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Below the Radar: Data, Narratives and the Politics of Irrigation in Sub-Saharan Africa

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ABSTRACT: Emerging narratives call for recognising and engaging constructively with small-scale farmers who have a leading role in shaping the current irrigation dynamics in sub-Saharan Africa. This paper explores whether new irrigation data can usefully inform these narratives. It argues that, for a variety of reasons, official irrigation data in sub-Saharan Africa fail to capture the full extent and diverse nature of irrigation and its rapid distributed growth over the last two decades. The paper investigates recent trends in the use of remote sensing methods to generate irrigation data; it examines the associated expectation that these techniques enable a better understanding of current irrigation developments and small-scale farmers' roles. It reports on a pilot study that uses radar-based imagery and analysis to provide new insights into the extent of rice irrigated agriculture in three regions of Tanzania. We further stress that such mapping exercises remain grounded in a binary logic that separates 'irrigation' from other 'non-irrigated' landscape features. They can stem from, and reinforce, a conventional understanding of irrigation that is still influenced by colonial legacies of engineering design and agricultural modernisation. As farmers' initiatives question this dominant view of irrigation, and in a policy context that is dominated by narratives of water scarcity, this means that new data may improve the visibility of water use by small-scale irrigators but may

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also leave them more exposed to restrictions favouring more powerful water users. The paper thus calls for moving away from a narrow debate on irrigation data and monitoring, and towards a holistic discussion of the nature of irrigation development in sub-Saharan Africa. This discussion is necessary to support a constructive engagement with farmer-led irrigation development; it is also challenging in that it involves facing entrenched vested interests and requires changes in development practices.

KEYWORDS: Irrigation, small-scale farming, water resource governance, remote sensing, data politics, narratives, sub-Saharan Africa, Tanzania

INTRODUCTION

Since 2015, the establishment of 230 indicators for monitoring progress towards the 169 targets of the 17 Sustainable Development Goals has created new expectations of development data. These increased expectations are due, in part, to the perception that data can now be compiled and analysed relatively quickly, cheaply, and over larger areas than before thanks to new technologies, including remote sensing and machine learning. Underlying these expectations is also the premise that policy makers in legislative and executive branches of government are responsive to data. In practice, however, the inclusion and interpretation of data in policy processes are mediated by narratives that are informed by pre-existing beliefs and thinking. Data interpretation is also influenced by working habits that may be resistant to alternative views, to new constellations of data or even criticisms of the empirical basis of existing datasets (Leach and Mearns, 1996; Jerven, 2015).

In this paper, we examine the interrelated issues of irrigation data, narratives and politics in sub-Saharan Africa. The dominant narrative emphasises the low levels of development of irrigated areas within sub-Saharan Africa, which are typically cited as being one-tenth of those in Asia (Svendsen et al., 2009). It also stresses the inefficient performance of existing irrigation systems, to which is attributed the lagging agricultural productivity across the continent. This narrative underpins an agenda of large-scale intervention in pursuit of an 'African Green Revolution' that has re-emerged following the 2008 food price rises. Conversely, however, an expanding literature highlights major discrepancies between the data that are commonly used to estimate irrigated areas, and observations of rapidly changing agricultural landscapes (see, for example, Beekman et al., 2014; Woodhouse et al., 2017) that suggest a need for new understandings of irrigation and new data, which may have significant implications for irrigation investment strategies.

It is also clear that narratives about sub-Saharan Africa’s agriculture, irrigation and rural economy are highly politicised, particularly where the use of natural resources such as water is concerned. This is illustrated in studies critiquing questionable or unjustified accusations that smallholders waste water that is needed by more 'efficient' or 'valuable' sectors such as wildlife conservation, power generation and large-scale commercial agriculture (Richards, 1983; Lankford et al., 2004; de Fraiture et al., 2014; Harrison and Mdee, 2017; de Bont et al., 2016).

The recognition that data and narratives are constitutive of each other has implications for research practices, namely the need to bring together people from a variety of disciplinary and professional backgrounds. With this in mind, this paper is a product of an interdisciplinary engagement among individuals with expertise in the development of remote sensing techniques, in irrigation engineering, and in the politics of environment and development in sub-Saharan Africa. The experience of such interdisciplinary engagement leads us to argue that irrigation data can indeed be improved, and numbers that we think better characterise some irrigation practices observed in sub-Saharan Africa can be generated. We also argue, however, that a critical perspective on new data generation efforts is needed in order to recognise the limitations of these numbers and of their efficacy in supporting alternative narratives and influencing policy.

We proceed in four stages. First, we review the data that are currently widely used at global level to assess the extent of irrigation. We stress that these data derive from a definition of irrigation – centred on the existence of hard infrastructure – that fails to grasp the current irrigation development trends in sub-Saharan Africa. Second, we investigate whether remote sensing techniques can improve our collective understanding of the extent and place of irrigation in sub-Saharan Africa. To do so we review past international attempts at using remote sensing to map irrigation in sub-Saharan Africa. We then present the results of a pilot study analysing radar-based images for three regions of Tanzania. Third, we argue that the invisibility of farmers' practices is not primarily linked to issues of data, but rather to the working cultures, narratives and politics that dominate irrigation development in sub-Saharan Africa. We stress that, in such context, putting smallholders' water use 'on the radar' through the use of new measurement techniques may create new difficulties for African irrigators. We conclude with a call to shift from a debate that centres on data and monitoring to a discussion on the nature of irrigation in sub-Saharan Africa and collective ways to engage differently with farmers' practices.

COUNTING AND CONCEPTUALISING IRRIGATION: PROBLEMS WITH OFFICIAL SOURCES

The Food and Agriculture Organization of the United Nations (FAO) currently compiles data about irrigation activity worldwide and publishes it through its AQUASTAT database (FAO, 2021). These data are used by international research and policy organisations when discussing irrigation activity (see Alexandratos and Bruinsma, 2012; FAO, 2011, 2017; Molden, 2007; World Bank, 2008a, 2008b, 2010, 2017; Svendsen et al., 2009; Wani et al., 2009; You et al., 2011). No other source provides such comprehensive coverage and consistent methodology. However, this does not necessarily make these data useful in all contexts. In order to understand why this is so, we need to explore how the data are compiled and what sorts of irrigation the database recognises.

Among other types of information, AQUASTAT contains data on "areas equipped for irrigation" and "harvested areas of irrigated crops". When first produced, its maps of irrigated areas showed for the first time where irrigated crops were actually grown worldwide. Up to that point, state agricultural censuses had recorded whether or not crops grown were irrigated but could not identify the precise location of the irrigated fields. Seminal work by Döll and Siebert (1999, 2000) enabled the first global map of irrigated areas, with subsequent iterations up to 2013 (Siebert et al., 2013). Their methodology digitises area and location data for known irrigation schemes, using protocols to determine the most relevant and accurate records among thousands of documents (Siebert and Döll, 2001; Siebert et al., 2005). Accuracy of mapping and modelling is enhanced by collecting information at the subnational (rather than national) scale. The digitised maps are then converted into rasterised maps with cells of 5 arc minutes which record the proportion of each cell equipped for irrigation (called 'irrigation density').

When first drawn, these maps were innovative and unprecedented in their scope. They were also primarily and deliberately *not* based on remote sensing, being described as "the only global database that is not based on remote sensing information" (Siebert et al., 2005: 535-6). This was welcome, given the poor spatial resolution and low temporal frequency of remote sensing at the time.[1] It is nevertheless important to recognise that AQUASTAT data depends on two sources – existing maps or records that can be digitised, and agricultural census statistics on irrigation – and that each of these introduces two potential inaccuracies. First, AQUASTAT data can only be as accurate as the most recent agricultural census figures. At the time of writing (2020), the current version of AQUASTAT is intended to be accurate for 2005, or as close to that year as possible, and most data that supported its elaboration date back to

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[1] Comparisons with land cover databases then available (Global Land Cover Characterization and the Global Land Cover 2000) show, for example, that 24 African countries with irrigation reported in AQUASTAT had no irrigation reported in either land cover database. For Tanzania, the 2005 version of AQUASTAT recognised 150,000 hectares (ha) equipped for irrigation, whereas no irrigation was reported by the (remote sensing based) land cover data (Siebert et al., 2005: 546). Later iterations of AQUASTAT maps do use some remote sensing based land cover analysis to identify irrigated areas in arid regions.

the period 2000 to 2008 (Siebert et al., 2013: 8). The current version of the database is thus at least a decade old. Second, although AQUASTAT irrigation and drainage categories (Table 1) are, in principle, inclusive of a broad range of techniques of water management, in reality they exclude many important practices used by farmers. This is because many of the ways that farmers manage water are not recognised as 'irrigation' by governments or by the FAO itself. These areas will therefore not appear on maps of irrigation activity.

Table 1. Categories of irrigation and drainage recognised by AQUASTAT.

Categories	Definition given in the AQUASTAT database
1A. Area equipped for full control irrigation: surface irrigation	Surface irrigation systems are based on the principle of moving water over the land by simple gravity in order to moisten the soil. They can be subdivided into furrow, borderstrip and basin irrigation (including submersion irrigation of rice). Manual irrigation using buckets or watering cans is also included.
1B. Area equipped for full control irrigation: sprinkler irrigation	A sprinkler irrigation system consists of a pipe network, through which water moves under pressure before being delivered to the crop via sprinkler nozzles. The system basically simulates rainfall in that water is applied through overhead spraying. These systems are also known as overhead irrigation systems.
1C. Area equipped for full control irrigation: localised irrigation	Localised irrigation is a system where the water is distributed under low pressure through a piped network, in a predetermined pattern, and applied as a small discharge to each plant or adjacent to it.
2A. Area equipped for irrigation: equipped lowland areas	The land equipped for irrigation in lowland areas includes: 1) cultivated wetlands and inland valley bottoms (IVB) that have been equipped with water control structures for irrigation and drainage (intake, canals, etc); 2) areas along rivers where cultivation occurs making use of structures built to retain receding flood water; 3) developed mangroves and equipped delta areas.
2B. Area equipped for irrigation: spate irrigation	Spate irrigation, also sometimes referred to as floodwater harvesting, is a method of informal irrigation using the floodwaters of a normally dry water course or riverbed (wadi).
3. Water harvesting (no data included on spatial extent)	Areas where rainwater is collected and either directly applied to the cropped area, and stored in the soil profile for immediate uptake by the crop (run-off irrigation), or stored in a water reservoir for future productive use (for example used for supplementary irrigation).
4A. Flood recession cropping area non-equipped	Areas along rivers where cultivation occurs in the areas exposed as floods recede (fadamas in north-east Nigeria). If the areas are equipped, they are included under irrigated areas, if unequipped they are not. The special case of floating rice is included in this category.
4B. Cultivated wetlands and inland valley bottoms non-equipped	Wetlands and IVBs that have not been equipped with water control structures but are used for cropping when covered with water. They are often found in Africa and have limited (mostly traditional) arrangements to regulate water and control drainage.

Source**:** FAO (2005, 2021) and www.fao.org/aquastat/en/databases/glossary/

The AQUASTAT database records four main categories of irrigation and drainage areas. These are largely defined on the basis of technologies: 1) areas equipped for full control irrigation, 2) areas equipped for partial control irrigation, 3) water harvesting areas, and 4) non-equipped cultivation in flood recession areas, wetlands, and inland valley bottoms (Table 1). Farmer-led irrigation development commonly intersects with the last two categories identified in the AQUASTAT database, but it can also be found in the vicinity of 'equipped areas' in the form of unplanned use of existing infrastructures (de Fraiture et al., 2014; Woodhouse et al., 2017; Veldwisch et al., 2019).

These different categories are then aggregated into three different classes whereby the broad notion of 'agricultural water management' is introduced to encompass irrigation categories (1A, 1B, 1C, 2A and 2B) and 'something else' (categories 4A and 4B) (Table 2). Those aggregations introduce the first omission, for *they deliberately exclude all forms of water harvesting* (category 3 in Table 1 is NOT included in category 3 of table 2).

Table 2. Aggregate classes of 'irrigation(s)' and 'agricultural water management' in AQUASTAT.

I. Area equipped for full control irrigation: total (1A+1B+1C)	The sum of surface irrigation, sprinkler irrigation and localised irrigation
II. Area equipped for irrigation: total (1A+1B+1C+2A+2B)	Area equipped to provide water (via irrigation) to crops; this includes areas equipped for full/partial control irrigation, equipped lowland areas, and areas equipped for spate irrigation
III. Total agricultural water managed area (1A+1B+1C+2A+2B+4A+4B)	Sum of total area equipped for irrigation and areas with other forms of agricultural water management (non-equipped flood recession cropping area and non-equipped cultivated wetlands and inland valley bottoms)

Source: FAO (2005, 2021).

Further exclusions derive from the way the categories of Table 1 are interpreted and operationalised by the national agencies that provide the FAO with their data. 'Equipping' for water control (hence infrastructures and technologies) is central to the categorisation used in Table 1. The AQUASTAT glossary defines water-control structures as "[a]nthropogenic modifications or controls set in place in order to control water movement" (FAO, n.d.a). This potentially inclusive definition is, in practice, often interpreted to exclude important forms of irrigation. For example, while definition 1A in Table 1 ('area equipped for full control irrigation') states that bucket irrigation is included, such areas are not captured in maps and statistics. As a result, category 1A is de facto limited to irrigation schemes served by permanent infrastructure. Similarly excluded are the individual or collective pumping systems that have mushroomed all over the continent over the last decades (de Fraiture and Giordano, 2014). Further, it remains unclear whether the category of 'equipped for (partial control) irrigation' (categories 2A and 2B in Table 1) includes traditional 'hill-furrow' irrigation systems. These entail stream diversions into earthen canals via temporary weirs constructed from stones and branches. They are widespread in East Africa and in some cases have existed for decades (Adams and Anderson, 1988), yet they are not well documented at the national level (as they are often not recognised as irrigation) and they are also missing from this AQUASTAT category.

Even in the broader assessment of irrigation and drainage practices through the category of 'total agricultural water managed area', under-reporting is evident. Although categories exist for 'flood recession agriculture' and 'non-equipped cultivated wetland areas and valley bottoms' (see categories 4A and 4B in Table 1), these are seldom recorded. In the period 2008 to 2017, only 4 out of 49 countries in sub-Saharan Africa reported on flood recession and only 6 reported on non-equipped cultivated wetlands (FAO, 2021). The AQUASTAT categories thus formally provide space for documenting areas under farmer-led irrigation development, but in practice the database reflects national statistics that tend to ignore these activities and focus on donor- or government-funded initiatives.

These problems are well illustrated when considering the case of Tanzania more specifically. The AQUASTAT database for Tanzania draws on two sources: the National Irrigation Master Plan of 2002 and the National Irrigation Census of 2003. These reported 184,000 and 193,000 hectares (ha) of irrigation respectively, but with significant differences in regional distribution. AQUASTAT documentation notes these discrepancies and observes that they could stem from differences in the *definitions* of irrigation used, depending on whether or not rainwater harvesting is included (FAO, n.d.b). For the country as a whole, this discrepancy is dealt with by taking the average of the two figures. A closer look at specific regions, however, raises further questions. In Shinyanga, a major rice-growing region, AQUASTAT records just 2,181 ha of land equipped for irrigation (FAO, n.d.b). The agricultural census for Shinyanga region, however, registered 10,266 ha of irrigated land in 2002/2003 (United Republic of Tanzania, 2007: 41) and 29,783 ha in 2007/2008 (United republic of Tanzania, 2012b: 50), thus indicating a potential underestimation of irrigation in the region by a factor of 5 and 15 respectively.

Beyond a mere battle of numbers, what is at stake here is the question of what constitutes 'irrigation'. There are different interpretations even within Tanzania, depending on the administrative agency considered. Critically, for the analysis we present below, there are no lands reported anywhere in Tanzania under the AQUASTAT categories 4A ('Flood recession cropping area non-equipped') or 4B ('Cultivated wetlands and inland valley bottoms non-equipped') while we argue such areas are instances of farmer-led irrigation development. The point here is not that these examples are *representative* of systematic errors. We do not advocate multiplying current figures for irrigation by 5 or 15 to arrive at true levels. We suggest, rather, that these examples are *indicative* of known problems with current irrigation data that relate to the inadequate understanding of irrigation development currently observed in sub-Saharan Africa. In the following section, we consider recent developments in the availability of data based on remote sensing and investigate whether this can support new framings of irrigation dynamics.

REMOTE SENSING ATTEMPTS TO DETECT IRRIGATION

A common application of remote sensing is quantifying the area of different land cover types through satellite image classification techniques. By combining available field observations of irrigation with satellite-derived attributes of the land surface, it is possible to produce maps that estimate irrigated area at regional to continental scales. This is not easy. Downloading and processing hundreds of satellite images requires a significant computing capacity and expertise. It also takes time. Teams at the International Water Management Institute (IWMI) have taken several years to produce their maps (Thenkabail et al., 2009). The technology and skills are not widely available and have generally been beyond the reach of most research and government agencies in sub-Saharan Africa.

The past decade, however, has seen the emergence of new techniques aimed at mapping irrigated area at global (Thenkabail et al., 2007, 2009), regional (Xiao et al., 2006), basin (Biggs et al., 2006; Cai and Sharma, 2010), or even irrigation system scale (Conrad et al., 2007; Venot et al., 2010). In the early 2000s, IWMI was at the forefront of such development and eventually published a Global Irrigated Area Map in 2009 (Thenkabail et al., 2009) with a resolution of 10 km^2. Since then, remote sensing analysis has mostly sought products with ever higher temporal and spatial resolution, as well as refining processing techniques to improve the accuracy of detection.

In 2016, after several years of hard work, IWMI published irrigated area maps for Asia and Africa (IWMI, n.d.), and further studies in Ethiopia, Ghana and the Limpopo Basin in South Africa. These were presented as a major achievement, markedly improving earlier mapping exercises: "It’s a huge step forward (…). IWMI pioneered the onerous task of mapping global irrigated areas back in 2006, but then we only had resolution to 10 km. The new maps have improved that forty-fold" (IWMI, 2016).[2]

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[2] IWMI used MODIS image composites (with a spatial resolution of 250 m by 250 m) every 8 or 16 days to differentiate between different types of crops (each crop having a different 'greenness' signal based on its growth) and combined these with higher resolution Landsat (30 m) or even Sentinel (10 m) images and ground-truthing to estimate irrigated areas.

Though remote sensing techniques may be able to capture some of the broad array of farmer-led irrigation practices, they have caveats. First, much uncertainty and many blind spots remain. As those involved in the most recent IWMI project put it (Ibid):

> We need to acknowledge uncertainties in our products (…). Other approaches, such as using census data are also important. This tool is designed to support and supplement other information systems rather than replace or compete with them. There is a role for both. We will not always be able to be 100% accurate, and accounting for informal irrigation and other new developments will remain a challenge (…). What maps like this show is essentially a range of probabilities. That still makes it a useful tool, but it should not be taken as precise mirror of ground conditions.

Second, for many years high-resolution image availability was an issue, as the best images were expensive to obtain or were reserved for military use. Today, major space agencies have adopted open data policies, with Landsat and MODIS – which are relatively easy to process and offer long-time series – being the most-used data sources. These sensors, though, cannot see through clouds, and irrigation is often practiced during cloudy rainy times of the year.

Open data policies, however, mean that new satellite products, and notably radar data that can 'see through clouds', have become more easily available. The use of radar to monitor irrigated rice is well established in parts of Asia (Ribbes, 1999; Chakraborty et al., 2005; Chen et al., 2007; Zhang et al., 2009, Bouvet and Le Toan, 2011). However, it has rarely been used to explore irrigation activity in Africa. This prompted us to undertake a pilot study in a number of sites in Tanzania to assess whether radar remote sensing analysis could help to detect farmer-led irrigation development there.

The mapping method we report here uses data from the Sentinel-1 satellites of the European Space Agency (ESA). The Sentinel-1 mission is a two-satellite constellation of C-band synthetic aperture radar (SAR) instruments, which provides global coverage on a regular repeat cycle (Torres et al., 2012). Unlike more commonly used optical sensors such as Landsat and MODIS, which measure sunlight reflected from the earth’s surface, radar sensors operate by actively transmitting a microwave signal and measuring the radiation that is reflected back to the sensor (Box 1). Accordingly, radar has advantages over optical sensors because it can collect time series imagery of consistent quality regardless of weather, cloud cover and illumination by the sun. A distinctive temporal pattern of returned radiation, or backscatter, is expected due to a sequence of changing reflection responses characteristic of flooding and inundation of vegetation (see Figure 1 in Box 1). This makes radar-based techniques particularly adapted to the detection of irrigated rice fields. Other irrigated agrosystems and practices in which water is less visible (because hidden by the canopy of agroforestry or because distributed through narrow furrows) may be more challenging to detect. Radar also has disadvantages relative to optical remote sensing, such as the noise-like interference inherent to this type of data and its relatively onerous pre-processing requirements (see Appendix 1).

We piloted the use of radar data to map irrigation in three study regions in Tanzania where we also have ground observations of farmer-led irrigation development. Shinyanga region is one of the most important rice-producing regions in the country, with agricultural practices that have been described in detail by Meertens (1999). Rukwa region has large areas of irrigated agriculture, and we have field observations of rice farming near Lake Rukwa. Kilimanjaro region is a smaller producer of rice, though we have detailed field information of farmer-led irrigation development from an area south of Moshi. Since September 2016, both Sentinel-1 satellites have been acquiring dual-polarised (VV, VH) images every 12 days over Tanzania (IW mode, ground range detected). We acquired all ascending orbit images from the ESA Copernicus Open Access Hub covering the three study regions from September 2016 to April 2017; this totals 324 images and covers roughly one rice-growing season.[3] We pre-processed Sentinel-1 images using Sentinel Application Platform (SNAP) software (see Appendix 1 for details on the procedure used).

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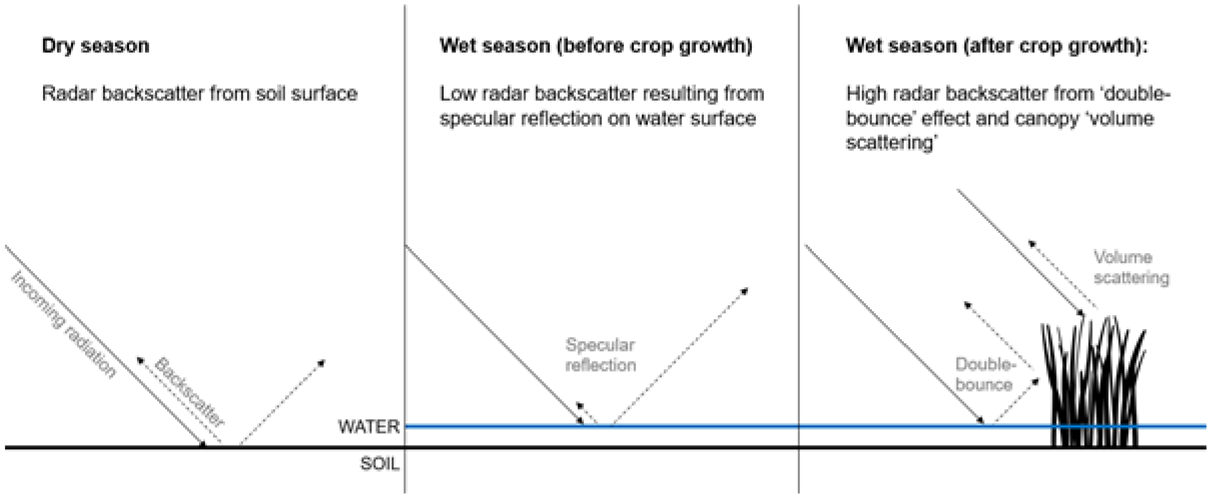
[3] Available from https://scihub.copernicus.eu/

Time series of Sentinel-1 data comprises multiple features and the first step is to identify those that best capture the specificity of irrigated fields (see Box 2 and Appendix 2).

Box 1. Principles of radar remote sensing

The magnitude of backscatter recorded by a synthetic aperture radar (SAR) instrument is influenced by the properties of the transmitted radiation (such as its wavelength, polarisation [orientation], and incidence angle), the properties of the reflecting surface (such as its geometric structure, surface roughness and water content), and the interaction between the transmitted radiation and surface properties. Of importance to the detection of irrigation, 'rougher' surfaces such as bare soil or vegetation tend to result in more backscattered radiation than 'smoother' surfaces like still water, where less radiation is reflected back towards the sensor. Surfaces with higher moisture content, such as wet soil, tend to be more reflective to microwave energy than dry surfaces. The combination of a smooth reflecting surface such as wet soil with vertical elements such as flooded vegetation can result in a 'double-bounce' effect, where backscattered radiation is very high. Where a radar signal is reflected many times (such as by a plant canopy), it is common to find that the backscattered radiation does not return to the sensor with the same polarisation as was transmitted, an effect known as depolarisation. The polarisation of backscattered radiation thus also contains information about surface properties.

Figure 1. Radio detection and radar satellites emit radio energy towards the earth's surface and measure the energy reflected back to the satellite sensor (backscatter)



Source: Authors.

A Random Forest classifier is used to distinguish 'irrigated' from 'non-irrigated' areas. To do this we first needed to 'train' the classifier to recognise the seasonal pattern of radar reflection for locations known to be irrigated.[4] To supplement field observations from our three study regions, we generated a training dataset by identifying areas that we deemed 'irrigated' and 'non-irrigated' using high-resolution imagery from Google Earth. We notably considered geometric field shapes and earth 'bund' boundaries to be a sign of irrigation as these are common features of irrigated rice areas. Although there is an increased probability of error in this training dataset relative to one derived from purely field-based observations, this method allows the rapid generation of large reference datasets. We performed a separate

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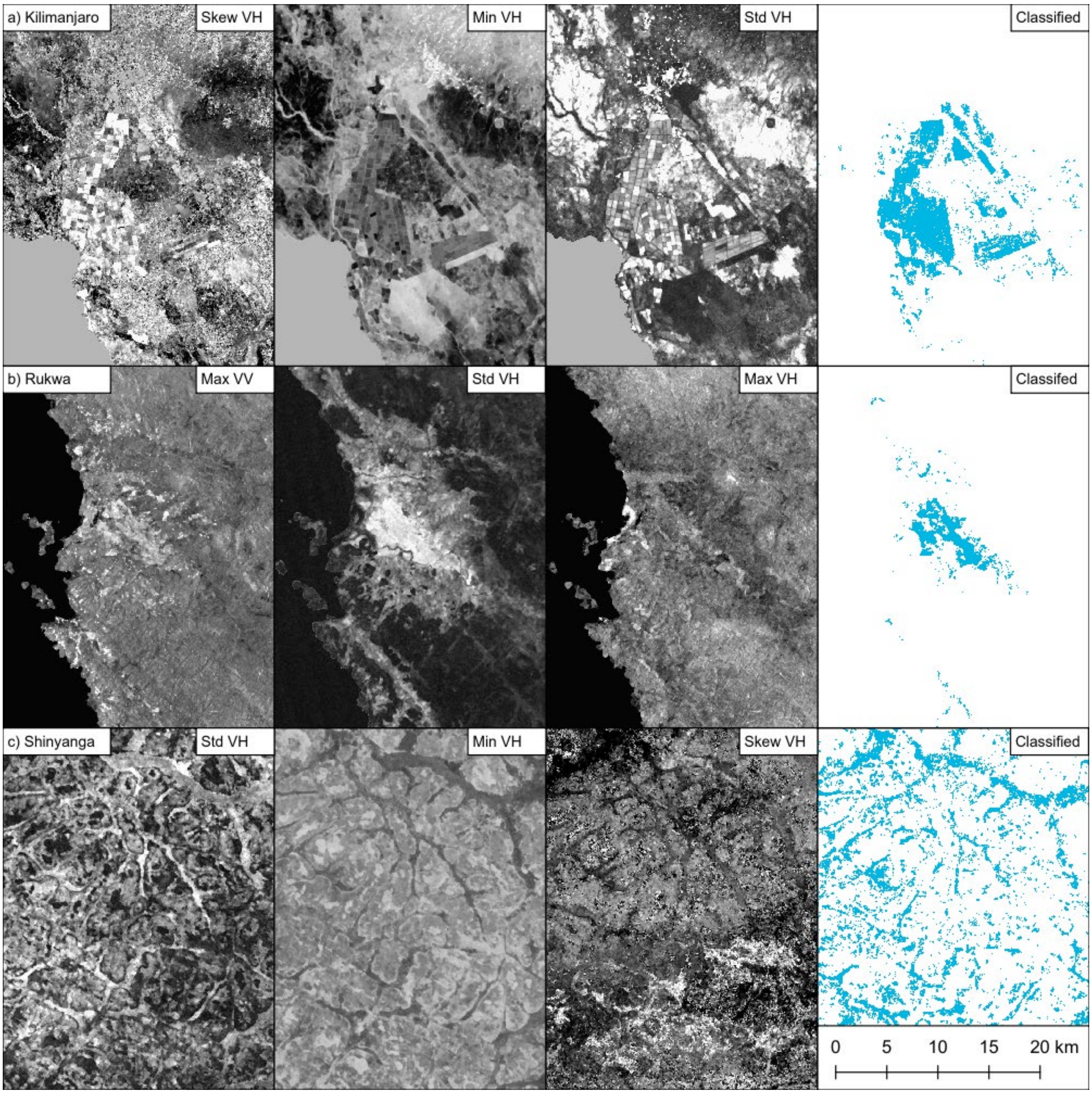
[4] Random Forest is a widely used classifier for remote sensing data. It is considered to be robust to non-linearity and outliers, and generally produces good results without extensive tuning or computationally intensive processing. We trained it using scikit-learn software (Pedregosa et al., 2011).

classification for each of the three study regions, employing independent training sites and accuracy assessment data. This means that, in effect, we adopted a context-specific definition of 'irrigation' that recognises that the form and timing of irrigated rice cultivation may be different across the three regions. Training the Random Forest classifier separately for each of the three sites enabled a comparison of the features of the radar signal that were important in predicting the presence of irrigated agriculture. The analysis across the three sites shows that no single feature from the radar signal is a consistently good predictor of irrigation (Figure 2; see also Appendix 2).

Figure 2. Image classification results over exemplar irrigated sites in (a) Kilimanjaro, (b) Rukwa and (c) Shinyanga regions.



Source: Authors. Note: For each case, the features of the Sentinel-1 imagery that contributed most to the classification are shown (see also Appendix 2), with the resulting irrigated area map in blue. VV= co-polarization; VH= cross-polarization.

Box 2. Identifying radar features to detect irrigation

Our analysis is based on the premise that irrigated pixels display more variability in their backscatter signal than do other land cover types. We generated a range of summary statistics from multi-temporal Sentinel-1 backscatter data (annual minimum, maximum, mean, standard deviation, skew and kurtosis). Together, these describe the backscatter properties and their temporal variability for each pixel. We also generated a measure of the maximum backscatter increase between two consecutive images, a metric similar to that used by Bouvet and Le Toan (2011) for mapping rice fields in the Mekong delta. This statistic aims to capture the rapid increase in backscatter between the specular reflection of a flooded field and the double-bounce effect that occurs once rice that has been initially grown in a nursery is transplanted in the fields. These summary statistics were duplicated for each polarisation (co-polarization – VV- and cross-polarization -VH) of Sentinel-1 imagery, totalling 14 features. Irrigated rice tends to be limited to areas of low elevation and locations that are topographically relatively flat. To capture this, we generated two further features using the Digital Elevation Model from the Shuttle Radar Topography Mission, a dataset of global topography (Farr et al., 2007).[5] The first feature records distance above sea level, and the second is an index of topographic roughness (calculated as the standard deviation of elevation within a 10-pixel radius circular window).

Figure 3 shows maps of irrigated areas obtained by radar analysis for the three study sites.

Mapped irrigation in Kilimanjaro region extends over 19,200 ± 7800 ha (± 95% confidence interval, or CI) and appears largely limited to the area south of Moshi and to a large irrigated commercial sugar estate near the towns of Ndungu and Kihurio in the southern part of the region. Similar to past remote sensing analysis, the radar does not spot the hill-furrow irrigation systems on Mount Kilimanjaro or the Pare Mountains though these have been extensively documented, including by authors of this paper (Grove, 1993; Gillingham, 1999; Mul et al., 2011; Komakech et al., 2012). These are systems found in elevated and uneven topography where small streams are diverted by farmers to irrigate agroforestry systems. Their invisibility to radar is likely linked to the fact that the permanent and dense canopy of agroforestry systems conceals the changes in soil roughness and moisture that the radar data detects. It is possibly also linked to the fact that hill-furrow irrigation was not added by the analyst into the training dataset on which the classification relies.

Irrigation mapped by radar in Rukwa region covers an area of 36,600 ± 11,800 ha (± 95% CI) located principally along the shore of Lake Rukwa and extending northwards along the Kavuu River. There is also a smaller area of irrigation along the shore of Lake Tanganyika in the western part of the region, particularly around the town of Kiranda.

Irrigation mapped by radar in Shinyanga region is extensive, covering 267,000 ± 37,000 ha (± 95% CI) and accounting for 16.1% of the region's total area. Irrigated fields are concentrated around the centre of the region, particularly along the river networks running into the Mwanza Gulf of Lake Victoria to the north. Irrigation is largely limited to river valleys, taking the form described in Meertens (1999), where water control is achieved through construction of temporary bunds and dams in low-lying areas adjacent to rivers, combined with harvesting of rainwater that flows down from higher slopes.

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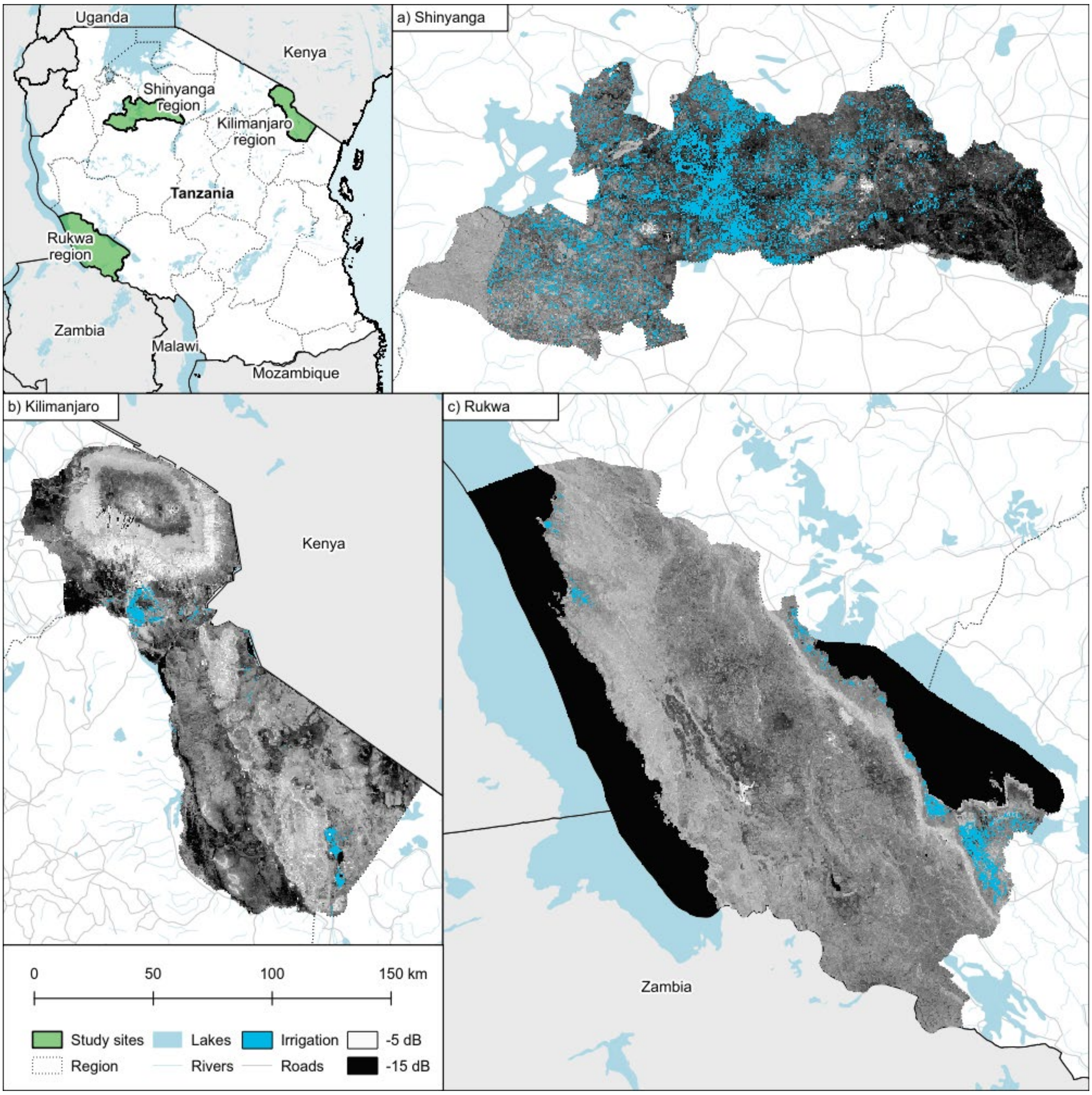
[5] Available from https://www2.jpl.nasa.gov/srtm/

Figure 3. Regional predicted extent of irrigation based on radar analysis (basemaps of each region are mean VV backscatter).



Source: Authors. VV= co-polarization. dB= Decibel

Comparing the radar classification to the reference data used for accuracy assessment indicates that the Random Forest classifier correctly identified most of the larger known irrigated areas across the three study sites and did not incorrectly flag large areas of non-irrigation as irrigated. Overall map accuracy varied from 86% in Shinyanga to 99% in Kilimanjaro and Rukwa (see Appendix 3 for a description of the methods employed for accuracy assessment). However, as irrigation covers a relatively small proportion of the Kilimanjaro and Rukwa regions, it is more informative to consider the accuracy of the irrigated class alone. Uncertainty in estimates of irrigated area was high in all three study regions, with producer's accuracy varying from 56% to 74% and user's accuracy between 55% and 83% (Appendix 3). Thus, as with census and FAO data, significant uncertainty characterises remotely sensed irrigation data. The greatest absolute uncertainty in detecting irrigated areas was found in Shinyanga region, where the relatively low accuracy of the irrigated class and widespread occurrence of irrigation inflated uncertainty. When expressed relative to the total area of irrigation, however, our estimates of irrigated area were most effective in Shinyanga. This is because in Kilimanjaro and Rukwa, where irrigation is relatively rare, uncertainty is large relative to the area of irrigation, hence our estimate of total irrigated area is less effective. Moreover, in these regions, where topography and environment vary significantly, irrigation is likely to exploit micro-level conditions that remain invisible to the radar. Any training data set derived from Google Earth image interpretation (such as that used in our analysis) is therefore unlikely to be able fully to address this diversity. This highlights the vital role for ground-truthing campaigns that reflect the diversity of irrigation practices observed in the fields.

These limitations notwithstanding, comparisons between the irrigated area mapped by radar and that reported in the most recent agricultural census (2007/2008) offer useful insights. In Kilimanjaro, the census figure of 36,607 ha (United Republic of Tanzania, 2012a) is 35% larger than the 27,000 ha upper estimate of our 95% CI for this region. This probably reflects the fact that the widespread hill-furrow irrigation systems of Mount Kilimanjaro and the Pare Mountains, while well known to government agencies, are less likely to be detected by radar. In Rukwa and Shinyanga, however, which do not have traditions of hill-furrow irrigation, we identified a significantly greater area of irrigation than had previously been reported. In Rukwa region, the 2007/2008 census recorded 8,316 ha as irrigated (United Republic of Tanzania, 2012c), which is 2.6 to 5.5 times lower than our estimate of 36,600 ± 11,800 ha. In Shinyanga region, the census figure of 29,783 ha (United Republic of Tanzania, 2012b), is 7.6 to 10.1 times lower than our radar estimate of 267,000 ± 37,000 ha (with AQUASTAT reporting a mere 2,181 ha of irrigation).

A discrepancy of this order suggests that our radar analysis considered as 'irrigated' large areas that are not recorded in official census data. This seems plausible if, instead of census data for 'irrigated crops', we consider the agricultural census data for 'paddy rice' at the regional level. This data shows trajectories of rapid growth by about 50% between 2002/2003 and 2007/2008 (from 110,673 ha to 175,192 ha; United Republic of Tanzania, 2007, 2012b). Projecting this trajectory forward suggests that in 2016/2017 (the years of the radar images) the total paddy area could be around 230,000 ha for the districts of the present day Shinyanga Region, a figure which falls within the estimates for irrigated rice generated by our radar methodology. Moreover, our estimate for irrigated rice area proved unsurprising to those who have worked on rice cultivation in Shinyanga (Meertens, personal communication, 4 November 2017). It is also consistent with the significant yield gain recorded by FAO for paddy rice in Tanzania (from 1.9 tonnes/ha in the 2000s to 2.4 tonnes/ha in the 2010s; FAO, n.d.c), a gain which suggests that an increasing number of farmers use some form of water control and management.

It is important to acknowledge that census data that report areas of 'equipped irrigation' cannot be expected to correspond to areas of paddy grown under other forms of 'agricultural water management'. This study, using radar images, suggests tantalising possibilities for better understanding the temporal and spatial dynamics of farmer-led irrigation practices. These dynamics include medium-term trends reflecting growth in population and markets, but also short-term changes responding to inter-annual fluctuations in water availability (Lankford and Beale, 2007). The method, however, shares some of the shortcomings of other (optical-based) remote sensing analyses of irrigated areas. It remains, for instance, difficult to detect whether orchards and agroforestry systems are irrigated, and it is hard to detect small patches of irrigation in rough terrain, such as small valleys in mountainous areas. Even in the case of paddy rice, estimates still come with a high uncertainty range (though lower, it seems, than in census data) and it can be difficult, for example, to distinguish flooded grassland near rivers from paddy fields.

Our radar analysis further stresses that accurate detection requires context-specific definitions in the form of specific training procedures. This makes it rather unlikely that these methods – already challenged by farmers' use of rapidly changing micro-spatial and temporal conditions – can be used in routine monitoring exercises. This underlines that tracking the dynamics of irrigation in sub-Saharan

Africa will always be challenging, whatever methods are used. Thus, in contrast to the widespread image of remote sensing analysis as generating accurate, timely and widely applicable products with relative ease, this study provides a stark reminder of their local character and the expertise and time that goes into meaningful interpretation of remote sensing data.

More fundamentally, our study shows that, as with other methods, radar-based analysis is underpinned by the need to use bounded categories of land use, even though farmer-led irrigation development often cuts across conventional boundaries (Woodhouse et al., 2017) and reality seldom conforms to neat boxes. As such, irrigation data generation efforts reflect first and foremost the analyst's understanding of what irrigation is, more than actual farming practices. This points to the need to analyse and discuss irrigation data and data generation methods in relation to the narratives and politics of irrigation development in sub-Saharan Africa.

BEYOND DATA: EXPLAINING THE INVISIBILITY OF FARMER-LED IRRIGATION DEVELOPMENT

The great diversity of agricultural water management practices in sub-Saharan Africa has long been recognised as rendering the conceptualisation of 'irrigation' in the region problematic. Too restricted a definition of irrigation may mean excluding many forms of water control by farmers (Woodhouse et al., 2017). As Paul Richards (1983: 28) observed almost 40 years ago:

> the absence of irrigation is (…) puzzling given the widespread significance of rainfall uncertainty in the tropical zone. The answer to this particular puzzle would appear to be that irrigation was not absent. The view that irrigation failed to spread beyond the Nile into sub-Saharan Africa is simply wrong.

We can illustrate this by exploring the way national governments and donors are thinking about irrigation. The legacy they inherited from colonial administrations neglected the diversity of precolonial agricultural water management practices in sub-Saharan Africa (Adams and Anderson, 1988; Widgren, 2004; Soper, 2006; Westerberg et al., 2010, Lang and Stump, 2017) and instead favoured large-scale irrigation on the floodplains of major rivers. The latter are exemplified by the Gezira scheme in Sudan that was constructed in the 1920s on the Nile, and the Office du Niger built ten years later in Mali. In both schemes, small-scale cultivators were allocated plots to produce cash crops (initially cotton) as tenants of a state corporation that was responsible for the management of the water infrastructure and of input and output markets (Barnett, 1977; Aw and Diemer, 2005; Ertsen, 2016).

The influence of these colonial schemes can still be seen in contemporary irrigation policy in Africa as the latter typically emphasises irrigation as distinct, spatially bounded enclaves embodying engineering design and modern farming methods (Harrison, 2018; Veldwisch et al., 2009). The colonial influence also infuses current definitions of irrigation. Indeed, as Adams and Anderson (1988: 522) observed some three decades ago, "Irrigation is often conventionally defined simply by the fact that the particular cadre of 'experts' from the discipline of engineering are employed in its planning, design or management".

This 'scheme' model of irrigation development has long been challenged by scholars and some development workers. Already by the 1980s, development practitioners considered that irrigation investment in Africa was underperforming. In part, this reflected a wider ideological agenda that saw state-managed activity as necessarily inefficient and prescribed turning over the management of irrigation schemes to the private sector to be constituted by irrigators (as water users associations) and commercial suppliers of inputs and services (Vermillion, 1991). Other critics, however, attributed the underperformance of irrigation investments to the failure of engineers to understand the relationship between the irrigation schemes they designed and farmers' existing use of land and water. This lack of understanding, they felt, resulted in displacement, disruption of existing production systems, and political resistance (see, for example, Moris and Thom, 1985; Adams, 1992; Diemer and Vincent, 1992).

This led to proposals for a more inclusive definition of irrigation (Vincent, 2003) and notably a growing recognition that irrigation was also taking place outside of official schemes. This 'non-scheme' irrigation, much of it small scale, could cover significant areas in aggregate terms, particularly where farmers managed water in seasonally flooded lowland areas (Underhill, 1984; Hocombe et al., 1986). The acknowledgement of non-scheme irrigation notably resulted in the introduction by the FAO of the category of 'informal' irrigation to their irrigation statistics for Africa (FAO, 2005). Defined in parallel to the other categories presented in AQUASTAT (see Tables 1 and 2), it was described as:

> [s]chemes under local responsibility, controlled and operated by local people in response to their perceived needs. In many areas with potential, farmers have attempted to enhance food production by introducing some form of irrigation, e.g. small earth dams, simple diversion structures and self-made conveyance canals, water harvesting, shallow groundwater abstraction. These schemes are often ad-hoc and therefore not included in 'irrigated area'. They are also called initiated smallholder schemes (FAO, n.d.a).

The diverse forms irrigation development can take in sub-Saharan Africa are increasingly recognised by researchers and development professionals (Giordano et al., 2012; Woodhouse et al., 2017) but much of this irrigation – especially that initiated by farmers outside state-supported or state-managed irrigation schemes – remains invisible in official accounts and databases of African irrigated agriculture.

We argue that this is not due simply to a lack of data, but rather to four interconnected conceptual difficulties: 1) a continuum of water management practices that escapes conventional irrigation categories; 2) the place of irrigation within farming and rural people’s other economic activities; 3) a widely held perception that farmer-led initiatives are incompatible with modern design and that they are unproductive and inefficient; and 4) the political narrative of water scarcity that shape engagement between irrigators and development agencies. We now consider each aspect in more detail.

In thinking about the nature of water management in African agriculture, Moris and Thom’s (1985: 71) observation about vertisols in the African savannah seems worth repeating:

> The valley-bottom 'vertisols' represent some of the best agricultural land available, provided they are intelligently used with suitable technologies. The division between 'irrigation' and 'rainfed' cultivation is here also arbitrary, since what usually occurs is not full irrigation, but rather a combination of drainage, impoundment (for 'wet' rice), and some supplemental water to extend the soil moisture regime.

Scholarly writing has recently embraced the idea of a continuum and combination of techniques which can range from 'rainfed' agriculture through rainwater harvesting and supplementary irrigation, to 'full' irrigation (Molden, 2007; Rockström et al., 2010). This continuum largely explains the discrepancies that may exist between different data sources, notably when reporting irrigated rice. Though the continuum is readily acknowledged by irrigation engineers, development practitioners and researchers, most still posit a binary division between practices that are, or are not, 'irrigation', with techniques that are not considered 'irrigation' often being broadly categorised under the term 'agricultural water management'. Practices 'at the margin' will be identified as belonging to one category by one analyst and to another category by another, pointing out a need to reassess the utility of such categories.

The second conceptual difficulty that explains why many farmers’ initiatives are not seen as irrigation is the way these practices are located alongside, as opposed to being exclusive of, other farming and livelihood strategies. One of the most comprehensive critiques of irrigation design in Africa was made almost three decades ago (Diemer and Vincent, 1992). It observed that engineers often made inappropriate assumptions about key aspects such as the availability and cost of household labour for agricultural work, the unity of 'household' decision-making, and producers’ access to markets. Put simply, irrigated agriculture was thought to be a commercial activity that small-scale subsistence farmers would not practice. This separation of irrigation planning from the broader conditions and characteristics of small-scale agriculture is still evident in policy documents that tend to conflate small-scale production with subsistence or non-market goals.[6] Where development actors operate with such assumptions, they will misread the dynamics of a farming landscape in which many small-scale producers use irrigation to produce commercial crops while often maintaining rainfed production for other purposes and possibly engaging in other economic activities such as trade or livestock production (Adams and Anderson, 1988; for recent case studies see Hebinck et al., 2019 and Scoones et al., 2019).

The third reason why irrigated areas developed through farmers' initiatives are not recognised in official statistics relates to value judgements regarding farmers' design and use of irrigation technologies. The weirs, canals, boreholes and pumps they use are similar to technologies designed by engineers, yet different. The difference stems from farmers combining different technologies in unexpected ways – both spatially and over the course of a growing season – in what is best defined as 'bricolage', a way of operating that is strikingly different from engineers' practices (Lévi-Strauss, 1964). This similarity between the technology designed by engineers and the combined techniques used by farmers makes comparison possible, but also lays the groundwork for disqualifying farmers' initiatives. Policy makers sometimes have difficulties in accepting the functionality of farmers' bricolage. Rudimentary techniques such as bucket irrigation, or pumps and pipes, do not fit the image of the 'modern' and 'high tech' sector to which policy aspires. As a consequence, they are often considered to be wasteful of scarce water resources (de Bont et al., 2019a, 2019b). Equally, farmer-led expansion of irrigation – which aims to take advantage of surplus or drainage water on the periphery of formal irrigation schemes – is often ignored, or is even considered detrimental to the existing infrastructure and farming that is 'within the scheme' (de Fraiture et al., 2014). According to this view, including these instances of irrigation in the statistics would amount to an official acceptance of 'bad performance'. Acknowledging the value or efficacy of farmers' inventive bricolage would also contradict the prevalent paternalistic approach whereby engineers and civil servants consider themselves to hold the only valuable form of irrigation knowledge, which they have a duty to 'transfer' to farmers.

A fourth and final conceptual issue that makes farmers' irrigation initiatives less visible to development agencies and national governments is the fact that a regulatory framework with which to engage smallholders is largely absent. It is not uncommon, for example, for small-scale water users to be excused from compliance with water licensing rules on the basis of the perceived small scale of their operations or their poverty. Water permits and payment of water fees are thus only required of those whose use exceeds a defined minimum volume. Such approaches may be welcomed by small-scale irrigators who thus avoid paying water fees but also by officials who are thereby not required to administer many hundreds of such payments. However, another consequence of allowing small-scale irrigation to go on unmonitored is that government administrations can then strategically ignore the water rights of small-scale irrigators whenever competing larger-scale water users require water allocations (Van Koppen and Schreiner, 2019). It is also evident that where state agencies recognise small-scale irrigation activity as significant, regulatory policy prioritises the organisation and registration of irrigators with a view to governing their activity and limiting their potential impacts on other constituencies (United Republic of Tanzania, 2016; de Bont et al., 2019b; Mdee and Harrison, 2019).

THE POLITICS OF NEW DATA AND CHALLENGES OF REDEFINING IRRIGATION

In the absence of a capacity for constructive regulatory engagement with the large numbers of small-scale irrigators, the political narrative of water resource management becomes critical. The discussion thus moves from data towards politics and ideologies. Forty years ago, Paul Richards (1983) observed that in debates over African land use simplistic ecological narratives often served to disguise political and,

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[6] In Tanzania's National Irrigation Development Strategy (2013), for example, the category of 'commercial' irrigation is differentiated from categories of both 'smallholder' and 'traditional' irrigation (whether improved or not, see pages xi and 17-19). The explicit vision of the strategy is to "facilitate the Tanzania agriculture sector to be transformed from subsistence to a modern and highly commercial sector" (page 1).

indeed, ecological complexity. Since then, and not least in Tanzania, experience has provided evidence of the persistence of ecological narratives in justifying decision-making on natural resource use, despite the absence or weakness of supporting data (cf. Brockington and Homewood, 2001).

This is evident in the ways that narratives of water conservation have been deployed to justify restriction and displacement of small-scale irrigators in favour of other economic interests. The polarised debate over the use of Tanzania's Great Ruaha River (Walsh, 2012) powerfully illustrates the political sensitivity of water resource allocation, but also the tensions between scientific evidence and the preferred narratives of those with vested interests (Lankford et al., 2004). Cessation of the flow of the river in the national parks during the dry season was said to have caused power cuts in Dar es Salaam. The problem was blamed on deforestation, overgrazing and irrigation by small-scale irrigators in the upper basin. Walsh (2012) shows that there were few data to support that case and that lack of water downstream for national parks and urban elites was linked, rather, to the modalities of dam management. Within an overarching narrative of generalised water scarcity that was blamed, in part, on wasteful water use by 'inefficient' irrigation systems, small-scale farmers were eventually evicted to make way for the Usangu Game Reserve (and later an expanded Ruaha National Park, ibid), clearly highlighting their vulnerability in this political environment.

Narratives of water scarcity and conservation continue to play an important role in shaping policy towards small-scale users of land and water in Tanzania, and in sub-Saharan Africa more generally. These narratives are mobilised to reinforce long-standing arguments demanding modernisation of small-scale agriculture to raise the efficiency and productivity of land and water use (de Bont et al., 2019b; de Bont and Veldwisch, 2020). In this context, what might ensue from the introduction of new data that makes farmer-led irrigation development more visible and put farmers' practices 'on the radar'?

Answering this question calls for understanding what actually governs policy decisions. Our attention thus turns towards a large body of literature that shows that the relation between science and policy making is, to say the least, ambiguous. Scholars, for instance, stress that policy is not solely – nor even primarily – based on research findings, but rather that it is at least equally influenced by other stakeholders and political processes (see, for example, Hoppe, 2005; Cleaver and Franks, 2008; Wesselink et al., 2013; Spruijt et al., 2014). Newly generated data may contradict existing data, or at least show some inconsistencies with them (as in this paper). Because of this, the legitimacy of the new data – how they are produced and by whom – will be scrutinised and the results of this scrutiny will influence whether the data are accepted as valid. To ensure that the methodological novelty of new data collection techniques and the quantified uncertainty of these data (likely to be contrasted with the familiarity and spurious precision of existing data) do not become further reasons to dismiss them, it is crucial to recognise and discuss these aspects of legitimacy and methodology. Whether and how the newly generated data are marshalled in policy then also relates to their level of fit with the various pre-existing, and possibly contradictory, narratives, policy objectives and related vested interests.

It is here that definitions are again central. They underpin the modalities of engagement between irrigators on one hand, and decision makers and development agents on the other. The debate is no longer about data accuracy, which can be improved (as shown in this paper). Instead, the discussion assumes a more holistic dimension around what can be officially defined as 'irrigation'. In this holistic debate, it is important to stress that farmers' practices openly confront dominant paradigms such as a widely held vision of irrigation as a distinct enclave of 'modern' cultivation, which uses permanent infrastructure and is separated from the broader farming landscape. Farmer-led irrigation development also conflicts with the official view that small-scale farmers are oriented only to subsistence and not to markets, and the inventive bricolage of farmers' practices exposes deficiencies in conventional engineering designs, particularly when applied in contexts of strong interannual variation of river flow (Lankford, 2004; Lankford and Beale, 2007). Finally, farmers' small-scale irrigation practices also pose challenges to regulatory authorities such as river basin agencies, which already suffer from lack of capacity to monitor and regulate spatially distributed water use (Mdee and Harrison, 2019).

More fundamentally, acknowledging farmer-led irrigation development as being widespread and accepting that it is indeed integrated with wider farming systems questions the dominant irrigation constituency that is made up of engineering design and construction companies, consultants, agribusiness operators and suppliers. It questions an investment approach characterized by a distinct infrastructural logic of 'build-neglect-rebuild' that is separate from the broader agricultural and rural economy (Veldwisch et al., 2009; Harrison, 2018; de Bont et al., 2019b). Officials and technicians in international development agencies or those working in ministries in charge of the irrigation portfolio may thus acknowledge figures quantifying the areas that are being watered by farmers using their own means. However, they may also reject these numbers as constituting 'irrigation' data for two reasons: first, to avoid legitimising such practices, and second, to justify efforts to curb farmer-led development of irrigation on the ground of their perceived negative impacts on water resources.

For a new trajectory to open up, farmers’ practices need to be seen through another lens. There needs to be an appreciation for their contribution to at least some policy objectives, such as increased agricultural Growth Domestic Product, economic growth, climate change adaptation, and 'building back better' after the Covid-19 pandemic. Their practices need to be seen for how they have helped achieve public targets set, for instance, in the framework of the Sustainable Development Goals or, even more prosaically, how they have helped reach 'on-paper' targets for expansion of irrigated areas that have been set in national strategies and development plans (Izzi et al., 2021).

As in the case of Farmer Managed Irrigation Systems (FMIS), which was mainstreamed in South Asia’s irrigation policy agenda over two decades ago (Liebrand, 2019), such reorientation requires building a supportive coalition. There are signs that the major role played by farmer-led irrigation development in sub-Saharan African rural economies is increasingly being recognised by a wide diversity of actors. These include national governments, international research institutes, and major development agencies (IWMI, 2019; World Bank, 2019; African Union, 2020). In such arenas, however, discussions tend to frame farmers’ practices as a 'model' alongside other static irrigation categories. The making of a model involves simplifying highly diverse practices and, more importantly, it gives centre stage to external funding agencies which are seeking uniform investment approaches that can be (easily) rolled out.[7] This may well lead to undermining the very processes meant to be supported and it risks losing valuable insights into the rationale and processes of innovation that could inform novel policy interventions.

We instead call for a 'fluid' understanding of irrigation (see also Lankford, 2004) which moves away from treating techniques of agricultural water management by small-scale farmers as "some kind of ethnographic curiosity" (Adams and Anderson, 1988: 522). It is crucial to recognise farmer-led irrigation development – where possible quantitatively – as a driving force in rural economies, to acknowledge its impacts on agricultural output and hydrological management, and to accept that, because it is driven by the food demands of rapidly urbanizing populations, they are at least to some degree independent of government and international development actions. As discussed earlier, this requires a change in working cultures that are deeply and too narrowly rooted in engineering and a shift away from paternalistic development practices on the part of irrigation 'experts'.

CONCLUSIONS

Irrigation development in sub-Saharan African contexts presents a challenge for critical research that seeks to engage policy makers constructively on the basis of knowledge that may go against current data and narratives. AQUASTAT’s monumental data-gathering effort – revisited and substantially revised over the last two decades – has become the main source of information about irrigation areas, activity and

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[7] We contend that the use of the expression 'farmer-led irrigation' in many of these international discussions, and the related omission of the word 'development', is not neutral. It illustrates the search for a 'model' and denotes a static – rather than a process-based – understanding of irrigation (see also Veldwisch et al., 2019).

water use. Despite AQUASTAT's own discussion of the methods it uses and their limitations, its numbers are often reproduced without question or caveat in authoritative documents on the state of irrigation in sub-Saharan Africa and what should be done about it. We have argued that the methodology and vision that underpins AQUASTAT – with its bias towards permanent infrastructure as a defining feature of irrigation – means that the database will struggle to keep up with the farmer-led development of irrigation that is widely observed in sub-Saharan Africa. We have argued that this offers opportunities for research to identify methods for generating new data. However, for these new data-generation efforts to usefully inform policy and intervention in the irrigation sector, they need to be embedded in propositions for a better contextualised understanding of what irrigation is.

From our pilot study, we conclude that radar-based remote sensing analysis can help in quantifying the extent of at least some farmers' practices (notably rice irrigated agriculture), though still with large, but quantifiable, levels of uncertainty. This offers a potential asset in the search for better monitoring of irrigated areas and water use in agriculture. How such data will be used, however, will depend upon the political context in which small-scale irrigators and competing water users operate.

As farmers' practices openly confront dominant irrigation paradigms and related vested interests, there is, in our assessment, a significant risk that new data-gathering techniques that put the extent of smallholders' water use 'on the radar' will be used in the context of more rigid and regressive regulation that is legitimised, notably, by a narrative whereby smallholders' irrigation practices are characterised as inefficient and unproductive. It is possible, therefore, that farmers who have thrived at the margins of state planning may find their enterprise both illuminated and constrained by the availability of new data.

This scenario leads us to a more fundamental argument in the paper: that techniques of measurement cannot, of themselves, resolve the tensions between the different qualitative judgements that define whether or not these farmers' strategies are indeed 'irrigation'. At stake here is an emphasis on the defining of boundaries either in terms of (engineering) infrastructure and expertise or in terms of an alternative, fluid (Lankford, 2004), framing of irrigation that puts farmers' decisions about purpose, location and design centre-stage. This latter conceptualisation of 'irrigation' includes an acknowledgement of the variability, innovativeness and adaptiveness of farmers' practices and an acceptance of their interactions over time and space with non-irrigated farming.

Thus, as well as engaging policy makers and development agencies on the methodology of quantifying irrigation in Africa, we argue that it is important to reappraise perceptions and underlying ideologies regarding what irrigation is and what constitutes efficient water use, and to propose alternatives framings. This is a challenging enterprise, but one in which new opportunities are discernible.

There are reasons to be cautious about how the increasing recognition of farmer-led irrigation development in sub-Saharan Africa may play out in specific investment initiatives (Veldwisch et al., 2019). But current discussions – even if they are mostly taking place in international arenas – do provide a platform for reframing small-scale farmers' irrigation practices both qualitatively (recognising farmers' leading role) and quantitatively (mapping the extent of land and water use). One likely implication of such a reframing will be the increased significance of small-scale farmers' water use in the eyes of hydrological planners and managers. This will potentially move small-scale irrigation development into policy arenas in which it must compete with powerful interests, not only for land but also for water. For this not to lead to detrimental consequences for these farmers, an alternative narrative that explicitly links farmer-led irrigation development to key policy objectives (notably increased agricultural outputs, food security, etc.) needs to be articulated, in order to 'speak to power'.

At the outset of this study, we embraced the challenge of developing new data-generation approaches to remedying existing shortcomings in the way irrigation in sub-Saharan Africa is measured. Our thinking significantly shifted along the way, including during the writing process. We conclude by locating these efforts in the arguably much broader politics of data production and decision-making with which researchers must engage. We stress that what is at stake are both conceptual issues around the definition of 'irrigation' and practical issues around development practices and vested interests. Alongside Zwarteveen et al. (2018), we contend that there is value in moving away from a modernist understanding of irrigation and instead recognising multiple ways of engaging with, and using, water that take into account political and economic context. This will not lead to any sweeping changes, but it may possibly lead to more pragmatic and incremental approaches.

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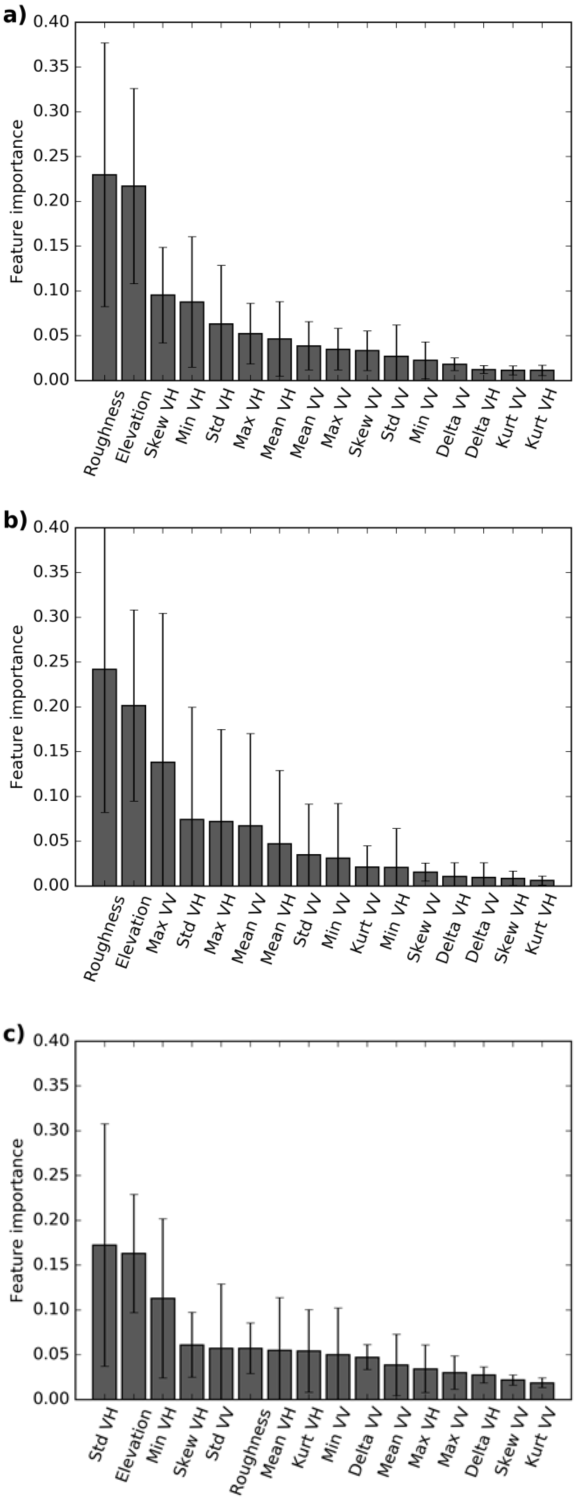
APPENDICES

Appendix 1. Preprocessing procedures for Sentinel 1 images

- *Application of orbit file*, which improves image georeferencing through precise orbit state data
- *Calibration* from digital numbers to pixel values directly related to backscatter in the scene
- *Slice assembly*, which stitches together consecutive satellite scenes to produce a continuous image for each satellite pass
- *Multi-looking*, which reduces noise by degrading image resolution; we reduced image resolution from 10 m to 50 m
- *Radiometric terrain flattening*, which corrects for the tendency for slopes facing towards the sensor appearing brighter than those facing away
- *Filtering*, which further reduces image noise from speckle; we applied a Refined Lee Filter, a radar-specific speckle filter that aims to preserve edges between field boundaries in images
- *Geometric terrain correction*, which aligns pixels with their geographical location and corrects for the tendency of topographic features to appear to lean towards the sensor (foreshortening)
- *Translation and mosaicking*, which aligns multiple radar passes to a common Universal Transverse Mercator (UTM) geographical grid; we output processed images in units of decibels

The Python scripts used to pre-process Sentinel-1 data and generate classified maps are available at https://bitbucket.org/sambowers/sen1mosaic and https://bitbucket.org/sambowers/undertheradar.

Appendix 2. Importance values from Random Forest classifiers for different input features (radar reflection characteristics) in (a) Kilimanjaro, (b) Rukwa, and (c) Shinyanga regions



Elevation and topographic roughness are ranked highly, especially in the topographically variable Kilimanjaro and Rukwa regions.

Standard deviation of the cross-polarisation (VH) tended to be highly ranked, with pixels in irrigated areas showing greater variability than non-irrigated areas across the three study regions.

Skew in the VH polarisation was a predictor of irrigation in Kilimanjaro and Shinyanga, but irrigation was associated with a positive skew in Kilimanjaro and a negative skew in Shinyanga.

High maximum backscatter in co-polarization (VV) and cross-polarization (VH) were highly ranked in Rukwa, whereas a low minimum backscatter in the VH polarisation was associated with irrigation in Shinyanga.

Source: Authors

Appendix 3. Accuracy assessment: Approach and proportion of pixels accurately identified

Accuracy assessment was performed using an independent 'reference' dataset of pixels that were generated using high-resolution imagery from Google Earth and Collect Earth software (Bey et al., 2016). In proportion to their area, we generated 1500 randomly located points across the Rukwa region, 870 in the Shinyanga region, and 699 in the Kilimanjaro region. We specified a 50m x 50m sample point size aligned to image pixels and recorded 'irrigation' where greater than half of the sample point (50m x 50m) was irrigated according to our interpretation of the Google Earth image. Where Google Earth imagery was of insufficient quality to identify irrigation (for example, low resolution or cloud cover), sample points were omitted from the accuracy assessment procedure. We used the methods described in Olofsson et al. (2013) to generate a robust error-adjusted estimate of irrigated area in the radar maps and an area-weighted error matrix. In the table below, we present estimates of irrigated area in each study region ± a 95% confidence interval (CI). We assess classification quality with measures of user’s accuracy (the proportion of radar-mapped area that is of the same class in the reference dataset), producer’s accuracy (the proportion of reference dataset that is of the same class in the radar-mapped data) and overall accuracy (the probability that a location on the map is correctly classified).

		Number of pixels							
		Radar map data	Reference data						
Region	Land use category		Irrigated	Not irrigated	Producer accuracy	User accuracy	Overall accuracy	Map area in hectares (ha)	Error-adjusted area (ha ± 95% CI)
Kilimanjaro	Irrigated	12	10	2	68.8%	83.3%	99.3%	15,879	19,200 ± 7800
	Not-irrigated	658	3	654	99.8%	99.5%		1,316,363	
	Total	669	13	656				1,332,242	
Rukwa	Irrigated	18	13	5	73.8%	72.2%	99.3%	37,450	36,600 ± 11,800
	Not-irrigated	1472	5	1467	99.7%	99.7%		2,822,314	
	Total	1490	18	1472				2,859,765	
Shinyanga	Irrigated	142	78	64	55.9%	54.9%	85.4%	271,954	267,000 ± 37,000
	Not-irrigated	706	60	646	91.2%	91.5%		1,384,837	
	Total	848	138	710				1,656,791	

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