda case study seasons

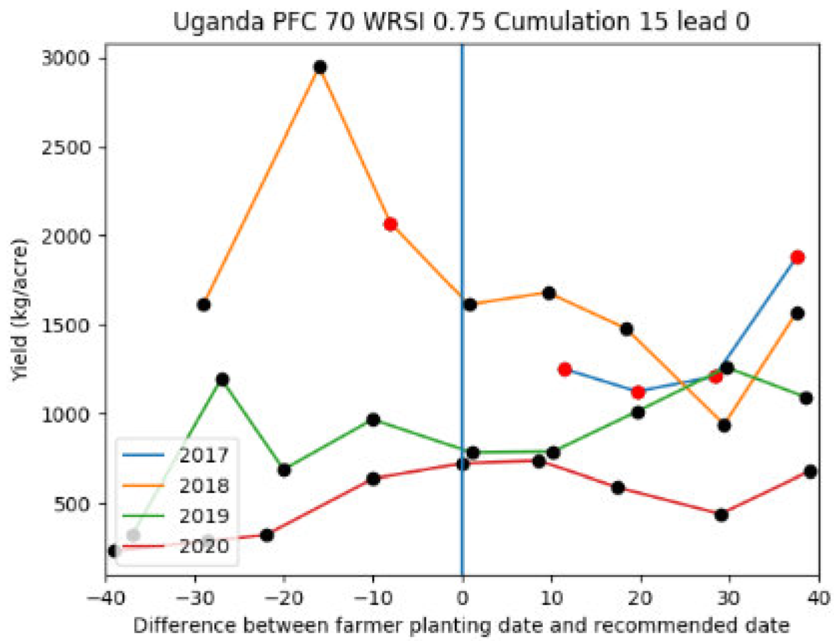


Figure 18. Yield plotted against the difference between actual and recommended planting time for Uganda. Red dots indicate that the yield is significantly different from the -5 to +5 day difference bin.

Malawi

Malawi has a very different climate to the East African countries described in the previous sections. There is a single, long growing season, with the rest of the year completely dry (*Figure 19*). This contrasts with the regions of Kenya, Rwanda and Uganda studied, which all have some rain during the dry season. It can be seen from *Figure 19* that planting starts early in the rainy season and may continue for several months, although this varies from year to year. *Figure 22* shows, moreover that late planting farmers do significantly worse, potentially because they have a significantly shorter growing season. In the sensitivity studies, it was clear that farmers do not wait to plant until the soil moisture in the upper soil layers is near an optimal level. Rather, they tend to plant as soon as the soil starts to moisten. For these reasons, the criteria for the planting date DST were adjusted from aiming to plant at 70PFC to 25PFC. At this threshold, *Table 6* and *Figure 31* indicate that the majority of farmers plant at around the recommended time, with only a few planting earlier. The farmers who plant later than recommended have statistically significantly lower yields.

Overall, the planting date DST performs effectively for Malawi. It is clear that planting near the optimal time is of benefit to farmers. It is, however, notable that in some years a substantial number of farmers plant far later than recommended (>2 months), and achieve very low yields. In 2018, this late planting occurred after a period of sporadic rain during January, perhaps suggesting re-planting. The need for replanting perhaps reflects the risky nature of planting in conditions of very low soil moisture. There is evidence to suggest that poor root growth during emergence leaves maize vulnerable throughout the growing season (Cutforth et al, 1983).

Table 6. Yield achieved by farmers categorised by difference between observed and recommended planting date (-5 to 5) for each of the growing seasons for which we have data in Malawi

Season	Metric	-45 to -35	-35 to -25	-25 to -15	-15 to -5	**-5 to 5**	5 to 15	15 to 25	25 to 35	35 to 45
2017LR	Median difference from recommended planting date (days)	-41	-29	-15	-11	**1**	9	19	29	39
2017LR	Median yield (kg/acre)	2226	481	1088	1619	**1517**	1467	1113	1062	1012
2017LR	Standard deviation in yield (kg/acre)	0	177	883	617	**688**	710	678	613	611
2017LR	P value	0.94	0.48	0.78	0.47		1.00	0.01	0.00	0.00
2017LR	Number of farmers	1	2	12	41	**187**	155	130	123	58
2018LR	Median difference from recommended planting date (days)	-35	-29	-18	-6	**0**	9	20	29	39
2018LR	Median yield (kg/acre)	1062	481	946	506	**809**	544	556	526	435
2018LR	Standard deviation in yield (kg/acre)	0	522	15	857	**847**	693	566	480	463
2018LR	P value	0.98	0.67	0.46	0.13		0.00	0.00	0.00	0.00
2018LR	Number of farmers	1	4	2	49	**274**	344	203	93	49
2019LR	Median difference from recommended planting date (days)	-39	-27	-16	-8	**1**	8	21	28	39
2019LR	Median yield (kg/acre)	545	618	635	528	**823**	736	641	815	1380
2019LR	Standard deviation in yield (kg/acre)	171	374	439	363	**576**	573	577	869	700
2019LR	P value	0.25	0.63	0.78	0.05		0.42	0.00	1.00	0.68
2019LR	Number of farmers	3	17	14	41	**264**	285	264	54	6

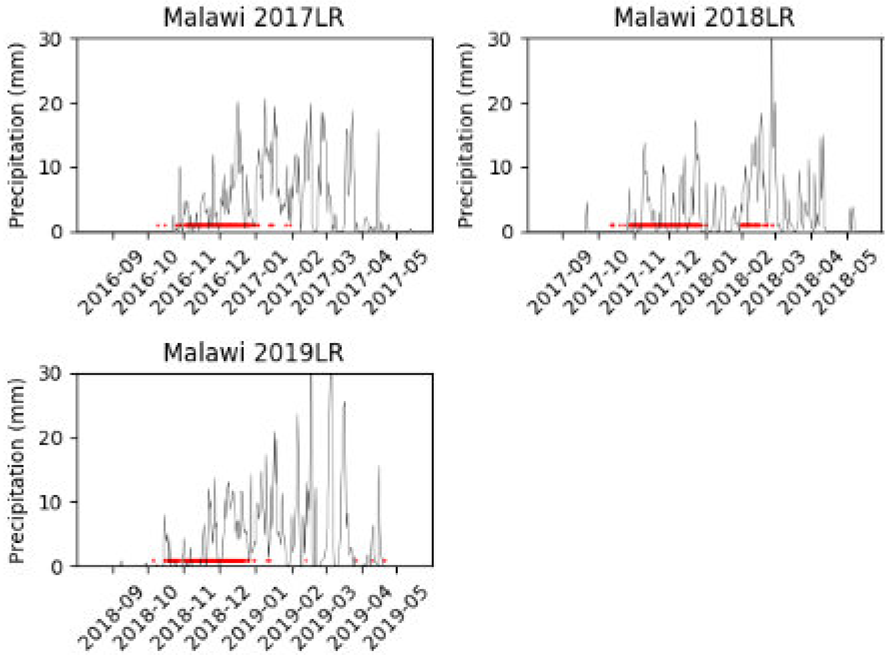


Figure 19. Precipitation time series for the Malawi case study seasons (grey line). The red marks indicate days on which planting occurred.

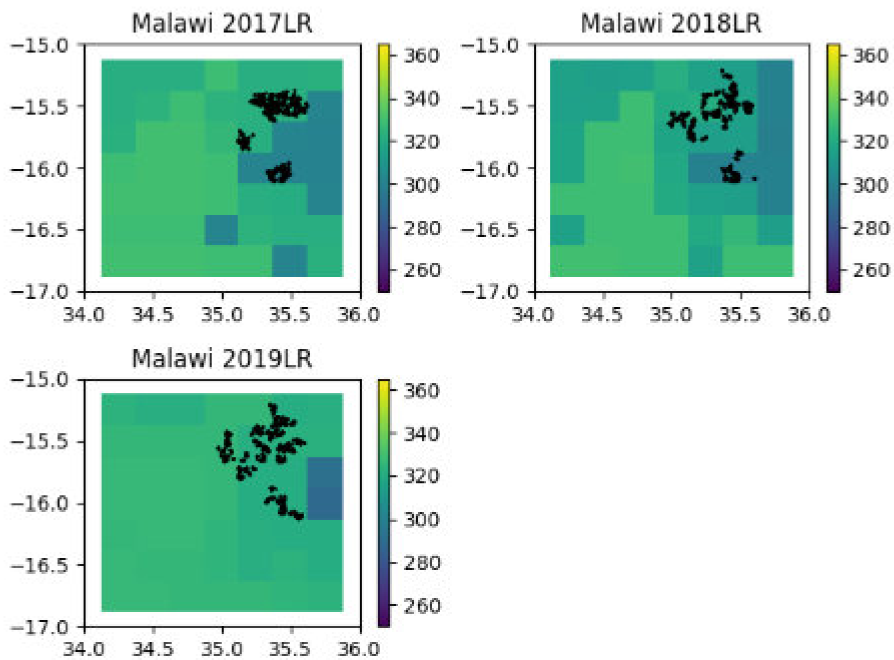


Figure 20. Recommended planting day of the year for the Malawi case study seasons

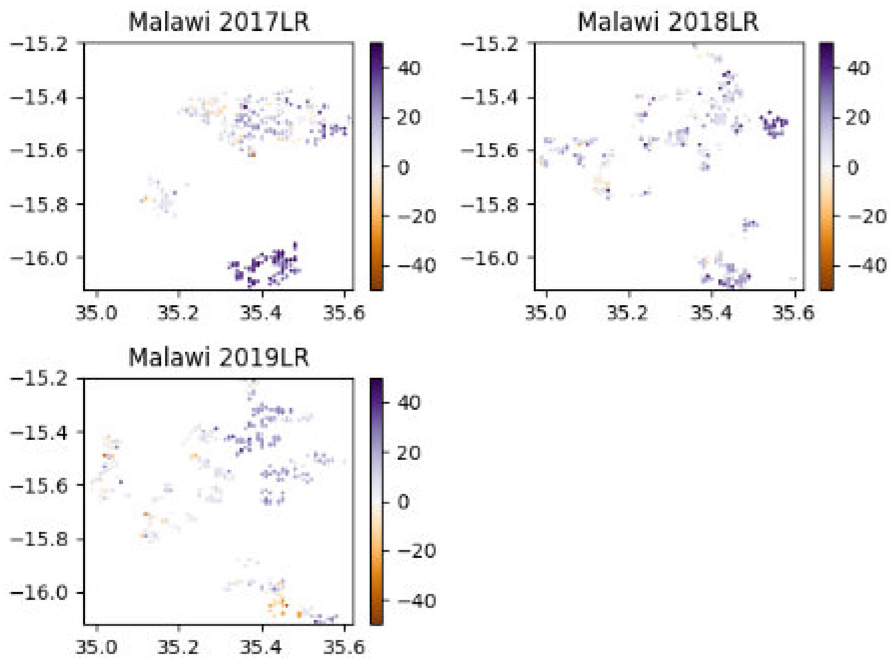


Figure 21. Difference between recommended and observed planting date for the Malawi case study seasons

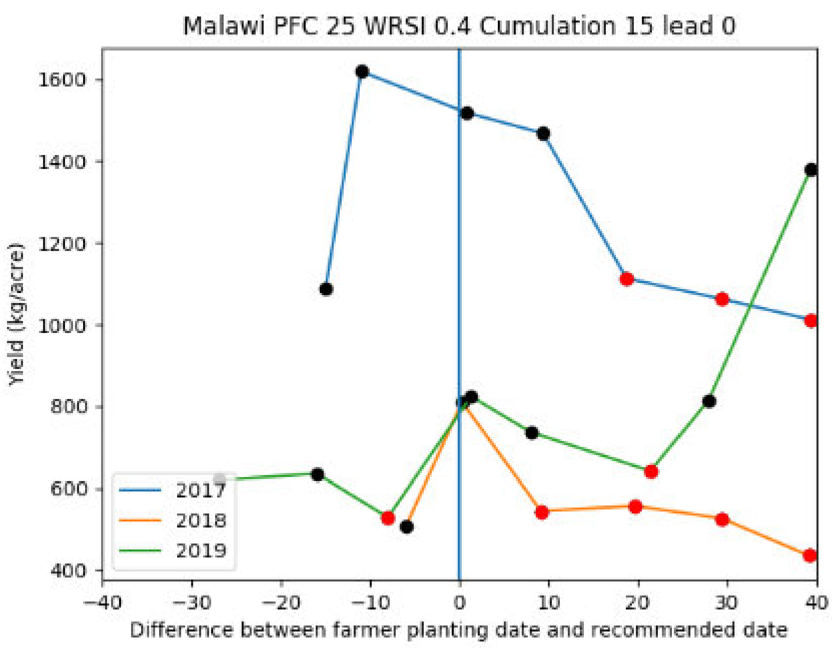


Figure 22. Yield plotted against the difference between actual and recommended planting time for Malawi. Red dots indicate that the yield is significantly different from the -5 to +5 day difference bin.

Zambia

In some respects, the climate in Zambia is similar to that in Malawi. There is a single, long growing season, starting in October-December and continuing until March/April. Unlike in Malawi, however, in Zambia, planting does not occur on nearly dry soils, probably because the rainy season is more intense (*Figure 23*). Rather, planting takes place slightly later, usually after there has been at least one strong rainy spell (*Figure 23*). The recommended planting date is consistent with this, with planting advised towards the end of the calendar year, with some variation from year to year (*Figure 24*). In both the seasons studied, the majority of farmers planted close to the recommended date (*Figure 25* and *Table 7*). In both 2019 and 2020, farmers who planted late had lower yield than farmers who planted close to the recommended date (*Figure 26*). However, these results were not statistically significant for 2020 because of the low number of farmers in the sample.

The Zambia study provides some evidence that the planting DST identifies the optimum planting date, although the quality and quantity of the data means that it is not possible to be definitive. Unlike in Malawi, there is no evidence from these data of re-planting or of dry planting. Anecdotally, successful early planting is reputed to improve yield in Zambia. The use of the DST may support farmers' attempts to plant early.

Table 7. Yield achieved by farmers categorised by difference between observed and recommended planting date (-5 to 5) for each of the growing seasons for which we have data in Zambia

Season	Metric	-45 to -35	-35 to -25	-25 to -15	-15 to -5	**-5 to 5**	5 to 15	15 to 25	25 to 35	35 to 45
2019	Median difference from recommended planting date (days)	-36	-28	-19	-10	**0**	9	17	29	40
2019	Median yield (kg/acre)	1329	1686	1106	1163	**972**	778	572	360	348
2019	Standard deviation in yield (kg/acre)	940	792	751	664	**628**	603	608	479	902
2019	P value	0.73	0.00	0.22	0.03		0.01	0.00	0.00	0.18
2019	Number of farmers	8	38	127	223	**438**	413	194	38	9
2020	Median difference from recommended planting date (days)	-36	-29	-20	-12	**0**	9	17	28	
2020	Median yield (kg/acre)	1242	1245	1338	1234	**1171**	1088	939	753	
2020	Standard deviation in yield (kg/acre)	587	596	617	658	**690**	645	677	584	
2020	P value	1.00	0.34	0.00	0.07		0.46	0.11	0.39	
2020	Number of farmers	25	159	306	290	**365**	173	99	23	

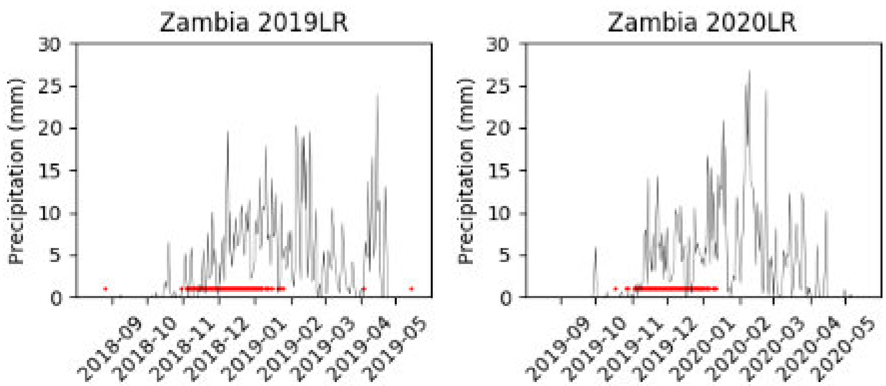


Figure 23. Precipitation time series for the Zambia case study seasons (grey line). The red marks indicate days on which planting occurred.

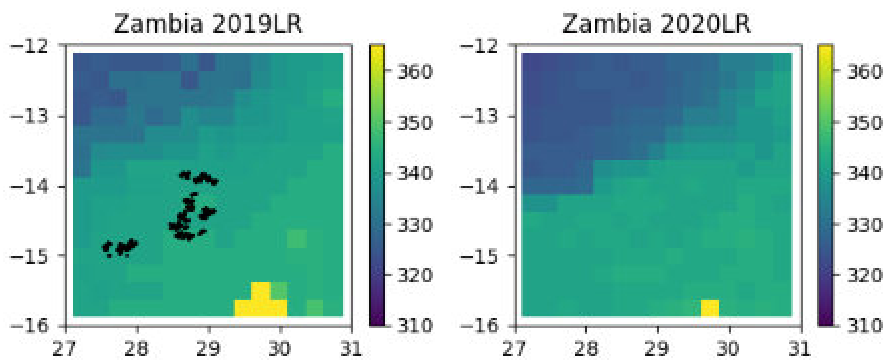


Figure 24. Recommended planting day of the year for the Zambia case study seasons

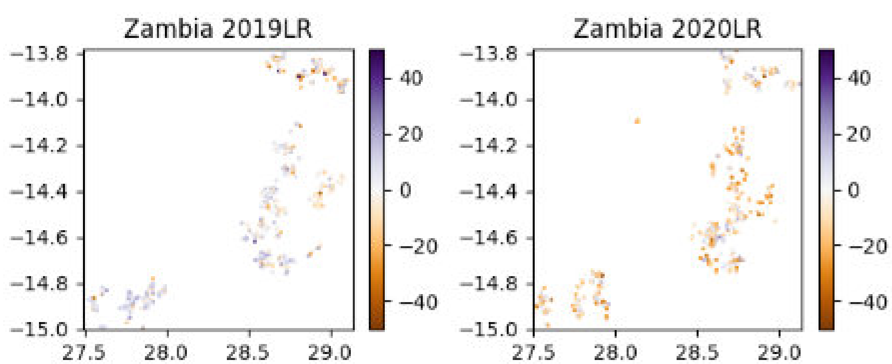


Figure 25. Difference between recommended and observed planting date for the Zambia case study seasons

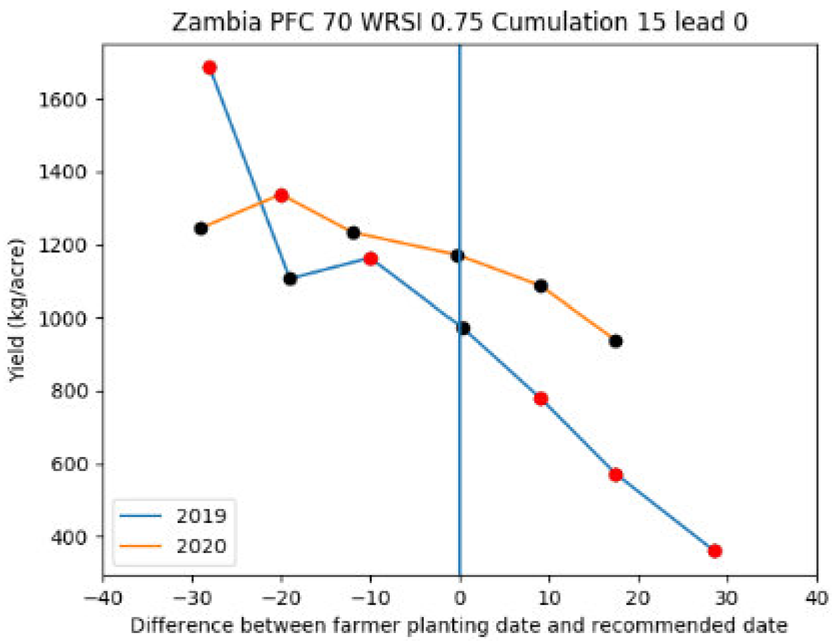


Figure 26. Yield plotted against the difference between actual and recommended planting time for Zambia

Nigeria

Because of its location in West Africa, Nigeria has a different climate to the other case study areas. Rainfall emanates from the West African monsoon, which starts around May and continues until October. In some parts of Nigeria, there is a break during the monsoon in early August, but this 'little dry season' does not affect the localities included in this study. There is a steep latitudinal gradient in rainfall in Ghana. The 2015 and 2016 seasons, for which data were available from a northern region, were therefore analysed separately from the 2018 and 2019 seasons.

It can be seen from *Figure 27* that, in the southern region, planting occurs over a very long window starting in April or May and continuing into July. A few localities recorded planting dates in September, but these may be erroneous and were excluded from the formal analyses. Planting is generally recommended by the DST during June/July, (*Figure 29*), with farmers planting either around the recommended date or before (*Figure 31*; *Figure 33*, *Table 8*). There is some indication that farmers who plant later tend to have lower yields, but it is not clear that the DST is skilful at selecting an optimal date – primarily because of the low number of farmers. In particular, it is evident from *Table 8* that, in most cases, the yields achieved by farmers planting away from the optimal date are not significantly different from those planting near the optimal date. This is likely because of the low number of farmers in each category.

Figure 28 shows data for 2015 and 2016 from an experimental study, further north in Nigeria. Comparison with *Figure 27* confirms that the region is drier. Because of the dry climate, it was necessary to change the soil moisture threshold from 70PFC to 45PFC to ensure that recommendations were provided at all grid points. *Figure 28* shows that the farmers in the experimental study plant over a short time period centred around late June for both years. The recommended planting dates tend to be early to mid-June with some variation between years (*Figure 30*). Farmers universally plant within 20 days of the recommended date, although in 2016, all farmers planted later than the recommendation (*Figure 32*, *Figure 34*, *Table 8*). As with the northern region, it is not clear that the DST is selecting an optimal planting date because of the low numbers of farmers in each bin. It is, however, encouraging that the DST recommends dates consistent with farmer behaviour in the controlled experimental setting.

Overall, because of the lack of the data and the variable climate, it is not possible, at this stage to have confidence in the DST for Nigeria. The recommendation is that One Acre Fund continue to collect data on planting date and yield, with the aim of calibrating a DST for the region, once more data are available.

Table 8. Yield achieved by farmers categorised by difference between observed and recommended planting date (-5 to 5) for each of the growing seasons for which we have data in Nigeria

Season	Metric	-45 to -35	-35 to -25	-25 to -15	-15 to -5	**-5 to 5**	5 to 15	15 to 25	25 to 35	35 to 45
2015	Median difference from recommended date (days)					**1**	11	15		
2015	Median yield (kg/acre)					**586**	709	406		
2015	Standard deviation in yield (kg/acre)					**529**	519	551		
2015	P value						0.65	0.02		
2015	Number of farmers					**53**	66	36		
2016	Median difference from recommended date (days)						10	17		
2016	Median yield (kg/acre)						638	752		
2016	Standard deviation in yield (kg/acre)						499	500		
2016	P value									
2016	Number of farmers					**0**	58	90		
2018	Median difference from recommended date (days)	-37	-29	-20	-6	**-1**	10	18	29	38
2018	Median yield (kg/acre)	899	1180	984	1237	**950**	1068	1068	1461	899
2018	Standard deviation in yield (kg/acre)	422	386	532	496	**237**	408	212	358	217
2018	P value	0.93	0.44	0.95	0.37		1.00	1.00	0.14	1.00
2018	Number of farmers	22	15	32	22	**5**	7	5	3	3
2019	Median difference from recommended date (days)	-39	-29	-21	-9	**0**	10	21	31	44
2019	Median yield (kg/acre)	826	871	444	742	**680**	540	506	438	1355
2019	Standard deviation in yield (kg/acre)	845	465	293	522	**379**	358	410	571	253
2019	P value	0.88	0.22	0.01	1.00		0.87	0.61	1.00	0.37
2019	Number of farmers	24	17	30	31	**27**	20	11	7	2

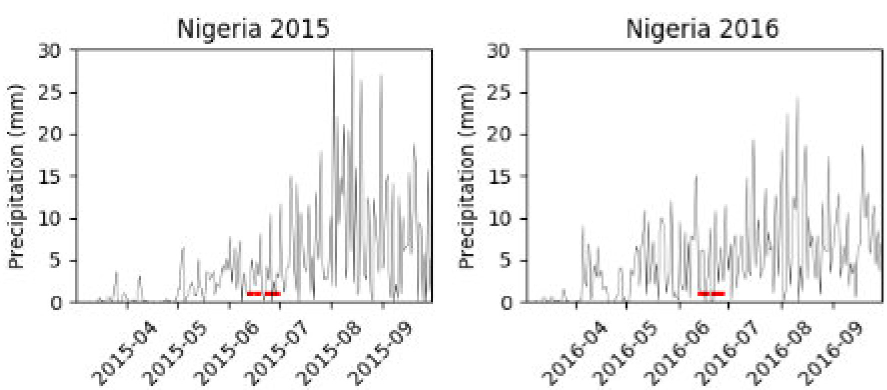


Figure 27. Precipitation time series for the Nigeria case study seasons (grey line). The red marks indicate days on which planting occurred (northern region).

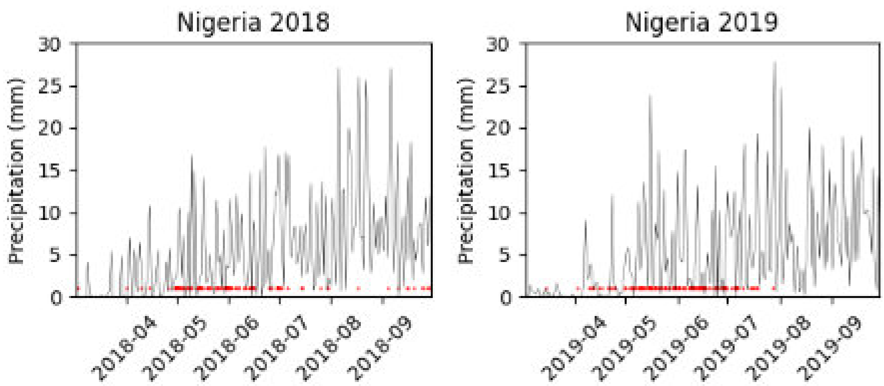


Figure 28. Precipitation time series for the Nigeria case study seasons (grey line). The red marks indicate days on which planting occurred (southern region).

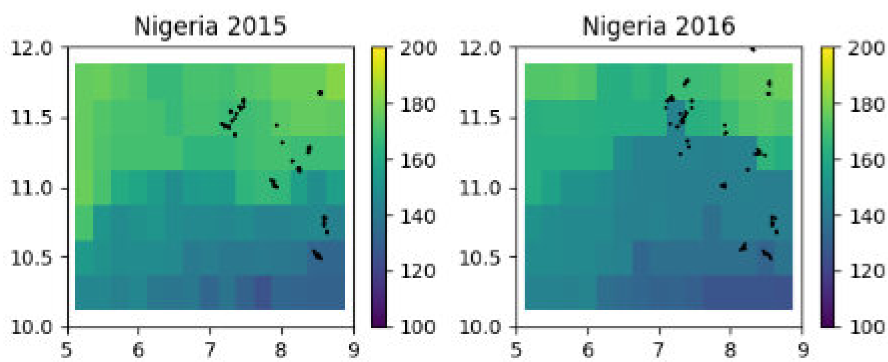


Figure 29. Recommended planting day of the year for the Nigeria case study seasons (northern region)

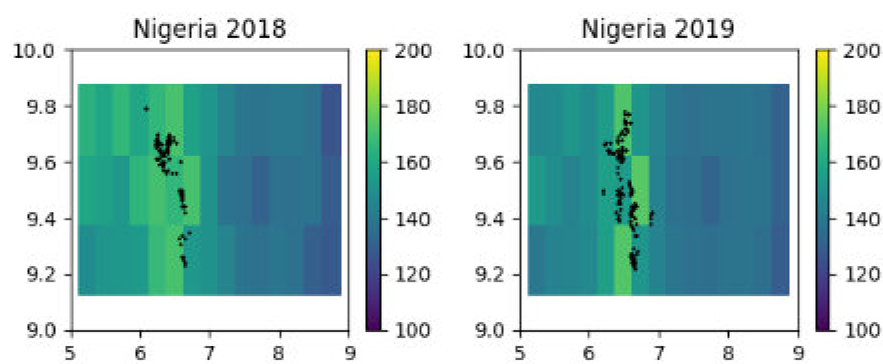


Figure 30. Recommended planting day of the year for the Nigeria case study seasons (southern region)

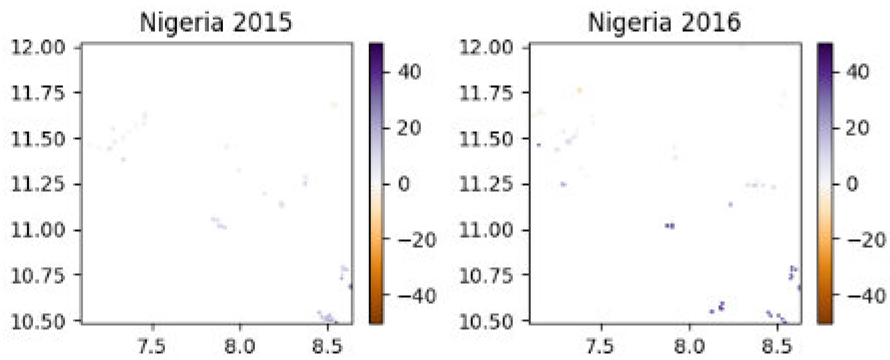


Figure 31. Difference between recommended and observed planting date for the Nigeria case study seasons (northern region)

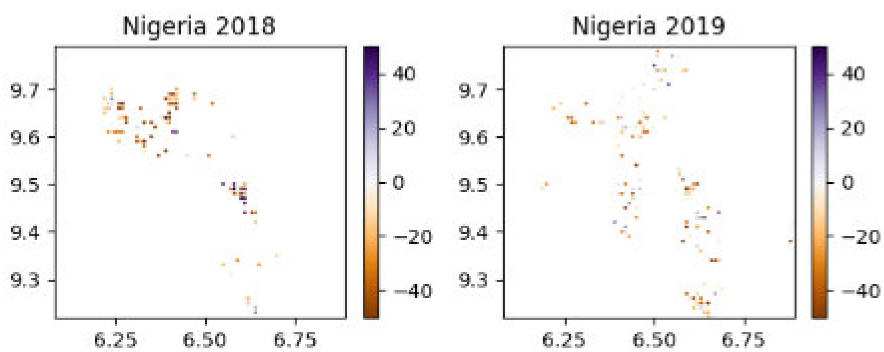


Figure 32. Difference between recommended and observed planting date for the Nigeria case study seasons (southern region)

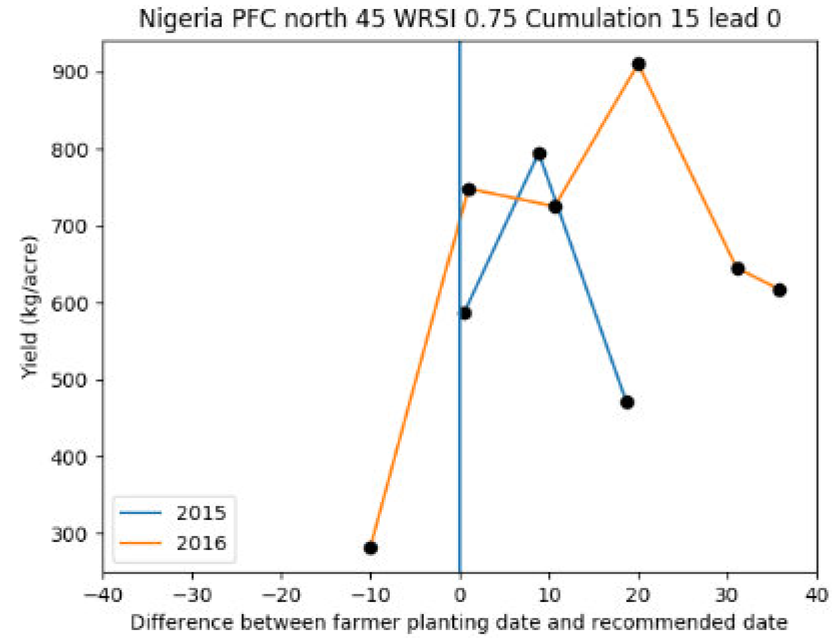


Figure 33. Yield plotted against the difference between actual and recommended planting time for Nigeria

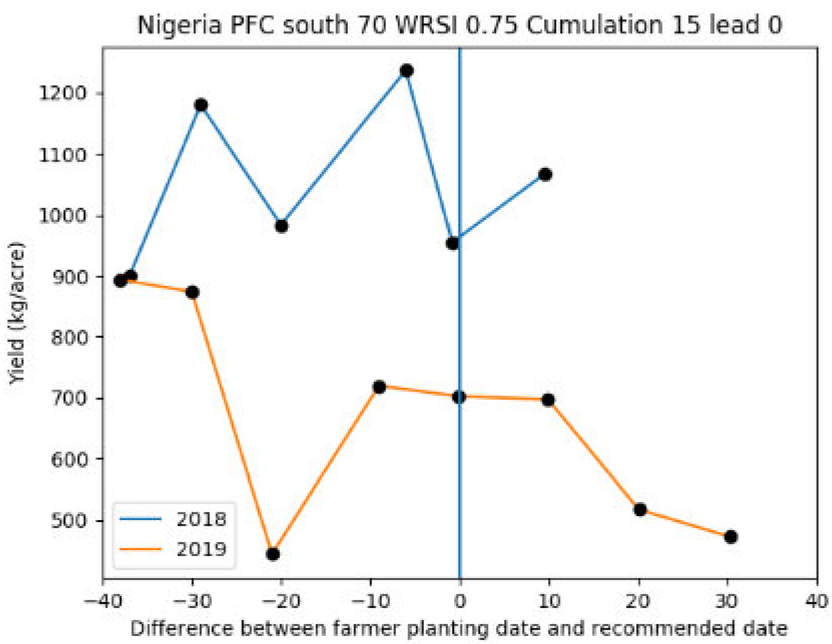


Figure 34. Yield plotted against the difference between actual and recommended planting time for Nigeria

Anticipatory planting advice

The analyses presented above assume that the planting date DST is run daily and that the advice is instantly relayed to farmers. In reality, however, this is not practical. In the previous pilots, planting advice was issued at weekly intervals. The rainfall and reanalysis data are, moreover, not updated daily, and there is a lag of up to 5 days.

The TAMSAT-ALERT forecasting system (described in previous sections) is capable of providing anticipatory advice. For example, it would be possible to provide notification on Monday of whether planting should take place on Thursday. The skill in anticipating planting suitability arises from incorporation of both the climatology and the antecedent soil moisture conditions. For example, if it is likely (based on past years) that the rainy season will soon be starting but we know that the soil is still very dry, planting might not be advised because there would need to be very heavy rainfall to provide sufficient soil moisture. Conversely, if the soil is already somewhat moist, the DST might predict that in a few days, once the rains are likely to be better established, planting is advisable. It should nevertheless be noted that the greater the lead time, the greater the uncertainty. It is possible that advice might change in the intervening period between the initial notice and the proposed day of planting.

In order to assess how far in advance it is possible to issue robust planting date advisories, the comparison between farmer compliance and yield was repeated for leads of up to 10 days. Note that no meteorological forecast data is included. Rather, the predictions are based on a climatological ensemble of meteorological data. *Figure 35* and *Figure 36* show the evaluations of lead times of 5 and 10 days respectively. It can be seen that, even with a 10-day lead there is some skill in anticipating suitability for planting, and that the 5-day lead time evaluations have similar results to the contemporaneous assessments. Indeed, the worst decline in skill over the 10-day lead period is for Malawi, where we are effectively trying to assess the timing of the first rains of the season - with little contribution from antecedent soil moisture. Incorporation of weather forecasts into the TAMSAT-ALERT based soil moisture forecasts (described in previous sections) would likely improve the anticipatory Malawi advice.

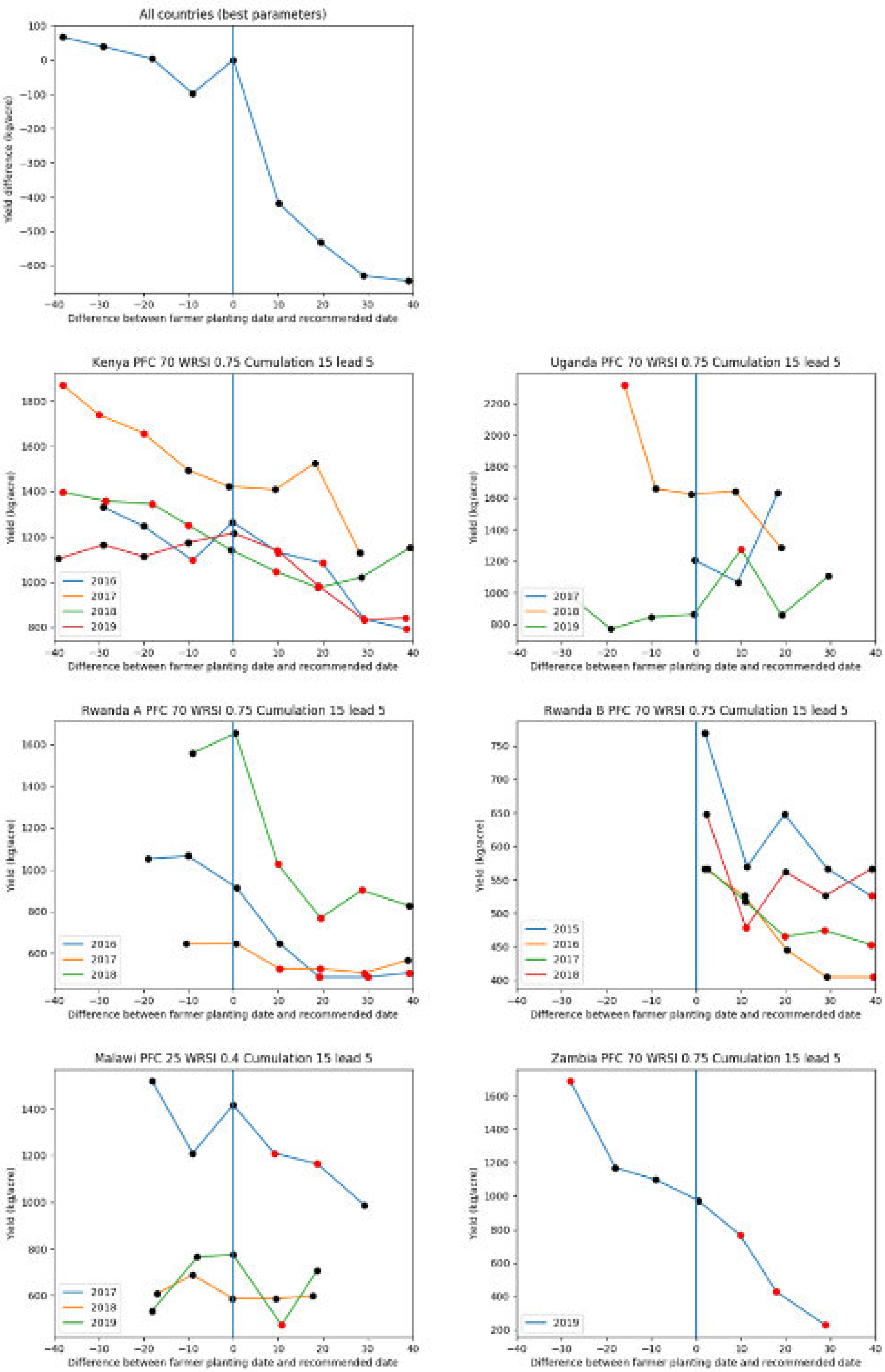


Figure 35. Yield or yield difference plotted against the difference between actual and recommended planting time for all countries (top) and for each of the case study regions, other than Nigeria, for a lead time of 5 days. Red dots indicate that the yield is significantly different from the -5 to +5 day difference bin.

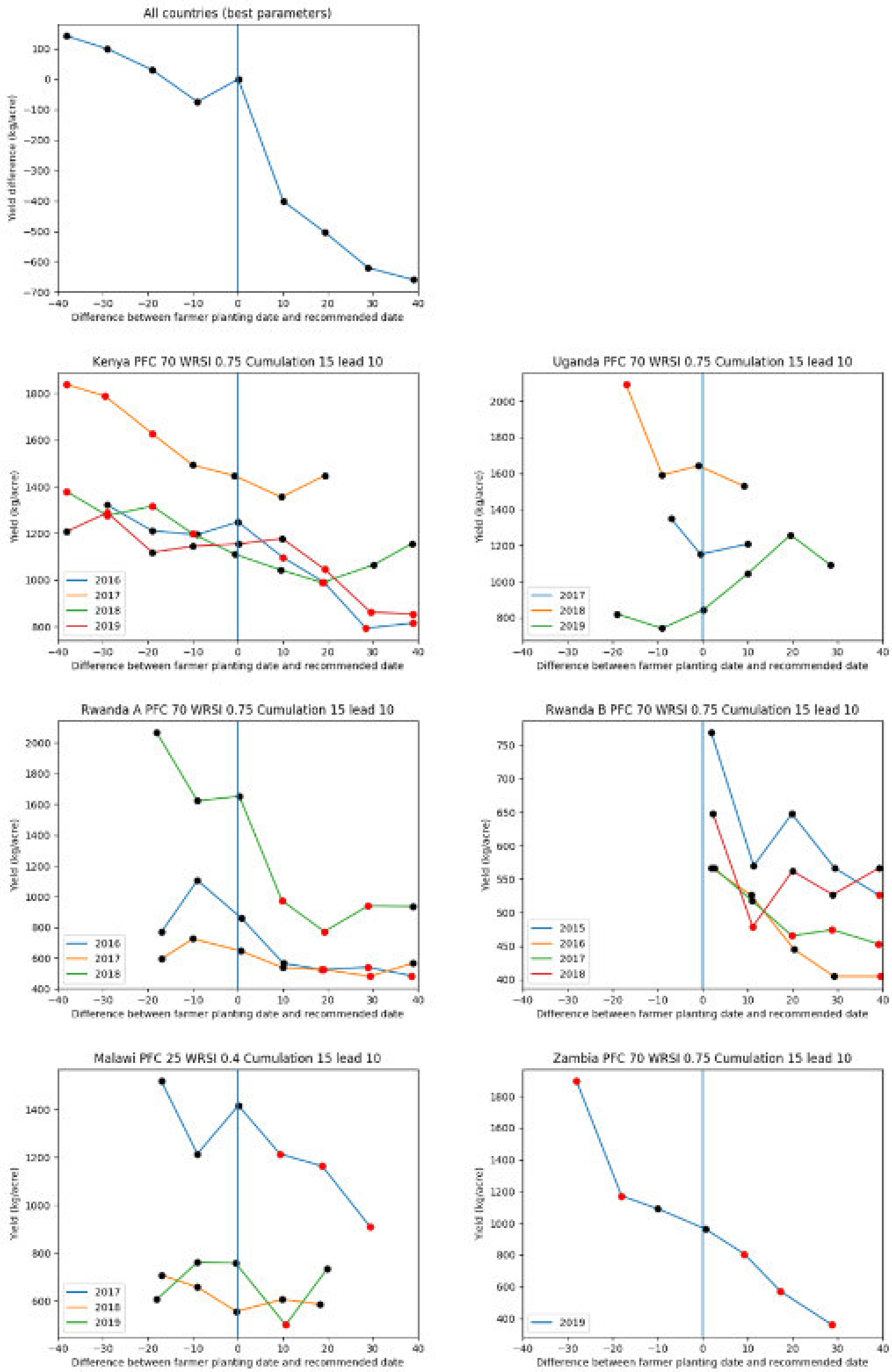


Figure 36. Yield or yield difference plotted against the difference between actual and recommended planting time for all countries (top) and for each of the case study regions, other than Nigeria, for a lead time of 10 days. Red dots indicate that the yield is significantly different from the -5 to +5 day difference bin.

Recommendations and Next Steps

The TAMSAT-ALERT planting date DST can skilfully identify optimal planting date, and can provide reliable advice up to 5 days in advance of a planting window. The planting date tool is ready to be piloted or scaled in Kenya, Zambia, Malawi, Uganda, and for the Rwanda A season throughout season onsets in 2021. More data are required to determine the decision-making criteria in Nigeria, Tanzania and Burundi. However, in the case of Burundi, it may be possible to rely on validation from agro-climatically similar regions in Rwanda. The decision making criteria vary spatially and so it would be necessary to re-calibrate when extending the DST to new areas.

The focus of the pilots should be on communication. For example, farmers are to be encouraged to plant early, it is likely that the suitability for planting will vary over the weeks following the first advice to plant. There needs to be careful consideration as to how the planting advice is phrased in order to maximise uptake but balancing this with the need to ensure farmers are appropriately informed of confidence levels.

Prediction of optimal planting date could likely be improved with the incorporation of high quality short-term rainfall forecasts, and potentially also higher resolution soil data and variety selection information. Further analyses will be conducted in 2021 to explore the potential of these options to improve performance.

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