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THE BOTTOM LINE

Sustainable Development Goal 7 (SDG 7) aims to ensure access to modern energy for all by 2030. Reaching the goal depends on ramping up electrification efforts. Most of the geospatial models developed to date to identify priority areas for energy access efforts focus on the electrification of households, giving short shrift to industrial and agricultural activities. But loads from those activities can be substantial. When combined with residential loads, they can affect the least-cost technology for electrification. Agrodem fills the modeling gap.


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Agrodem: An Open-Source Model That Quantifies the Electricity Requirements of Irrigation

Why was the Agrodem model developed?

Most geospatial electrification models provide inadequate coverage of electricity requirements stemming from agricultural activities

Achieving Sustainable Development Goal 7 (SDG 7), which aims to ensure access to affordable, reliable, sustainable, and modern energy for all by 2030, depends on ramping up electrification efforts worldwide. To pinpoint energy access targets and the technologies, capacity, and investment best suited to meet them, several geospatial models have been developed over the past decade (Moner-Girona et al. 2018; Morrissey 2019). Most focus on residential loads and electrification of households, often omitting, or covering only partially, loads from commercial and agricultural activities (Korkovelos et al. 2019), which are known as productive loads.

But those loads can be substantial. When combined with residential loads, they can affect the least-cost technology for electrification. Moreover, combining and diversifying the power load can create a stronger case for grid expansion in energy-poor regions or underpin the development of business models for off-grid technologies, like minigrids, in other regions.

By 2030 the electricity requirements of Africa's agricultural sector could be as high as 9 GW, or double the 2013 level (Banerjee et al. 2017). Mapping the sector's irrigation and electricity requirements together could illustrate how sustainable uses of water complement sustainable uses of energy. The use of efficient and renewable energy in agriculture—from irrigation to farm-gate enterprises—supports sector growth, productivity, and welfare, particularly in rural communities.

This Live Wire introduces Agrodem, an open-source model that uses publicly available data to simulate climatic conditions, crop-yield distribution, and other agro-ecological features to generate estimates of the water and electricity required for irrigation. The estimates can be integrated into other geospatial electrification modeling efforts, for example, the Global Electrification Platform (GEP).[1]

The Agrodem framework was built on publicly available data and open-source software, including Python (Jupyter Notebooks) and Qgis for all data preparation, modeling, data analysis, and visualizations. It honors the principles of reproducible science (Rule et al. 2019) by publishing all scripts on a public repository on GitHub. Supporting documentation, with a step-by-step guide on running the analysis anew (or for a different geography), is also available online.[2]

How does Agrodem work?

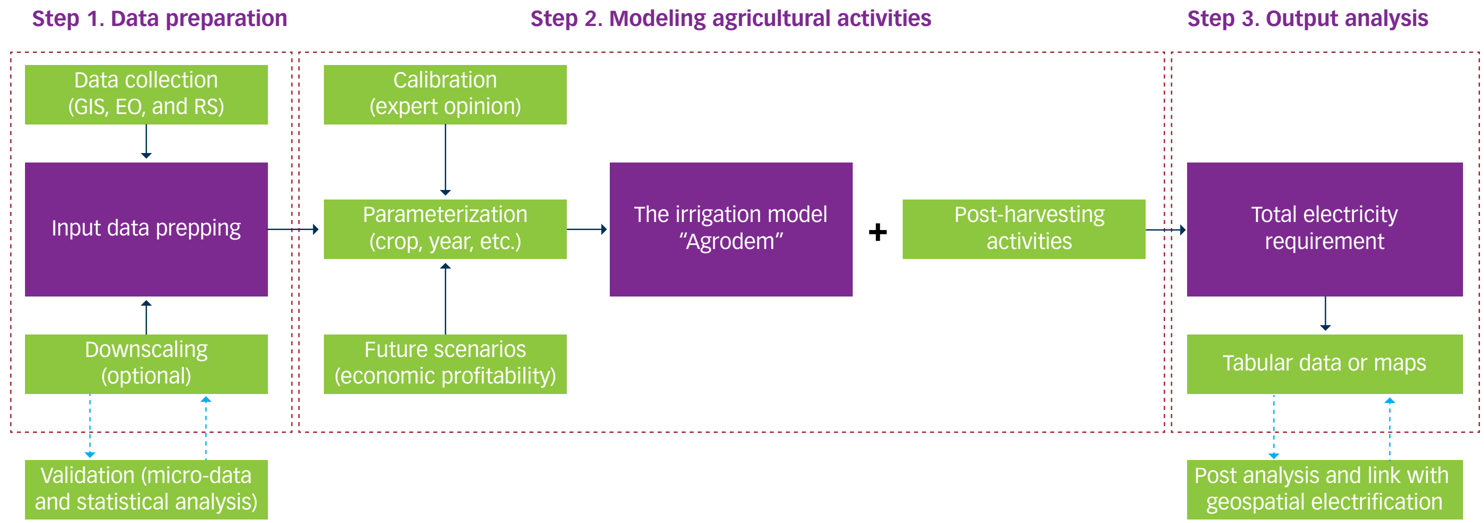
The model consists of three main steps

The first step is the identification, collection, and processing of available data. In the second step, the model is calibrated, scenarios are constructed, and the model is run. The third step consists of analyzing the output, producing visualizations, and interpreting the results. The methodological flow is presented in figure 1; each step is then briefly described.

1 GEP is a collaborative effort involving the World Bank's ESMAP, KTH, and five other international institutions. It aims to serve as a hub of open data and models for geospatial electrification modeling. https://electrifynow.energydata.info/
2 https://github.com/akorkovelos/agrodem; https://agrodem.readthedocs.io/en/latest/

Agrodem is an open-source model that uses publicly available data to simulate climatic conditions, crop yield distribution, and other agro-ecological features to generate estimates of the water and electricity required for irrigation.

Figure 1. Methodological flow of the agrodem modeling framework



Step 1: Data collection and processing. The first step involves data collection and curation as well as preparation of the input files needed for the irrigation model. The key geospatial datasets are as follows:

- Crop extent and harvested area
- Distribution of surface water (rivers, lakes, and reservoirs)
- Distribution and depth of groundwater
- Climate data (e.g., rainfall, temperature, wind)
- Soil characteristics (e.g., water-storage capacity).

Other parameters not generated by geographic information systems are also used as inputs. These include crop attributes (e.g., crop calendar, yields), technology characteristics (e.g., field application and distribution efficiency, motor and electric efficacy), and water-management practices (e.g., irrigation schemes, pumping hours per day). These values are generally available in the literature, but they must be reviewed and calibrated on a case-by-case basis. The methodology is developed around FAO analyses of evapotranspiration and other phenomena that determine the water requirements of a given crop (FAO 1998; Kay and Hatcho 1992). Agrodem is flexible enough to incorporate a range of changes in input data and can accommodate study-specific constraints and assumptions.

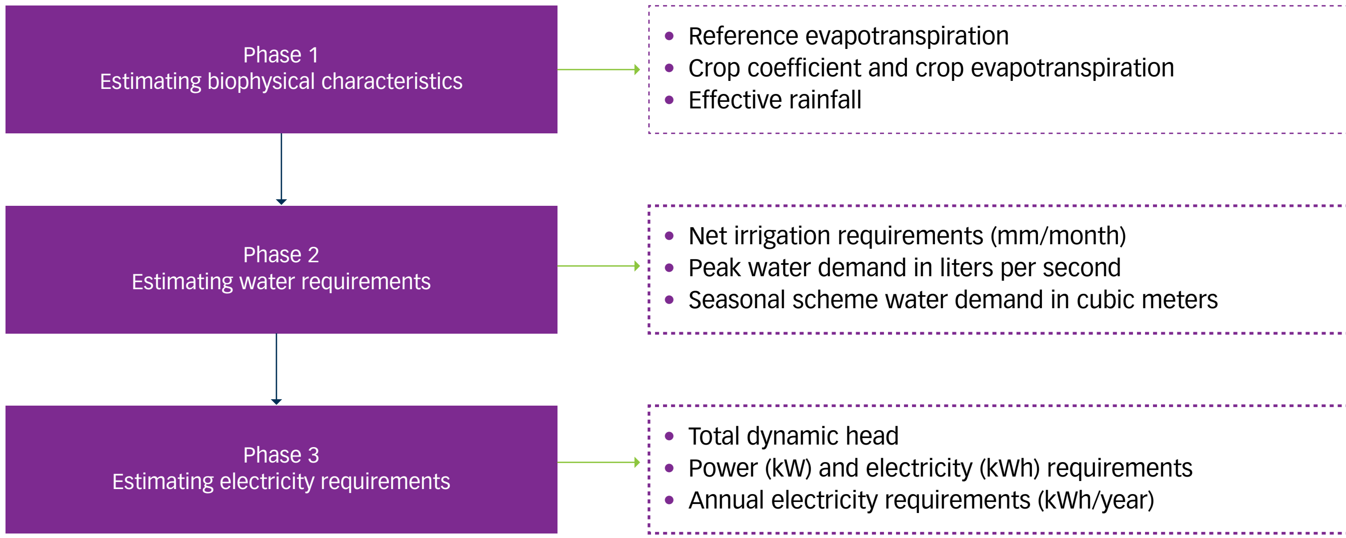
Step 2: The irrigation model. The second step is to calibrate the irrigation model using the the quantitative and qualitative material collected in Step 1, and then to fine-tune its assumptions and parameters to the geospatial context. Once this is done, the model is ready to estimate the electricity needed to pump ground and surface water for irrigation.

The Step 2 processing pipeline has three phases (figure 2).

Agrodem is flexible enough to incorporate a range of changes in input data and can accommodate study-specific constraints and assumptions.

Figure 2. Step 2 of the Agrodem irrigation model

Electricity requirements for irrigation are based on a three-phase model



Source: World Bank; KTH-dES; Vivid Economics.

In phase 1, the model estimates crop-specific evapotranspiration and effective rainfall at any given location by using the crop calendar (planting, growing, and harvesting seasons) and the corresponding climatological characteristics. Evapotranspiration is the process by which water moves from crops and soils into the atmosphere. It includes the evaporation of water from plant and soil surfaces, as well as transpiration of water through plant tissues. Evapotranspiration coefficients differ by crop and location. Together with local climatic conditions (e.g., rainfall, temperature, wind), they are used to calculate the "effective rainfall"—the water remaining for the plant to use. Evapotranspiration is computed based on the FAO-56 Penman-Monteith formula (FAO 1998, paper 56).

In phase 2, the model estimates the total water requirements in a given locale, taking into account seasonal variations, irrigation techniques, and water-management schemes. These may vary based on agroecological zone, land conditions, or specific policies. The output yields the total volume of water required in a given area over the modeling period (usually a year).

Finally, in phase 3, the model estimates the electricity (kWh) needed to supply the required water (figure 3, panel A). Electricity requirements depend on the morphology of the land, both underground and aboveground, and on the application pressure levels of different irrigation techniques and technologies.

Step 3: Analysis, visualization, and interpretation of results. Results are typically presented in .csv format, with each row showing the target location (e.g., farm) and each column an attribute of the location (e.g., harvested area, rainfall, water and/or electricity requirement). The spatial resolution of the results depends on that of the inputs; it can range from kilometers down to meters, with 1 kilometer the typical resolution. Results can be transferred to any GIS/OGC-compatible format (e.g., .shp, .csv, .gpkg, .tiff) for further use. Results can also be aggregated, layering the combined electricity requirements for multiple crops and regions (figure 3, panel B).

Three sample visualizations are depicted in figure 3. They are samples only, not meant to be closely interpreted here, as the data points are generally too numerous and the axes of some of the figures have been omitted.

The model estimates the total water requirements in a given locale, taking into account seasonal variations, irrigation techniques, and water-management schemes.

How can Agrodem help modelers, planners, and policy makers improve energy access?

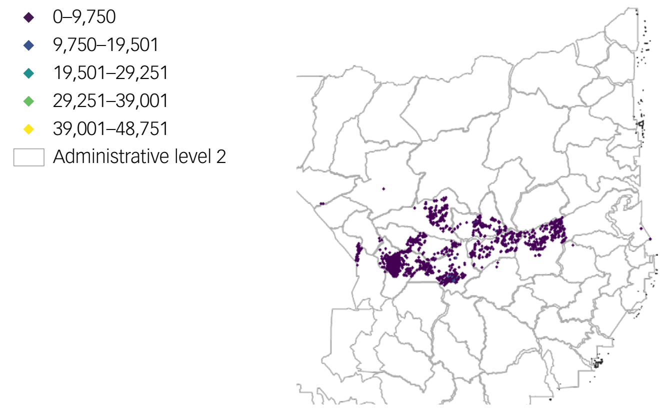
Agrodem can be applied to inform planning related to agriculture and other productive uses of electricity

Because Agrodem is spatially explicit—that is, its estimates cover a specific area of interest—it can quickly pinpoint geographic areas for priority intervention. It can also complement least-cost electrification plans, such as the ones appearing in GEP. Estimates of the electricity required to irrigate a given area can be combined with the residential, institutional, and industrial loads—which are also geographically estimated—for a more inclusive load profile. The underlying geospatial least-cost model can then be run to select the most affordable technology option for the target location—whether a settlement or a farm.

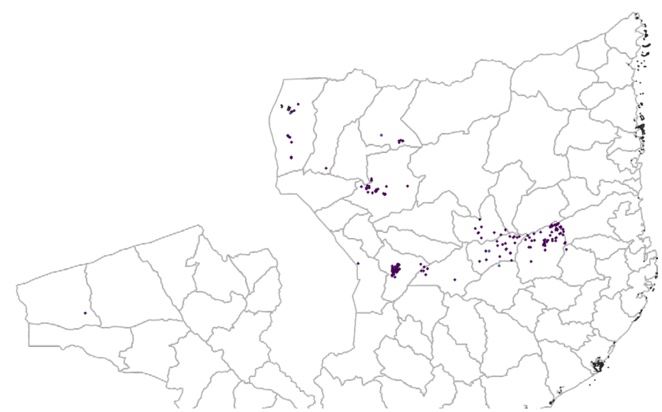
Both GEP and OnSSET were developed to enable the generation and visualization of multiple scenarios (Korkovelos et al. 2019; KTH et al. 2020; Mentis et al. 2017)—for example, to permit comparisons of the electrification mix with and without agricultural loads. Such comparative exercises address the feasibility issues posed by various electrification technologies. For example, does the agricultural load create a stronger case for grid expansion where agriculture's energy

Figure 3. Sample visualizations of Agrodem model results, using Mozambique as an example

Panel A. Distribution of electricity requirements for irrigation of maize (top) and rice (bottom)



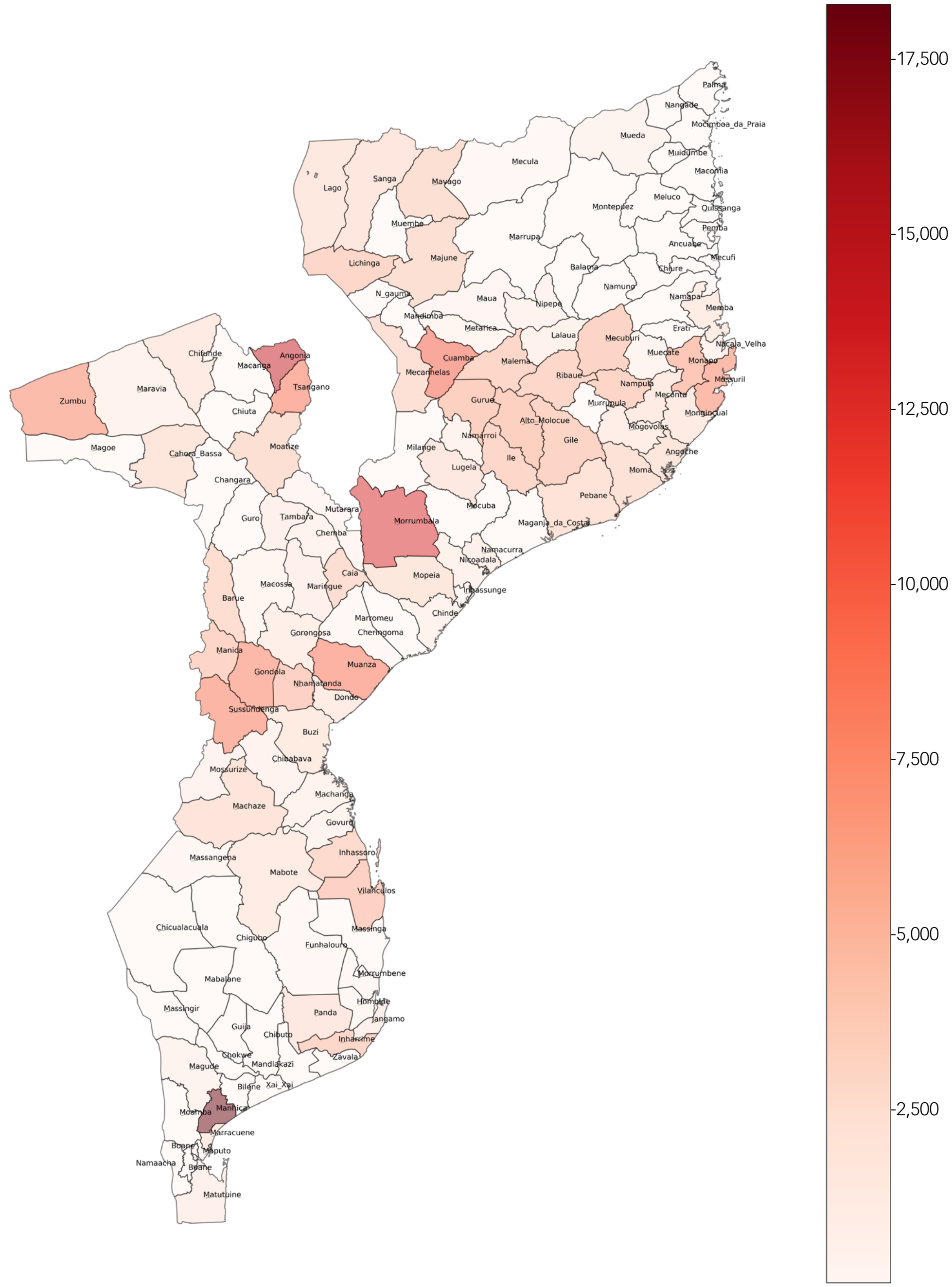
Electricity requirements for irrigation of maize
kWh/year (for base year)



Electricity requirements for irrigation of rice
kWh/year (for base year)

Note: Only the northern half of the country is shown.

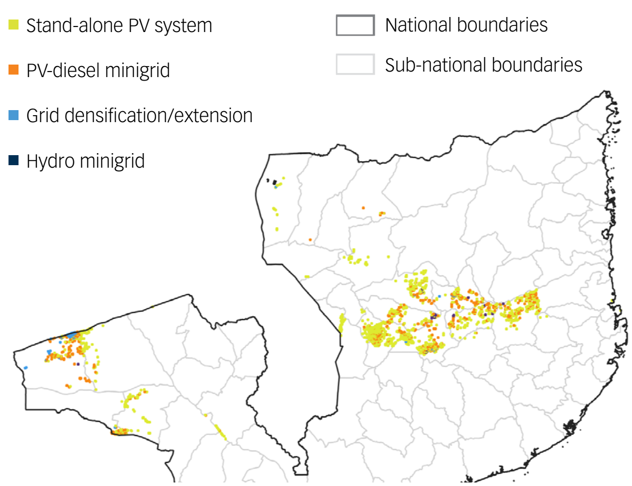
Panel B. Indicative electricity requirements (MWh/year) for irrigation of maize, cassava, and rice in Mozambique, as estimated by the Agrodem model, aggregated by administrative division

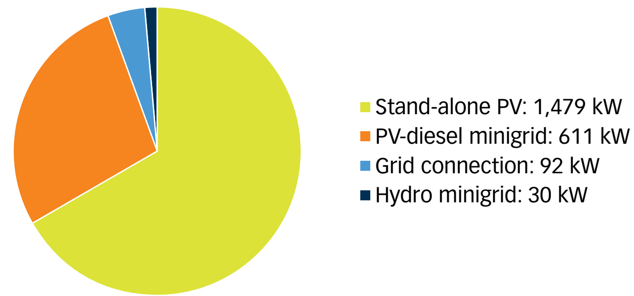


The spatial resolution of the results can range from kilometers down to meters.

Panel C. Least-cost electrification options for 2,375 farms in water-deprived areas, mapped and graphed

Least-cost electrification technology





Average additional capacity per location: 1.23 kW
Average investment per location: US$3,893

Note: Only the northern half of the country is shown.

Because Agrodem's estimates cover a specific area of interest, the model can quickly pinpoint geographic areas for priority intervention. It can also complement least-cost electrification plans. Estimates of the electricity required to irrigate a given area can be combined with the residential, institutional, and industrial loads—which are also geographically estimated—for a more inclusive load profile.

requirements are high? Does it create a robust business case for minigrids? Does it indicate areas that would be better served by solar pumps?

The results shown in panel C of figure 3 indicate the electrification technology that can provide irrigation at the least cost in water-deprived agricultural areas in Mozambique. Most of the sites find PV-based systems as the least-cost option, whether in the form of standalone systems (solar pumps) or PV-diesel minigrids. Grid connection was identified as the least-cost option in a small fraction of locations, mostly where annual electricity requirements were very high. Hydro-based minigrids were selected for an even smaller fraction of sites.

What have we learned to date?

Basically, that it's hard to estimate electricity requirements for irrigation

To do a better job, two elements in the methodology require special attention, and several caveats are in order.

First, the unit of analysis must be aligned with the granularity of input data.

Open access and spatial data showing the distribution of specific crops, with pertinent attributes (e.g., volumes harvested or produced, by area), are available only at relatively low granularity (10 km). The unit of analysis, therefore, will also be coarse. Although statistical

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downscaling methods exist (and can generate more granular spatial input data for the irrigation model), they are time- and data-intensive exercises that need to be properly designed, executed, and cross-validated.

Running times depend on the spatial granularity of the input data. The model requires a couple of hours to run a typical 1 km^2 input file of crop distribution. Lower-resolution input files (e.g., 10 km^2) require less time to run. Higher resolutions (e.g., 250 m^2) demand considerably more running time. The reported computation times are based on modeling exercises undertaken for Mozambique, which is used as a reference case in this publication.

Analysis of model outputs would benefit from a vector polygon layer, with each polygon representing a target field with the crop type, harvested area, and total production for a given year. Although not yet available at scale, this type of visual presentation would boost the amount of data available to the model. Recent innovations with remote-sensing techniques suggest that higher-resolution datasets may soon become available. Land-cover products are now readily available at high granularity (e.g., 30 meters). These indicate cropland distribution but do not specify the type of crop or other features required to estimate irrigation requirements. Other interesting initiatives include AtlasAI (Tadlaoui 2021), Digital Earth Africa (n.d.), and the Radiant Earth Foundation, whose products are still under development and not available at scale. Such products would increase the granularity and thus the degree of insight obtainable using the Agrodem model.

Second, the model's parameters and assumptions should be customized to the local context.

The modeling results are significantly affected by the selection and calibration of input parameters and assumptions. In Agrodem, changes in modeling inputs may drastically alter the results, and many of the parameters must factor in local context. Maize cultivation, for example, varies by location. Water-management techniques may vary, as well. The same is true of available irrigation technologies and their specific characteristics. Although the literature provides a good starting point, the modeling must engage local stakeholders from the energy and agriculture sectors and calibrate the exercise in light of their knowledge and experience.

To allow for that, Agrodem is structured transparently to allow flexibility in setting parameters while achieving replicability and reproducibility. That is, end users can easily adjust parameters to suit the local context. This allows multiple scenarios to be run in a relatively short period of time and used to assess the sensitivity of primary or secondary parameters.

Finally, several caveats should be borne in mind, at last until future work can resolve them.

The Agrodem model uses simplified assumptions to achieve flexibility, modularity, and reproducibility. For example, the model assumes that water reservoirs (both surface and underground) have unlimited flow capacity. In reality, withdrawal limits do exist; these are usually covered in hydrological models and analyses that are not yet part of Agrodem's modeling process. Similarly, the modeling granularity of crops' physical properties, soil composition, climatic variability, and projection is fairly low, a limitation that must be acknowledged both when deploying the model and when reviewing the results. In other words, the model is best at producing high-level insights from a variety of scenarios. It cannot provide a full-fledged engineering analysis of the subject parameters.

The time framework is another aspect of the model and its analysis requiring attention—that is, the time period over which the model estimates the irrigation requirements. Agrodem can identify irrigation requirements for current crops and future ones with a modeling component that enables users to explore hypothetical alternatives of cropland expansion ("extensification") so they can evaluate both the effect of expected changes to crops and any impact policy might have on extensification over time. The script is available, but it needs additional work to properly develop such scenarios. Another component worthy of further exploration is "intensification," meaning the increased harvest, or yield, over the modeling period in an area already under cultivation. Intensification analysis involves more complex energy inputs (e.g., fertilizer), which are not presently covered in Agrodem.

Finally, electrifying farm-gate activities (heating, drying, de-husking, milling, pressing, cold storage) can also increase productivity. A modeling component within the Agrodem framework identifies the electricity requirements of such activities, which can be spatially

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identified and roughly quantified. At this stage, however, estimating farm-gate activities and their energy requirements uses generic assumptions about the potential yield and type of equipment used. In reality, sensible estimates of the energy demands of farm-gate activities require more detailed and informed methods capable of incorporating dynamic elements (e.g., logistics, supply chain, access to market, etc.). Agrodem can therefore be used presently only for a quick screening analysis of the estimated power requirements of farm-gate activities. Even so, when combined with the requirements imposed by irrigation, the analysis can help delineate the spatial contours of electrification for productive agricultural uses.

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