Africa RiskView Methodology Technical Note: Drought

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1. OVERVIEW

The objective of *Africa RiskView* (ARV) is to estimate the number of people affected by a drought event during a rainfall season and then the dollar amount necessary to respond to these affected people in a timely manner. To do this, ARV translates satellite-based rainfall information into near real-time impacts of drought on agricultural production and grazing using existing operational early warning models; by then overlaying these data with vulnerability information, the software produces a first-order estimate of the drought-affected population, and in turn response cost estimates.

Through this process, ARV combines four well-established disciplines: crop monitoring and early warning, vulnerability assessment and mapping, operational response, and financial planning and risk management. It covers all of Africa's different rainfall seasons and employs four basic information layers that are combined to estimate drought response costs per season. The layers, in subsequent order of interaction in ARV analysis, are: rainfall, drought index, estimated populations affected and estimated response costs. They are shown in the ARV main interface[1] in Figure 1 and described in the sections below.
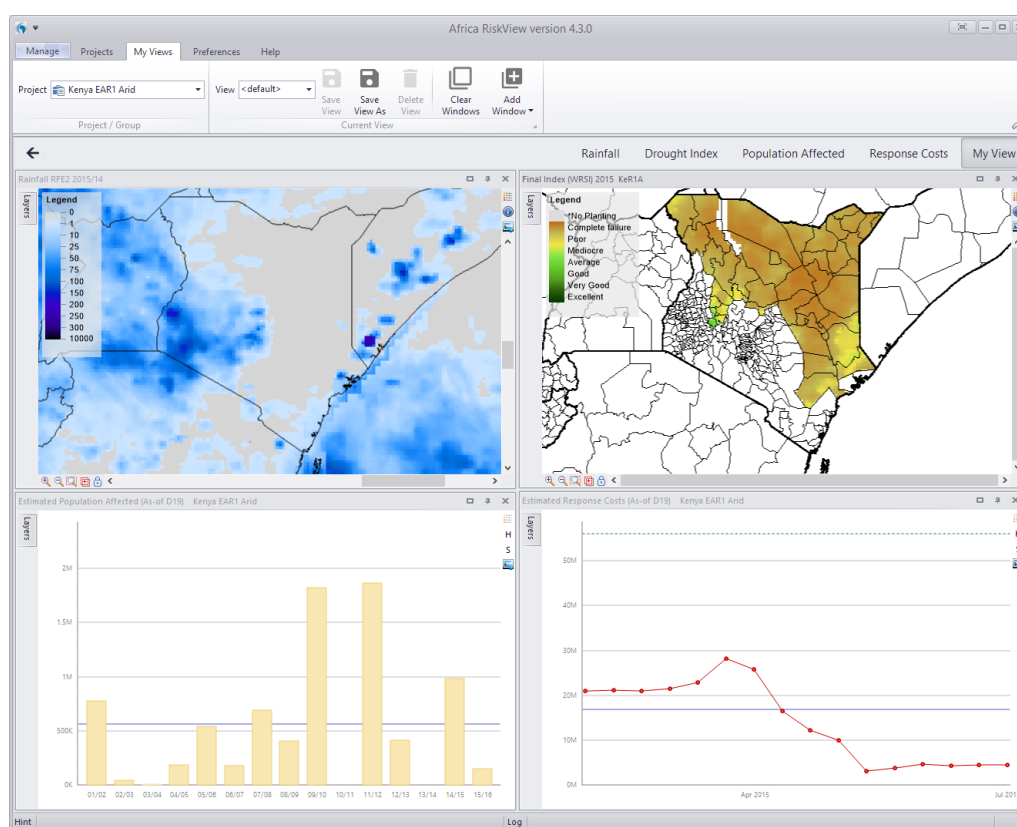

Figure 1: *Africa RiskView* **v4.3 default My View showing Kenya EAR1 Arid (long rains) season**

ARV has been designed to be adapted and customised to work within national frameworks, strengthening existing systems and allowing governments and their partners to carry out their own risk analyses, as well as define their own risk management strategy and ARC risk pool participation. Specifically, part of the

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[1] See the ARV Quick Start Manual or the ARV Wiki (F1 from anywhere on the ARV Desktop Interface) to understand how to navigate the ARV software. The ARV Desktop Interface offers full functionality that allows customisation of the different components, whilst the *Africa RiskView* Online portal has limited functionality. Here users can view the performance of the current and past seasons of projects with pre-defined settings, but cannot change settings nor perform additional analyses.

process leading to official participation of a country in the risk pool consists of the ARC Secretariat engaging each potential participating country and its in-country partners in a year-long process to customise ARV to the respective national context, using local expert knowledge and information to adjust settings and assess the model's performance and ability to capture the impact of drought events on vulnerable populations.[2]

As countries customise and validate their new settings for each rainfall season that happens in the country, these new settings will replace the default settings in ARV. These customised country-seasons, known as Projects in ARV, are clearly delineated in the software.[3]

2. RAINFALL

To satisfy criteria of transparency and objectiveness required for a parametric insurance contract, ARV uses dekadal (10-day) cumulative rainfall estimate data to compute the model's drought index. The default dataset used in ARV is provided by the U.S. Climate Prediction Center (CPC), National Oceanic and Atmospheric Administration (NOAA). Called RFE2[4], the dataset relates to specified grid cells, or pixels, across the African domain, from 40.00S to 40.00N northward and from 20.00W to 55.00E eastward, with a resolution of 0.1 degrees latitude by 0.1 degrees longitude. This roughly translates to an area of 10 x 10 kilometres per pixel. It is produced by merging Global Telecommunications System (GTS) ground station gauge observations and three kinds of satellite estimates and has been produced every dekad[5] since 2001. Dekadal RFE2 data are published on the internet by NOAA on the second day of the following dekad and are downloaded directly to the ARV software by clicking the software's "Update" button.[6] Alternate rainfall estimate datasets available in ARV include ARC2[7] and TAMSAT[8], which are available starting from 1983 and are also produced every dekad and available in ARV at the same spatial resolution. These can be selected by countries during the customisation process.[9] Rainfall, as estimated by these datasets, is the only real-time varying input used in the ARV model.

As part of the in-country ARV customisation process, countries must compare the satellite-based rainfall

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[2] See the ARV Customisation Standard Operating Procedures and ARV Customisation Manual for more information on the customisation process and the parameters that can be customised.

[3] See the ARV Quick Start Manual or the ARV Wiki (F1 from anywhere on the ARV Desktop Interface) to understand how to navigate the ARV software.

[4] NOAA, 2001. FEWS-NET/MFEWS/AFN Data Archive, CPC/Famine Early Warning System Dekadal Estimates (RFE2). Climate Prediction Center, College Park, Maryland, USA. Available Online:
http://www.cpc.ncep.noaa.gov/products/fews/data.html (metadata);
ftp://ftp.cpc.ncep.noaa.gov/fews/newalgo_est_dekad (RFE2 data);
http://www.cpc.ncep.noaa.gov/products/fews/RFE2.0_tech.pdf (technical description)

[5] Every month in a year is comprised of three dekads. Dekad 1 is days 1 – 10 of a month, dekad 2 is days 11 – 20 of a month, and dekad 3 is the last 8 to 11 days of a month.

[6] As long as there is an internet connection, see the ARV Quick Start Manual.

[7] Climate Prediction Center (CPC) Africa Rainfall Climatology Version 2.0 (ARC2). Climate Prediction Center, College Park, Maryland, USA. Available Online:
https://catalog.data.gov/harvest/object/c5170f0f-9094-4d54-8cad-95cae0c3d237/html (metadata);
ftp://ftp.cpc.ncep.noaa.gov/fews/fewsdata/africa/arc2/bin (ARC2 data);
http://www.cpc.ncep.noaa.gov/products/fews/AFR_CLIM/arc2_201303_final.pdf (technical description)

[8] TAMSAT African Rainfall Climatology And Time-series (TARCAT v2.0), University of Reading, 2013. TAMSAT Research Group. University of Reading, England. Available Online:
http://www.met.reading.ac.uk/~tamsat/docs/TAMSAT_Data_Policy_TARCATv2.0_2014.pdf (metadata);
http://www.met.reading.ac.uk/~tamsat/public_data/TAMSAT_rfe_dekadal.zip (TARCAT v2.0 data)

[9] To date TAMSAT (TARCAT v2.0) has not been fully quality controlled by the ARC Secretariat Technical Team for use in ARC insurance contracts; however no country has yet requested to use the dataset and data have been only used for comparison purposes.

estimate datasets available in ARV to ground station rainfall data, and other data sources, and select the dataset that captures ground station rainfall data variability best for their country.[10] For un-customised countries RFE2 is used as the default dataset. More technical information on the satellite-based rainfall datasets used and how they are treated in ARV is given in Annex 1.

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3. DROUGHT INDEX

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ARV converts the rainfall dataset the user has selected into a drought index called the Water Requirement Satisfaction Index, WRSI, which is an indicator of crop performance based on the availability of water to the crop during a growing season. The index captures the impact of timing, amount and distribution of rainfall on staple annual rain-fed crops. Originally developed by the United Nations Food and Agricultural Organisation (FAO), studies have shown that WRSI can be related to crop production using a linear yield-reduction function specific to the crop in question.[11] A simple crop model, the WRSI requires few parameters for calculation and as such is part of many existing operational drought early warning models across Africa. Most African countries use WRSI as part of their own drought assessment crop models and several early warning and technical organisations, such as Famine Early-Warning Systems Network (FEWS NET), the Joint Research Centre of the European Commission (JRC), and FAO, through their own software, AgroMetShell and subsequent tools, use the same basic methodology for calculating WRSI and consider the index a meaningful indicator for their similar drought monitoring purposes.

In addition to rainfall, the WRSI needs several other static inputs in order to calculate a final drought index value for a season, such as normal potential evapotranspiration, soil water holding capacity and information on crop types and cropping calendars. This information – available from technical organisations such as FAO and FEWS NET – is used in ARV; however as part of the in-country ARV customisation process, countries are required to review and, where necessary, improve this input data to ensure it reflects the best and most recent information available and faithfully reflects the agricultural practices in their country. ARV has been designed to allow users to change WRSI settings used in the model and to support this customisation work.[12]

WRSI is calculated at each pixel, as per the input rainfall data. The index is a number that can range from 0 to 100, where 100 indicates no water deficit for a crop and therefore no expected water deficit-related reduction in yield from optimal levels. A number less than 100 indicates some water deficit stress and therefore some expected yield reduction as a result; 0 indicates a situation where not enough rainfall was received during the season to successfully plant a crop at all. In simple terms, the higher the WRSI value, the less likely there has been a drought, as the water available to the crop from rainfall and storage in the soil has been adequate to meet a crop's growth needs.

The WRSI calculation at a pixel requires two steps: first a calculation to determine the planting dekad, which determines the start of the WRSI calculation; secondly, the WRSI calculation itself which uses rainfall data from the starting or planting dekad, and dekadal rainfall up to and including the last dekad considered. The difference in dekads between the starting and last dekad is equivalent to the crop cycle length (in dekads) associated with that pixel.

The starting dekad must be based on an objective and consistent criterion for identifying the planting dekad — the dekad during the potential planting window when farmers choose to plant. There are several

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[10] See the ARV Rainfall Customisation Standard Operating Procedure for more information.

[11] FAO, 1986. Yield Response to Water. Irrigation and Drainage Paper No. 33. Food and Agriculture Organization of the United Nations, Rome.

[12] See the ARV WRSI Customisation Standard Operating Procedure for more information.

rainfall-accounting methods for identifying the starting or planting in the literature. There are currently two methods available in ARV from which countries customising ARV can select:

- Planting based on rainfall thresholds: For every dekad *i* within the specified planting window that records greater than X mm of cumulative rainfall [13], with greater than Y mm of cumulative rainfall in dekad *i*+1 and Z mm of cumulative rainfall in dekad *i*+2, a WRSI calculation is performed for the crop, taking the dekad *i* as the first dekad of the crop's growing period. As part of the customisation process, countries can choose to specify rainfall planting thresholds for all three dekads (*i*, *i*+1, *i*+2), two dekads (*i*, *i*+1) or just for the first dekad *i*. This is the default planting dekad methodology in ARV with a default value for X set at 20mm, with thresholds for the following two dekads not specified, so that only dekads that record 20mm or more can be considered as potential planting dekads.

- Planting based on a percentage of crop water requirements[14]: For every dekad *i* within the specified planting window that records greater than X % of the selected crop water requirements for that dekad, with greater than Y % in dekad *i*+1 and Z % in dekad *i*+2, a WRSI calculation is performed for the crop, taking the dekad *i* as the first dekad of the crop's growing period. As part of the customisation process, countries can choose to specify crop water requirement percentage thresholds for all three dekads (*i*, *i*+1, *i*+2), two dekads (*i*, *i*+1) or just for the first dekad *i*.[15]

Once all the data for the planting window has been reported, the final WRSI value at a pixel is expressed as some function over all of the WRSI values that have been calculated starting at each potential planting dekad. ARV users can select whether this function is the maximum, the average or the first planting opportunity found, to define the final WRSI value, or some other rainfall-based algorithm that reflects local practices well. If no starting condition is met during the potential planting window, it is assumed that farmers would not have planted, or would have unsuccessfully planted.

If farmers are not acting optimally, for example because of unavailability of seeds or fertilisers, and do not plant when the rains start and conditions are good for planting, then objective planting rules may not correctly reflect those decisions. Finding the correct planting dekad or dekads therefore is often the most difficult part of the WRSI calculation in terms of capturing what happens on the ground accurately. This is why several approach options have been made available to ARV users for testing. The default planting opportunity aggregation method[16], or function, is set as the maximum, which considers the best possible planting opportunity for farmers. The full WRSI calculation used in ARV is given in Annex 2.

The way in which WRSI is defined in ARV and, in particular, the way in which planting opportunity

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[13] In fact cumulative effective rainfall is used in ARV for the planting criteria and WRSI calculations. Effective rainfall in ARV is defined as the actual rainfall reported multiplied by the effective rainfall percentage. The default value of the effective rainfall percentage in ARV is 100% (see Annex 2).

[14] A crop's water requirement for a given dekad is defined as the crop coefficient (KC) for that dekad multiplied by the potential evapotranspiration for that dekad (see Annex 2).

[15] This is very similar to another method that is often used. It defines the first dekad in the planting window where the ratio of cumulative rainfall recorded to normal potential evapotranspiration (PET) for that dekad is greater than 50 percent, as the starting dekad. It is suggested in the literature that once this ratio exceeds 50 percent, the soil favours germination. For many parts of sub-tropical Africa this method usually corresponds to the first dekad in which cumulative rainfall exceeds 25 mm, another trigger often used in other rainfall accounting methods. Hence 20mm (ARV's default setting) is in line with other criteria, given that RFE2 data is known to have a dry bias compared to actual rainfall station data (Dinku, T., Ceccato, P., Grover-Kopec, E., Lemma, M., Connor, S. J., Ropelewski, C. F., 2007. Validation of satellite rainfall products over East Africa's complex topography, International Journal of Remote Sensing, 28:7, 1503 – 1526).

[16] See Early Warning, Normals & Alternative Data section to see how the planting opportunity aggregation domain setting in ARV can be used to define what ARV displays on WRSI maps during an on-going planting window.

aggregations are handled, allows this drought index – which is usually used for monitoring crop development – to be successfully applied to both crops and rangeland. ARV users can select from 15 pre-specified rain-fed crops[17] and rangeland (grass) to create corresponding WRSI values (see WRSI for Rangeland in Annex 2).

Although it can be estimated and therefore monitored throughout a rainfall season as the rainfall data is reported (see Early Warning, Normals & Alternative Data section below), the final WRSI value is produced at the end of each rainfall season when all the rainfall data has been received. In ARV it is used as a seasonal indicator of drought and is the main variable used by the model to calculate drought-affected population estimates at the end of a rainfall season.

For the purposes of identifying a drought, and then estimating populations affected, WRSI is aggregated at the "vulnerability polygon". Vulnerability polygons are specific geographical units within a country for which information on household vulnerability to drought exists and is statistically representative (see below); they are usually administrative units or livelihood zones. The WRSI is aggregated at the vulnerability polygon level by taking the arithmetic mean of all WRSI pixel values that fall within each polygon.

In order to determine if drought conditions at the end of a season are "abnormal" and therefore if it can be considered that there is a drought, the aggregated WRSI at the end of a rainfall season (hereafter WRSI) is compared to its "expected" level in the polygon (hereafter Benchmark). In its default settings, ARV uses the median WRSI value of the previous five years as the Benchmark for a polygon.[18] Therefore, the Benchmark calculation method is the same across all polygons, but the Benchmark values are polygon-specific. Comparing each WRSI value to its location-specific and time-specific reference allows converting an "absolute" drought severity into a "relative" drought severity, which is measured by the WRSI/Benchmark ratio (hereafter Drought Ratio).

4. ESTIMATING POPULATIONS AFFECTED

Once the WRSI is compared to its Benchmark as explained in the section above, and the "relative severity" of a drought in a polygon is defined, the next step in the ARV methodology is to convert this information into a drought-affected population estimate for that polygon. This is done by comparing each Drought Ratio to a polygon-specific Vulnerability Profile to determine the impact of that particular drought in terms of number of affected people in that polygon. These Vulnerability Profiles are static within ARV and illustrate the relationship between relative drought severity and affected population, and are defined by the four following points:

1. **Drought Detection Point, T_0** (default value = 95% = 5% deviation from the Benchmark)
2. **1st Drought Impact Calibration Point, T_1** (default value = 90% = 10% deviation from the Benchmark)
3. **2nd Drought Impact Calibration Point, T_2** (default value = 80% = 20% deviation from the Benchmark)

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[17] Millet, sorghum, maize, grains (a composite of several short-cycle cereal crops used by FEWS NET in East Africa), teff, barley, wheat, chick peas, field peas, haricot beans, horse beans, lentils, potatoes, sweet potatoes, groundnut. Default crop coefficient values at different stages of the crop development can be changed in ARV, and additional crops can be added on request.

[18] During the customisation process countries can select different benchmarks from the following options: considering different aggregation periods, e.g. 10 years instead of five years; using the arithmetic average instead of the median as the aggregating function; setting fixed, absolute benchmark values by polygon.

4. **3rd Drought Impact Calibration Point, T_3** (default value = 70% = 30% deviation from the Benchmark)

As part of the in-country ARV customisation process, countries are required to revisit ARV's default WRSI settings and define polygon-specific Drought Detection and Impact Calibration Points.

These profiles are calculated outside of the software from available household survey data, such as the government and WFP Comprehensive Food Security and Vulnerability Analysis (CFSVA) surveys available in many countries, which provide information on the income-generating activities and wealth of households living within each geographic area. Since the amount of data available in those surveys would be too much to be handled by ARV, using modelled Vulnerability Profiles allows ARV to make accurate estimates of affected population on the basis of just a few reference points.

The purpose of adjusting the Drought Detection Point and the three Calibration Points is to provide an optimal match between the modelled Vulnerability Profile and the "real" vulnerability profile which is defined by the distribution of income profiles among the surveyed population. The details of how Vulnerability Profiles are calculated from household survey data are given in Annex 3.

As outlined above, these surveys, and the geographical areas over which they are statistically representative, determine the polygons that can be used within the ARV model for a country. Revising the default Vulnerability settings within ARV, including, where possible, updating with the most recently available household survey data, is a core part of the in-country ARV customisation process.[19] Annex 3 lists the survey data that have been used do date.

Although the work to determine the Vulnerability Profiles can be quite involved, once they are set, the way they are used in ARV to estimate populations affected is straightforward. If P is the population of the polygon, V_1 is the 1st Vulnerability Level (i.e. the percentage of the population that is vulnerable to a drought of severity T_1), V_2 is the 2nd Vulnerability Level (i.e. the percentage of the population that is vulnerable to a drought of severity T_2) and V_3 is the 3rd Vulnerability Level (i.e. the percentage of the population that is vulnerable to drought of severity T_3), the estimated number of people affected by a drought in the polygon, N, having experienced a rainfall season described by a WRSI value, w, is as follows:

$$\text{If } w > T_0*W, N = 0$$
$$\text{If } T_0*W \geq w > T_1*W, N = P * b_1 * (T_0*W - w)$$
$$\text{If } T_1*W \geq w > T_2*W, N = P * [V_1 + b_2 * (T_1*W - w)]$$
$$\text{If } T_2*W \geq w > T_3*W, N = P * [V_2 + b_3 * (T_2*W - w)]$$
$$\text{If } w \leq T_3*W, N = P * V_3$$

where $b_1 = V_1/(T_0*W - T_1*W)$; $b_2 = (V_2 - V_1)/(T_1*W - T_2*W)$; $b_3 = (V_3 - V_2)/(T_2*W - T_3*W)$; W is the Benchmark for the polygon; and T_0, T_1, T_2 and T_3 are the Drought Detection Point, 1st, 2nd and 3rd Drought Impact Calibration Points respectively, defined as percentages of the Benchmark.

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[19] See the ARV Vulnerability Customisation Standard Operating Procedure for more information.
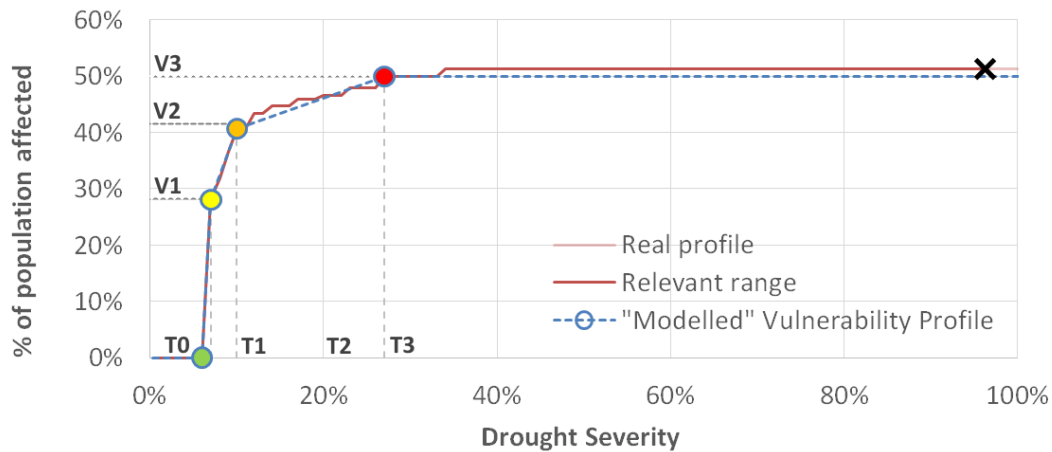
Figure 2: Estimated percentage of population affected in a polygon as a function of deviations in WRSI from the benchmark

In other words, if a drought of severity T_0, T_1, T_2 or T_3 occurs, it is assumed that the number of people affected by drought in that polygon is respectively 0, V_1*P, V_2*P and V_3*P.

For all other Drought Ratio values, the estimated affected population can be found through a simple process of linear interpolation between those different values (see example in Figure 2). If there is no drought (when the Drought Ratio is above the Drought Detection Point), the estimated population affected is 0; for all Drought Ratio values below the 3rd Drought Impact Calibration Point, the estimated population affected is considered equal to the population affected by a drought severity of T_3.

5. RESPONSE COSTS

The final calculation step within ARV is to calculate response costs for the estimated populations affected. Of all the calculations in ARV, response cost is by far the easiest, as the approach simply involves multiplying the estimated populations affected by a response cost per person – although the response cost per person may vary by polygon if appropriate. However, this simple mathematical operation requires a nuanced discussion that will involve many government actors, and the entire ARC in-country technical and operational planning working groups, during the ARV customisation process. Because ARC is an early response programme executed by a national government, historic international response costs may be an inappropriate or inaccurate measure for ARC response costs given a response plan scalability and scope. As such, the final response cost per person per season used in ARV will necessarily rely on conclusions from a country's ARC operations planning activities as well as discussions on the current costs associated with responses beyond those covered in the operations plan and by other actors, particularly in the case where an ARC pay-out will cover a smaller fraction of the costs required to respond to a drought event.[20]

The default settings of ARV use a response cost of US $100 per person in countries with one rainfall season (unimodal) and US $50 per person per season in countries with two rainfall seasons (bimodal). Default settings also have a single response cost number for an entire country. Customisation of the response cost thus means if and how to adjust the US $100 or US $50 figure and whether to keep response costs the same across the country, or change response costs at the vulnerability polygon level. Countries may also want to change response costs by drought severity, a modification that could be incorporated into the ARV

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[20] See ARV Response Costs Customisation Note for more information.

model if requested.

6. MODEL VALIDATION

At the end of the ARV customisation process, countries working towards participation in the ARC risk pool must validate the final model settings selected and recommend their use for ARC insurance contracts. Given the complex nature of food security in many African countries, and the limitations of historical data available, validation is both a qualitative and quantitative process.

As historical response costs at both the national and international humanitarian level are difficult to collect in a consistent and therefore comparable manner over time[21], the validation of ARV focuses on the model's ability to correctly identify the frequency and magnitude of past drought events in terms of populations affected, keeping in mind ARV is adjusted to today's population and today's vulnerability. Although the rainfall and WRSI outputs are compared to station rainfall data and yield data respectively during the customisation process, those comparisons have limitations, so the final discussion of model performance focuses mainly on how well ARV estimates of populations affected compare to historical data of populations affected and/or assisted because of drought given the known constraints of that historical data in terms of quality and its consistency over time.

Sources for such historical data include the government themselves, annual food security assessments and National Vulnerability Assessment Committee (NVAC) reports, in-country early warning systems, WFP project document narratives, WFP country office records and records from partner NGOs or other UN agencies. Comparing such external sources of data with one another allows the in-country team tasked with customisation and validation to define a consensus list of historical seasons during which ARV is expected to indicate the existence of a drought-related food security problem and its magnitude, adjusting for changes in population size and/or vulnerability where appropriate. This process naturally leads to discussions on past food security emergencies, their chronology and their drivers, and therefore whether ARV should be able to, and does, capture these events or not.

On the quantitative side, validation involves using various performance indicators to determine each parameter combination's ability to result in ARV estimates that are as close as possible to the consensus historical data. Such performance indicators may include: the correlation between ARV estimates and historical data, in both absolute terms and in terms of the ranking of events; the ability of the model to pick up the worst drought years accurately; the average over- or underestimation between the modelled estimates and the historical data; the standard deviation of the over- or underestimation, etc. On the qualitative side, the in-country teams must discuss the quality and reliability of the historical data used and take into consideration any other factors that might affect crops and/or food security other than drought (e.g. floods, price increases, locust invasions, fertiliser availability, changes in population and vulnerability) that need to be taken into account when assessing the quantitative performance of the model. By looking at the model's performance through both quantitative and qualitative lenses, in-country teams are then in a position to decide which ARV settings best reflect the impact of drought events on vulnerable households in past emergencies and can make recommendations as to which ARV settings should be used as the underlying basis for ARC insurance contracts.

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[21] Such response costs are subject to many other temporal factors beyond the direct emergency they are addressing, e.g. for international food assistance global commodity prices and transportation costs, which can vary significantly from year to year and over time and geographic location, can have a major influence on the overall cost of a response. Costs are also very sensitive to the type of intervention they are supporting and the organisation implementing that intervention; intervention types (e.g. food aid versus cash transfers) and intervention actors also vary from year to year and over time.

7. RISK TRANSFER

Once the in-country customisation is complete[22], participating countries will be able to select their ARC insurance risk transfer parameters based on their underlying customised model.[23] Once ARV has been customised, a country will have to decide what portion of its total modelled drought risk it wants to transfer to the ARC insurance pool. This decision will depend on several factors unique to each country, such as its risk profile, available response mechanisms, budget limitations, and the country's premium payment capacity. While customisation of ARV may change the drought years and the ranking of drought events it does not directly affect pay-out frequency or premiums; rather it is the risk transfer parameters selected that dictate these aspects of an insurance contract. These parameters can be adjusted to define insurance contracts that have the same premium value, but different underlying ARV customisations. As noted above, customisation, however, may influence the years in which pay-outs could be triggered and the magnitude of those pay-outs relative to one another. In principle, the process of setting risk transfer parameters to specify an ARC insurance contract is separate to the ARV customisation process. However, in practice, both work-streams do overlap at the country level to ensure the ARV customisation results lead to coverage that the country wants and needs and historical pay-outs that align well with past drought responses.

The process of ARV customisation, validation and risk transfer parameter setting is revisited by each country, to the extent necessary, before each insurance renewal date.

8. EARLY WARNING, NORMALS & ALTERNATIVE DATA

As noted above, ARV outputs such as final end-of-season WRSI, populations affected and response costs can be estimated and monitored throughout a rainfall season as the rainfall data is reported. ARV does this in two ways.

At the WRSI level, specifically the pixel WRSI that can be seen on maps in the software, if a season is on-going and not yet completed, ARV uses reported rainfall up to and including the most recent dekad and then uses normal rainfall to complete the season and therefore the WRSI calculation to estimate an end-of-season, final WRSI value. The normal rainfall data used is the average determined by taking the arithmetic mean of the historical satellite-based rainfall for each dekad and pixel. The average starts from the first fully complete year of satellite-based rainfall for each dataset (e.g. 2001 for RFE2 and 1983 for ARC2), up to the most recently completed year.[24] As, by nature, normal dekadal rainfall doesn't capture in-season variability, it therefore underestimates the magnitude and frequency of actual dekadal rainfall deficits, which – particularly at the beginning of the season – can create a more optimistic picture of what can happen in the remainder of the season.

During an on-going planting window, when planting opportunities are yet to occur or can still occur in the remaining dekads of the planting window, ARV users can choose how to use the normal data to estimate

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[22] When the drought risk in a country cannot be covered with one set of parameters, ARV uses *fusion projects* to combine two or more projects into one set of response costs, which are the basis for determining risk transfer parameters. A fusion project determines RTPs over the combined response costs of the underlying projects, instead of evaluating each project separately.

[23] See ARC Risk Transfer Note for more information.

[24] This definition of the normal is also applied to the pixel WRSI values. These pixel normal WRSI values can be seen in the normal WRSI and compare to normal WRSI maps calculated by and displayed in ARV (see ARV Quick Start Manual)

future possible planting opportunities, and therefore how to present the pixel WRSI information on map displays. ARV allows users to do this by selecting a planting opportunity aggregation domain (see Annex 2):

- By selecting "Actual Plantings" as the planting opportunity aggregation domain, only possible planting dekads found using actual dekadal rainfall reported in the planting window at each pixel are taken into account. For monitoring the water balance calculation in-season, the growing cycle can be completed using normal rainfall if the season has not yet finished. Otherwise the WRSI is not yet defined and those not-defined pixels are denoted as having "no planting" on the map.
- By selecting "Actual and Forecast Plantings" all possible planting dekads in the planting window are taken into account: those based on actual dekadal rainfall and on normal dekadal rainfall for the period of the growing cycle for which rainfall is yet to be reported.
- By selecting "Actual and Forecast Plantings, only when planting has started", if one possible planting dekad has been found using actual dekadal rainfall reported in the planting window, all possible planting dekads in the planting window are taken into account: those based on actual dekadal rainfall and on normal dekadal rainfall for the period of the growing for which rainfall is yet to be reported. Otherwise the WRSI is not yet defined and those not-defined pixels are denoted as having "no planting" on the map.

At the estimated populations affected and response costs level, ARV looks forward to the end of the season in a different way. Instead of finishing the WRSI calculation with normal rainfall for rainfall that has not yet been reported, the WRSI calculation is finished using available historical rainfall years. The approach overcomes some of the overestimation issues outlined above with respect to using normal rainfall and provides a spread of possible future end-of-season scenarios. Specifically, for an on-going season, ARV uses actual rainfall up to and including the most recently reported dekad and then historical rainfall for the dekads yet to be reported to calculate possible end-of-season WRSI values. For example, for RFE2-based WRSI values during an on-going 2015 rainfall season, ARV calculates the WRSI by finishing the season with rainfall from 2001, 2002, 2003 and so on up to and including 2014 respectively, generating 14 possible end-of-season WRSI scenarios.

For each historical year, these WRSI end-of-season scenarios are aggregated at the polygon level and used to estimate populations affected and response costs using the methodology outlined above to create 14 possible end-of-season projections of these indicators. These projections can be seen in the "in-season" populations affected and response costs graphs in ARV. They give users an indication of what could happen in the remainder of the season given what has happened before. The spread in the projections denotes the rainfall-related uncertainty in the final ARV populations affected and response costs estimates – and therefore potential insurance pay-outs – for the remainder of the season. At the end of the season, when all actual rainfall is reported and no historical rainfall is needed, all the projections report the same value: the final ARV populations affected and response costs estimates for the season.[25]

This approach of using historical rainfall to complete the season, and then creating projections of indicators based on that rainfall, also allows for the application of seasonal forecasts to these projections based on an analogous years approach.[26] This functionality, initially developed for ARV in partnership with the International Research Institute for Climate and Society (IRI) at Columbia University, has been currently disabled in ARV.

If any rainfall data is missing in RFE2, or from the period January 2014 onwards for ARC2 and TAMSAT, that missing data is replaced by Alternative Data, automatically calculated by ARV (see Annex 1). The Alternative

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[25] See ARV Quick Start Manual for more information.
[26] See ARV Seasonal Climate Forecasts for Enhanced Drought Impact Estimates note from 2011.

Data is determined by taking the arithmetic mean of the historical satellite-based rainfall for the dekad (or day in the case of ARC2) and pixel for the available rainfall in the preceding thirty years as of today, or, if thirty years are not available (as is the case of RFE2, for example), for the preceding years that are available starting with the first year for which data is available for every dekad in the year (i.e. 2001 in the case of RFE2).

9. HISTORICAL DATA FOR INSURANCE RISK ASSESSMENT WHEN USING RFE2

For each country and season, ARV produces historical WRSI, population affected and response cost estimates using the methodology outlined above. The number of historical values produced depends on the number of years included in the rainfall dataset selected as the input into the model. By using ARC2, or TAMSAT, ARV can produce consistent historical values going back to 1983. However, if countries selected RFE2 as the input rainfall dataset, ARV can only produce consistent historical values going back to 2001. Obviously, for the purposes of insurance risk assessment of RFE2-based contracts, having the longest possible consistent historical dataset available for analysis is preferable. Moreover it would be important to study the well-known recent severe drought events, such as 1984 in East and West Africa and 1991/2 in southern Africa, both of which are captured in the ARC2 and TAMSAT datasets but not in RFE2. While ARC2 and RFE2 are both produced by NOAA and very similar, the ARC2 data exhibits a systematic dry bias when compared to the RFE2 data so the RFE2 dataset cannot be simply extended by adding on ARC2 data for the period 1983-2000 without some kind of adjustment to that data.[27]

In response to this problem, the ARC Secretariat Technical Team has regressed RFE2 data against ARC2 data in order to extend the RFE2-based results back in time and to create a historical record as if RFE2 data were available from 1983. Despite the dry bias, the results show a very close and statistically significant relationship between inter-annual variations in RFE2-derived WRSI and inter-annual variations in ARC2-derived WRSI for the period 2001-present, which means the ARC2 data can be used with confidence to extend the RFE2-based dataset back in time to create an over 30 year historical record of WRSI values consistent with RFE2 data.[28] The regression procedure used is described in Annex 4 and is carried out at the polygon-averaged WRSI level. This WRSI dataset is used to calculate population affected and response cost estimates and is used as the basis of all risk assessment work on ARC insurance contracts that are based on RFE2. It is not, however, provided within the ARV software and is calculated outside the ARV tool in spreadsheets.

This regression analysis is of course not required for insurance contracts that are based on ARC2 or TAMSAT, as these datasets start in 1983. However, using this "synthetic" RFE2 data for the period 1983-2000 for RFE2-based contracts, allows the risk assessment to be conducted consistently across all insurance contracts, irrespective of the rainfall data selected.

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[27] This is to be expected as ARC2 does not include microwave sensor input data.
[28] ARC2 is produced by NOAA using a very similar methodology as for RFE2, but it does not include microwave sensor data as an input, thus the strong agreement is not surprising.

ANNEX 1: RAINFALL DATASET SPECIFICATIONS & PROCESSING

NOAA produces two types of satellite-based rainfall data estimates: RFE2 and ARC2. The raw data produced by NOAA for both datasets is processed before use in ARV, as outlined below:

RFE2 Data

The raw RFE2 data is available directly from NOAA via ftp server at ftp://ftp.cpc.ncep.noaa.gov/fews/newalgo_est_dekad/. The "Read Me" text file, RFE2.0_10day_readme.txt, providing information about the RFE2 data is available at the NOAA FTP-site. Full metadata can be found at http://www.cpc.ncep.noaa.gov/products/fews/data.htm. The first year for which RFE2 data is available for every dekad in the year is 2001.

The following steps are performed on the data before it is used in ARV:

Step 1. Each file downloaded via FTP protocol from NOAA comes as a *.gz archive containing one binary file inside. The naming convention for a RFE2 data file produced by NOAA is as follows:

10day_precip.bin.YYYYMMP

where YYYY is the four digit year, MM is the two digit month and P is either 1, 2 or 3 depending on whether the file refers to RFE2 for the first, middle or last dekad in the month.

The geographic coverage of each file is -40.00S to 40.00N northward and 20.00W to 55.00E eastward which corresponds to 751 pixels in the east-west direction and 801 pixels in south-north direction. The data contained within the file is in single precision floating point format.

Step 2. Before use in ARV all raw RFE2 data values at each pixel are rounded to the nearest integer using symmetric arithmetic rounding and any pixel with a RFE2 value higher than 253mm is replaced by the value 253.

Step 3. To date there is no missing data in the RFE2 record since 2001. If there is any missing data in the future, that missing data will be replaced by ARV with the Alternative Data for that pixel and dekad. The Alternative Data is defined as the arithmetic mean of the historical data for each dekad and pixel for preceding thirty years that are available as of this year, or, if thirty years are not available (as is the case of RFE2), for the preceding years that are available starting with the first year for which data is available for every dekad in the year (i.e. 2001 in the case of RFE2).[29]

ARC2 Data

The raw daily ARC2 data is available directly from NOAA via ftp server at ftp://ftp.cpc.ncep.noaa.gov/fews/fewsdata/africa/arc2/bin/. The "Read Me" text file providing information about the data is available at ftp://ftp.cpc.ncep.noaa.gov/fews/fewsdata/africa/arc2/ARC2_readme.txt. Full metadata can be found at https://catalog.data.gov/harvest/object/c5170f0f-9094-4d54-8cad-95cae0c3d237/html.

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[29] This means that if RFE2 data will be missing in the future, but before thirty years of RFE2 data is available, the normal data used to fill-in those missing data points will change as new RFE2 data is reported. Once thirty years of RFE2 data is available, the normal used to fill-in missing data during that thirty year period will no longer change.

The raw ARC2 data is provided by NOAA in daily format. There are missing daily values in the ARC2 data history from 1983 to 2013. For use in ARV these missing daily values have been filled in using a similar procedure to that outlined above for missing data in RFE2. For missing data in the period 1st January 1983 to 31st December 2013, missing data has been replaced with the arithmetic mean of the available historical data for that day and relevant pixel in the 1st January 1983 to 31st December 2012 period. To calculate this arithmetic mean, the raw daily ARC2 data for every day and pixel is first rounded to the nearest eighth (8th) decimal place using symmetric arithmetic rounding. Once the arithmetic mean of the available historical data for each day and pixel in the 1st January 1983 to 31st December 2012 period is calculated using this procedure, the arithmetic mean value is also rounded to the nearest eighth (8th) decimal place using symmetric arithmetic rounding. Any missing days from 1st January 2014 onwards will be filled in using the Alternative Data procedure outlined below.

Specifically, the following steps are performed on the raw daily ARC2 data before it is used in dekad format in ARV:

Step 1. Each file downloaded via FTP protocol from NOAA comes as a *.gz archive containing one binary file inside. The naming convention for a RFE ARC2 Data file produced by NOAA is as follows:

daily_clim.bin.YYYYMMDD.gz

where YYYY is the four digit year, MM is the two digit month and DD is the two digit day.

The geographic coverage of each file is -40.00S to 40.00N northward and 20.00W to 55.00E eastward which corresponds to 751 pixels in the east-west direction and 801 pixels in south-north direction. The data contained within the file is in single precision floating point format.

Step 2. If there is any missing data for days from 1st January 2014 onwards, that missing data will be replaced by ARV with the Alternative Data for that pixel and day. The Alternative Data is defined as the arithmetic mean of the historical data for each day and pixel for the preceding thirty years that are available.

Step 3. Before use in ARV the daily ARC2 data at each pixel is summed up into cumulative ARC2 data values for each dekad going back to and including Dekad 1 1983.

To calculate the cumulative ARC2 data value for each pixel for a given dekad, the daily ARC2 data, which has been filled in for missing values as outlined above, for each pixel for each day associated with that dekad are first rounded to the nearest eighth (8th) decimal place using symmetric arithmetic rounding and are then summed.

Step 4. These dekad-level values are then rounded to the nearest integer using symmetric arithmetic rounding, and any pixel with a value for a dekad higher than 253mm is replaced by the value 253, to produce the final dekadal ARC2 data.

TAMSAT Data

ARV uses the most recent TAMSAT dataset, called the **T**AMSAT **A**frican **R**ainfall **C**limatology **A**nd **T**ime-series (**TARCAT Version 2.0**) released in January 2012.[30] It is produced in daily and ten-daily (dekadal) cumulative rainfall estimates at 0.0375 degrees latitude by 0.0375 degrees longitude resolution for the whole of Africa from 1983. ARV uses the dekadal product and aggregates the data onto the lower resolution 0.1 degrees

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[30] http://www.met.reading.ac.uk/~tamsat/data/

latitude by 0.1 degrees longitude grid of the NOAA products.   The TAMSAT data used within ARV has not yet gone through the same quality control and due diligence process as outlined above for RFE2 and ARC2 and cannot therefore be yet used to support ARC insurance contracts. However no country has yet requested to use the dataset and have only used it for comparison purposes. As soon as a request is made, this due diligence will be conducted by the ARC Secretariat Technical Team to enable the country or countries in question to take out insurance based on TAMSAT.

ANNEX 2: WRSI CALCULATION

This Annex provides a formal definition of the water balance calculation used in the ARV software. After defining the input data, all subsequent calculations are defined and, where applicable, clarified with examples.

Input Data

The following input data is defined at the country-level for each season, i.e. for all 0.1 degrees latitude by 0.1 degrees longitude pixels in the country.

FIRST YEAR WITH FULL RANGE RAINFALL AVAILABLE
Symbol: FRY
Unit: year
Domain: integer; $1900 \leq FRY \leq EY$
Description: The earliest year for which dekadal rainfall is available for all dekads in the year.

EARLIEST YEAR
Symbol: EY
Unit: year
Domain: integer; $1900 \leq EY < CY$
Description: The earliest year to start the calculations, excluding calculations on available dekadal rainfall for earlier years.

POLICY YEAR
Symbol: CY
Unit: year
Domain: integer; CY = {Year of Policy Issuance Date}
Description: The year of the Policy Issuance Date.

START OF SEASON
Symbol: SOS
Unit: dekad
Domain: integer; $1 \leq SOS \leq 36$
Description: Start of the agricultural season. Not directly used in calculations; it is used for defining the domain of PWS and PWE only.

END OF SEASON
Symbol: EOS
Unit: dekad
Domain: integer; $1 \leq EOS \leq 36$
Description: End of the agricultural season. Not directly used in calculations; it is used for defining the domain of PWS and PWE only.

RAIN PLANTING THRESHOLD 1
Symbol: PTH1
Units: mm/dekad
Domain: integer; 0 ≤ PTH1 ≤ 100
Description: If Water Requirement Threshold 1 is specified, this parameter should not be specified and must be left blank. If specified, and if all other planting criteria are satisfied, only dekads that record rainfall equal to or greater than PTH1 can be considered as possible planting dekads.

RAIN PLANTING THRESHOLD 2
Symbol: PTH2
Units: mm/dekad
Domain: integer; 0 ≤ PTH2 ≤ 100
Description: This parameter does not need to be specified and can be left blank. If Water Requirement Threshold 2 is specified, this parameter should not be specified and must be left blank. If specified, and if all other planting criteria are satisfied, only dekads that are followed by rainfall equal to or greater than PTH2 in the subsequent dekad can be considered as possible planting dekads.

RAIN PLANTING THRESHOLD 3
Symbol: PTH3
Units: mm/dekad
Domain: integer; 0 ≤ PTH3 ≤ 100
Description: This parameter does not need to be specified and can be left blank. If Water Requirement Threshold 3 is specified, this parameter should not be specified and must be left blank. If specified, and if all other planting criteria are satisfied, only dekads that are followed by rainfall equal to or greater than PTH3 in the dekad two dekads ahead can be considered as possible planting dekads.

WATER REQUIREMENT THRESHOLD 1
Symbol: WR1
Units: percentage points
Domain: integer; 0 ≤ WR1 ≤ 100
Description: If Rain Planting Threshold 1 is specified, this parameter should not need to be specified and must be left blank. If specified, and if all other planting criteria are satisfied, only dekads that record rainfall equal to or greater than WR1 multiplied by the crop Water Requirement (WR) for that potential growing dekad can be considered as possible planting dekads.

WATER REQUIREMENT THRESHOLD 2
Symbol: WR2
Units: percentage points
Domain: integer; 0 ≤ WR2 ≤ 100
Description: This parameter does not need to be specified and can be left blank. If Rain Planting Threshold 2 is specified, this parameter should not be specified and must be left blank.   If specified, and if all other planting criteria are satisfied, only dekads that are followed in the subsequent dekad by rainfall equal to or greater than WR2 multiplied by the crop Water Requirement (WR) for that potential subsequent growing dekad can be considered as possible planting dekads.

WATER REQUIREMENT THRESHOLD 3
Symbol: WR3
Units: percentage points
Domain: integer; 0 ≤ WR3 ≤ 100
Description: This parameter does not need to be specified and can be left blank. If Rain Planting Threshold 3 is specified, this parameter should not be specified and must be left blank.   If specified, and if all other planting criteria are satisfied, only dekads that are followed two dekads ahead by rainfall equal to or

greater than WR3 multiplied by the crop Water Requirement (WR) for that potential growing dekad two dekads ahead can be considered as possible planting dekads.

EXCESS RAIN REDUCTION THRESHOLD
Symbol: ETH
Units: mm/dekad
Domain: integer; $1 \leq ETH \leq 200$
Description: For every dekad in the growing period of the crop for which the soil water moisture (SW) surplus is greater than ETH, the WRSI is decreased by ERV.

EXCESS RAIN REDUCTION VALUE
Symbol: ERV
Unit: WRSI units
Domain: integer, $1 \leq ERV \leq 15$
Description: The amount by which the WRSI will be reduced when an excess rainfall event, defined by the ETH, is applicable.

PLANTING OPPORTUNITY AGGREGATION METHOD
Symbol: POAM
Domain: {Maximum, Average, First}
Description: The method that is applied to aggregate the WRSI calculated from each possible planting dekad to which the POAD is applicable.

PLANTING OPPORTUNITY AGGREGATION DOMAIN
Symbol: POAD
Domain: {Actual Plantings; Actual and Forecast Plantings; Actual and Forecast Plantings, only when planting started}
Description: The definition of the domain for the possible planting dekads to be taken into account when aggregating the corresponding WRSI values.

CROP DEVELOPMENT END OF PHASE LENGTH PERCENTAGE
Symbol: CP_{phase}
Domain: $0 < CP \leq 1$ for each phase, where $0 \leq phase \leq 8$ and phase 0 defines the start of the growing period
Description: The percentage of LGP completed at the end of each crop development phase.

CROP DEVELOPMENT END OF PHASE KC COEFFICIENTS
Symbol: CKC_{phase}
Domain: $0 < CKC \leq 2$ for each phase, where $0 \leq phase \leq 8$ and phase 0 defines the start of the phase 1 CKC coefficient
Description: The definition of the crop coefficient for each crop development phase.

The following input data is defined at the pixel level as matrices. These matrices represent center points in a defined geographical grid with a 0.1 degree resolution in both directions (latitude and longitude). One point out of this matrix represents a pixel, or grid point. For each grid point a full water balance calculation is performed.

CALCULATION MASK
Symbol: CM
Domain: integer; {0, 1}
Description: The definition of the geographical calculation domain of the country/season considered. For every grid point with a value of 1 a water balance is calculated.

LENGTH OF THE GROWING PERIOD
Symbol: LGP
Unit: dekads
Domain: integer; 5 ≤ LGP ≤ EOS-SWE
Description: The length of the growing period of the crop.

PLANTING WINDOW START DEKAD
Symbol: PWS
Unit: dekad
Domain: integer; SOS ≤ PWS ≤ EOS-LGP-1
Description: The first dekad in the season for which planting is considered.

PLANTING WINDOW END DEKAD
Symbol: PWE
Unit: dekad
Domain: integer; SOS ≤ PWE ≤ EOS-LGP-1
Description: The last dekad in the season for which planting is considered.

PRE SEASON KC
Symbol: PSKC
Domain: float; 0 ≤ KC ≤ 2
Description: The crop coefficient, KC, that is used in the soil water moisture initialisation phase.

WATER HOLDING CAPACITY
Symbol: WHC
Unit: mm
Domain: float; 0 ≤ WHC ≤ 253
Description: The maximum amount of water that the soil is able to hold.

PERCENTAGE EFFECTIVE RAIN
Symbol: EFFR
Domain: integer; 1 ≤ EFFR ≤ 200
Description: A correction factor applied to the recorded and normal dekadal rainfall.

DEKADAL RAINFALL
Symbol: $R_{y,d}$
Units: mm/dekad
Domain: integer; $0 \leq R_{y,d} \leq 253$ where EY ≤ y ≤ CY and 1 ≤ d ≤ 36
Description: The recorded amount of rainfall for a given dekad in a given year.

NORMAL EVAPOTRANSPIRATION
Symbol: Et_d
Unit: mm/dekad
Domain: integer; $0 \leq Et_d \leq 253$ where 1 ≤ d ≤ 36
Description: The amount of evapotranspiration that is expected to occur for this dekad at this location if a sufficient water source were available for a reference crop.

GENERIC CALCULATIONS

Note: No rounding is used in the calculations, except where clearly stated in the mathematical expression.

For all dekads in a year the normal rainfall, RN_d, is calculated as follows and rounded to the nearest integer:

$$RN_d = \left\lceil \frac{\sum_{y=FRY}^{CY-1}(R_{y,d})}{CY-FRY} \right\rceil \quad for \quad 1 \leq d \leq 36 \quad (1)$$

Next, the applicable crop development phase is determined for each growing dekad, gd, in the growing cycle ($1 \leq gd \leq LGP$) as follows:

First determine the growing period percentage (gpc) for each gd as:

$$gpc = (gd - 0.5)/LGP \quad (2)$$

The applicable crop development phase (gph) for a growing dekad is the phase that corresponds to the smallest CP_{phase} which is greater than the growing dekad percentage for the growing dekad, i.e.

$$gph = \min_{CP_{phase}>gpc}(phase) \quad for \quad 1 \leq phase \leq 8 \quad (3)$$

The applicable crop coefficient KC for a growing dekad is a linear interpolation of the CKC values:

$$KC_{gd} = CKC_{gph-1} + (\frac{CKC_{gph}-CKC_{gph-1}}{CP_{gph}-CP_{gph-1}}) * (gpc - CP_{gph-1}) \quad (4)$$

For illustration, an example is given below. Consider maize which has the following crop definition:

Phase	CP_{phase}	CKC_{phase}
0	0 %	0.3
1	3 %	0.3
2	6 %	0.3
3	9 %	0.3
4	13 %	0.3
5	17 %	0.3
6	40 %	1.2
7	79 %	1.2
8	100 %	0.6

These are the calculated values for each gd assuming a maize crop with a LGP of 5 dekads:

gd	gpc	gph	CP_{gph-1}	CKC_{gph-1}	CP_{gph}	CKC_{gph}	KC_{gd}
1	10 %	4	9 %	0.3	13 %	0.3	0.3000
2	30 %	6	17 %	0.3	40 %	1.2	0.8087
3	50 %	7	40 %	1.2	79 %	1.2	1.2000
4	70 %	7	40 %	1.2	79 %	1.2	1.2000
5	90 %	8	79 %	1.2	100 %	0.6	0.8857

Calculation of the Water Balance

For each grid point and dekads d within the range $PWS \leq d \leq PWE$, a water balance calculation is performed. After, the WRSI values calculated from each possible planting dekad are aggregated using $POAD$ and $POAM$.

Dekadal working rainfall is used in the water balance calculation. The working rainfall (Rw_{gd}) for a growing dekad is defined as:

$$Rw_{gd} = (R_{y,d} * (\frac{EFFR}{100})) \quad (5)$$

If actual dekadal rainfall data $R_{y,d}$ is not available for a dekad (*i.e.* it has not yet been reported or is missing), weighted normal rain is used and defined as follows:

$$Rw_{gd} = (RN_d * (\frac{EFFR}{100}))$$ (6)

A water balance is calculated for all dekads d within the range $PWS \leq d \leq PWE$ using the following method:

First check if planting is possible:

$$No\ planting\ if\ any\ of\ the\ following\ occur:$$
$$Rw_d < PTH1\ or\ Rw_{d+1} < PTH2\ or\ Rw_{d+2} < PTH3\ or\ Rw_d < WR1 * WR_{gd=1} or\ Rw_{d+1} < WR2 *$$
$$WR_{gd=2}\ or\ Rw_{d+2} < WR3 * WR_{gd=3}$$ (7)

If any of the parameters PTH1, PTH2, PTH3, WR1, WR2 or WR3 are not specified, their respective equations can be ignored in the logic operation described by equation (7).

If planting is not possible the result WRSI at the end of the growing cycle, $WRSI^d$, is undefined:

$$WRSI^d = undefined$$ (8)

Otherwise the dekad d is a possible planting dekad (ppd) and the following calculation is performed for that dekad:

The soil water moisture initialisation phase is defined as the 10 dekads preceding the ppd dekad. The soil water moisture (SW) for the first dekad in the soil water moisture initialisation phase is initialised at 0, *i.e.*

$$SW_{ppd-11} = 0$$ (9)

The WRSI at the start of a water balance calculation is set at 100:

$$WRSI_{ppd-1} = 100$$ (10)

The Water Requirement (WR) for a growing dekad, *gd*, is calculated as follows:

$$WR_{gd} = Et_{gd} * KC_{gd}$$ (11)

The Total Water Requirement (TWR) for the entire growing cycle is calculated as follows:

$$TWR = \sum_{gd=ppd}^{ppd+LGP-1} Et_{gd} * KC_{gd}$$ (12)

Initialisation of the soil water moisture is computed by iteration over the dekads (d) in the period $ppd - 10 \leq d \leq ppd - 1$ as follows:

For each d:

$$SW_d = \min(WHC, \max(0, SW_{d-1} + Rw_d - Et_d * PSKC))$$ (13)

After the initialisation of soil water moisture, the water balance is calculated for the growing dekads (gd) within the range $ppd \leq gd < ppd + LGP - 1$ as follows:

For each gd:
$$SW_{gd}^{unlimited} = SW_{gd-1} + Rw_{gd} - Et_{gd} * KC_{gd} \tag{14}$$

$$SW_{gd} = \min(WHC, \max(0, SW_{gd}^{unlimited}))$$

And then:

$$\text{If } SW_{gd}^{unlimited} < 0 \; \rightarrow WRSI_{gd} = WRSI_{gd-1} + \frac{(SW_{gd}^{unlimited} * 100)}{TWR} \tag{15}$$

$$\text{If } SW_{gd}^{unlimited} > WHC + ETH \; \rightarrow \; WRSI_{gd} = WRSI_{gd-1} - ERV \tag{16}$$

$$\text{Otherwise, if } 0 \leq SW_{gd}^{unlimited} \leq WHC + ETH \; \rightarrow \; WRSI_{gd} = WRSI_{gd-1} \tag{17}$$

The resulting WRSI value is the WRSI at the end of the growing cycle, $WRSI^{ppd}$, defined as:

$$WRSI^{ppd} = WRSI_{gd=(ppd+LGP-1)} \tag{18}$$

Below is an example water balance calculation for illustration purposes.

Crop: Maize   LGP: 10   WHC: 125mm   PSKC: 0.25   ERT: 100mm   ERV: 3
Calculating Planting Dekad 2012/30
TWR: 416.8mm $WRSI^{ppd=30}$ = 80.5

gd	$Rw_{y,d}$	Et_{gd}	KC_{gd}	WR_{gd}	$SW_{gd}^{unlimited}$	SW_{gd}^{l}	$Acc.Def.$	$Excess\ Event$	$WRSI_{gd}$
2012/20	0.0	36.9	0.25	9.2	-9.2	0.0			
2012/21	12.0	39.3	0.25	9.8	2.2	2.2			
2012/22	0.0	41.5	0.25	10.4	-8.2	0.0			
2012/23	0.0	43.1	0.25	10.8	-10.8	0.0			
2012/24	0.0	44.8	0.25	11.2	-11.2	0.0			
2012/25	0.0	47.4	0.25	11.9	-11.9	0.0			
2012/26	0.0	51.1	0.25	12.8	-12.8	0.0			
2012/27	0.0	55.1	0.25	13.8	-13.8	0.0			
2012/28	0.0	58.6	0.25	14.7	-14.7	0.0			
2012/29	0.0	60.0	0.25	15.0	-15.0	0.0			
2012/30	24.0	59.4	0.30	17.8	6.2	6.2	0.0	0	100.0
2012/31	0.0	56.5	0.30	16.9	-10.8	0.0	10.8	0	97.4
2012/32	14.0	52.7	0.61	32.3	-18.3	0.0	29.1	0	93.0
2012/33	19.0	49.7	1.00	49.9	-30.9	0.0	60.0	0	85.6
2012/34	49.0	48.1	1.20	57.7	-8.7	0.0	68.7	0	83.5
2012/35	57.0	47.6	1.20	57.1	-0.1	0.0	68.8	0	83.5
2012/36	101.0	47.1	1.20	56.5	44.5	44.5	68.8	0	83.5
2013/1	89.0	45.7	1.20	54.9	34.1	78.7	68.8	0	83.5
2013/2	24.0	42.9	1.03	44.2	-20.2	58.5	68.8	0	83.5
2013/3	210.0	39.8	0.74	29.5	180.5	125.0	68.8	1	80.5

*Acc. Def. Stands for "Accumulated Deficit", defined as the accumulation of the negative unlimited SW values.

Aggregation of the Water Balance Values

Unlike the classic WRSI calculation where only one planting dekad is considered for a season and for the water balance calculation, ARV can consider multiple planting opportunities defined by possible planting

dekads. ARV also has forecasting capabilities. This is achieved by completing a not yet finished season with normal dekadal rainfall and calculating a WRSI for all actual and forecast possible planting dekads. Using the definition of a possible planting dekad given above, actual possible planting dekads are identified using actual reported rainfall data and forecast possible planting dekads are those identified using normal dekadal rainfall data for the period of the growing cycle for which actual rainfall is yet to be reported.

The calculated WRSIs for all possible planting dekads are aggregated to one WRSI value for a grid point. This aggregation is driven by two methodologies that are specified by the country:

– Planting Opportunity Aggregation Domain (POAD) and
– Planting Opportunity Aggregation Method (POAM)

POAD Selection Options	
Actual Plantings	Only possible planting dekads found using actual dekadal rainfall reported in the planting window are taken into account. For monitoring the water balance calculation in-season, the growing cycle can be completed using normal rainfall if the season has not yet finished. Otherwise the WRSI is not yet defined.
Actual and Forecast Plantings	All possible planting dekads in the planting window are taken into account: those based on actual dekadal rainfall and on normal dekadal rainfall for the period of the growing cycle for which rainfall is yet to be reported.
Actual and Forecast Plantings, only when planting has started	If one possible planting dekad has been found using actual dekadal rainfall reported in the planting window, all possible planting dekads in the planting window are taken into account: those based on actual dekadal rainfall and on normal dekadal rainfall for the period of the growing for which rainfall is yet to be reported. Otherwise the WRSI is not yet defined.

Important Note: once actual dekadal rainfall data is reported for all dekads in the planting window, the results from any POAD selection are the same. The impact of the POAD is only on ARV monitoring during the season and not on the final WRSI value of the grid point.

After limiting the solution space by POAD, the final WRSI is aggregated over the possible planting dekads that meet the POAD. Undefined WRSI values are not taken into account. If the solution space defined by POAD is empty, that is only undefined WRSI values are available, the WRSI is defined as zero, otherwise the table below defines the aggregation method to calculate the final WRSI for a grid point:

POAM Selection Options	
First	The WRSI value calculated from the first (earliest) possible planting dekad identified in the planting window.
Maximum	The maximum WRSI value calculated from all the possible planting dekads identified in the planting window.
Average	The arithmetic average of all the WRSI values calculated from all the possible planting dekads identified in the planting window.

After this aggregation at grid point level a WRSI value exists for every grid point considered.

WRSI for Rangeland

Given the way ARV calculates WRSI, the settings can be adjusted to model the impact of rainfall on forage, or rangeland, as well as for rain-fed crops. As a default setting for rangeland WRSI calculations, ARV assumes a 50 day (5 dekad) grass crop and calculates the WRSI for that crop assuming it is planted every dekad in the season. The model assumes the grass crop is "planted" in every dekad, even if the rainfall is zero. This is equivalent to setting the rain planting threshold (PTH) to 0mm. As a result a WRSI value for each dekad within the season defined is calculated and as such this WRSI closely mimics the Normalized Difference Vegetation Index (NDVI) – the remote sensing data type that is usually used to monitor rangeland – greening and browning throughout a season as rainfall is received. These WRSI dekadal values are averaged across the season – using an average planting opportunity aggregation method (POAM) – to give an indication of seasonal performance.

<h2 style="background-color:green;color:white">ANNEX 3: VULNERABILITY MODELLING METHODOLOGY</h2>

In order to quantify drought impact, the ARV model compares the average WRSI-to-Benchmark deviation in each area unit (or "polygon") to static polygon-specific drought Vulnerability Profiles. These Vulnerability Profiles establish the link between drought severity and percentage of the population considered as significantly affected. Specific values are calculated for the three chosen Drought Impact Calibration Points and the rest of the profile is interpolated linearly. More precisely,

- The Vulnerability Profile of each polygon consists of four Vulnerability Levels (corresponding to the Drought Detection Point and the 1st / 2nd / 3rd Drought Impact Calibration Points respectively, and the interpolations between those values. In turn, the Drought Detection and Impact Calibration Points are defined by specific WRSI deviations from a benchmark.
- The Vulnerability Level for the Drought Detection Point is specifically set to zero, while the Vulnerability Levels corresponding to the 1st, 2nd and 3rd Drought Impact Calibration Points are generated through an analysis of the most recently available household survey data which determines the extent to which households in a specific area unit are unable to cope in the event of a drought. Generally this is done by determining the percentage of households that are both a) exposed to drought (defined by their percentage of total income generated by agriculture-related activities), and b) have low resilience to income shocks (defined by their ranking on a wealth scale compared to the national poverty rate).

To facilitate the generation of Vvulnerability Profiles, a standard methodology has been developed by the ARC Secretariat.[31] It consists of the following steps:

- Categorisation of the exposure level of each household into four different groups – exposed to a drought severity of T_1, T_2 or T_3, or not exposed – based on the share of total income that would be lost as a direct consequence of the corresponding drought severity, as compared to a threshold value.
  - The exposed income (EI) is all income that is generated from agricultural-related activities and livestock. What exactly is included in EI can depend on the drought severity: while income from crop production is always included (meaning that any drought severity is considered to have an impact on crop production and its derived income), livestock-related income is often considered to be exposed only once the drought severity exceeds a certain level. In any case, income exposed to more severe drought cannot be less than income exposed to milder droughts.

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[31] In 2014 it was adopted by the World Bank to for its Drylands Report (forthcoming 2016)

− The loss of EI due to drought is considered to increase proportionally to the WRSI-to-Benchmark deviation by a factor (called the Scaling Factor, or SF) that combines the impact of WRSI deviation on agricultural yields and the impact thereof onto agricultural income of households (the SF is set during the customisation process and generally ranges between 1 and 2).

− The loss of EI (in %) is then averaged to the total income. For a household to be classified as "exposed", the resulting loss of its total income (in %) should exceed a threshold value (called the Loss of Livelihood Threshold, or LLT). (The LLT is set during the customisation process and generally ranges between 8 and 15%).

− Since the loss of EI is proportional to the WRSI-to-Benchmark deviation, the less EI a household has, the higher the threshold drought severity that will result in the household being considered as exposed.

− In summary:

$$EI_{T1} = Ag \text{ (+ Ls if appropriate)}$$
$$EI_{T2} = Ag \text{ (+ Ls if appropriate)}$$
$$EI_{T3} = Ag \text{ (+ Ls if appropriate)}$$
$$EI_{T1} \leq EI_{T2} \leq EI_{T3}$$
$$HE_i = \text{if } [EI_i * SF * T_i \geq LLT, 1, 0]$$

where:

EI = Share of Exposed Income (in % of total income)
Ag = Share of total income generated from agricultural related activities (in %)
Ls = Share of total income generated from livestock related activities (in %)
SF = Scaling Factor
LLT = Loss of Livelihood Threshold
T = Drought Impact Calibration Point
i = 1, 2 or 3
HE_i = Household Exposure to drought of severity T_i
1 = True
0 = False

• Categorisation of the resilience level of each household into two groups – resilient or unresilient – based on the household Wealth Index (WI) as a proxy indicator of their poverty status. Sorting the households by ascending WI allows for the ranking of households in the dataset from the poorest to the richest. The WI percentile corresponding to the share of people below the national poverty line (WI_{PL}) is used as threshold value to determine whether a household is above or below the poverty line in the specific dataset, i.e.

$$LR = \text{if } [WI < WI_{PL}, 1, 0]$$

where:

LR = Low Resilient household
WI = Wealth Index
PL = Poverty Line (National Poverty Line preferred wherever available)
1 = True
0 = False

- Categorisation of the vulnerability (V) of each household based on its combined exposure and resilience level, i.e.

$$HV_i = LR * HEI_i$$

where:

HV = Household Vulnerability to drought of severity T_i
LR = Low Resilient household
i = 1, 2 or 3

- Calculation of the percentage of total households categorised as Vulnerable within each polygon, for drought of severities T_1, T_2 or T_3 (depending on the representativeness of the household survey data). Those three percentage values combined, plus the value of zero for the Drought Detection Point, and the interpolation between them, constitute the Vulnerability Profile of the polygon.

What has been outlined above is the suggested methodology for vulnerability profiling, but countries are free to develop different approaches, bearing in mind that the common goal is to determine the percentages of people that are to be considered as vulnerable to drought severities T_1, T_2 or T_3 in each polygon. Countries who decide to apply the standard methodology (and have the required data) can customise all parameters mentioned above to better reflect their internal situation. These include:

- The Drought Detection Point and Drought Impact Calibration Points, i.e. the percentage deviations of WRSI from its benchmark.
- Impact of drought on the households' income – by changing the Scaling Factor and therefore the way the WRSI-to-benchmark deviation is translated into income loss.
- Definition of exposure – by changing the threshold of excessive income loss (LLT).
- Definition of resilience – by using a different poverty indicator than the Wealth Index or by adjusting the poverty rate.

Exposure Data

- 20 CFSVAs by WFP-VAM (Angola, Benin, Burkina Faso, Burundi, Cameroon, Chad, Cote d'Ivoire, DRC, Ghana, Guinea, Madagascar (2010), Malawi, Mozambique, Rwanda, Senegal (2011), Sudan (including South Sudan), Tanzania, Uganda) ranging from 2005 to 2013;
- CSA/FAO survey on vulnerability (Mauritania, 2014)
- 4 DHSs (CAR, Ethiopia, Namibia, Swaziland) ranging from 1994 to 2007;
- 2 MICS (Togo and Guinea Bissau) 2006;
- WFP/VAM study: Kenya Livelihood Zones Baseline Survey 2008;

Figure 3: *Africa RiskView* household survey providers

- Household Economic Approach (HEA) data (Lesotho 2012)
- Vulnerability Analysis Committee data (Zambia 2011, Zimbabwe 2014);
- Vulnerability Assessment (SAP) (Niger, 2014)
- National Survey on Food and Nutrition Security (Enquête Nationale de Sécurité Alimentaire et Nutritionnelle (ENSAN)) (Mali, 2014)
- WFP PRRO Baseline Assessment (The Gambia, 2013)
- Living Standards Measurement Survey, World Bank (Nigeria, 2012/13)
- No household survey data on Eritrea was collected and placeholder vulnerability data is used in the analysis to be updated when better data can be secured. The Eritrean data was based on estimates of vulnerability in Tigray, Ethiopia.

Resilience Data

- Population living below the National and International poverty line (%) by UNDP Human Development Report 2014.
- CIA – The World Fact Book for Sudan population below the poverty line (%)
- Wealth Index from CFSVA, MICS, DHS, FSA surveys and VAC data (see exposure data)
- Poverty groups division from the HEA 2012 for Lesotho

The methodology applied to DHS and MICS surveys is the same, but the percentage of household falling in each exposure categories cannot be carried out from these databases. For countries without CFSVA the exposure distribution has been estimated by the distribution in countries with similar agro-ecological characteristics.

ANNEX 4: REGRESSED RFE VALUES FOR THE PERIOD 1983-2000 (FOR RFE2 DATA ONLY)

To enable a consistent risk assessment across all potential ARC Ltd insurance contracts, irrespective of the rainfall dataset on which they are based, the aim of this analysis is to create a dataset of polygon-average WRSI estimates for the period 1983-2000 for those insurance contracts that are based on RFE2. It is important to include years such as 1984 and 1992 as input for the risk assessment as they correspond to the worse drought events in the recent African history – events that should be considered when defining a country's and a portfolio's drought risk profile. As they start in 1983 these years are available for insurance contracts based on ARC2 and TAMSAT, but not for RFE2 (which starts in 2001) without some additional analysis to extend the dataset back in time. Relevant data available from NOAA for this analysis are:

- RFE2 rainfall estimates from 2001 to present[32]
- ARC2 rainfall estimates from 1983 to present: produced using a very similar methodology as for RFE2, but not including microwave sensor data as an input

The aim of this analysis is to find a stable relationship between the ARC2 and RFE2 datasets in order to be able to estimate how RFE2 values would have been calculated with the same algorithm and input data now used by NOAA as if they had been available since 1983.

In the approach used, RFE2-based seasonal WRSI data is regressed against ARC2-based seasonal WRSI data for each polygon considered and then a "synthetic" RFE2 WRSI is calculated for the period 1983-2000 using the regression coefficients and the ARC2 data. This analysis is carried out after January of each year ahead

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[32] RFE1 rainfall estimates from 1996 to 2000, the prototype version of RFE2, are not recommended for use by NOAA and as such are not used in this analysis. However RFE1 is still used by partners such as FEWSNET to extend the RFE2 dataset back in time.

of each ARC insurance pool (which incepts in May). Regression parameters are calculated from the two overlapping datasets over the period 2001 up to and including the most recently completed WRSI seasonal value as of end January.

For example, for the first ARC insurance pool in May 2014, the following analysis was carried out for the three countries (covering four seasons) that selected RFE2 as the basis for their inclusion in the pool:

The following countries selected RFE2 for their ARC drought insurance contracts in May 2014: Senegal (main rainfall season, May-December 2014), Mauritania (main rainfall season, July-November 2014) and Kenya (for both the short rains (August 2014-January 2015) and the long rains season (from February-June 2015)).

RFE2-based and ARC2-based WRSI values were calculated using the same WRSI settings for all countries and seasons. RFE2 and ARC2 WRSI values were extracted for the 75 polygon/seasons in the three countries for seasons starting in 2001-2013 and 1983-2013 respectively. It is important to note that only those seasons finishing by January 2014 were considered, i.e. for the Kenya long rains, only the period 2001-2013 was considered and the ongoing 2014 season WRSI value was not extracted.

Figure 4: RFE2-based WRSI (2001-2013) and ARC2-based WRSI (1983-2013) (shown as an average across all 75 polygons)

Figure 5: RFE2-based WRSI extended back to 1983 (shown as an average across all 75 polygons)

Graphically, one can see in Figure 4 how the two satellite-based rainfall estimate algorithms used by NOAA lead to WRSI estimates that are very similar for the 75 polygons/seasons. As can be expected from Figure 4, the correlation coefficients between ARC2 and RFE2 data in the overlapping period 2001-2013 are on average 93% over the 75 polygons-seasons combinations. As such one can assume the linear relationship between the two sets of data is strong and that a linear regression analysis between the two will yield statistically significant results. Indeed, all correlation coefficients are significant at the 99% confidence level for all polygons.

RFE2-based WRSI data was regressed against ARC2-based WRSI data for 75 polygons/seasons to determine polygons-specific intercepts and slopes. These parameters were tested for significance at 99% confidence level and all were found to be significantly different from zero, confirming a significantly strong linear relationship between ARC2 and RFE2-based WRSI data. RFE2-based WRSI value estimates, or "synthetic" values, for the period 1983-2000 were calculated by multiplying the ARC2-based WRSI values for each polygon by the regression coefficient for that polygon and adding the polygon intercept, i.e.
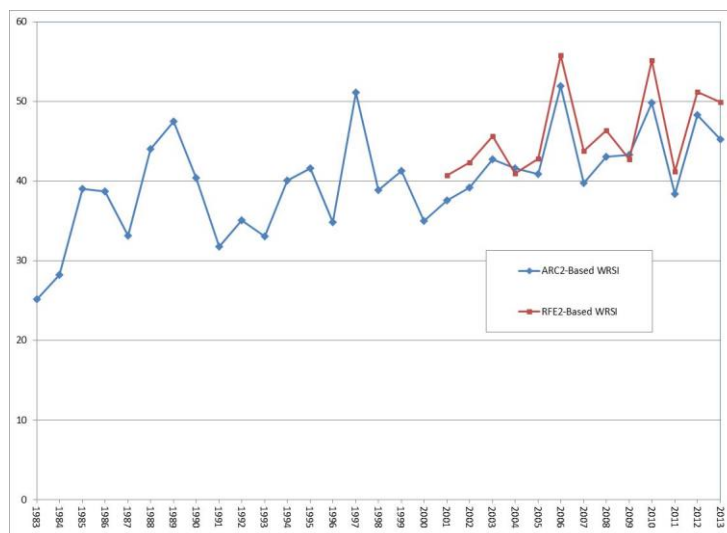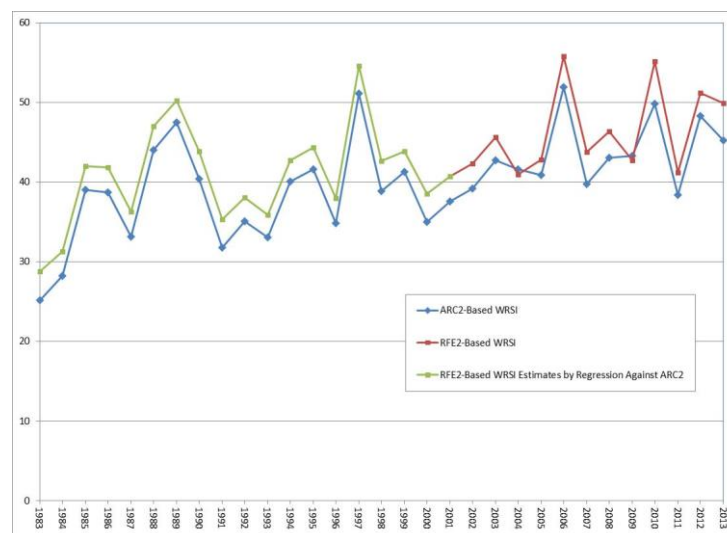
$$\text{Synthetic RFE2-Based WRSI} = (slope*\text{ARC2-Based WRSI}) + intercept$$

where the *slope* and *intercept* are the best-fit results of the linear regression. Fitted values are represented in Figure 5 in the green (for graphing purposes the average across all 75 polygons is shown).

For the second ARC insurance pool in May 2015, and for subsequent annual renewals in May of each year, the process above will be repeated using the same rules, but simply adding an additional year (or years) into the overlapping RFE2 and ARC2 period over which the linear regression is conducted.

TECHNICAL NOTE MODIFICATION SUMMARY

Date	Version Information
June 2016	Update crop options, planting vocabulary, fusion project (*Africa RiskView* V4.3)
Jan. 2016	Update planting criteria, vulnerability terminology
June 2015	Update vulnerability profile methodology, figure update
May 2015	Update data references, formatting, figure update
Feb. 2015	Draft Technical Note *Africa RiskView* V3.0
June 2013	Formula correction p.28-29
Nov. 2012	Update Data availability Annex 2
Oct. 2012	Update content, graph, figure Draft Technical Note *Africa RiskView* V2.0
July 2012	Update (move version info table, footer, title) Draft Technical Note *Africa RiskView* V2.0
May 2012	Update content Draft Technical Note *Africa RiskView* V2.0
April 2012	Draft Technical Note *Africa RiskView* V2.0
June 2011	Draft Technical Note *Africa RiskView* V1.0