
Mapping small-scale irrigation for climate adaptation

Anna Boser

University of California, Santa Barbara
Santa Barbara, CA 93106
annaboser@ucsb.edu

Jackson Coldiron

University of California, Santa Barbara
Santa Barbara, CA 93106
jcoldiron@ucsb.edu

Karena Lai

University of California, Santa Barbara
Santa Barbara, CA 93106
karena_lai@ucsb.edu

Jasper Luo

University of California, Santa Barbara
Santa Barbara, CA 93106
ruiming_luo@ucsb.edu

Madhav Rao

University of California, Santa Barbara
Santa Barbara, CA 93106
madhav@ucsb.edu

Kathy Baylis

University of California, Santa Barbara
Santa Barbara, CA 93106
baylis@ucsb.edu

Tamma Carleton

University of California, Berkeley
Berkeley, CA 94701
tcarleton@berkeley.edu

Kelly Caylor

University of California, Santa Barbara
Santa Barbara, CA 93106
caylor@ucsb.edu

Abstract

Irrigation is vital for climate resilience and food security in Sub-Saharan Africa (SSA), yet small-scale, farmer-led systems remain poorly measured, especially during the dry season when they are most common. This gap limits research and policy on water management. We created a training dataset of over 2,000 hand-labeled images across Zambia from 2016–2024, which revealed that 95% of dry season irrigated fields are small-scale, accounting for one-third of irrigated land, with prevalence rising significantly over the past decade. Building on this, we will produce the first country-scale, multi-year maps of dry season irrigation in SSA by training models on Sentinel-2 time series, evaluating approaches from tree-based baselines to geospatial foundation models. These maps will fill a critical data gap for climate adaptation and water governance while providing a benchmark for geospatial AI in agricultural monitoring.

1 Introduction

Sub-Saharan Africa (SSA) has among the lowest irrigation rates globally, with only 4–6% of cultivated land irrigated compared to global averages exceeding 20% [Rosa, 2022, Wiggins and Lankford, 2019]. At the same time, a large share of the population depends on agriculture for livelihoods, leaving households highly exposed to increasingly erratic rainfall and prolonged droughts under climate change [Trenberth, 2011, Nakawuka et al., 2018]. Expanding irrigation—including small-scale irrigation—offers a promising pathway to build climate resilience and boost food production [Xie et al., 2014, Rosa et al., 2018], but limited information on current irrigation use and extent constrains effective management and policy.

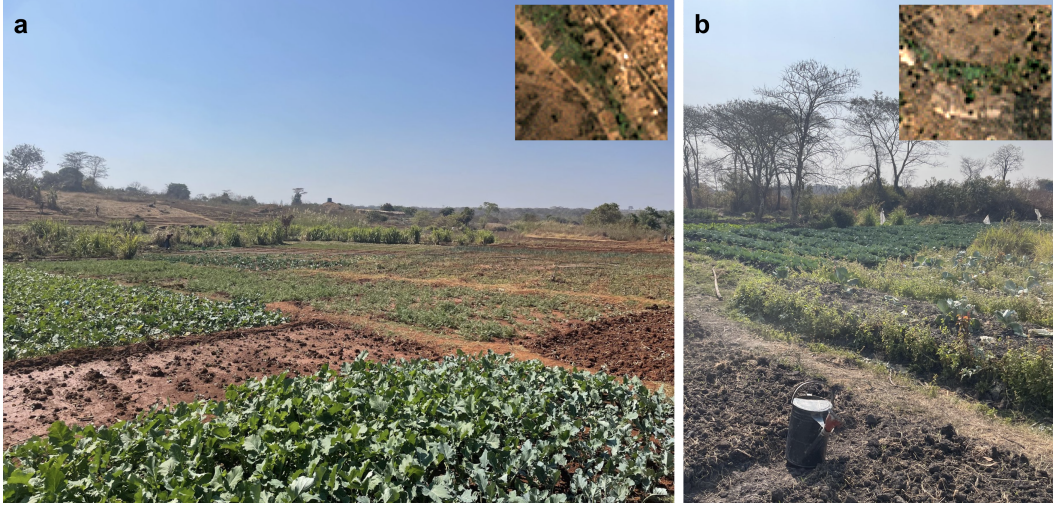


Figure 1: Dry season smallholder gardens near (a) Kitwe, Zambia, and (b) Masaiti, Zambia in July 2024. Insets show greening visible at these locations in PlanetLabs satellite basemaps for July 2024.

Small-scale irrigation is particularly promising because it is less dependent on capital-intensive, large-scale schemes that have often underperformed in SSA [Higginbottom et al., 2021], can be deployed incrementally by farmers, and leverages locally available water sources [African Union, 2020, de Fraiture and Giordano, 2014]. Dry season irrigation is especially important—it enables cultivation when rainfall is absent and prices for horticultural crops are highest [Nakawuka et al., 2018]. Additionally, numerous localized studies report substantial nutritional and income benefits stemming from dry season irrigation development [Burney and Naylor, 2012, Duker et al., 2020, Shah et al., 2020].

Despite this promise, the extent and dynamics of small-scale irrigation remain poorly understood, hampering research and investment. Official statistics often overlook farmer-led systems [Venot et al., 2021, Beekman et al., 2014], while many surveys under-sample or omit dry season practices—precisely when small-scale irrigation is most prevalent [Haile et al., 2022]. This limits our ability to answer basic questions essential for climate adaptation and water governance:

- How widespread is dry season small-scale irrigation, and how fast is it expanding?
- Where are irrigation hotspots forming, and how can that guide investment and water management?
- What climate, environmental, and economic factors shape adoption patterns?

Satellite-based mapping provides a scalable path forward, enabling consistent, repeatable monitoring across space and time. Preliminary efforts show promise, with accuracies exceeding 90%. However, a lack of high-quality labeled data limits spatial and temporal coverage [Conlon et al., 2022, Weitkamp et al., 2023]. Without a large-scale, representative mapping effort, satellite-based maps remain limited in both policy and scientific impact.

We propose to map annual dry season irrigation across Zambia from 2016 to 2025, producing the first country-scale estimates of small-scale and industrial irrigation in SSA. Zambia, specifically, is an ideal testbed, with strong climatic gradients, abundant renewable water resources [Xie et al., 2014, Rosa et al., 2018], and recent exposure to severe droughts. Building on our training dataset of over 2,000 nationally representative images from 2016–2024, we will train a multi-temporal classifier to automatically detect small-scale irrigation. We will also test state-of-the-art pre-trained geospatial foundation models, [e.g. Tseng et al., 2024, Brown et al., 2025] assessing their ability to improve performance with relatively small sample sizes and generalize across space and time. This work will reveal the first robust estimates of small-scale irrigation extent in SSA and set the stage for analyses of irrigation drivers, constraints, and climate-adaptation potential.

2 Dataset

2.1 Labels

Our hand-annotated dataset covers 936 unique locations and 2,674 satellite images. First, we randomly selected tiles of $1 \text{ km} \times 1 \text{ km}$ in Zambia that contain at least 5% agricultural land, determined from the 2015 GFSAD cropland extent map [Xiong et al., 2017]. We then used Google Earth Pro and Collect Earth to load the tiles, restricting images to non-mosaics in the dry-season (June–October) from 2016–2024. In each image, labelers followed a detailed protocol to identify irrigated areas – any actively cultivated (green) agricultural plots in the dry season. Identified irrigated land is delineated using hand drawn polygons. Survey data is collected for each polygon, gathering information on time, confidence levels, and distinctions between small- and industrial-scale systems.

2.2 Features

Although the images for labeling were accessed via Google Earth Pro, they cannot be downloaded for training and lack continuous coverage. To generate annual maps, we use Sentinel-2 optical bands and derived indices (e.g., NDVI) as primary features, following prior work [Conlon et al., 2022, Weitkamp et al., 2023]. Rather than relying mainly on spatial context, these models leverage the annual phenological signal of greening and browning during the dry season, when unirrigated areas remain brown and wetlands stay consistently green. The time series for each location is composited into 10-day mosaics to reduce cloud contamination while preserving seasonal dynamics.

3 Proposed Modeling Strategy

We evaluate a range of modeling approaches, from tree-based baselines to state-of-the-art geospatial AI methods for multi-temporal data. Baselines include random forest and gradient boosting models trained from scratch on aggregated vegetation index features, without explicit spatial context. To capture both spatial context and phenological patterns while remaining data-efficient, we will test lightweight pre-trained transformers for remote sensing time series [Tseng et al., 2024], more heavyweight models such as Prithvi or Terramind [Szwarcman et al., 2025, Jakubik et al., 2025], as well as pre-computed embeddings [Brown et al., 2025].

Because the end goal is to estimate irrigation presence (binary) and extent (continuous) at a 1 km scale, as well as change over time, our performance metrics reflect both traditional segmentation metrics and application-oriented goals. Precision, recall, area under the precision–recall curve (AUPRC), and F1 score will be calculated at both the pixel and image level. R^2 will be used to assess accuracy of extent predictions. We will also measure the model’s ability to detect changes between years by testing its performance on image pairs from the same location at different times.

A spatial test set will be held out from training to assess model generalization to unseen regions.

4 Contributions to Climate Adaptation

Preliminary results from the training dataset show 95% of dry-season irrigated fields in Zambia are small-scale, accounting for 33% of irrigated land. The likelihood of small-scale dry season irrigation in a given 1 km^2 tile has increased by 1.5% annually—equivalent to a 15% increase over the past decade. In a country that is both vulnerable to climate change and built on contributions of smallholder farmers, novel quantification of the irrigation landscape is crucial.

By generating consistent, high-resolution annual maps of dry season irrigation from 2016–2025, our project will:

- Provide the first country-scale, multi-year estimates of small- and industrial-scale irrigation in SSA.
- Enable targeted irrigation expansion in water-available but under-irrigated regions [African Union, 2020, Shah et al., 2020].
- Support water management by identifying irrigation hotspots and emerging trends that may affect groundwater and surface water [MacDonald et al., 2012, Cobbing and Hiller, 2019].

- Establish a benchmark dataset for evaluating geospatial AI in agricultural water monitoring.

Through capacity building efforts, relationships have been established with key stakeholders in Zambia and potential end users of the maps and accompanying findings. Research organizations like the University of Zambia and the Zambia Agricultural Research Institute will use insights from the maps for research and to inform irrigation investment policy. NGOs like iDE Zambia will be able to monitor and evaluate irrigation development efforts, while government agencies, such as the Water Resources Management Authority (WARMA), will integrate the irrigation maps into ground and surface water planning and conservation.

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