4.5 Comparison of existing modeling approaches

The various modeling traditions are best understood as complementary tools rather than competing ideologies. Empirical models are attractive when transparency and low input demand matter most. Process-based models are preferable when the user needs biological realism, trait testing, or future scenario analysis. Remote sensing improves spatial monitoring and in-season updating. Machine learning is especially useful when relationships are complex and observation streams are large. The real challenge is not to choose one method forever, but to align method with question. If the purpose is local seasonal diagnosis, regression may be enough. If the purpose is trait-by-environment adaptation research, APSIM or DSSAT is more suitable. If the purpose is spatial forecasting or operational monitoring, remote sensing and machine learning become more important. Increasingly, the strongest studies combine them (Jones et al., 2003; Holzworth et al., 2014; Mihret et al., 2024).

5 Case Study: Modeling Sorghum Yield Responses to Temperature and Rainfall Variability in Semi-Arid Regions

5.1 Background and climatic characteristics

A useful published example comes from semi-arid Ethiopia, where sorghum is central to rainfed livelihoods and climate variability is already strongly visible in farm outcomes. In Babile district, eastern Ethiopia, the agro-climatic setting is semi-arid, the growing period is relatively short, rainfall is bimodal and highly erratic, and long-term average annual rainfall is about 731 mm. The area's rainfall pattern includes Belg rainfall from March to May and Kiremt rainfall from June to September, but what matters agronomically is not that there are two rainy windows; it is that their reliability is low and their intra-seasonal distribution is unstable. Published work from Kobo, Miesso, and Melkassa extends the same logic across semi-arid Ethiopia: these areas differ in rainfall response, baseline temperatures, and future vulnerability, but they share a dependence on rainfed sorghum under high interannual variability. This makes them ideal for examining how temperature and rainfall signals are translated into yield through empirical and simulation methods (Tolosa et al., 2023; Gardi et al., 2025; Ali and Kothari, 2026).

5.2 Effects of temperature variability on yield

In Babile, observed sorghum yield showed a negative relationship with both maximum and minimum temperatures during the crop-growing period, and specific monthly temperature variability explained part of the year-to-year yield fluctuation. The logic is biologically plausible: warmer conditions can accelerate development, intensify evapotranspiration, and raise the probability that reproductive processes occur under suboptimal moisture. The more recent Ethiopia modeling study reinforces this concern in forward-looking terms. Using DSSAT-CERES-Sorghum, Gardi (2025) et al. projected warming of up to about 4°C by the 2080s in semi-arid Ethiopian sites and identified Kobo as especially vulnerable where higher temperatures and reduced rainfall coincide. Taken together, the observational and simulation evidence suggests that temperature is not merely a background variable in semi-arid sorghum systems. It is an active driver of phenological compression and water-stress escalation (Tolosa et al., 2023; Gardi et al., 2025).

5.3 Effects of rainfall variability on yield

Rainfall variability in the same case-study region appears even more nuanced. In Babile, monthly rainfall and number of rainy days during the growing season were positively correlated with sorghum yield, and rainfall in August and September was more informative than crude seasonal totals. This suggests that late-season water availability supports reproductive success and grain development in that environment. Yet rainfall does not work as a simple "more is better" factor. The Zimbabwe meta-analysis on rainwater harvesting found that some adaptation practices produced neutral or even negative yield responses under specific rainfall bands and soil conditions, showing that poor alignment between technology and rainfall environment can undermine expected benefits. The lesson from these dryland case studies is that rainfall variability must be modeled at a finer temporal scale than annual or even seasonal totals. Temporal sequencing matters (Kubiku et al., 2022; Tolosa et al., 2023).