Crop Weather and Climate Vulnerability Profiles

A collection of crop temperature and water requirement profiles to help reduce the exposure of smallholder farmers to weather and climate-related shocks

CONCERN worldwide

ACKNOWLEDGEMENTS

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ACRONYMS AND ABBREVIATIONS

CRS	Catholic Relief Services
CSA	Climate Smart Agriculture
DAS	Days After Sowing
NERICA	New Rice for Africa

Cover image: Coconut plantations in Zambezia province, Mozambique have been decimated in recent years by Lethal Yellow Disease, leaving communities without a vital source of food and income. Concern Wolrdwide has been working to encourage small farmers to grow replacement crops such as sesame as a more profitable alternative. Photo by Kieran McConville, 2014.

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1. INTRODUCTION

Smallholder farming systems in the tropics and sub-tropics need to adapt to the consequences of climate change. Most farming systems have[1] traditionally evolved and adapted to a changing climate by shifting to different crops, agricultural production systems or even through transformative changes (i.e. moving out of agriculture as a main livelihood source). However, the rapid climate shifts expected to happen over the next years as a result of climate change require immediate agricultural adaptation actions to be put in place[2,3,4].

The first step in helping farmers adapt to climate change is to work with farmers to identify climate change risks and vulnerabilities and assess:

- Their **Exposure** to various climate change risks.
- The **Sensitivity** of their crops and livestock species to the risk identified.
- Develop **Adaptive** responses to avoid or reduce sensitivities.

The full details of this approach can be found in the Catholic Relief Services (CRS) guide: *Preparing smallholder farm families to adapt to climate change* (Pocket Guide 1: Extension Practice for Agricultural Adaptation)[5].

For this type of crop weather vulnerability assessments, two main factors need consideration: water requirements and optimum temperatures/temperature thresholds. This booklet provides a simplified visual guide for field extension staff in relation to these two factors, although there are also other important sensitivity factors including photoperiod, wind, and waterlogging that should be considered.

An essential component of this approach is to consider growth-stage specific crop requirements. This information can be used to adjust planting dates so that critical growth stages avoid temperature and water stresses predicted by weather and climate modelling. In some cases predicted changes in weather patterns may require farmers to change to alternative varieties or entirely new crops. This information also provides an indication of supplementary irrigation needs, if this is an option.

This guide is based on the approach used by Alfonso del Rio and Brent M. Simpson in their **Review of fifteen crops cultivated in the Sahel**[6] and was the result of an extensive literature

1. IPCC5 Climate Change 2014: Impacts, Adaptation, and Vulnerability
2. Thornton and Cramer, 2012 (https://cgspace.cgiar.org/rest/bitstreams/17024/retrieve)
3. Ramirez-Villegas and Thornton, 2015 (https://cgspace.cgiar.org/rest/bitstreams/54957/retrieve)
4. Thornton et al., 2015. (https://cgspace.cgiar.org/bitstream/handle/10568/66474/CCAFSWP120.pdf)
5. CRS Pocket Guide 1 http://www.crs.org/our-work-overseas/research-publications/pocket-guide-1-extension-practice-agricultural-adaptation
6. Alfonso del Rio, Brent M. Simpson, 2014. **Review of fifteen crops cultivated in the Sahel**. http://pdf.usaid.gov/pdf_docs/pa00k697.pdf

review with a special focus on sources for crops grown in the tropics and for specific regions of interest, provided that enough data was available. A detailed list of the reference sources for each crop is provided as an annex. For field use this guide should be printed without the annex.

The guide provides a set of diagrams on temperature needs, and water requirements for a range of common tropical smallholder crops through their respective developmental stages. The guide covers maize, pearl millet, sorghum, rice, common bean, cowpea, groundnuts, pigeon pea, soybeans, Bambara groundnuts, cassava, potato, sweet potato, yam, taro (*Colocasia* spp.), banana, sesame and sunflower. For temperature sensitivity, maximum and minimum ceiling (lethal) temperatures and optimum temperature ranges are represented for both daytime and night-time (whenever enough data is available). For water requirements, average daily temperatures (mm/day) are presented according to a range of agro-ecological zones (semi-arid, sub-humid and humid) and temperature regimes (medium: 15 °C – 25 °C; high: > 25 °C).

Limitations

This guide only considers the potential interaction between temperature and water requirements. However, other interactions influence crop growth and development: temperature responses change with different photoperiods[7], water requirements are influenced by wind speeds[8] and the rate of crop development is linked to degree-days experienced by the crop. Unfortunately, this review did not find enough consistent data to provide accurate assessments of these interactions, though as the majority of the papers reviewed were for research carried out in the tropics, the charts assume a more or less constant photoperiod regimes.

The review looked at approximately 300 references, both published papers and agriculture reference books. Crop temperature and water requirements are integral to processed-based crop yield models but there was insufficient time to interrogate crop modelling software to understand the temperature and water requirement variables used and the only software used was the United Nations Food and Agriculture Organisation (FAO) crop water requirement software.

The references reviewed varied widely in quality and usefulness. Many failed to mention the crop variety under trial, or even the location of the trials. Some of the published results were so far from the mean of the results reviewed that they have been treated as outliers and removed from the dataset.

Climate-Smart Agriculture (CSA) includes management practices that enhance the resilience of farming systems by physically reducing the **exposure** of crops to water and temperature stresses. Few of the references mentioned the farming practices use, so the data is assumed to come from conventionally managed crops.

7. Hatfield and Prueger, 2015 (http://dx.doi.org/10.1016/j.wace.2015.08.001)
8. Doorenbos and Pruitt, 1977 (http://www.fao.org/3/a-f2430e.pdf)

2. CEREALS

2.1 Maize

ECOLOGY

Maize grows at regions with latitudes ranging from 40° S to 52° N. This encompasses a number of geographical regions ranging from Russia and Northern Europe, on the northern side; to South Africa, southern Asia (Himalayas, China and Southeast Asia) and Pacific Islands on the southern side. Most producing regions are however found in the humid subtropics and in warm parts of temperate regions. Reported elevations range from sea level to 3,800 m and optimal annual rainfall conditions in the tropics fall between 600 and 900 mm. Maize varieties are classified by starch type (Dent, Flint or Soft), colour (white or yellow) and maturity. White dent maize is the staple food crop for East and Southern Africa, while yellow flint maize predominates in the rest of the world. Flint maize tends to be early maturing.

GENERAL ENVIRONMENTAL CONDITIONS

Full sunlight conditions are needed for the proper development of the maize plant (a C4 plant). Maize is a short day plant, though photoperiod sensitivities vary between cultivars. The short day requirement determines the latest planting date in Southern Africa, with ≈1.5% yield reduction for each day of delayed planting. Optimum soil conditions are characterized by deep, well-drained and aerated soils with plenty of organic matter and a pH range from 5.4 to 7.4. It does not generally withstand waterlogged conditions, especially during its early development stages (first five weeks).

CROP TEMPERATURE REQUIREMENTS

In general, the optimal air temperatures for the maize crop range from 18° to 32° C. Temperature needs are higher for the first development stages (up to flowering), whereas temperature requirements for kernel development and ripening tend to be somewhat lower. Slightly higher temperature requirements are also observed at the flowering stage. Minimum lethal temperatures range from about 8° to 10° C, whereas maximum lethal temperatures tend to become lower as the plant develops (Figure 1). The crop germinates well at soil temperatures between 16° and 18°C. For proper growth, mean night temperatures should not fall below 14° C. Optimum night temperatures for germination are up to 30° C and those for vegetative development range from 16° to 23° C, whereas night temperatures in the flowering period should not exceed 30° C.

Total degree-day accumulated for the whole growing season determines maturity and a maize crop might require from 1600° to 1800° C. Seed companies are not consistent in their classification of maturity but varieties generally range from very early (90-100 days to maturity) to early (100-135 days), medium (120-140 days) and late (130-150 days).

CROP WATER REQUIREMENTS

For the whole crop growth cycle, a total amount of rainfall between 500 and 1200 mm is needed for maize, with short-season varieties even withstanding a minimum of 300 mm. The highest water requirements for maize are found from the flowering until the late grain filling phase (mid- and late season; Figure 2), with a peak during the tasselling and silking phases.

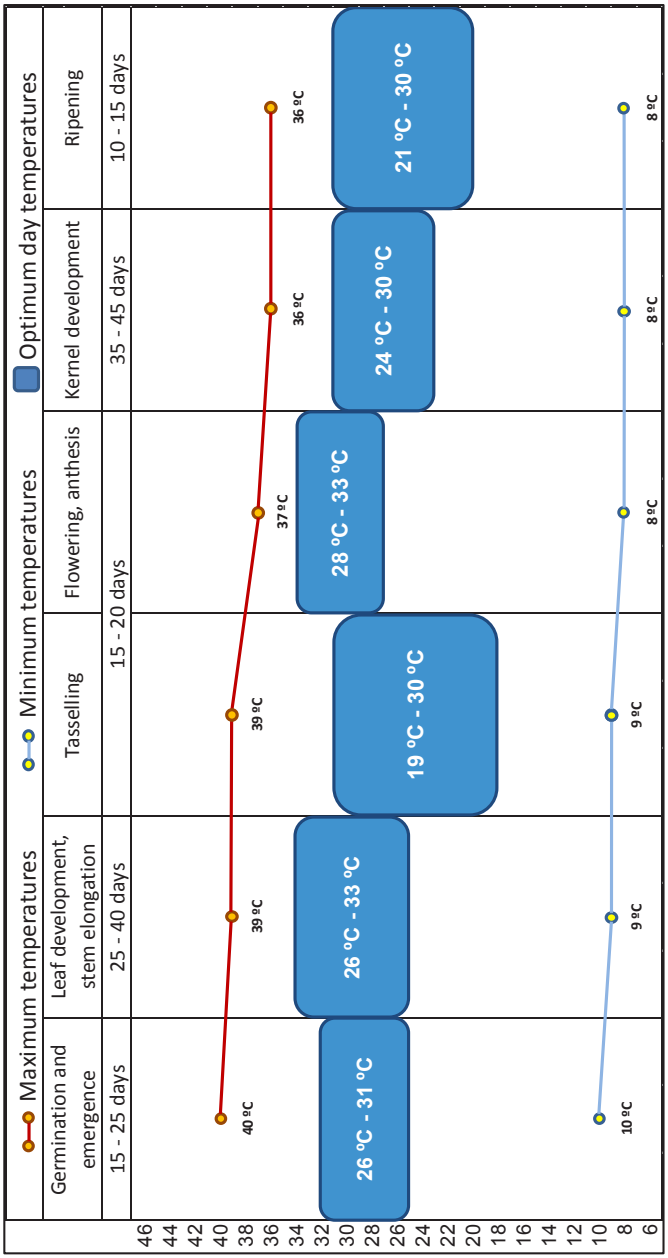

FIGURE 1. Maize temperature requirements by growth stage.

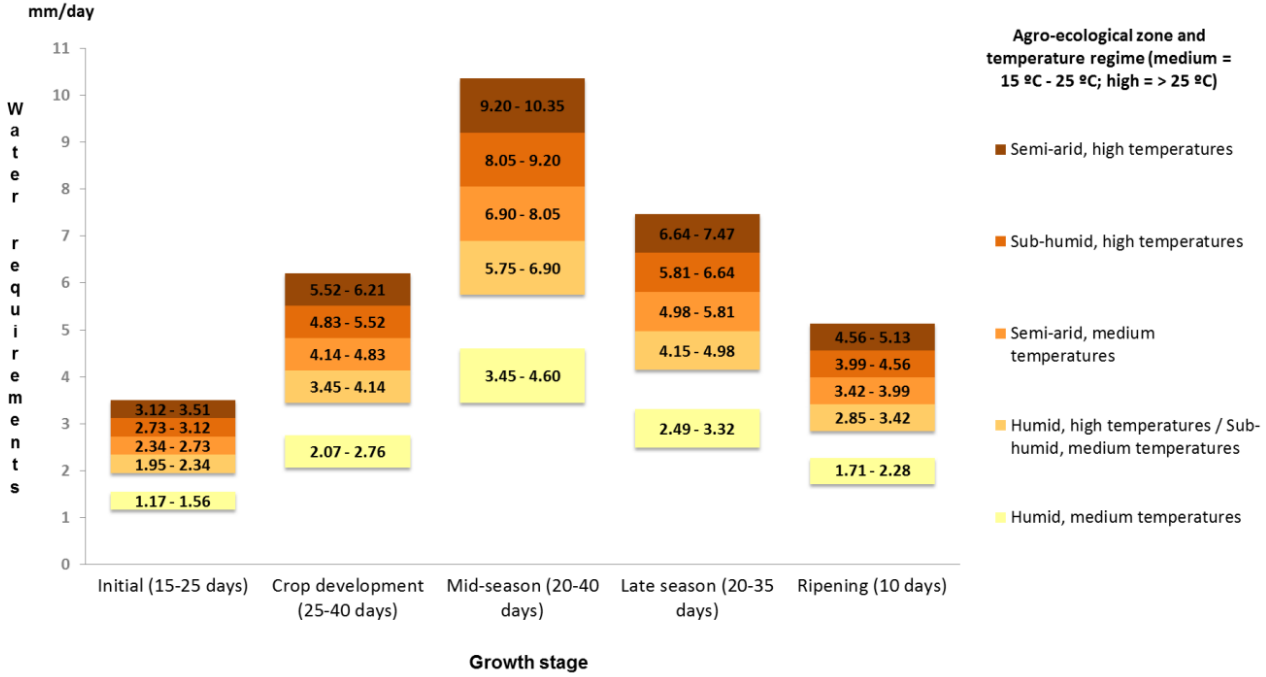

FIGURE 2. Maize water requirements by growth stage in the tropics and subtropics.

2.2 Pearl millet

ECOLOGY

The main producing regions of pearl millet can be found in India and in the African tropics and subtropics. It is mostly grown in semi-arid environments and rainfed conditions, especially in the West African Sahel, and it is one of the most important crops in the Sahel. It is mainly grown in areas with an annual rainfall pattern from 200 mm to 800 mm falling within a period of three to six months and matures in 55-65 days.

GENERAL ENVIRONMENTAL CONDITIONS

Pearl millet, a C4 plant, is generally a highly drought tolerant crop able to withstand high temperatures, low soil fertility, salinity and soil acidity. However it is highly sensitive to waterlogging and soil crusting at germination. The best suited type of soils for pearl millet production are light loam soils and sandy soils. Different varieties are adapted to either short or long photoperiods.

CROP TEMPERATURE REQUIREMENTS

The optimal average temperature for pearl millet generally falls between 25° and 30° C, although for West Africa it has been reported to be between 30° C and 35° C. Optimal temperatures remain somewhat constant throughout all the development stages (Figure 3). Minimum night-time temperatures should generally be above 10 ° C. Little or no germination occurs below 12° C.

CROP WATER REQUIREMENTS

Pearl millet requires between 250 and 700 mm of rainfall during the growth season, although in some cases it can grow with as little as 250 mm if there is little water evaporation and enough soil water retention. The plant is especially susceptible to drought at its early stages and to some extent during the grain filling phase, whereas for the other stages it can withstand droughts up to one month. A minimum accumulated rainfall of 20 mm is recommended for planting. Earlier varieties should be chosen in areas with less amount of rainfall, whereas late varieties are common in areas with rainfall levels above 800 mm. According to the few available studies covering the Sahel and northern Africa (more concretely in Nigeria, Senegal and Southern Tunisia), the studied varieties seem to generally have higher water demands than those consulted for India and the Middle East (UAE) (Figures 4 and 5).

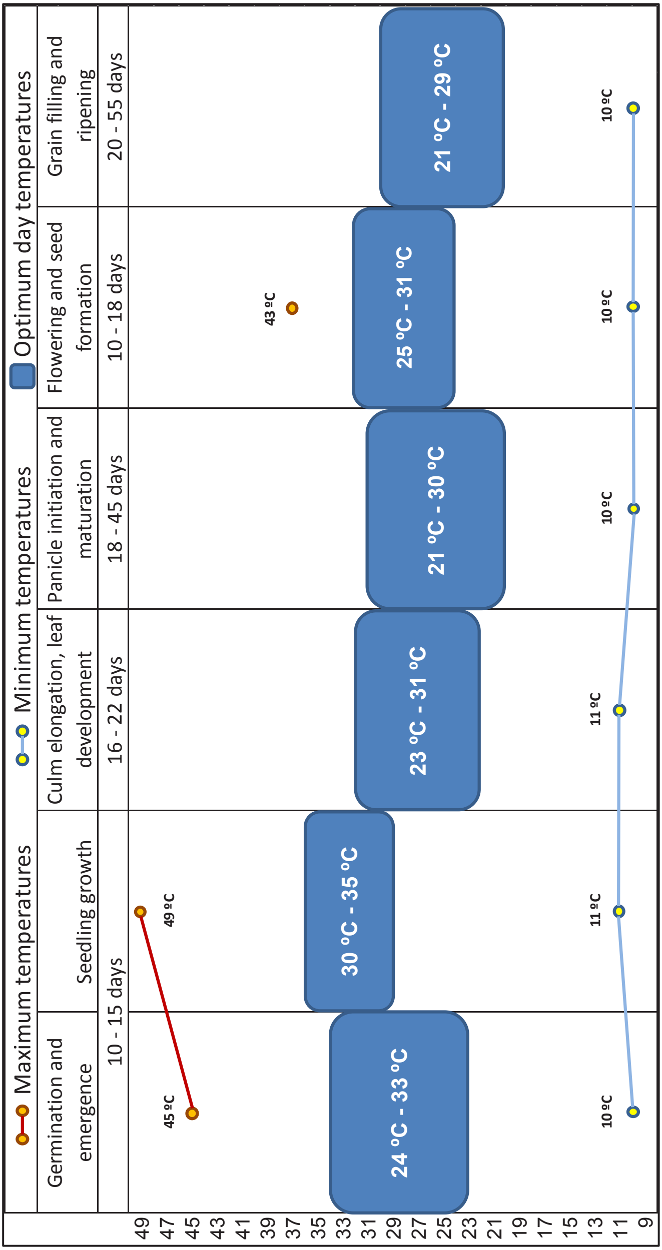

FIGURE 3.
Pearl millet temperature requirements by growth stage.

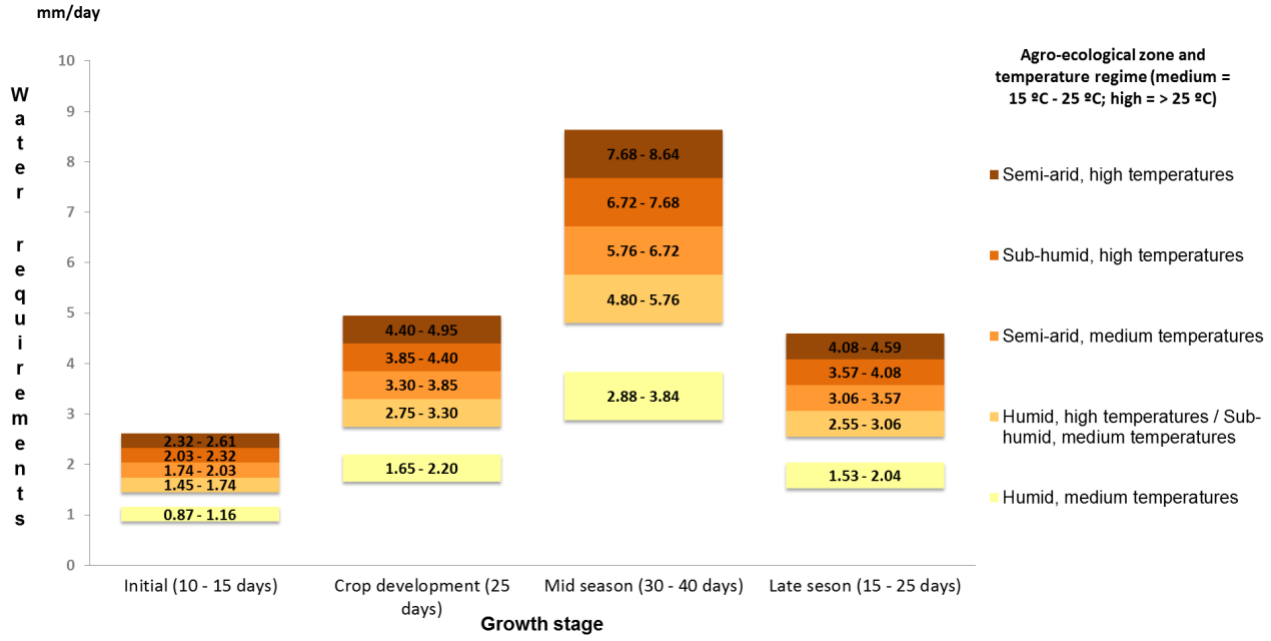

FIGURE 4. Pearl millet water requirements by growth stage in India and Middle East.

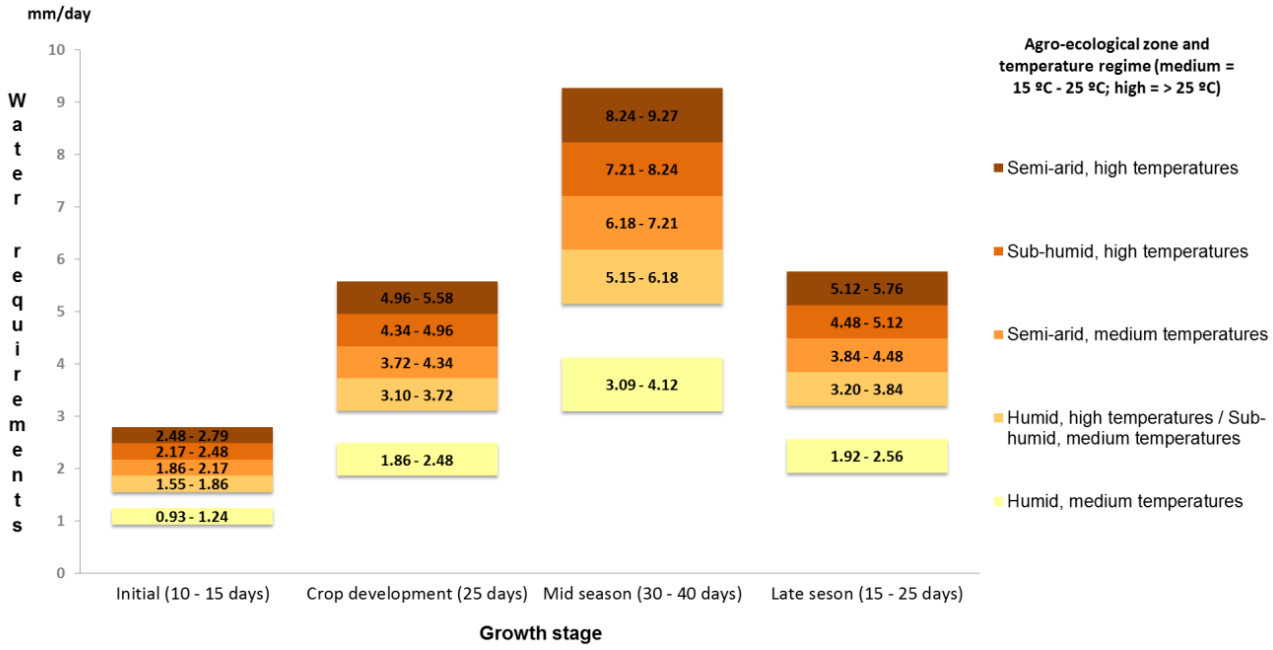

FIGURE 5. Pearl millet water requirements by growth stage in northern Africa and the Sahel.

2.3 Sorghum

ECOLOGY

Sorghum is grown in areas ranging between 40 °N and 40 °S from the equator, covering a range of 105 countries in the drier parts of Asia, the Americas, Africa and Australia; and with India, United States, Mexico, Nigeria, Sudan and Ethiopia as major producers. It is a typical crop in warm and hot semi-arid environments, although it can grow well in different conditions in the tropics. It normally grows in zones with yearly rainfall amounts from 500 to 1,500 mm and it is cultivated at altitudes up to 2,000 m, as in Ethiopia, Burundi, Uganda and Rwanda.

GENERAL ENVIRONMENTAL CONDITIONS

Sorghum is a drought tolerant C4 crop and is more tolerant to low soil fertility conditions and salinity than other common crops such as maize. It can grow in waterlogging conditions, though it is susceptible to fungal diseases. The crop is extremely vulnerable to frost. It grows best on medium to light textured soils. It tolerates heavy vertisols and light sandy soils, as well as soils with different drainage conditions, with an optimum pH ranging from 5.5 to 8.2. Sorghum is generally a short-day plant, although there are a range of varieties adapted to different photoperiod regimes and tropical varieties may fail to flower at higher latitudes.

CROP TEMPERATURE REQUIREMENTS

Sorghum tolerates a wide range of temperatures and is particularly resistant to high temperatures. Optimum temperatures range from 23° to 31° C, and soil temperatures for planting should be at least 17° C. The reproductive and yielding stages are the most sensitive to high temperatures, with an optimum up to 28° – 30° C and a maximum lethal temperature at flowering of 37° C, whereas higher temperatures are usually required at the younger stages (Figure 6). According to the few sources available, maximum (lethal) night temperatures might range from 28° to 34° C. Prolonged night temperatures below 15° C during the flowering stage are critical.

CROP WATER REQUIREMENTS

Sorghum requires between 400 to 900 mm of rainfall during the whole growing season and it is considered as a drought tolerant crop, being able to remain dormant during prolonged dry spells. However, it is particularly susceptible to water stress during the reproductive stages, especially during flowering, where yields can be greatly affected (Figure 7). A minimum accumulated rainfall of 20 mm is recommended for planting.

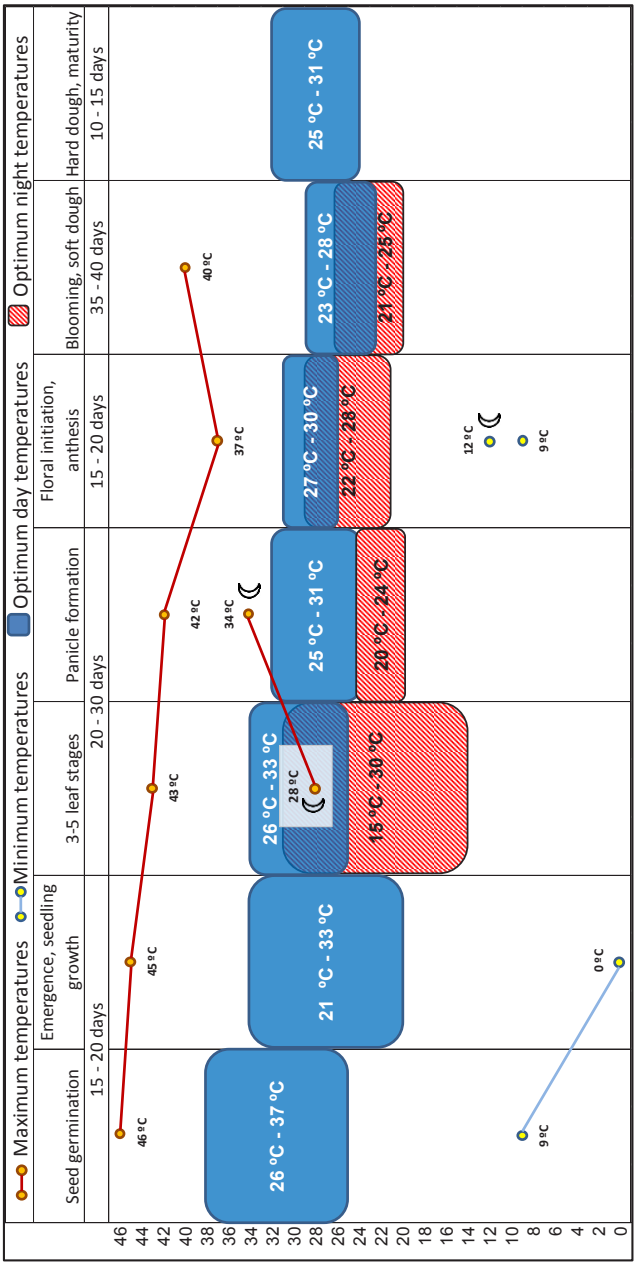

FIGURE 6.
Sorghum temperature requirements by growth stage.

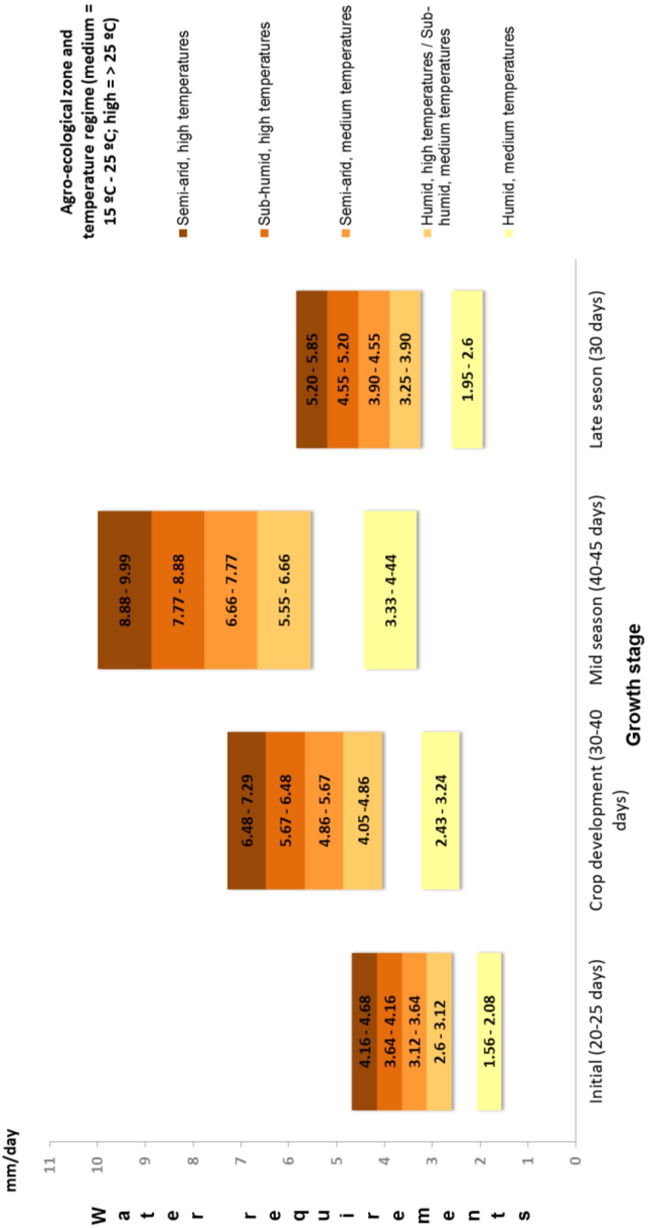

FIGURE 7.
Sorghum water requirements by growth stage in the tropics and subtropics.

2.4 Rice

ECOLOGY

Rice, (*Oryza sativa*), is a common crop cultivated in both temperate and tropical environments under a wide range of climatic conditions, ranging from 35 °S and 50 °N and from sea level to high altitudes (up to 3,000 m). This is due the different existing varieties, growth periods and cultivation methods, which can either be upland (hill or dryland) and paddy (lowland, flooded). The three sub-species are ssp. *indica* (tropical rice), ssp. *japonica* (temperate rice) and ssp. *javanica* (Javanese rice).

GENERAL ENVIRONMENTAL CONDITIONS

Rice generally requires humid and hot climates. Although being a short-day plant, most modern varieties are insensitive to photoperiod. It is sensitive to strong winds and to frost. It tolerates a wide range of soils, with preference for those with a heavy texture and moderately well drained. It does not grow well in sandy soils and optimum is pH between 6.0 and 7.0. Rice is sensitive to sunlight levels and shade or clouds during the reproductive and ripening phases will reduce yields. Yields are therefor higher in rice grown under irrigation in the dry season.

A relatively new rice variety for Africa, the New Rice for Africa (NERICA) (Africa Rice Centre)[9] is also gaining relevance, due to its special resistance to drought and pests. Currently there are 15 different NERICA varieties, most of them for upland production.

CROP TEMPERATURE REQUIREMENTS

In general, daytime temperatures between 24° and 30° C can be considered optimal, whereas optimal night-time temperatures should be between 18 and 25 °C, with a maximum of 33° C. Rice tolerates relatively high temperatures during the vegetative stage, although African varieties are not able to withstand night temperatures above 25° C during this phase. The range of temperatures at which it can grow becomes narrower as the crop develops (Figures 8, 9). Cold temperatures during flowering can also be detrimental. The subspecies *indica* is not very tolerant to high temperatures during the flowering and grain filling stages (Figure 9).

CROP WATER REQUIREMENTS

Upland rice requires between 800 to 1,000 mm of water for the whole growth period, while paddy rice requires between 1000 and 1500, or even much more. Rice is especially sensitive to drought before tillering and during the flowering stages (mid-season). Paddy rice water requirements do no vary much along growth seasons, remaining constantly high (Figure 10). With regards to lowland rice, the reproductive stage is especially sensitive; and NERICA varieties do generally require slightly less water than average upland varieties, with a notable lower requirement at the late period (Figures 11 and 12).

9. http://www.africarice.org/warda/guide-compend.asp

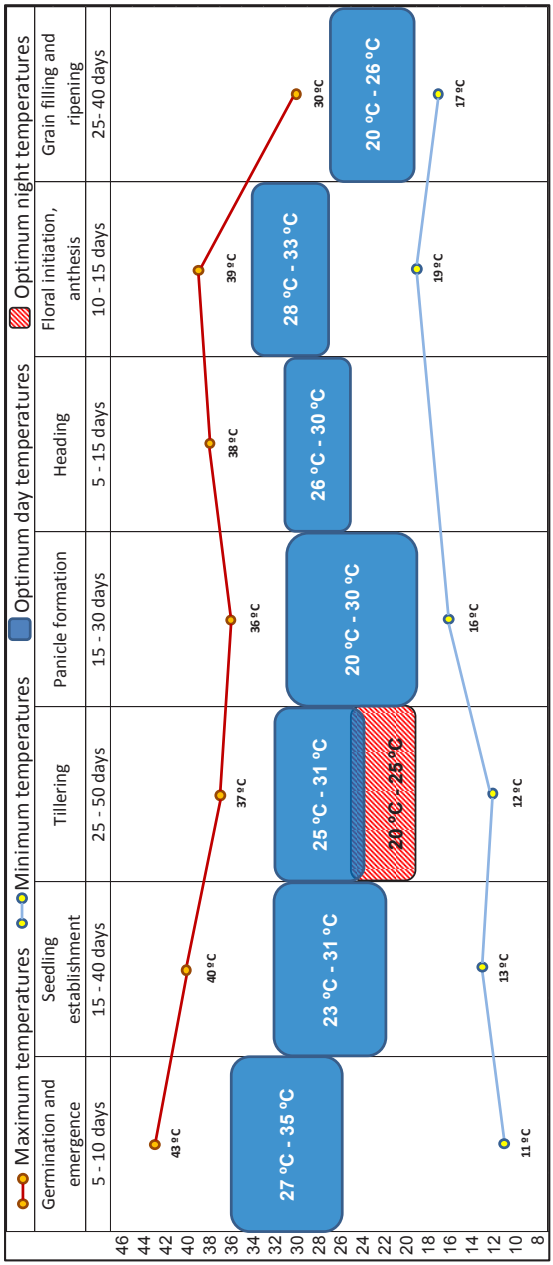

FIGURE 8.
Rice (Oryza sativa) temperature requirements by growth stage.

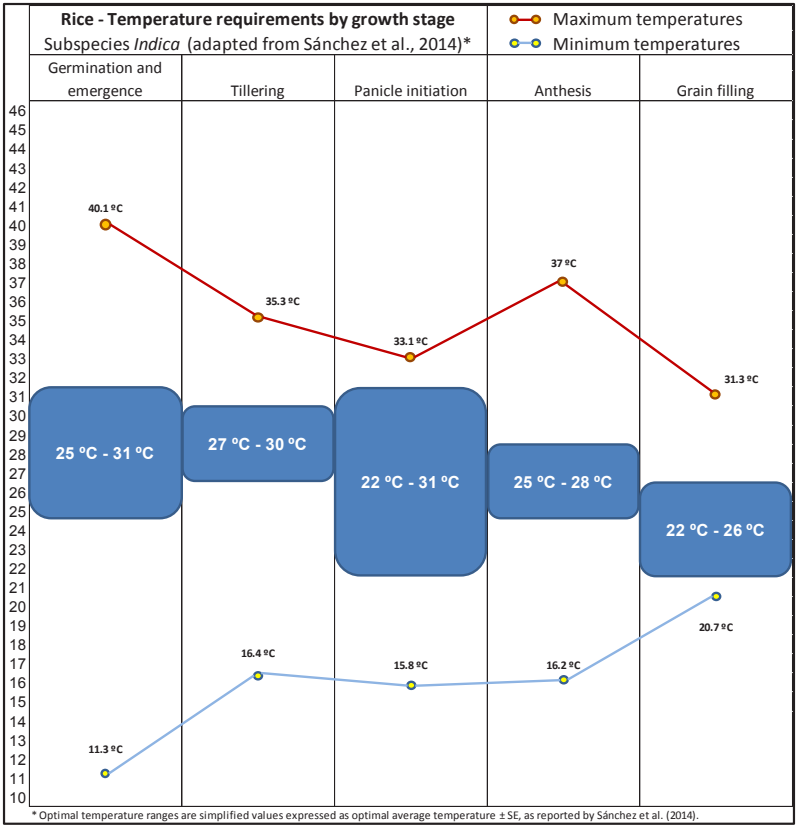

FIGURE 9.
Rice (sp. indica) temperature requirements by growth stage.

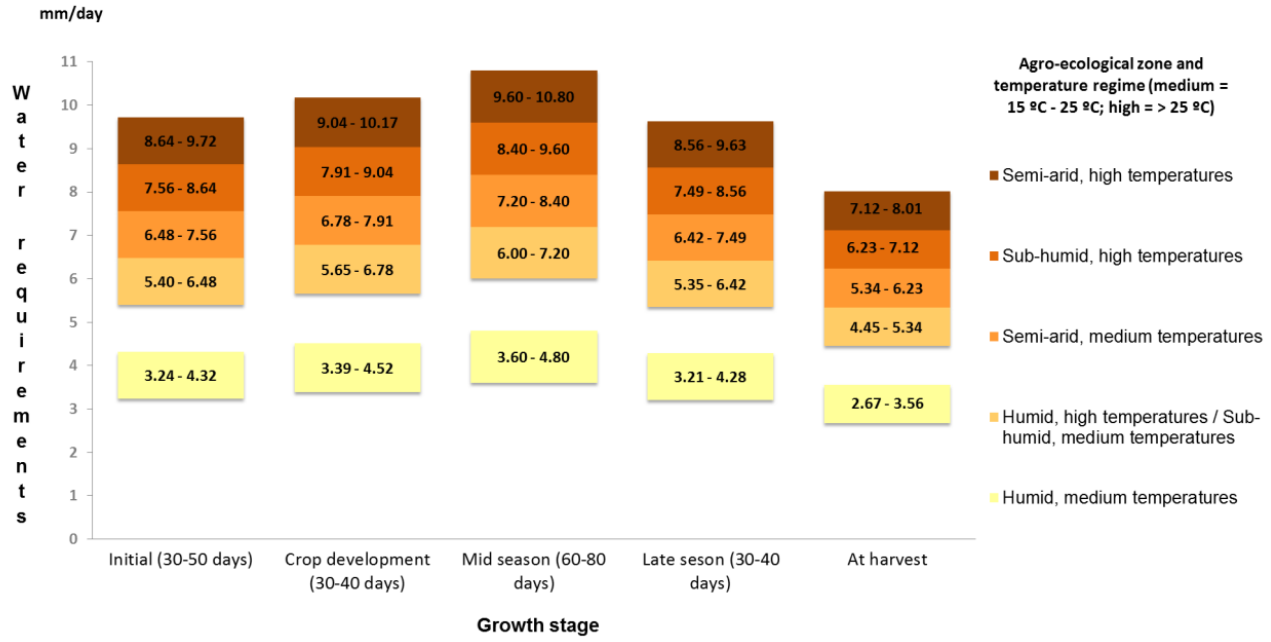

FIGURE 10. Paddy rice water requirements by growth stage.

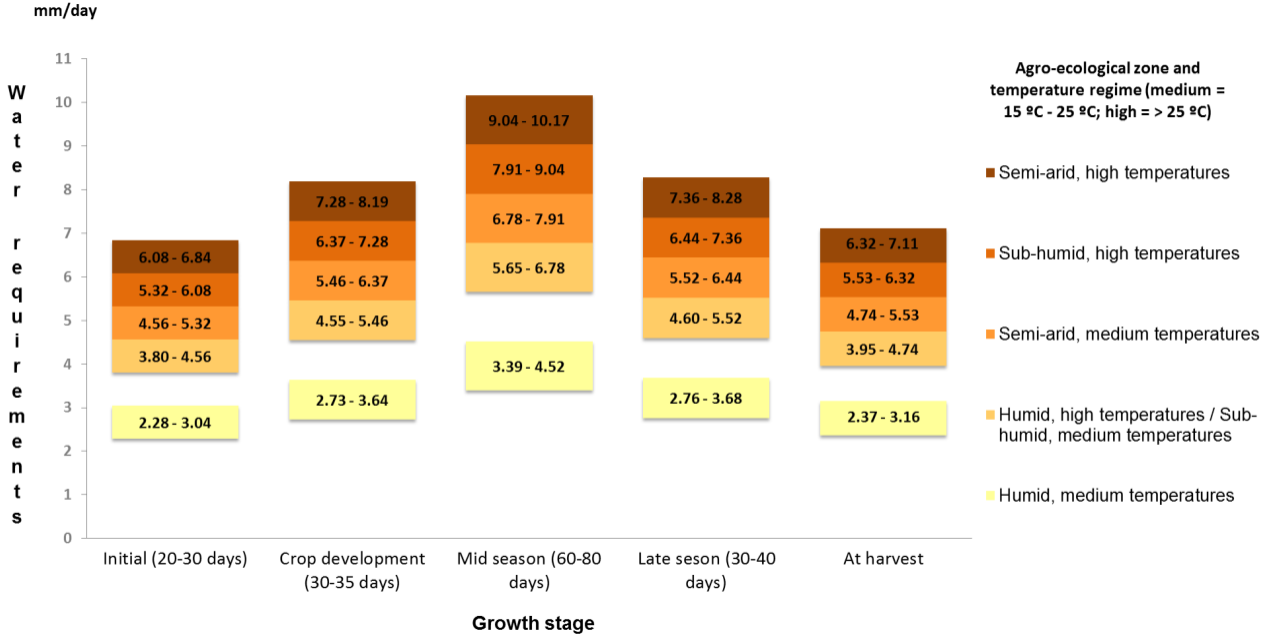

FIGURE 11. Upland rice water requirements by growth stage.

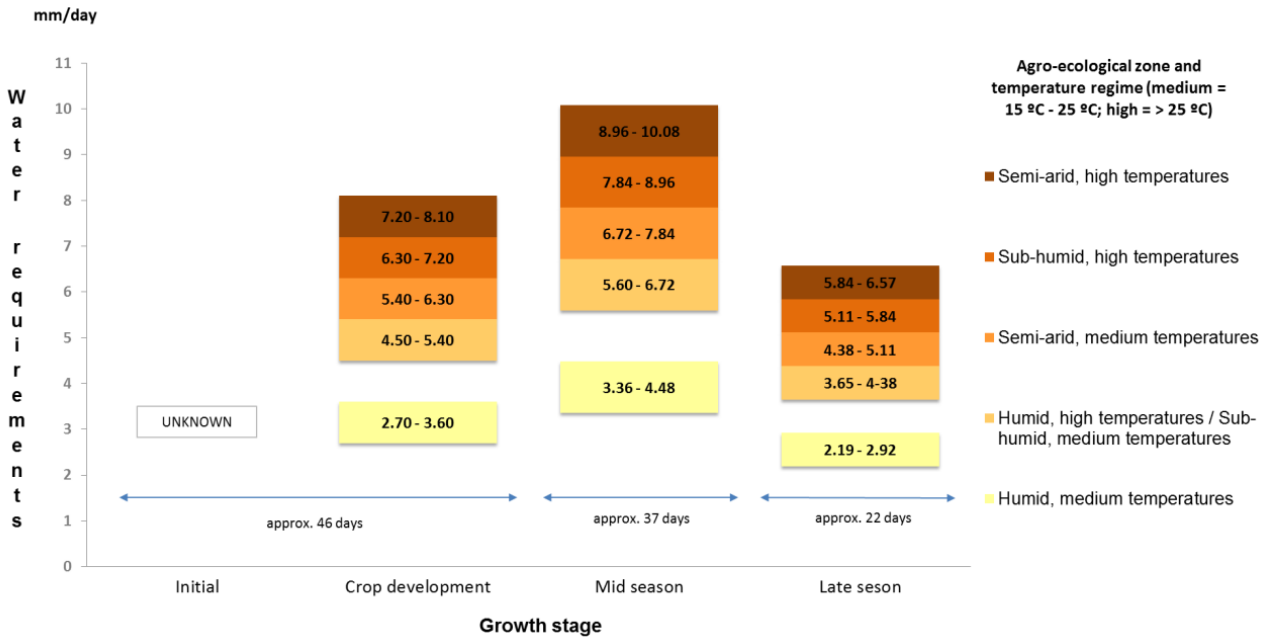

FIGURE 12. New Rice for Africa (NERICA) water requirements by growth stage.

3. LEGUMES

3.1 Common bean

ECOLOGY

The common bean (*Phaseolus vulgaris*), a C3 crop, is widely grown throughout the tropics, subtropics and in temperate regions. In the tropics beans are most commonly found in high altitude regions (800 – 2,800 m) and in humid and moderately warm climates. Most of the African production is concentrated in Uganda, Rwanda, Burundi, Tanzania and Kenya, whereas the crop is generally not well suited to ecological conditions in West Africa. It generally grows in regions with an average annual rainfall between 500 to 1,200 mm. Varieties may show determinate (bush beans) or indeterminate (climbing beans) growth.

ENVIRONMENTAL CONDITIONS

Beans are susceptible to frost, waterlogging and strong winds. They are not well suited to wet tropical conditions. Excessive rains causes flower drop and increase the risk of diseases. Moderately to well-drained soils are needed, with an optimum depth from 0.5 m. Beans require a soil pH from 6.0 to 7.5 and a loam to clay loam texture.

CROP TEMPERATURE REQUIREMENTS

Optimum temperatures range from 21° to 26° C. Temperatures from 20° to 28° C are needed for germination. The early vegetative phase is especially sensitive to high temperatures and optimal temperature ranges are higher as the crop progresses to the next stages.

CROP WATER REQUIREMENTS

The crop needs an average of 400 to 500 mm during the growth cycle, with a highest demand during the flowering and pod filling phase. Excessive rains (above 1,500 mm) are detrimental. Growing green beans generally implies higher water demands than growing dry beans, with a notably higher requirement during the late growth stages (bean development and maturation) (Figure 14). For dry beans, water demands during the reproductive and early pod filling phase (mid-season) are two to three times higher than for the other phases, whereas a dry weather is required towards the harvesting stage (Figure 15)

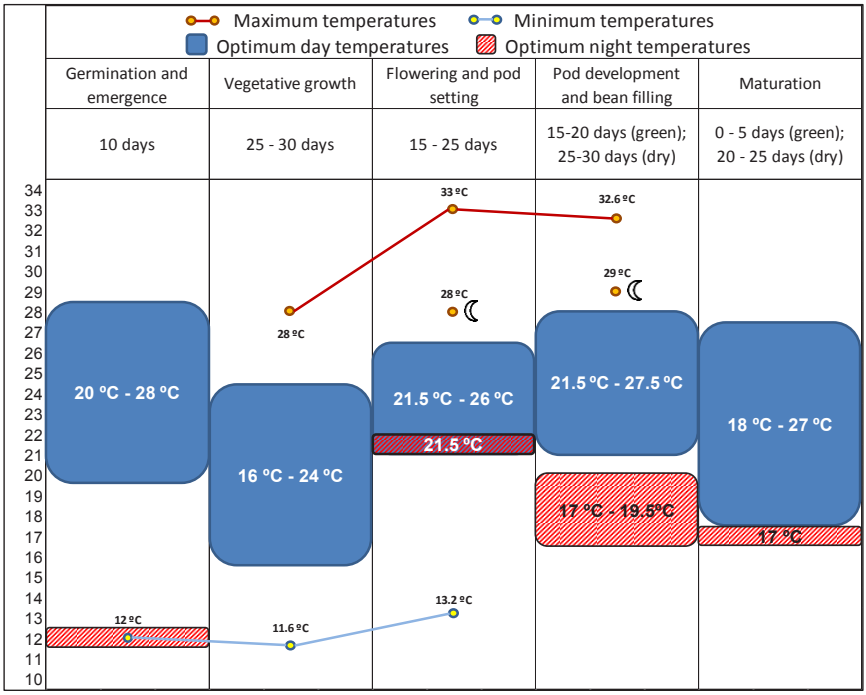

FIGURE 13.
Common bean temperature requirements by growth stage.

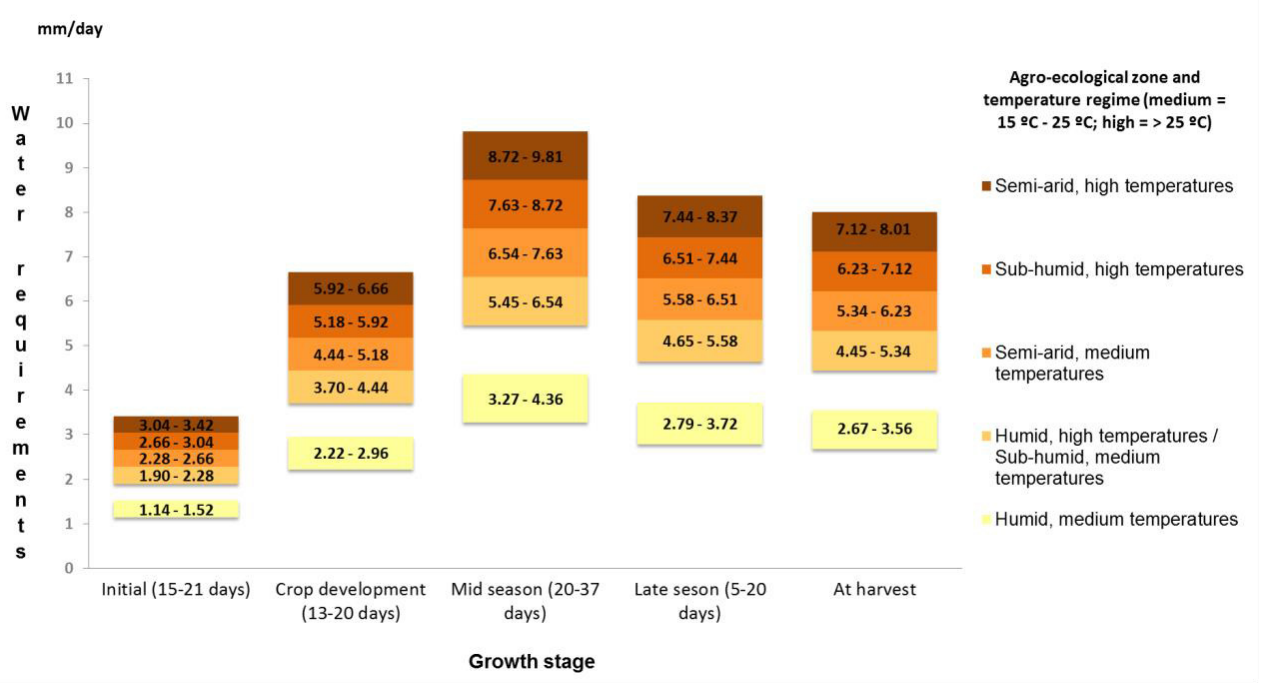

FIGURE 14. Green bean water requirements by growth stage.

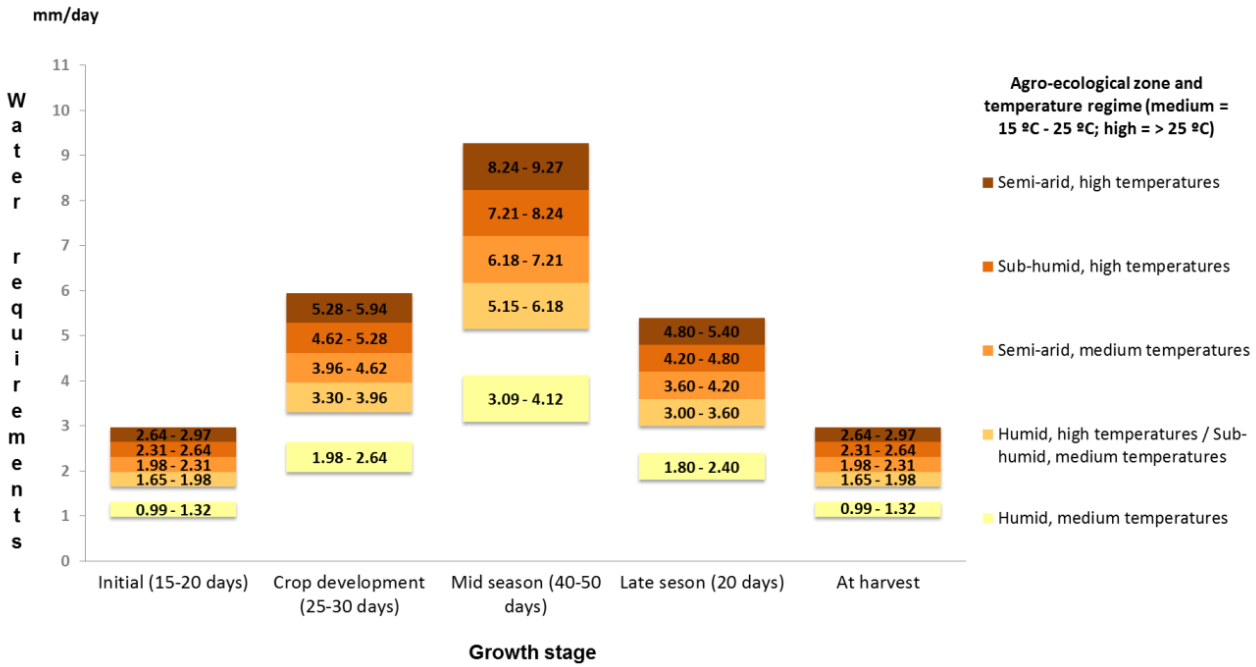

FIGURE 15. Dry bean water requirements by growth stage.

3.2 Cowpea

ECOLOGY

One of the most widely grown beans in the world, *Vigna unguiculata* is indigenous to Africa and is well adapted to semi-arid regions. Cowpea is grown throughout Africa, and is the staple legume for most of the Sahel (*Niebe*). Cowpea is fast maturing (60-65 days) and, depending on the variety, almost all the plant can be eaten. The dried grains contain 25% protein, the pods can be eaten green, the leaves are an important source of green leafy vegetables in Uganda and the roots are used to make a non-alcoholic drink in Zambia. Cowpea is a useful soil improver, fixing more N than the common bean, but is often severely attacked by aphids.

ENVIRONMENTAL CONDITIONS

Cowpea is a low altitude crop and is rarely grown above 1,200m. Cowpea tolerates heat and drought but not frost. It can grow on a wide range of soils types, with light soil preferred. Cowpea tolerates a wide range of soil pH, with an optimum pH of 6.0-7.8. Cowpea is shade-tolerant and is usually intercropped or relay cropped with sorghum, millet or maize. Cowpea is a short day C3 crop.

CROP TEMPERATURE REQUIREMENTS

Optimum temperatures range from 24 to 31.5 ° C, with temperatures of 31.5-38.5 ° C required for germination. Emergence and pod formation is the most sensitive stages for high temperatures, and germination is restricted to temperatures above 11 ° C. Night temperatures should not exceed 29 ° C, and should ideally be between 17 and 20 ° C during flowering.

CROP WATER REQUIREMENTS

Cowpea needs 300-50mm of rainfall during the growth cycle. Too much rain will increase incidents of pests and diseases, with significant reductions in yields above 900mm. The highest water requirements are mid-season (30 DAS). Water requirements are low during germination and harvest, and should not exceed 4mm per day. Local varieties have been selected over generations to flower at the end of the rains. Excessive rainfall will extend the flowering period, resulting in asynchronous maturity.

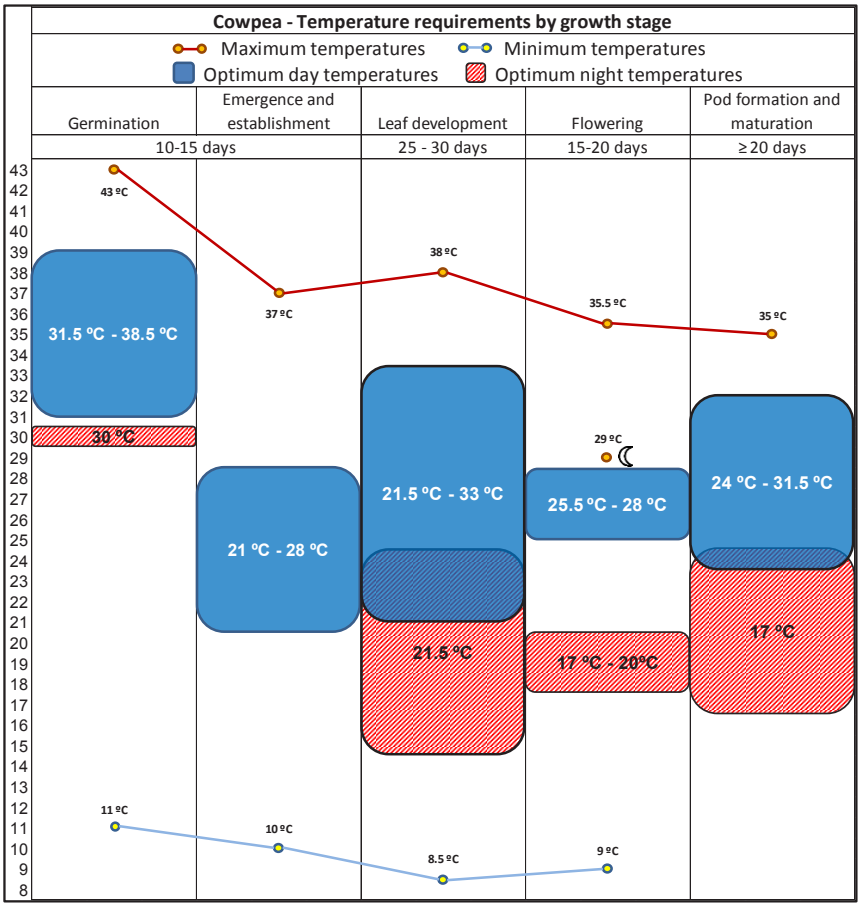

FIGURE 16.
Cowpea temperature requirements by growth stage.

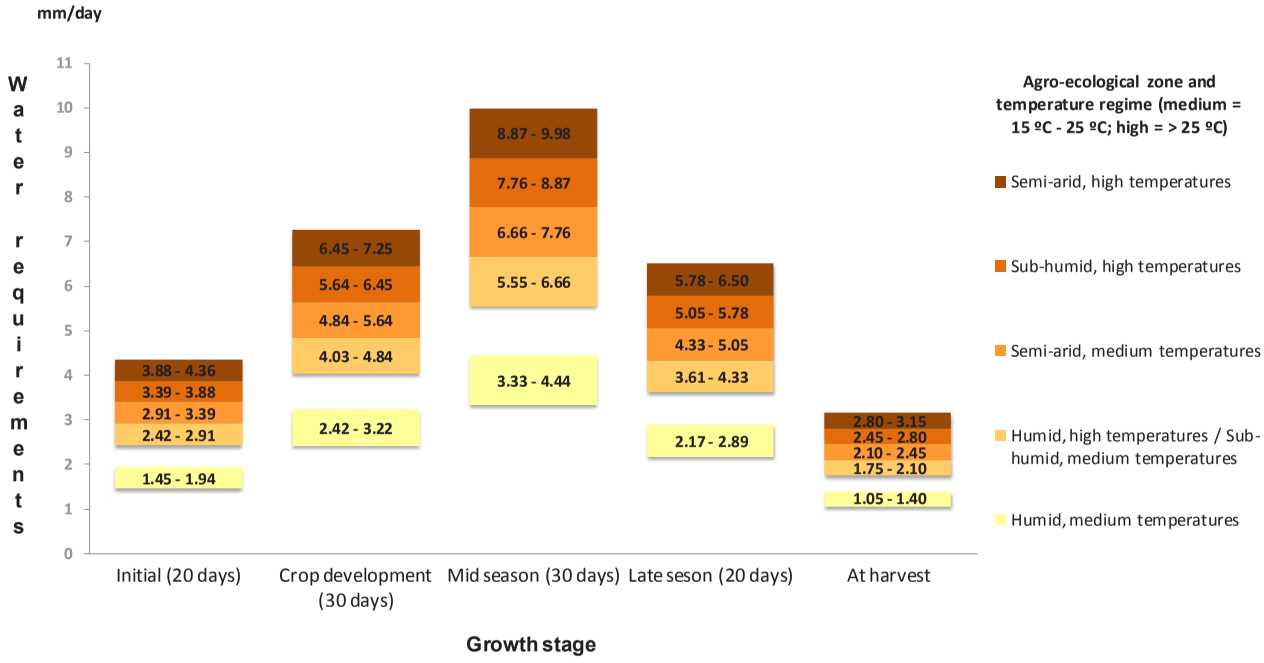

FIGURE 17. Cowpea water requirements by growth stage.

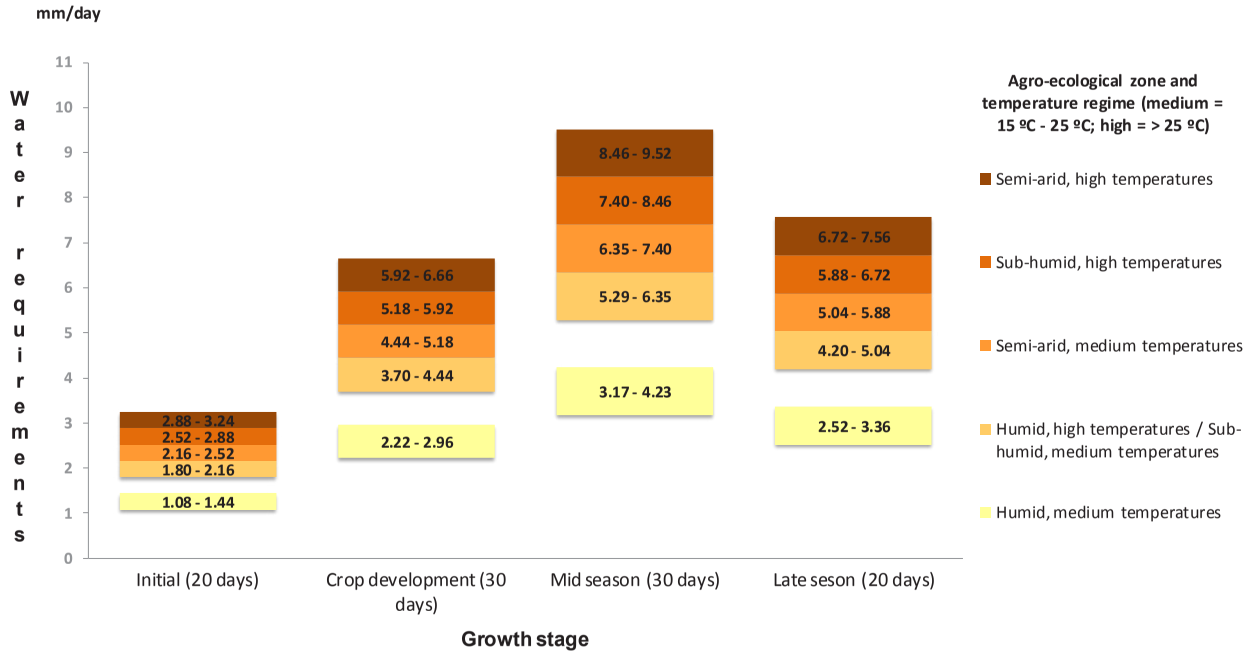

FIGURE 18. Cowpea water requirements by growth stage in Nigeria.

3.3 Groundnut

ECOLOGY

Groundnuts, *Arachis hypogaea*, originated in Peru and are grown throughout the tropics, sub tropics and warm temperate regions, between 40° N and 40° S. Groundnuts are subdivided into runner and bunch types, runner types predominating in West Africa and bunch types in East Africa, with strong cultural preferences. In Uganda red bunch types are preferred in the centre and west of the country and white runner types in the North. White runner-types are grown for direct consumption as a snack, and Red bunch/ Spanish types are grown as an oil crop. Groundnuts may be ground into a flour that is used as the basis for sources. Though high in protein, groundnuts are highly susceptible to mycotoxins, particularly aflatoxins from *Aspergillus flavus* infections.

ENVIRONMENTAL CONDITIONS

Groundnuts need hot and sunny conditions and are sensitive to frosts. Long days (>14 hours) increase vegetative growth while short days (>10 hours) stimulate reproductive growth. Though often intercropped, most groundnuts varieties are not very shade tolerant. Groundnuts grow best on light sandy to sandy loam soils as heavier soils hamper the penetration of the pegs during flowering. Groundnuts fix N and only require additional N during the early growth stages, until *Bradyrhizobium* has become established. Optimum pH is 6.0-7.5, though Spanish types tolerate lower pH. Calcium deficiencies will cause empty pods "pops", so Ca should be applied as either gypsum if the pH >6.5 or lime if the pH <6.5. Correct spacing reduces aphid infestations, vectors of groundnut rosette virus.

CROP TEMPERATURE REQUIREMENTS

Though groundnuts can tolerate temperatures as high as 45°C, optimum temperatures are between 24 and 30°C. High temperatures are tolerated during seedling establishment but should be between 24-31°C during flowering, peg and pod formation. Cool temperatures delay flowering. Unlike other legumes, groundnuts can tolerate high night temperatures.

CROP WATER REQUIREMENTS

Groundnuts cannot tolerate waterlogging and optimum water requirements are 400-1,200mm for the growing cycle, depending on variety grown. The highest water requirements are during crop development (30-45 DAS) and mid-season (30-50 DAS), up to 10mm per day in hot semi-arid regions. Rainfall over 1,100mm for the growth cycle will significantly reduce yields.

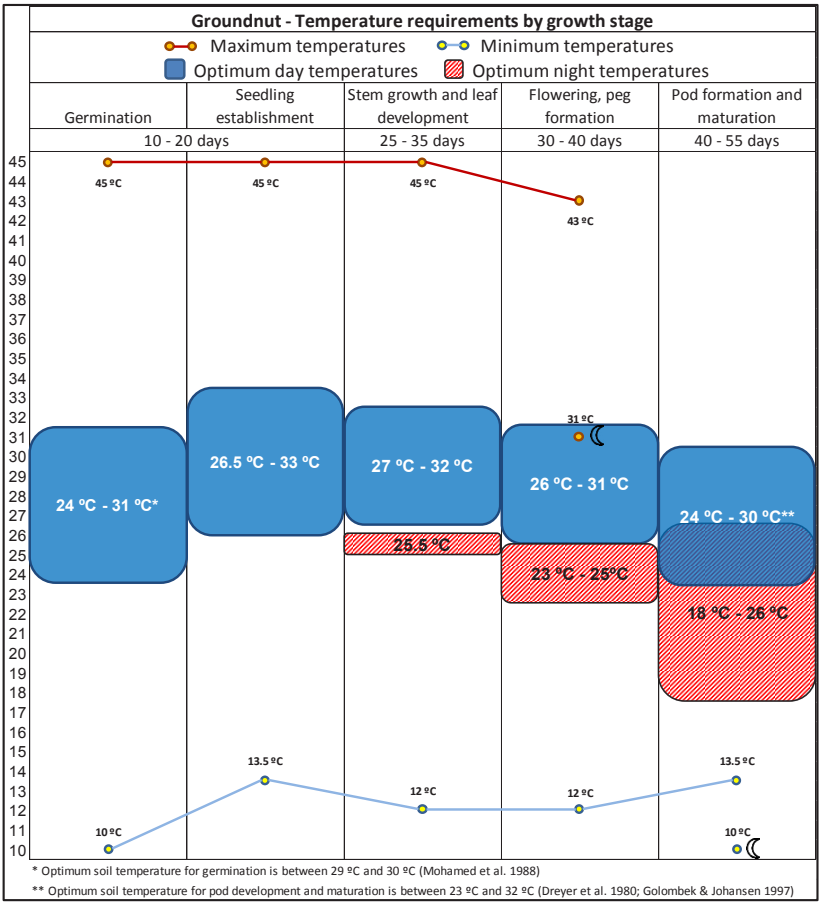

FIGURE 19.
Groundnut temperature requirements by growth stage.

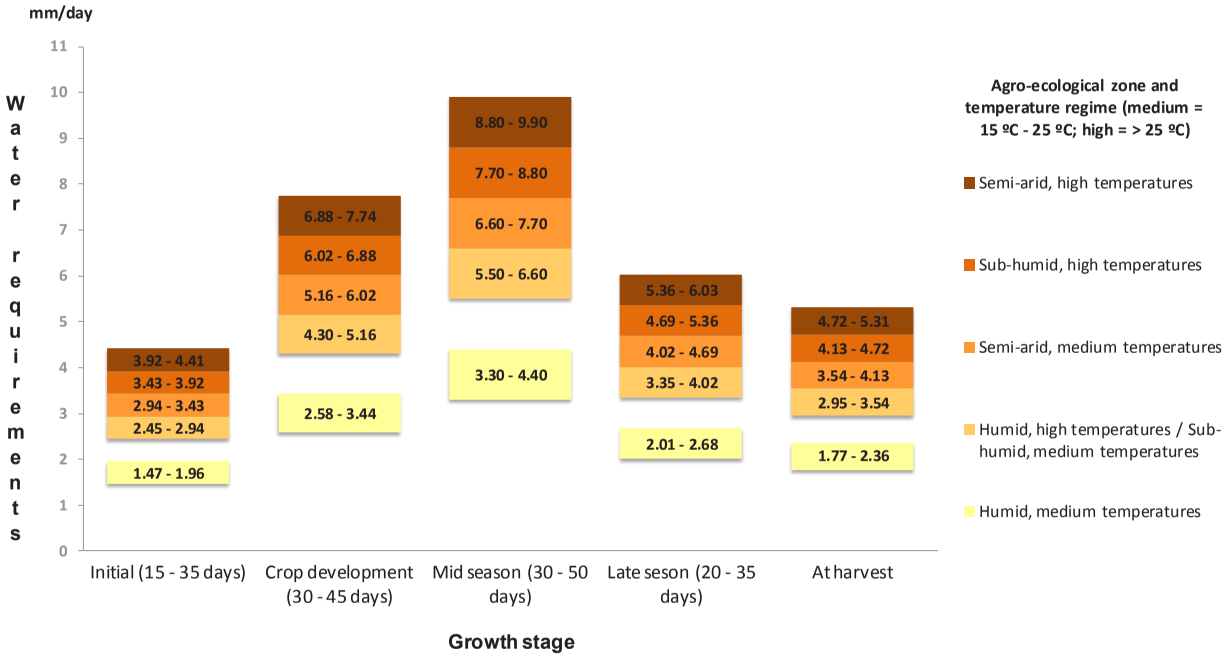

FIGURE 20. Groundnut water requirements by growth stages.

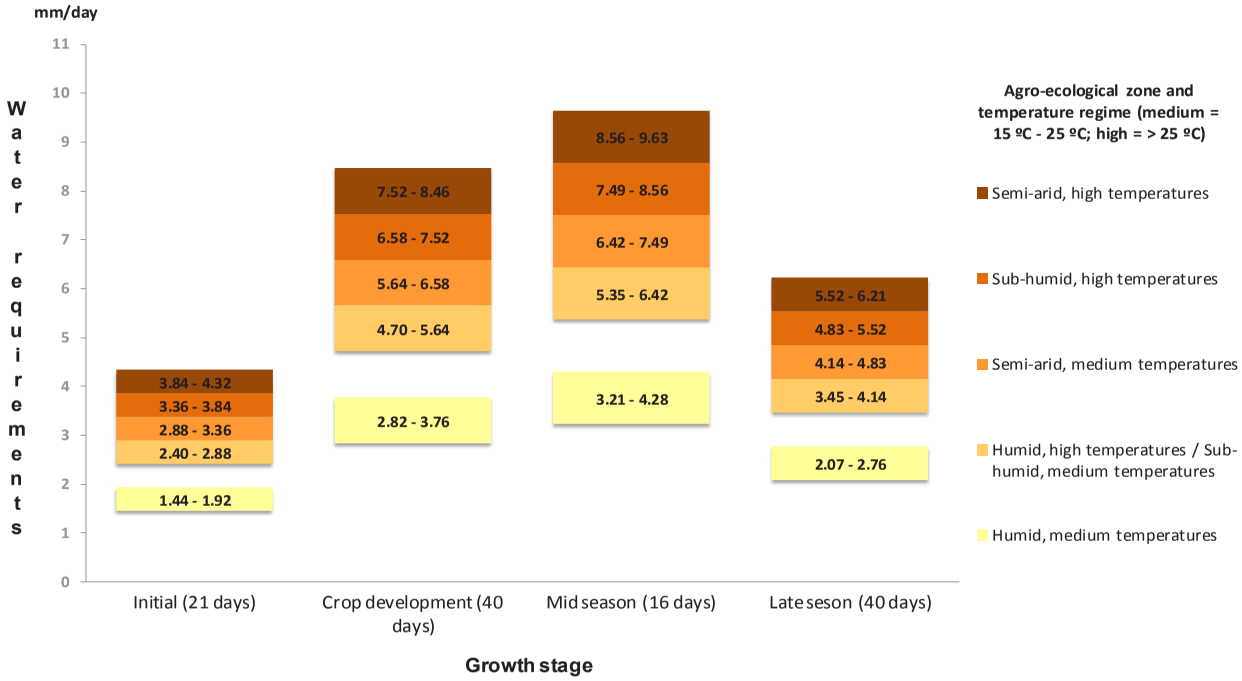

FIGURE 21. Groundnut water requirements by growth stage in Sudan.

3.4 Pigeon pea

ECOLOGY

Originally from India, Pigeon Pea, *Cajanus cajans* spread early to East Africa, which has become a secondary centre of diversity. Pigeon pea is a perennial shrub but is usually grown as an annual. Until recently Pigeon pea was largely ignored by plant breeders but export opportunities to India and the promotion of Pigeon pea as an agroforestry species with multiple uses that can be intercropped with maize has created new markets. Pigeon pea is a short-day plant and takes 60 – 250 days to reach maturity, depending on variety and temperature.

ENVIRONMENTAL CONDITIONS

Pigeon Pea is mainly grown in the semi-arid tropics, from sea level to 1,200m. Pigeon pea can be grown on a wide range of soils, including Vertisols and Alfisols and has a wide soil pH tolerance 5.0-8.5. Pigeon pea fixes N through the same rhizobium as cowpeas and fertilisers are rarely used. High rainfall will increase the risk of fungal diseases and in some areas the very high losses due to pod borers and Bruchids (up to 40%) discourage farmers from growing Pigeon Pea.

CROP TEMPERATURE REQUIREMENTS

Pigeon pea can tolerate high temperatures up to 45°C, except during flowering when the optimum temperatures are between 22 and 26°C. Pigeon pea is also tolerant of high night temperatures, but temperatures should not fall below 9°C. Temperature will influence the time of flowering.

CROP WATER REQUIREMENTS

Pigeon pea is drought tolerant, shedding flowers during drought, but is intolerant of waterlogging and is unsuitable for high rainfall areas. Between 500-1,000mm of rainfall is required for the crop cycle. Water requirements, 6-12 mm per day, are relatively constant from crop development (35 DAS) onwards as long as the soil is free draining.

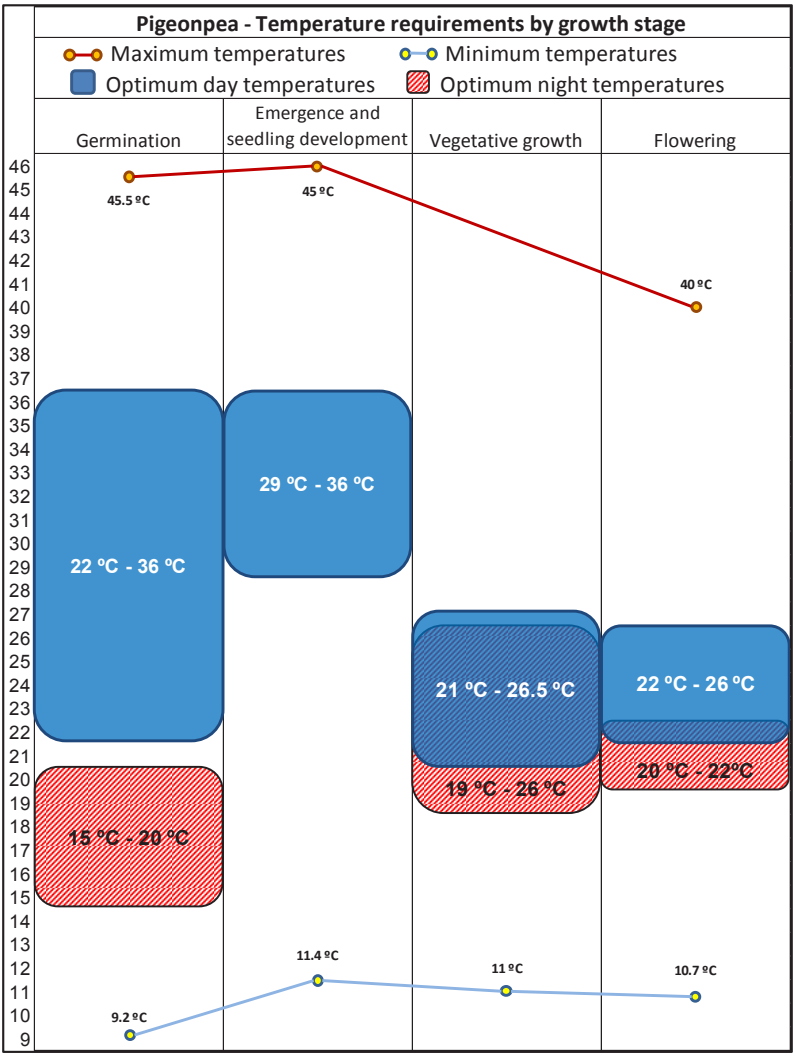

FIGURE 22.
Pigeon pea temperature requirements by growth stage.

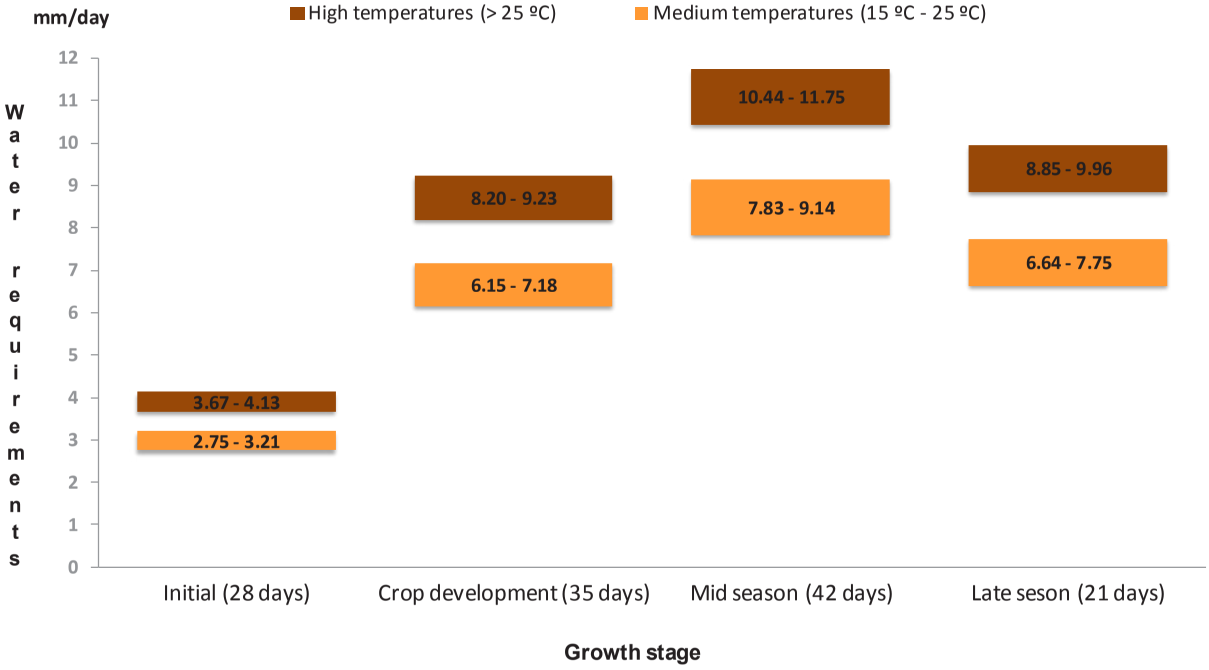

FIGURE 23. Pigeon pea water requirements by growth stage in semi-arid India.

3.5 Soybean

ECOLOGY

Soybean, *Glycine max*, originates from China and Japan and has become the most important legume in world trade. Soybean has a high protein and oil content and is traded internationally for oil and animal feeds. Soybean has considerable potential for improving the nutrition of smallholder farmers as it fits well into smallholder farming systems, is a complementary food for maize and rice, can be stored for up to three years and, as a very effective N-fixing crop, increases soil fertility. Soybean requires careful processing to remove anti-nutritional factors and off-favours. Roasted soybeans are often sold as a roadside snack and there is increasing demand from the poultry industry for soybean for poultry feed.

ENVIRONMENTAL CONDITIONS

Soybean is a short-day plant and soybean varieties have specific day-length requirements. Soybean will grow in a wide range of soils provided they are not waterlogged, with pH from 5.5-7.5, but low pH soils may create iron and aluminium toxicity issues and liming is recommended to correct the pH and supply calcium. Commercial soybean varieties normally require inoculation with *Bradyrhizobium japonicum*. Some local varieties nodulate well with local rhizobia (promiscuous varieties) but yields improve with inoculation.

CROP TEMPERATURE REQUIREMENTS

Though originally a temperate crop soybean can tolerate high day temperatures up to 40°C and dislikes low temperatures particularly at flowering. Soybean is particularly sensitive to low night temperatures. Ideally day temperatures should be between 18 and 29°C and night temperatures should not fall below 20°C.

CROP WATER REQUIREMENTS

Soybean requires 350-1,100mm of water in the growing cycle and has the greatest water demand mid-season (25-65 DAS), requiring 9.5mm per day in semi-arid climates. Water demand declines towards harvest (<5mm per day), which should be timed for the end of the rains. Unlike most legumes soybean is tolerant of temporary waterlogging,

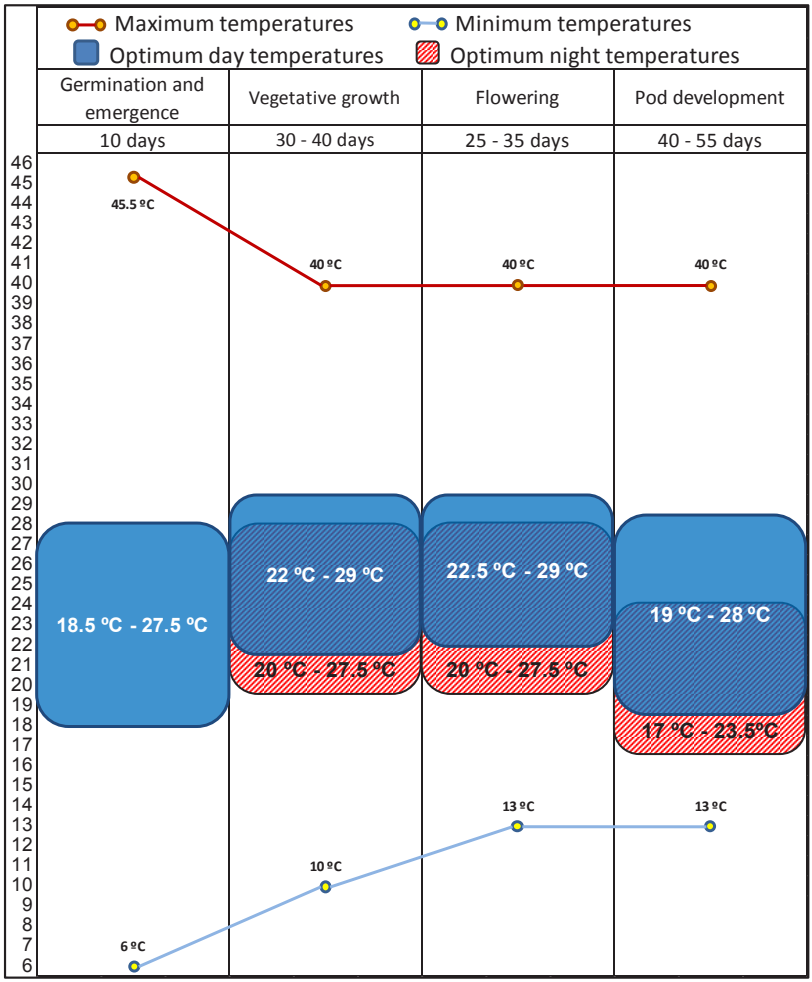

FIGURE 24.
Soybean temperature requirements by growth stage.

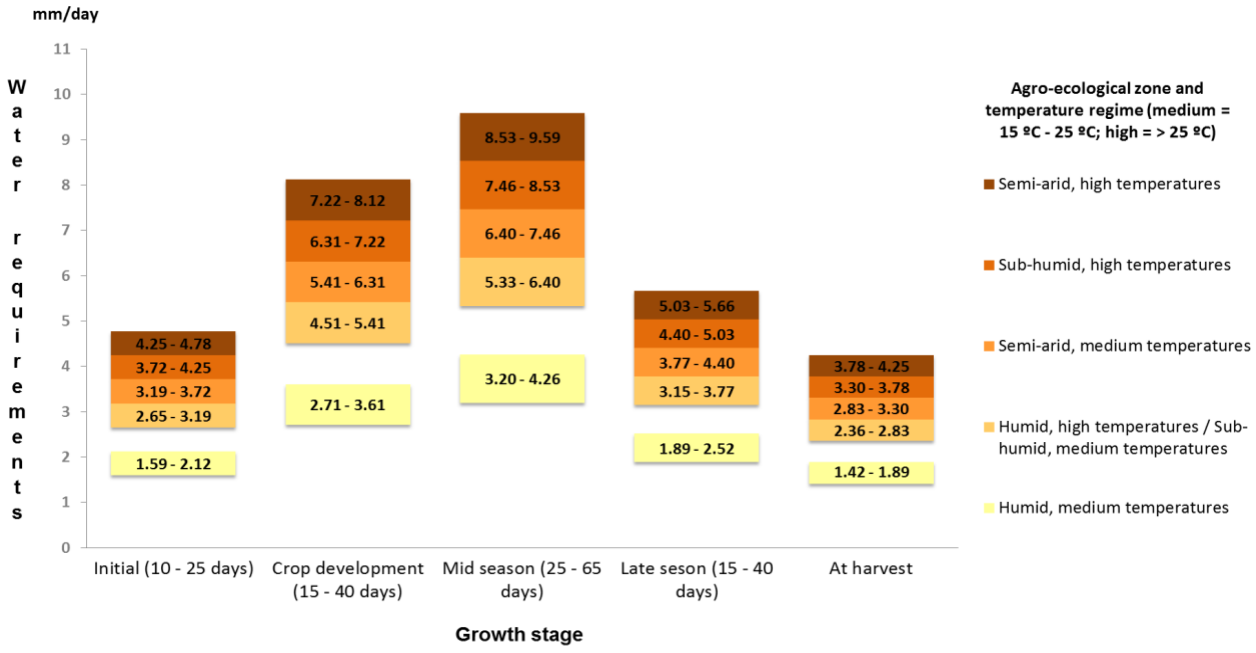

FIGURE 25. Soybean water requirements by growth stage in the tropics and subtropics.

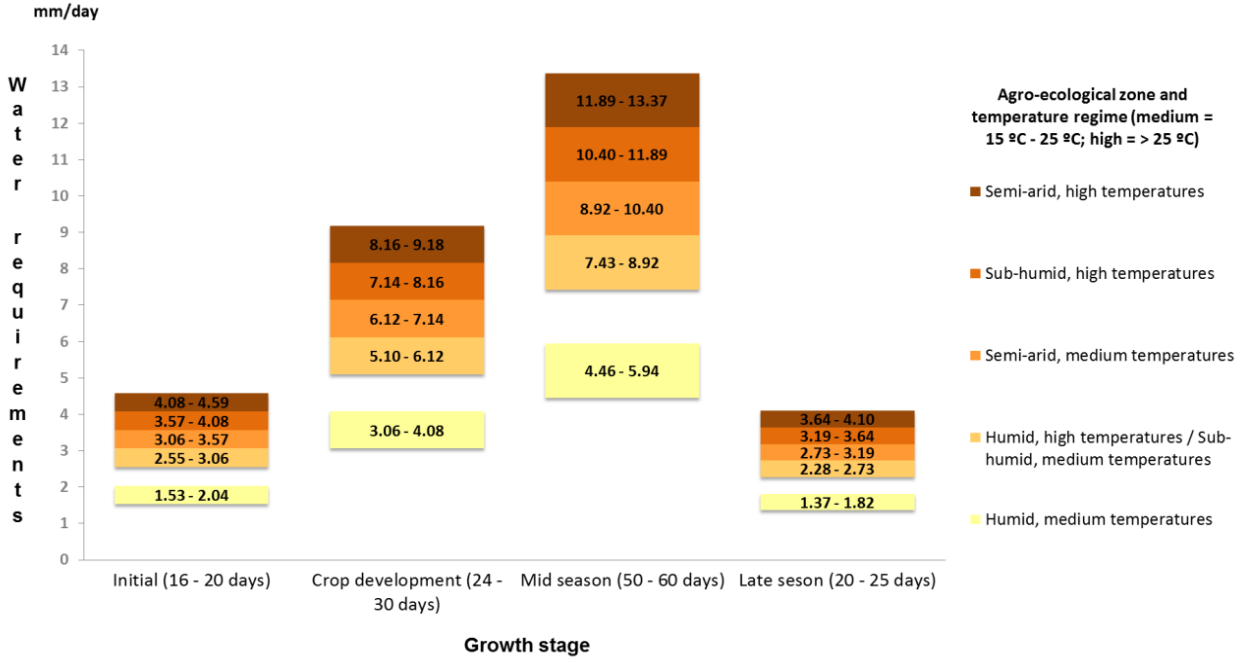

FIGURE 26. Soybean water requirements by growth stage in West Africa (Nigeria, Senegal)

3.6 Bambara groundnuts

ECOLOGY

Bambara nuts *Vigna subterranea (syn. Voandezeia subterranean (Lin))* are indigenous to the sub-humid and semi-arid regions of Africa south of the Sahara[10, 11]. It is probably the most drought-tolerant of the legumes. The Bambara Groundnut is practically free of pest problems. The underground nature of the plants pod development protects the seeds from airborne insect predation, and the seeds, if left unshelled and properly dried, are less susceptible to rodent and bean weevil (*Bruichinae*) than most pulses. Bambara nuts are becoming a premium product in local and urban markets, popular with Africa's emerging middle-classes. Bambara nut has a balanced mix of carbohydrates (50-60%), proteins (16-21%), and fat (4.5-6.5%), with micronutrients potassium, magnesium, calcium, and phosphorous. The proteins contain high levels of methionine. Maturity is between 100 and 180 days.

ENVIRONMENTAL CONDITIONS

Bambara nuts grows in a wide range of soils, ranging from loose sand to dense clay and is one of the few crops that thrive sub-Saharan Africa's widespread lateritic (reddish, acidic) soils. The pH range, 5.0-6.5 is ideal for most African soils and it can be grown from sea level to 1,600m.

CROP TEMPERATURE REQUIREMENTS

Optimum and maximum temperatures decline as growth progresses, from 29-35°C at germination to 21-25°C at pod development. Bambara groundnuts can tolerate high night temperatures but may be sensitive to low night temperatures.

CROP WATER REQUIREMENTS

Bambara groundnuts are probably the most drought-tolerant of the legumes, surviving on as little as 600-750mmf rainfall per year, though the best yields are achieved at 900-1,200mm. The plants can tolerate heavy rain, though not flooding. Highest water requirements are at 45 DAS, 3.45- 10.35mm depending on the climate.

10. FAO Traditional Crop of the Month: http://www.fao.org/traditional-crops/bambaragroundnut/en/
11. Swahili: Njugu mawe (hard stone).

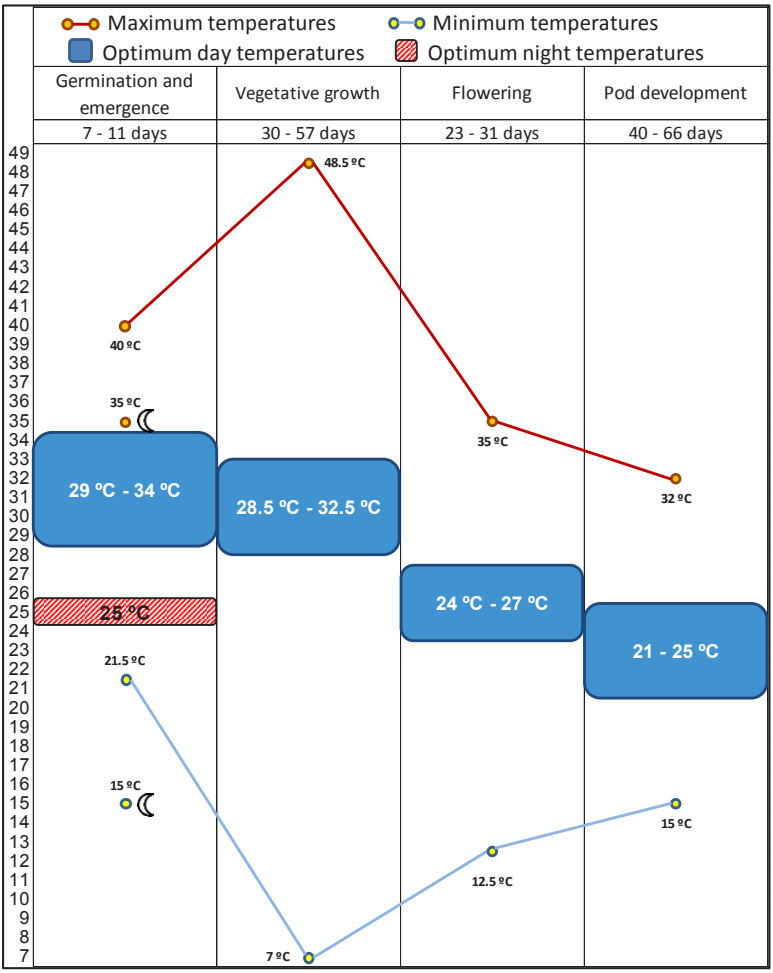

FIGURE 27.
Bambara groundnut temperature requirements by growth stage.

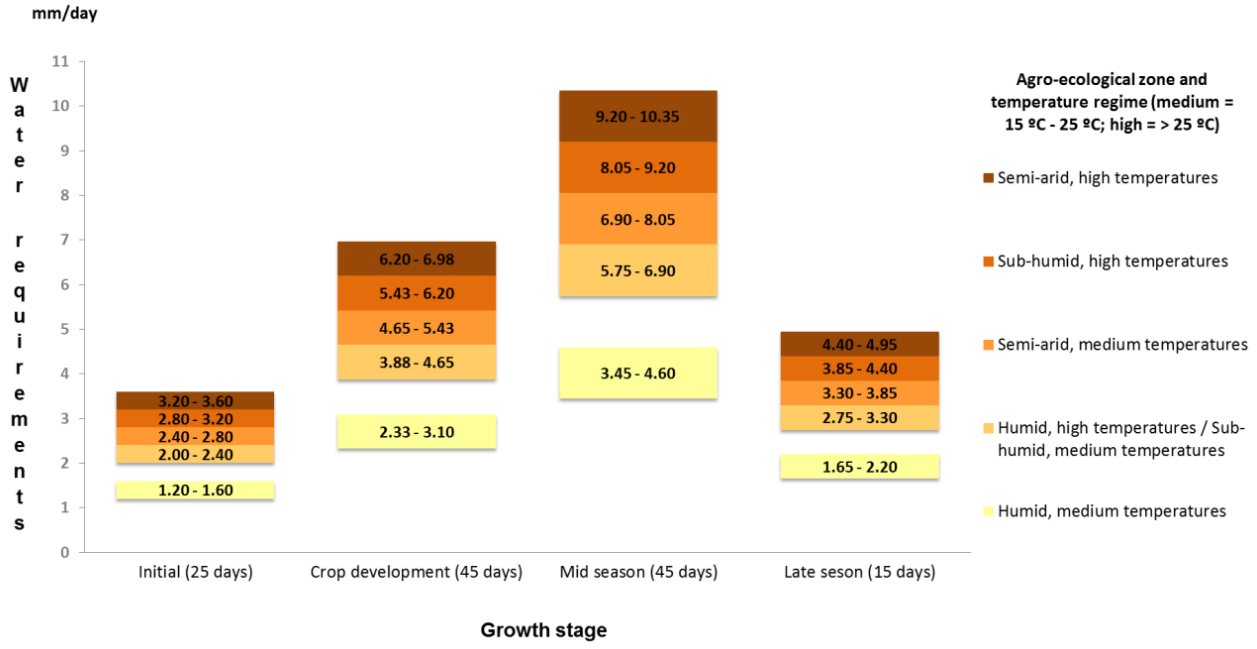

FIGURE 28. Bambara groundnut water requirements by growth stage in the tropics and subtropics.

4. ROOT CROPS

4.1 Cassava

ECOLOGY

Cassava, *Manihot esculenta*, is native to South America and was spread throughout the tropics and sub tropics by the Portuguese. Cassava has become the staple carbohydrate crop for many cultures, and the standby, famine, food for others. Maturity varies with variety, traditional varieties may require up to three years, newer varies 9 months. Cassava is hardy, requires little labour and produces very high carbohydrate yields per ha. Cassava contains a cyanogenic glucoside which decomposes to produce cyanide and glucose. Traditional cassava processing removes the cyanide but is adapted to local varieties and may not work well for introduced varieties. Farmers class cassava as "sweet" or "bitter", depending on the level and distribution of the cyanide in the root tissues. Cassava production in East and Southern Africa has been severely affected by African Cassava Mosaic Virus and Cassava Brown Streak Virus. Cassava is always grown from cuttings, which is responsible, together with whitefly and green mites, for the spread of cassava viruses.

ENVIRONMENTAL CONDITIONS

Cassava grows on a wide range of soils but is typically grown on poorer sandy soils or at the end of crop rotation cycles as Cassava can grow on very poor soils due to the presence of very effective endomycorrhizal (fungal) symbiosis. Very fertile soils may even reduce tuber formation. Deep soils, without a hard pan, are required for full tuber formation. Cassava can grow on a very wide range of pH values, from 4.5 -8.2, but does best at 5.2-7.0.

CROP TEMPERATURE REQUIREMENTS

Temperature requirements for cassava are more or less constant for the growth cycle. Cassava grows best at 22-33°C and is damaged by low temperatures and frosts.

CROP WATER REQUIREMENTS

Cassava requires 500-5,000mm/year, with an optimum of 1,400-1,80mm. Cassava is very sensitive to waterlogging and grows best on well-drained soils. Water requirement is very low at planting 1-3mm, but full drought will kill the cuttings. Maximum water requirement is reached when the full canopy has developed (11mm/day). Cassava can survive extended droughts.

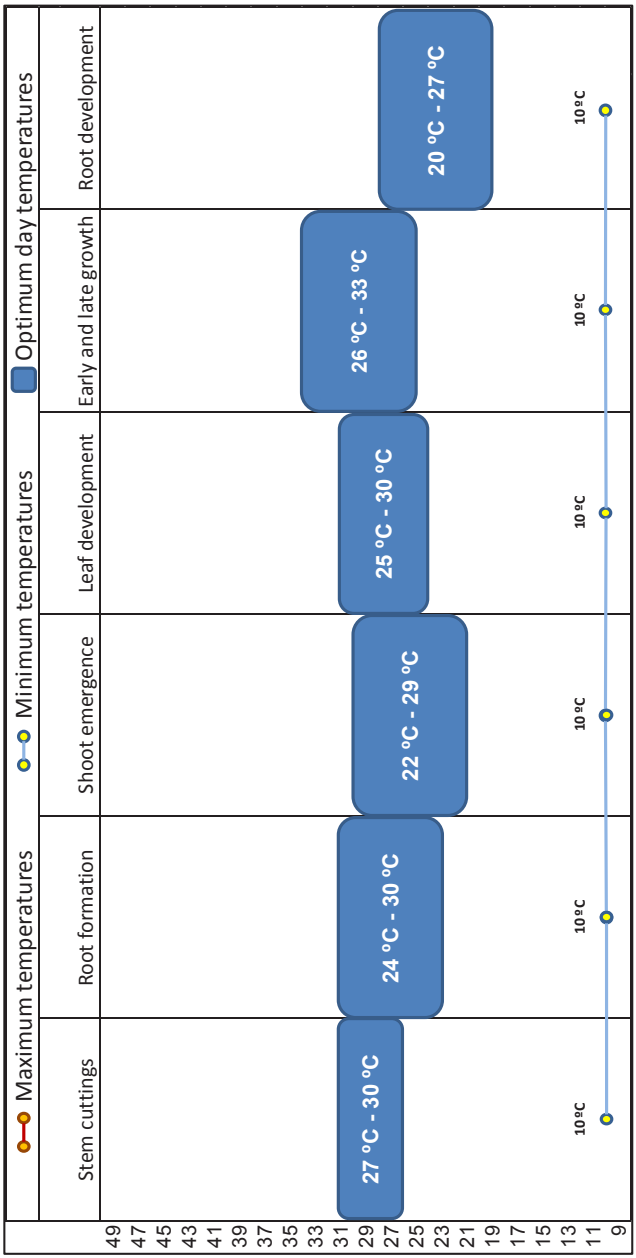

FIGURE 29. Cassava water requirements by growth stage. Adapted from Del Rio and Simpson (2014).

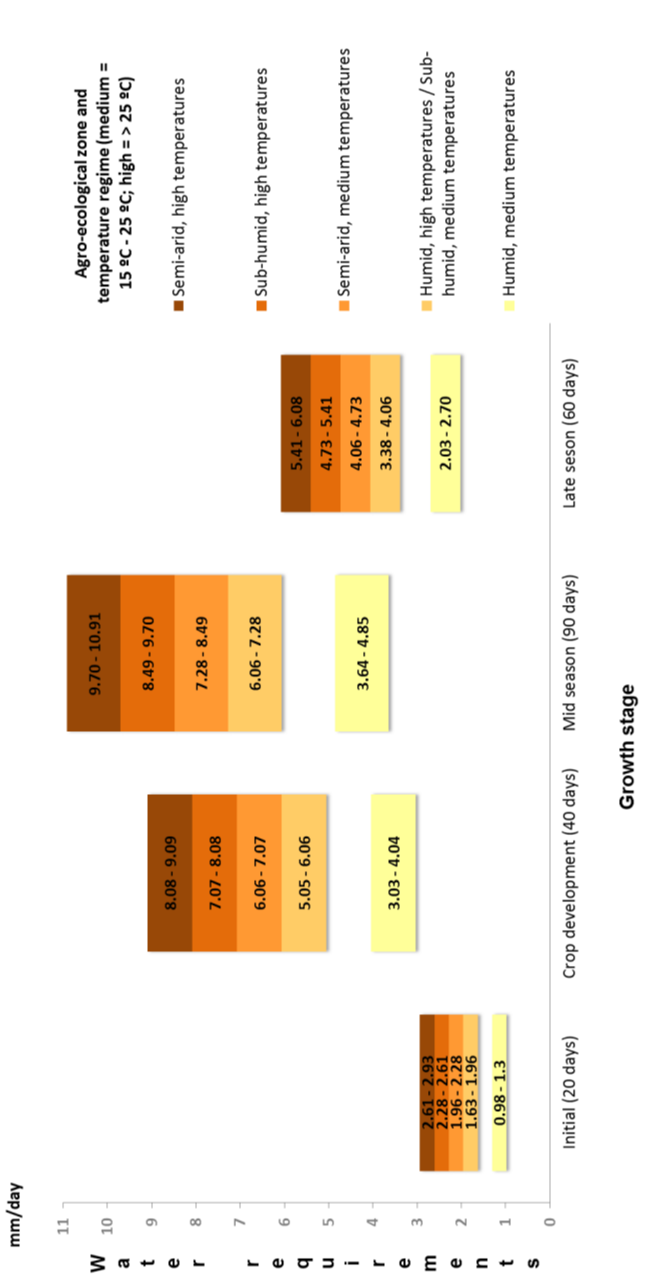

FIGURE 30. Cassava water requirements by growth stage in the tropics: Year 1.

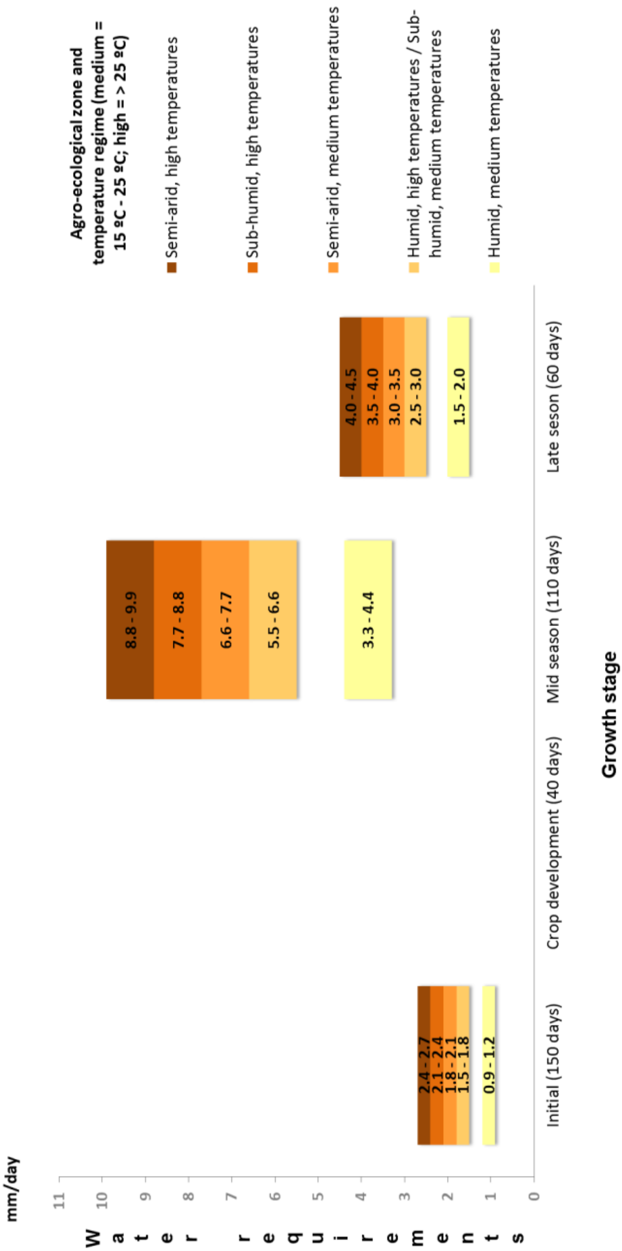

FIGURE 31. Cassava water requirements by growth stage in the tropics: Year 2. Adapted from Allen et al., 1998.

4.2 Solanum Potato

ECOLOGY

Irish / Solanum Potato, *Solanum tuberosum*, is a hardy crop, native to the Andes that is now grown worldwide. In the topics and sub tropics the best crops are achieved at high altitudes (1,800-2,300m), where few other staple crops can be grown, or during the cool season in lowland areas. Potatoes can be grown under irrigation in desert areas as long as the nights are cool. Tuber formation is triggered by the short days in the tropics (<12 hours).

ENVIRONMENTAL CONDITIONS

Potato grows on a wide range of soils, from sandy soils to the deep organic and volcanic soils of Rwanda and Burundi. Deep, friable soils are required for good tuber formation, and potato does not do well in clays. Potatoes prefer an acidic soil, as low as 4.8, with optimum pH 5.6-7.0.

CROP TEMPERATURE REQUIREMENTS

Low night temperatures are critical for tuber formation. Potato can tolerate high day temperatures as long as the nights are cool. Low day and night temperatures are required for tuber formation (15.5-19°C day, 15-16°C night). Potato is not frost tolerant.

CROP WATER REQUIREMENTS

Potato has a small root system and is easily water stressed and a regular water supply is required for good quality tubers. Maximum water requirement is 11mm/day in semi-arid areas. Potato does not tolerate waterlogging – raised beds should be used if the water table is high.

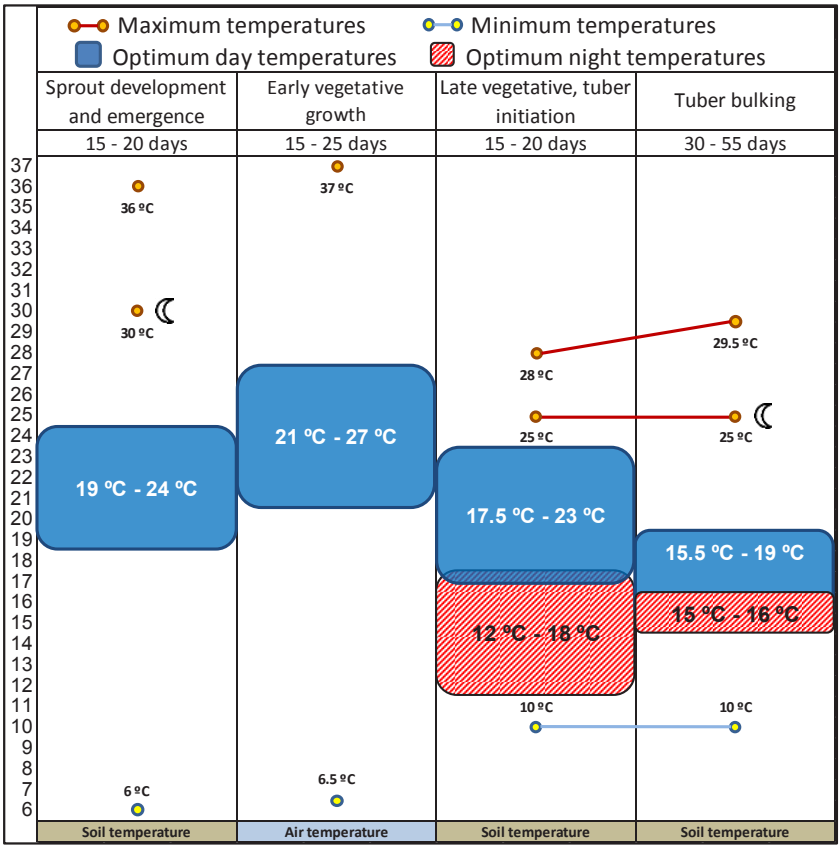

FIGURE 32.
Potato temperature requirements by growth stage.

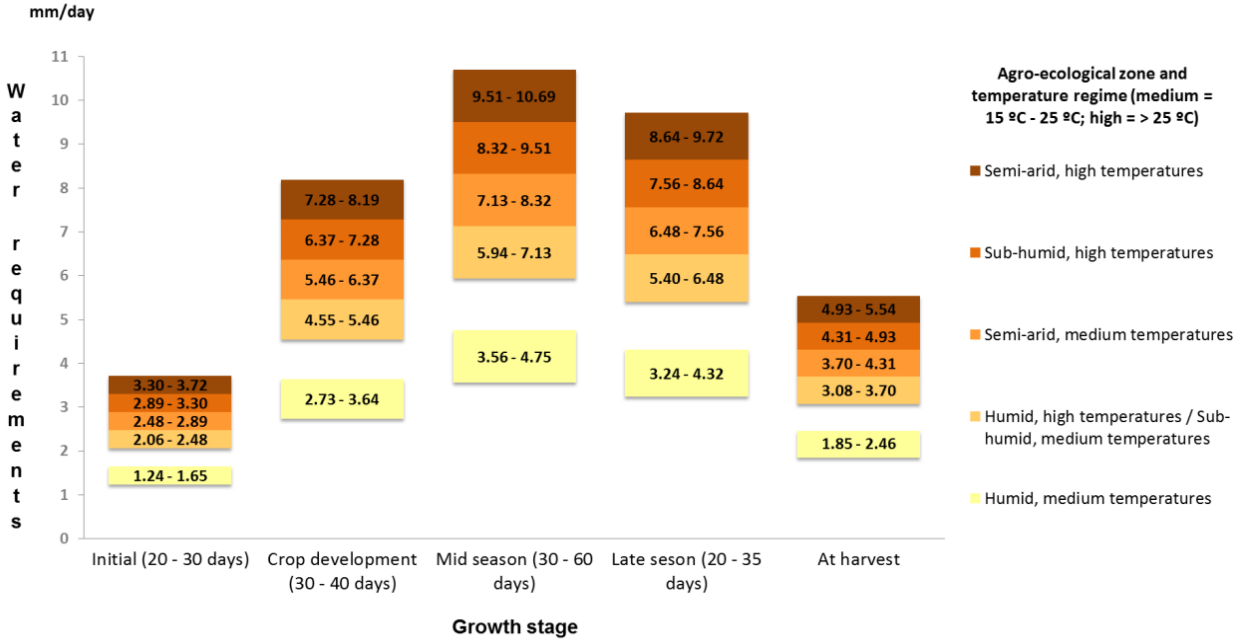

FIGURE 33. Potato water requirements by growth stage in the tropics.

4.3 Sweet Potato

ECOLOGY

Sweet Potato, *Ipomoea batatas*, also originates from the Andes. It is grown across Africa and Asia, up to an altitude of 2,000m, and is the stable carbohydrate in the Papua New Guinea Highlands. Vine cuttings are used for propagation and the leaves are often used as a vegetable.

ENVIRONMENTAL CONDITIONS

Sweet Potato grows well on acid soils and, as it is also tolerant of aluminium, it is the crop of choice for very acid soils, down to pH4. Sweet potato grows on a wide variety of soils but, like most tubers, deep, loose, well-drained soils produce the best yields. Sweet potato is often planted in mounds or ridges to ensure good drainage and friable soil.

CROP TEMPERATURE REQUIREMENTS

As with most vegetative propagated crops temperature requirements are consistent through the growth cycle. The optimum temperatures range is 21-30°C, with a minimum of 16 and a maximum 40°C. Night temperatures should be between 18°C and 21°C. Growths stops below 4°C and is reduced below 10°C. Sweet Potato is frost sensitive.

CROP WATER REQUIREMENTS

Sweet potato has very little resistance to drought and requires 550-1,270 mm of rainfall in the growing season. The highest water requirement is mid-season, 4-12mm/day of water, with reduced water requirements at harvest.

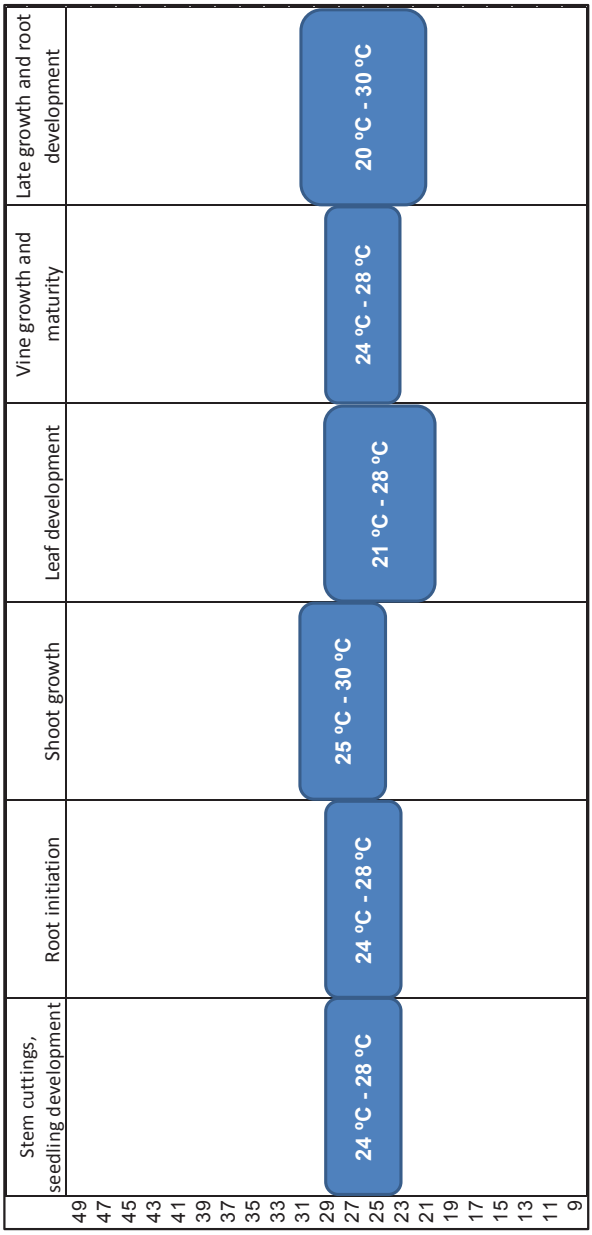

FIGURE 34. Optimum temperatures for sweet potato by growth stage. Adapted from Del Rio and Simpson (2014).

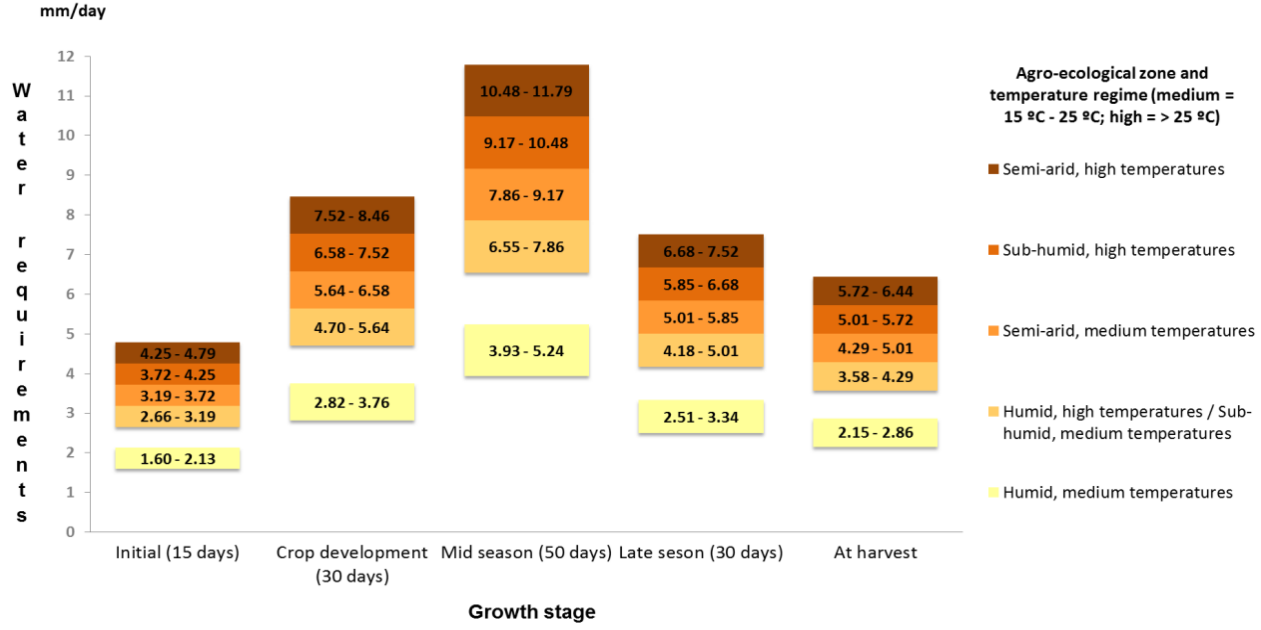

FIGURE 35. Sweet potato water requirements by growth stage in the tropics.

4.4 Yam (Dioscorea spp.)

ECOLOGY

There are many *Dioscorea* species, originating in West Africa, South America and Asia and grown throughout the humid and sub-humid regions. The preferred habitat is the border between tropical moist forest and savanna. An important crop in West Africa but a minor crop elsewhere, where it is usually grown as a "plant and forget" reserve food crop.

ENVIRONMENTAL CONDITIONS

Dioscorea yams need a hot humid climate with deep, fertile, friable and permeable sandy-clay soils with a pH of 5.0-7.0. Yam is often the first crop after the forest has been cleared. Yams are normally staked but may climb up trees or maize stalks.

CROP TEMPERATURE REQUIREMENTS

Yams dislike low temperatures, growing best at 20-33°C, and night temperatures above 19°C. Temperatures should not fall below 11°C and 17°C during tuber formation.

CROP WATER REQUIREMENTS

Yams require an annual rainfall of 1,000 to 1,500mm, but are tolerant of irregular rainfall. The critical period is mid-season, when the plants are in full growth and the reserves of the seed tubers (sets) have been exhausted when the plants will require 3.3-10mm per day.

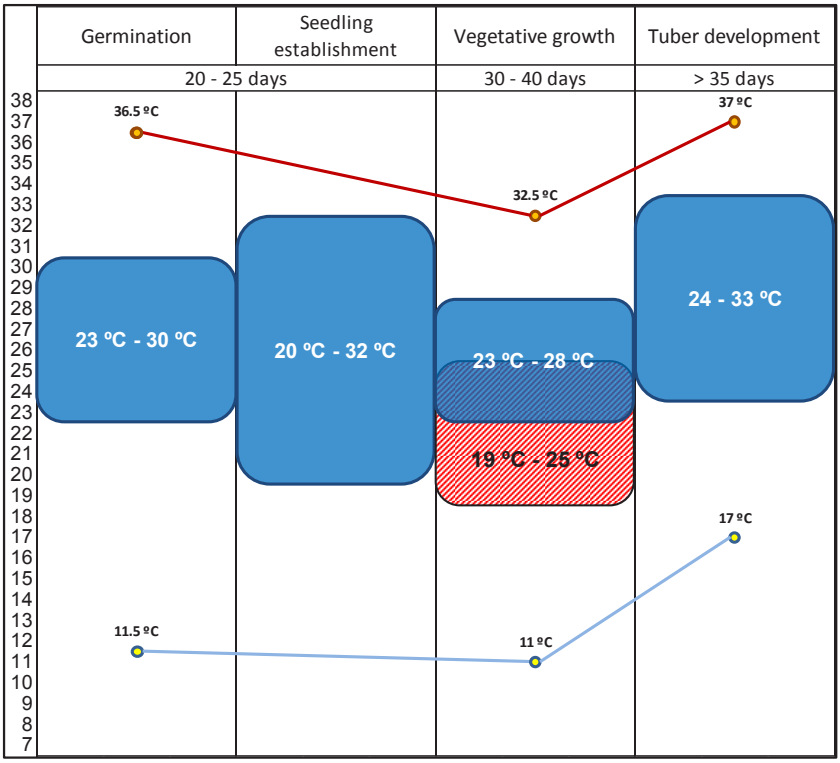

FIGURE 36.
Yam (Dioscorea spp.) temperature requirements by growth stage.

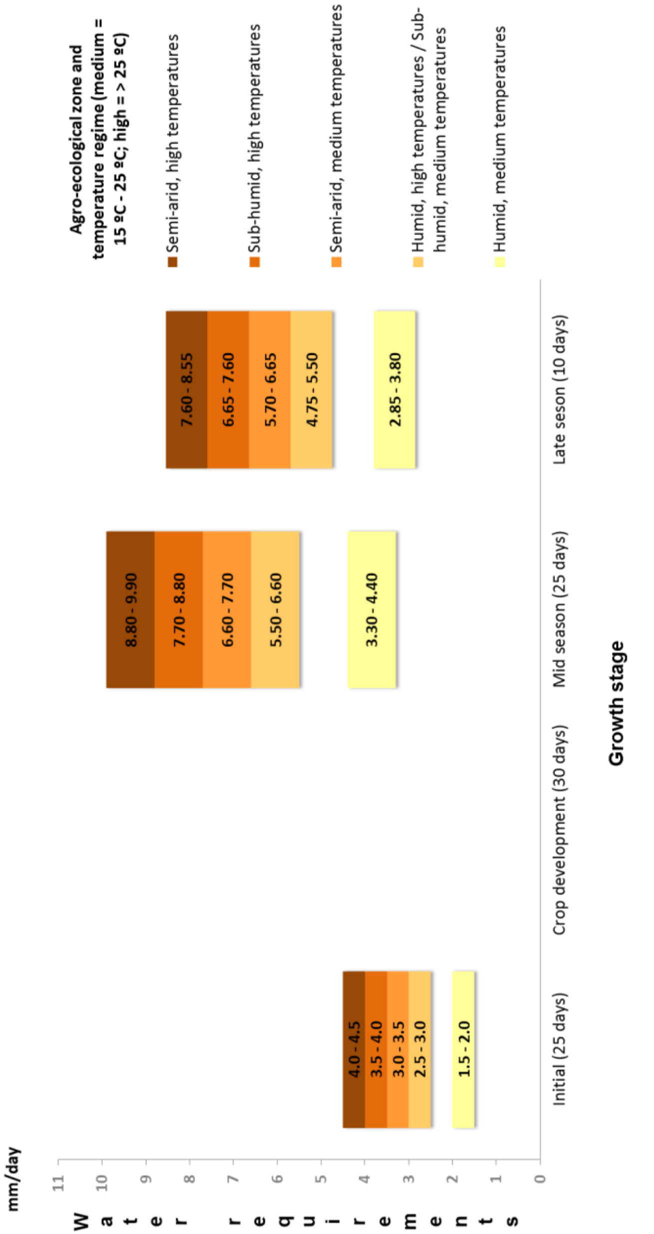

FIGURE 37.
Yam water requirements by growth stage in the tropics (Chapagain and Hoekstra, 2004).

4.5 Taro (Colocasia & Xanthosoma)

ECOLOGY

Taro is often called yam is East Africa and the terms cocoyam, eddo, dasheen, tannia and yam may be used without distinction. This data refers to *Colocasia sp.* and *Xanthosoma sagittifolium.* Colocasia originated in South Asia while Xanthosoma came from Central America and the Caribbean. Taro is recognisable by its large heart-shaped leaves. Taro is an important crop in West Africa and is the starch staple for several of the Pacific and Caribbean Islands.

ENVIRONMENTAL CONDITIONS

Taro requires high temperatures, a light, deep soil, high water table and a pH of 5.5-6.5. In East Africa and the Pacific Islands taro is often grown in swamps and seasonal wetlands however a high yielding drought tolerant variety, *Berekat*, has been developed in Ethiopia. Taro prefers shade and is often intercropped with bananas, coffee or breadfruit.

CROP TEMPERATURE REQUIREMENTS

Given the lack of available reports documenting temperature effects on taro at different growth stages, it has not been possible to graphically represent taro temperature requirements by growth stage.

The optimal daily temperature ranges from 21 °C to 27 °C. Best photosynthesis is achieved between 25 °C and 29 °C. Plants die with air temperatures below 10 °C. According to a few available reports, it is suggested that optimum temperature ranges for vegetative development fall between 22 and 30 °C, whereas optimum temperatures for tuber development may lie between 19 °C and 32 °C. Taro corms must be stored at cool temperatures. Temperatures around 25 °C result in low germination rates. Low temperatures (10 °C or lower) can effectively break dormancy of taro corms.

CROP WATER REQUIREMENTS

An annual rainfall of 2,000mm is required for most taro varieties. Once growth is underway water requirements are high, up to 13mm/day, until harvest.

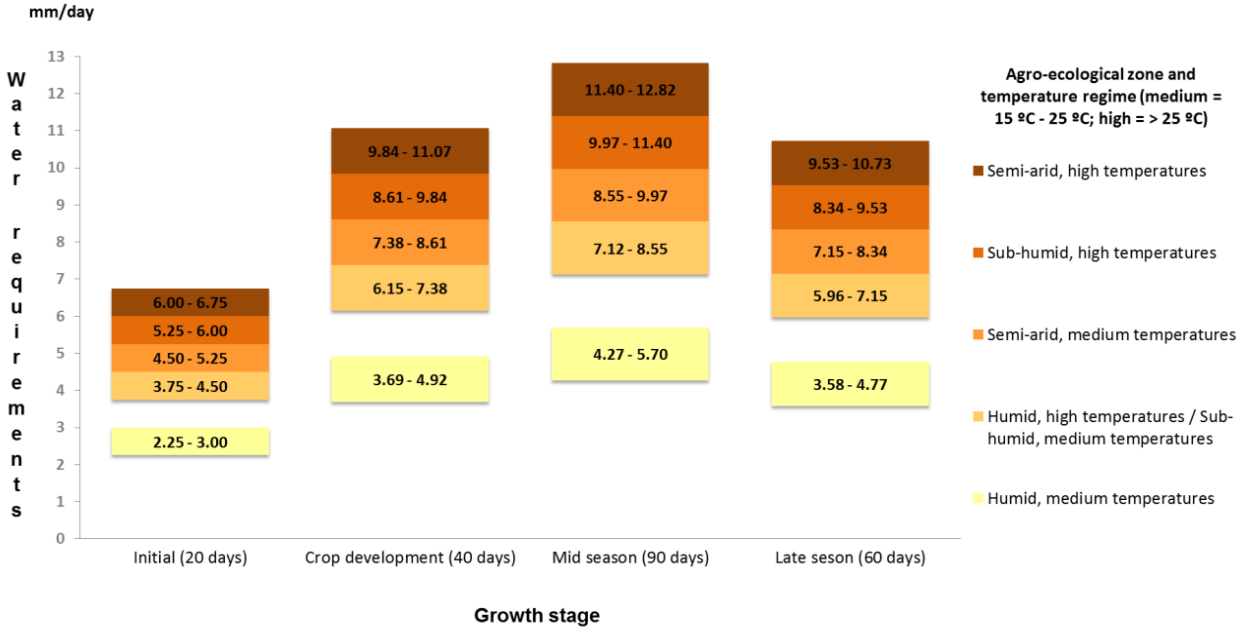

FIGURE 38. Taro water requirements by growth stage.

5. CASH CROPS

5.1 Banana

ECOLOGY

Bananas (*Musa acuminate; Musa × paradisiaca L. = hybrid M. acuminata* **× *M.*** *balbisiana)* are a genetically diverse group of plants. Banana classification is complexed and common names are used interchangeably (banana v plantain). Bananas for export (Cavendish) are grown in large monoculture plantations while smallholders in Central Uganda and the Great Lakes Region of Africa, where bananas are the staple crop, grow a diverse range of banana types for cooking, beer, fibre, and as a desert fruit. East African Highland bananas are often intercropped with coffee, beans, taro, papaya and timber trees like *Albezia* sp.

ENVIRONMENTAL CONDITIONS

With the exception of the East Africa Highland bananas which are grown up to 1,800m, bananas are grown in the lowlands, desert bananas require high humidity and protection from strong winds. Most bananas grow well in full sun and shading or clouds prolong the growth cycle. Bananas are heavy feeders and require a fertile, deep loam, pH 4-8, with plenty of organic material and manure.

CROP TEMPERATURE REQUIREMENTS

Not enough data was found for a proper graphical assessment of the temperature needs of banana throughout all its development stages.

In general, banana trees prefer temperatures around 27 °C. Temperatures below 21 °C negatively affect growth, leaf production and shooting rates. Temperatures below 10 °C can cause a lethal chilling damage to the plant, though “Mysore”, “Dwarf Cavendish” and “Pome” can tolerate temperatures near 0 °C.

For plant growth and leaf development, the optimum temperature range could fall between 28 °C and 30 °C during the day while optimum temperatures during the night could be between 18 and 26 °C. Minimum lethal day temperatures fall between 9 and 17 °C, with an estimated average value of 14 °C, while maximum lethal day temperatures have been commonly measured at 38 °C. Minimum and maximum lethal temperatures at night might be 10 °C and 30 °C, respectively.

The maximum temperature for the following phases (flowering, fruit development and maturation) is 38 °C. For flowering, estimated optimal temperature range between 22 and 31 °C and temperature of 24 °C for ripening.

CROP WATER REQUIREMENTS

Bananas require 60-100% humidity and and annual rainfall of 1,300-3,600mm. Water requirements increase with age and leaf area and, due to their large leaf area, high winds will increase transpiration rates. As the bunch matures water requirments may be as high as 10mm per day. Soil moisture should not fall below 60-70% of field capacity.

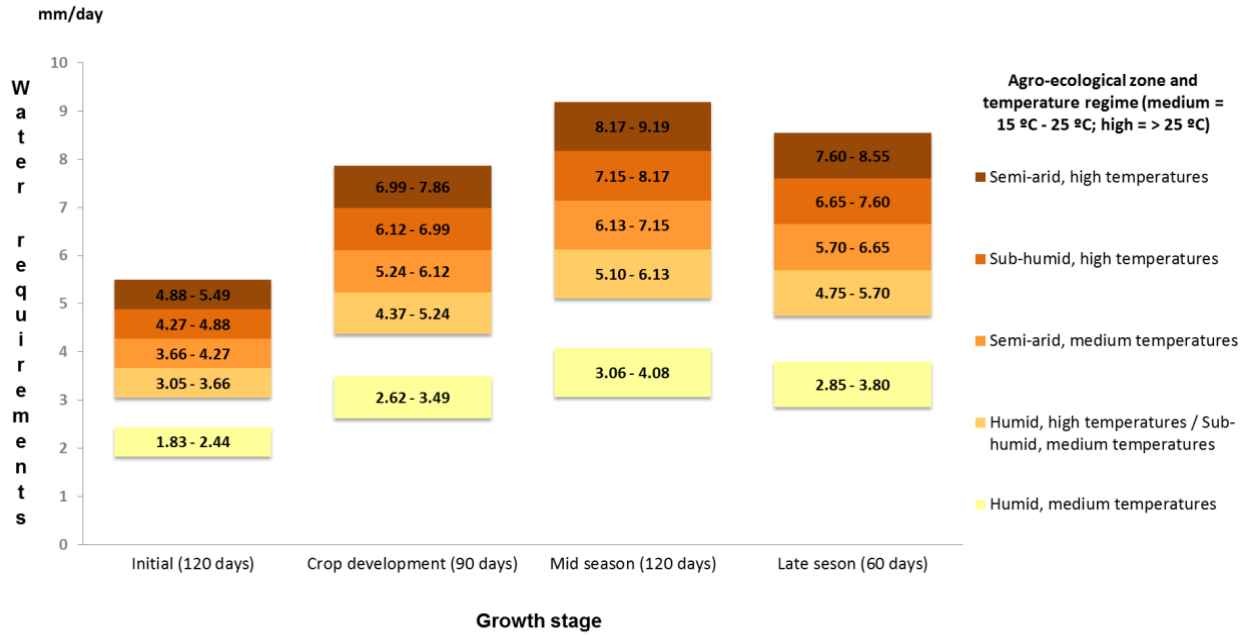

FIGURE 39. Banana water requirements by growth stage: year 1.

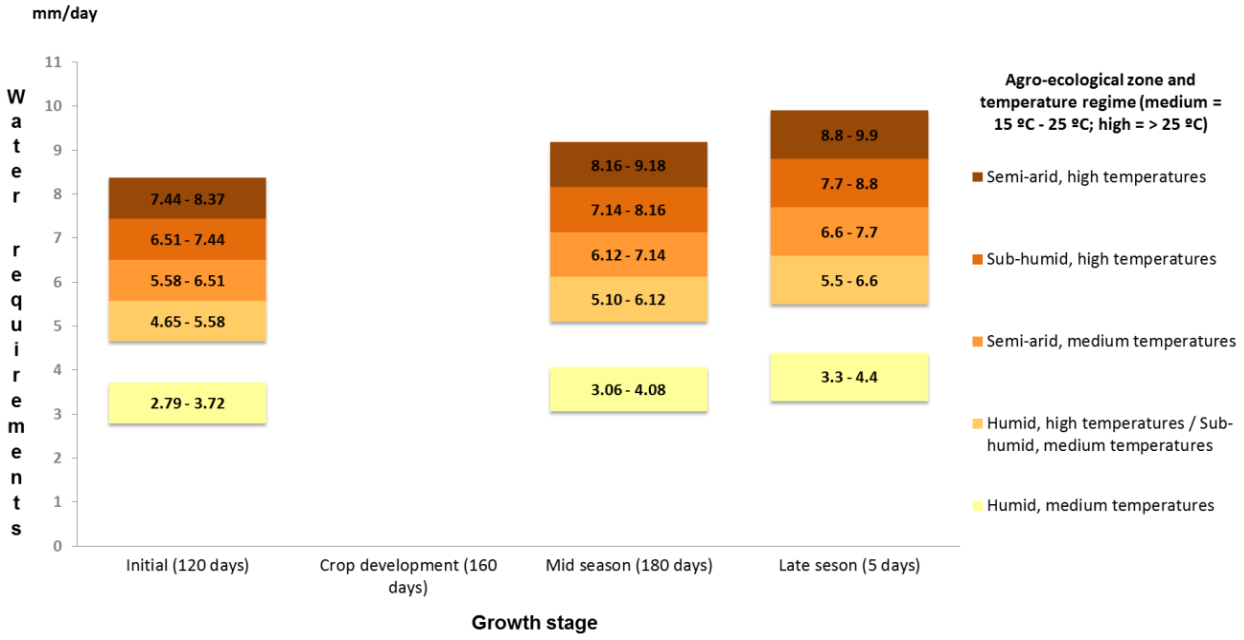

FIGURE 40. Banana water requirements by growth stage: year 2.

5.2 Sesame

ECOLOGY

Sesamum indicum is a high value oilseed, also known as simsim, benniseed and gingelly. Grown throughout the topics and sub tropics, there is a high market demand for export to the Middle East and the Indian Sub-Continent.

ENVIRONMENTAL CONDITIONS

Sesame is grown from sea level to 1,500m on fertile, well-drained soils. A fine tilth is required as the seeds are very small. Sesame needs thinning after emergence and regular weeding.

CROP TEMPERATURE REQUIREMENTS

Optimal annual average temperatures for growing sesame should be between 24 and 27 °C. For germination, a minimum temperature of 12 °C is needed, and preferably above 18 °C for optimal germination rates. Optimal temperatures for flowering and grain development range from 26 °C to 30 °C. Temperatures above 40 °C cause flower sterility. Growth is significantly reduced below 20 °C.

CROP WATER REQUIREMENTS

Generally 400-500mm of rainfall is required during the growing season. The seedlings are very sensitive to water stress and require between 2.2mm/day to 7mm in Sudan. Heavy rains will wash out the small seeds. In mid-season sesame will require up to 10mm/day but water demand reduces towards harvest.

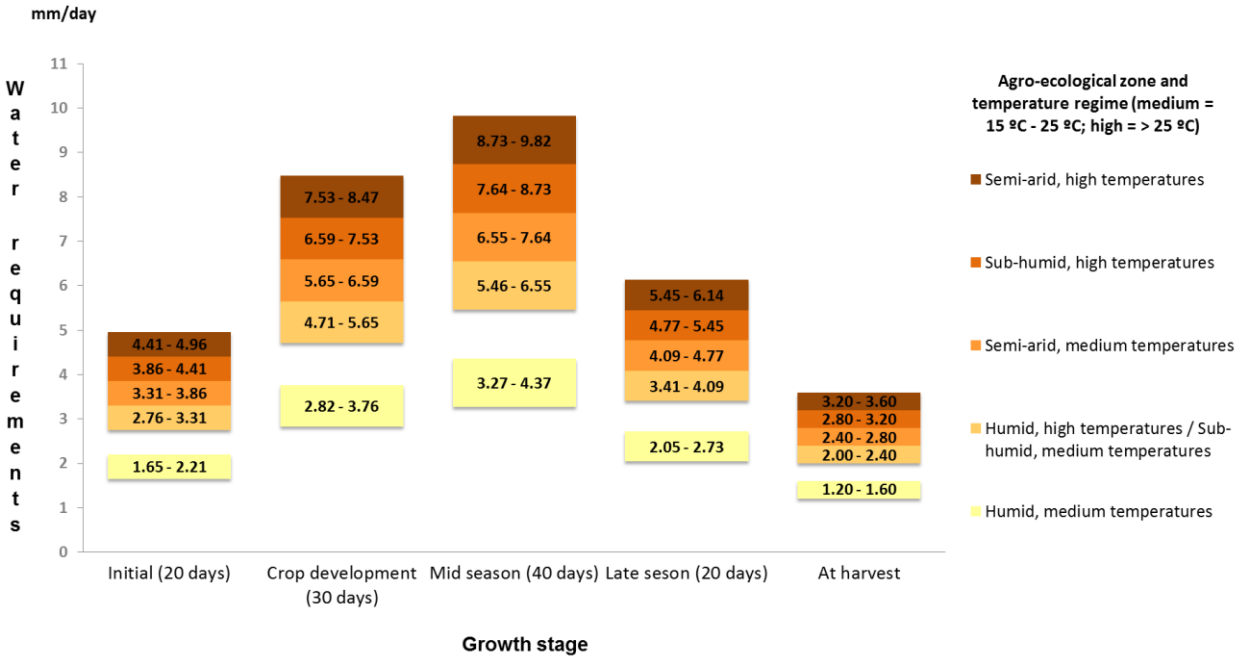

FIGURE 41. Sesame water requirements by growth stage in the tropics.

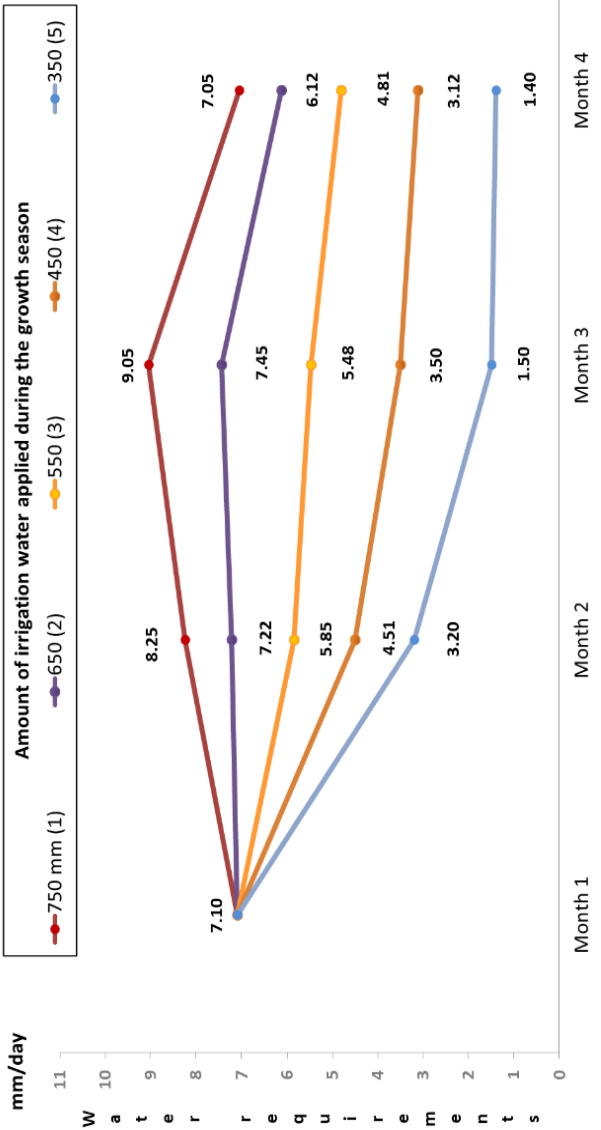

FIGURE 42. Sesame - Water requirements for Khidir and Promo varieties in Sudan by growth period and irrigation regime (Ahmed & Mahmoud 2010).

5.3 Sunflower

ECOLOGY

Sunflower, *Helianthus anuus*, a Central American crop, grows well across the World and is mainly grown for oil. Sunflower is mainly grown in East and Southern Africa, where demand exceeds supply. In West Africa palm and groundnut oil predominates.

ENVIRONMENTAL CONDITIONS

Sunflower can be grown from sea level to 2,500m but it does not tolerate high humidity. Sunflower does best on deep (1.5m or more), well drained, heavy soils with a p of 6.0-7.5. sandy soils often give poor yields and in Africa sunflower often does well on the clay-rich soils of old termite mounds. Liming is required on soils <pH 6. Sunflower is a heavy feeder and requires fertilisers for good production. Strong winds will cause lodging

CROP TEMPERATURE REQUIREMENTS

Optimal air temperatures for growth range from 18 to 26 °C, with maximum yields achieved around 22 °C. Though sunflower can tolerate frost, minimum temperatures should not go below 2°C. The ideal temperature range is 18-30°C, with higher temperatures required for ripening. Night temperatures should not fall below 12°C, ideally 17-22°C.

CROP WATER REQUIREMENTS

Sunflower grows in areas with a wide range of rainfall, from 250-4,000mm. Sunflower has a very deep taproot, up to 2m, and is drought-avoiding, but is intolerant of waterlogging. The highest water requirements are at mid-season, and may reach 10mm/day. Rainfall should be low at harvest, < 3mm/day.

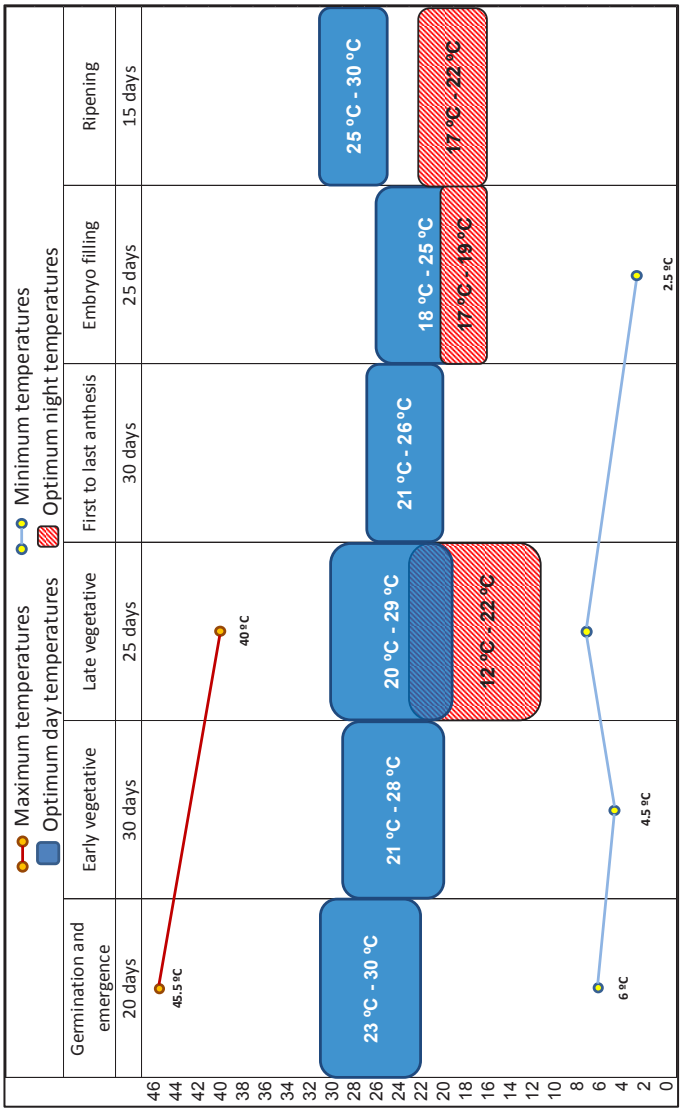

FIGURE 43. Sunflower temperature requirements by growth stage.

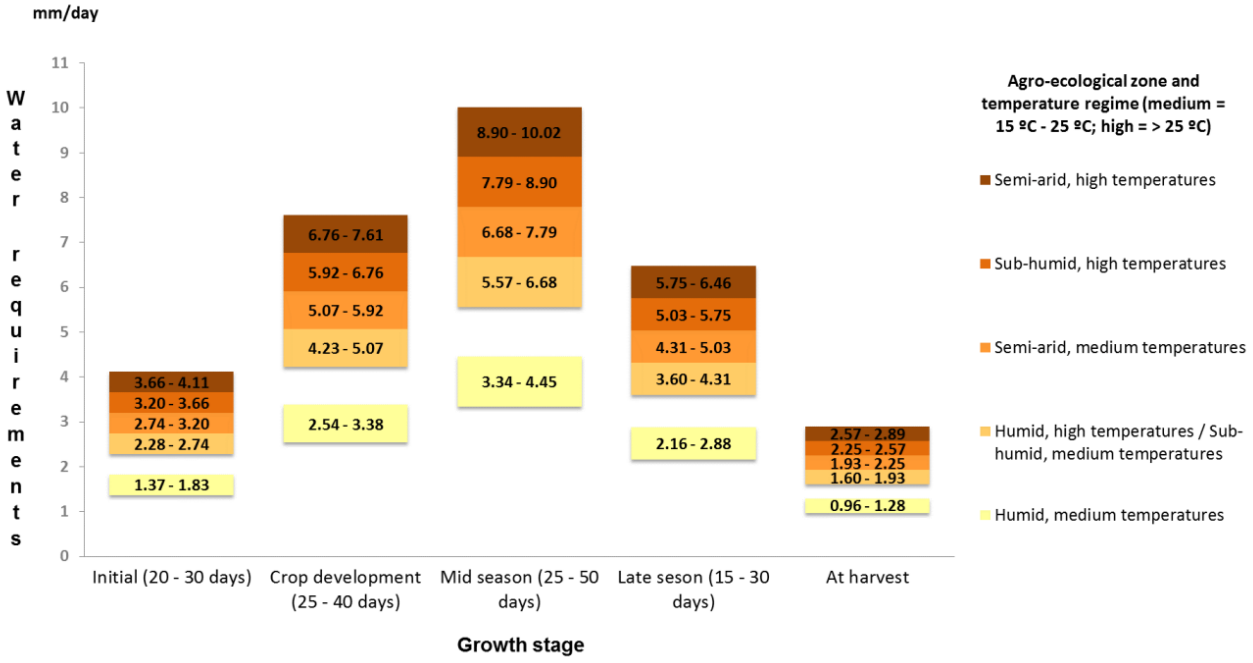

FIGURE 44. Sunflower water requirements by growth stage in the tropics and subtropics.

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