



ECOPHYSIOLOGY OF CULTIVATED PLANTS

CASSIO PEREIRA HONDA FILHO




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– CHAPTER 1 –

Ecophysiology of Soybeans (*Glycine max*) in Brazil

Soybean ecophysiology seeks to understand how metabolism (photosynthesis, respiration, biological N₂ fixation, growth, and reproduction) responds to the environment (radiation, temperature, water, CO₂) and management (sowing season, maturity group, plant arrangement, fertility, soil biology). In Brazil, which ranges from subtropical (South/Southeast) to tropical (Cerrado and MATOPIBA) latitudes, the key is to position the critical reproductive stages (R3–R6) in windows of lower thermal/water risk, maintaining plants that are efficient in terms of light and water, and a soil-root system with good physical and chemical quality. The Agricultural Climate Risk Zoning (ZARC), updated annually by MAPA, is the guide for lower-risk sowing dates by municipality/soil type/cycle, and today comprises specific ordinances by state for each crop.

The adaptation of soybeans to tropical Brazil was catalyzed by the use of a long juvenile period, which delays floral induction under short days and allows for greater vegetative growth before flowering, opening up cultivation frontiers at low latitudes and making sowing windows more flexible.

Phenology, architecture, and photoperiod: foundations of temporal management

Development follows the Fehr & Caviness scale: vegetative stages (V1...Vn) and reproductive stages R1 (beginning of flowering) to R8 (maturation). For risk and yield management, the R3–R6 window (beginning of pods to grain filling) is the most sensitive, as it defines the number and mass of grains.

Soybeans combine trifoliate leaves, variable branching, and

determinate or indeterminate growth habits depending on the maturity group (MG). This plasticity allows for moderate stand failures to be compensated for via branching and adjustment in flower and pod retention/abortion, provided there is sufficient light, water, and nutrients in the R3–R6 window.

A short-day species, soybeans flower when the day falls below a critical threshold (genotype-dependent). The long juvenile period reduces initial sensitivity to photoperiod, allowing earlier sowing at low latitudes without “too early” flowering. The rate of development is thermo-photoperiodic: average temperature modulates the speed at which the plant transitions between stages, conditioning the suitability of the GM to the latitude and sowing date.

Practical implication: adjust GM $\times$ date so that R3–R6 occurs when the probability of dry heat and/or water deficit is lower, using the local ZARC (and the state health calendar).

Ecophysiological processes that “manufacture” yield

Photosynthesis (A) in C_3 responds to PAR (photosynthetically active radiation), CO_2 concentration, leaf temperature, and stomatal conductance (g_s). Under conditions of water deficit and/or high VPD (vapor pressure deficit), the stomata close to contain transpiration (E), causing g_s to fall and, to a lesser extent initially, A ; this increases the intrinsic water use efficiency, $iWUE = A/g_s$.

However, under severe stress, A falls sharply and the balance collapses. Radiation use efficiency (RUE) quantifies the conversion of absorbed radiation into biomass

($g\ MJ^{-1}$). In soybeans, field values typically range from ~ 0.6 to $1.6\ g\ MJ^{-1}$, with studies reporting ranges by genotype/environment of ~ 0.84 – $1.15\ g\ MJ^{-1}$ and up to ~ 0.62 – $1.59\ g\ MJ^{-1}$ in R6 evaluations. This range reflects climate, canopy architecture (LAI, leaf angle), health, and nutrition.

Quick and non-destructive metrics:

Chlorophyll fluorescence (F_v/F_m) indicates PSII photoinhibition/stress. In well-adapted, non-stressed leaves, $F_v/F_m \approx 0.83$ is the reference; persistent drops suggest stress (light, thermal, water, nutritional).

SPAD (chlorophyll index) correlates with chlorophyll content and, with reservations, with foliar N. The relationship varies by species/tissue/light condition; it is advisable to calibrate by cultivar/environment and integrate with visual diagnosis and foliar analysis.

Yield formation: number $\times$ grain size

Yield = plants $\times$ pods/plant $\times$ grains/pod $\times$ 100-grain weight. The canopy needs to intercept and use radiation with functional foliage in R3–R6. Heat and drought in this window reduce flower/pod setting, number of grains, and grain size; recent analyses confirm that combined hot and dry events are the most damaging to reproduction.

Biological nitrogen fixation (BNF), inoculation, and co-inoculation

Soybeans supply most of their N via symbiosis with *Bradyrhizobium*; annual inoculation increases the chance of effective nodulation, especially in new areas, warm soils, and soils with low organic matter. Co-inoculation with *Azospirillum* has been gaining ground: Brazilian and international publications report average gains and, in years of drought, productivity increases of over 10%. Recent Embrapa guidelines standardize doses and routes for co-inoculation (via seed/furrow), warning against “overdosing” bio-inputs. In crops under water stress, studies from 2024 observed consistent positive responses to co-inoculation.

Determining soil and climate factors**Climate: temperature, water, and season**

Temperature. The crop performs best at 20–30 °C throughout the cycle; peaks $\geq \sim 35$ °C during flowering/filling increase the risk of abortion and reduce grain mass (with extra sensitivity to high nighttime

temperatures).

Water (E_{Tc}) and distribution. Water demand is concentrated in stages R1–R6, accounting for >60% of seasonal use. Daily peaks in water use can reach $\sim 5\text{--}7.5\text{ mm day}^{-1}$ ($\approx 0.2\text{--}0.3\text{ in day}^{-1}$) in hot, dry, and windy conditions. Thus, moderate deficits in the vegetative stage are more tolerable than deficits in the reproductive stage.

Planning by K_c (FAO-56). For supplemental irrigation (where applicable), use $E_{Tc} = E_{To} \times K_c$ (or $K_{cb} + K_e$ in the dual method). K_c varies by stage and water management; the dual method allows canopy transpiration (K_{cb}) and soil evaporation (K_e) to be treated separately—useful in wide rows and/or exposed mulch.

Sowing season and climate risk. In Central Brazil, prioritize the effective onset of rains; in the South, avoid cold weather during emergence and heat/drought during filling. Use the ZARC for the current crop to choose windows $\leq 20\text{--}30\%$ municipal/soil/cycle risk.

Soil — chemistry (pH, V%, K, P, S)

Acidity and base saturation. Working at $\text{pH}(\text{CaCl}_2) \approx 5.4\text{--}5.9$ and compatible V% (often $\sim 50\text{--}60\%$ in Latosols) reduces toxic Al^{3+} and optimizes availability; proper liming deepens roots and improves water and nutrient efficiency.

Potassium (K). Soybeans absorb $\sim 38\text{ kg K}_2\text{O t}^{-1}$ of grain produced and export $\sim 20\text{ kg K}_2\text{O t}^{-1}$ via harvest, which supports maintenance at around $\sim 20\text{ kg K}_2\text{O}$ per ton of expected grain (adjust according to soil analysis, texture, history, and system balance).

Phosphorus (P) and Sulfur (S). Follow regional manuals (SBCS, Embrapa) and balances; sandy soils/oxisols usually require maintenance S.

Agricultural gypsum. Recommended when there is subsurface acidity/ Al^{3+} in the subsoil and low Ca^{2+} at depth; improves root profile and water resilience.

Soil — physics and water in the profile

Physical quality determines how much soil water is actually accessible to roots. The Optimal Water Interval (IHO/LLWR) integrates available water, aeration porosity, and penetration resistance in a moisture range in which root growth is not limited. Under compaction and/or inadequate moisture, the LLWR narrows (to zero in severe cases), increasing the frequency of stress even with “normal” rainfall. In Latosols under traffic, studies with soybeans show a drop in productivity even before the LLWR “zeroes out,” reinforcing SPD practices with straw, traffic control, gypsum application (when indicated), and rotation with exploratory roots.

Ecophysiology applied to management

Sowing season (ZARC) and positioning of R3–R6

Use the ZARC ordinances for the current harvest in your state and choose windows with a risk class $\leq 20\text{--}30\%$ (according to local regulations).

Objective: to fit R3–R6 outside of likely droughts and heat peaks, maintaining LAI and architecture favorable to light interception/use during filling.

In the Cerrado/MATOPIBA, use the onset of effective rains; in the South/Southeast, avoid cold weather at emergence and dry heat in R5–R6.

Plant population and spacing

Soybeans are plastic; however, short cycles (smaller leaf area per plant) respond better to higher densities and narrower rows (early canopy closure, greater internal diffuse fraction, less soil evaporation). Long cycles value emergence uniformity and control of dominated/late plants. Avoid densification that increases lodging or excessive shade in the lower strata.

Nutrition and FBN — integrating SPAD and analysis

K maintenance: plan by balance (export $\times$ replacement) and soil analysis.

FBN: inoculate annually; co-inoculate when recommended,

respecting product dosage/compatibility (seeds/furrow). In areas with a history of problems, reinforce the quality of the operation (inoculant adhesion, avoid mixing with incompatible chemicals, logistics to avoid heat/UV).

Water/supplementary irrigation (when applicable)

Adopt $E_{Tc} = E_{To} \times K_c$ (or $K_{cb} + K_e$ in the dual method); monitor local E_{To} and effective rainfall.

In low CAD soils, it is preferable to anticipate blades in the V→R transition and maintain a minimum deficit in R1–R5 rather than trying to “recover” late.

Abiotic stresses: mechanisms, signs, and management

Water deficit (drought)

Rapid signs: drop in g_s , A, and higher leaf temperature; SPAD and F_v/F_m may drop if stress persists. In reproductive stages, drought strongly reduces pods/grains and grain weight—especially when coinciding with heat; the literature shows that compound events (hot + dry) events generate the greatest losses. Strategies: ZARC, deep root profile (gypsum when indicated; avoid compacted layers), mulch to reduce evaporation and soil temperature range, and genotypes with higher iWUE.

Heat and nighttime heat

Temperatures above ~30–35 °C in R2–R5 reduce setting, alter carbohydrate metabolism, and accelerate leaf senescence. High nighttime temperatures impair the use of assimilates and reduce yield. Adjust GM × date, use densities/architectures that favor moderate ventilation and heat mitigation in the canopy.

Waterlogging/flooding

Causes hypoxia, epinasty, and senescence; the plant reacts with adventitious roots and aerenchyma formation, mechanisms that increase

internal aeration and reduce radial O_2 loss, processes mediated by ethylene/ABA/ROS. Avoid sowing in poorly drained lowlands, correct drainage, and use cover crops/rotation to improve structure.

Salinity (localized scenarios)

Reduces water use efficiency, conductance, and root growth. In fine-textured soils with limited drainage, effects are more pronounced; prioritize controlled leaching, agricultural gypsum when indicated, and more tolerant cultivars.

– CHAPTER 2 –

Ecophysiology of Corn (*Zea mays*) in Brazil

Corn (*Zea mays* L.) is a C₄ species with a CO₂ concentration mechanism that minimizes photorespiration and sustains high photosynthetic rates over a wide range of radiation and temperature. This anatomical-biochemical arrangement creates a high “physiological ceiling” for the conversion of light into biomass, especially when water and nitrogen are not limiting factors.

In Brazil, corn is grown in the summer crop (mainly Sept.–Dec., with regional variation) and in the second crop (“safrinha”), usually sown from January to April after early soybeans in the Midwest, Southeast, South, and MATOPIBA regions. The precise definition of the sowing window is guided by the Agricultural Climate Risk Zoning (ZARC), established by specific MAPA Ordinances for first and second corn crops by municipality and soil type.

Thermal phenology, morphology, and yield definition

Corn phenology is strongly modulated by the thermal sum (degree days, GDD), with the base temperature often taken as 10 °C ($\beta=10$ °C) for planning purposes (adjustable to hybrids and environments). The VT (tasseling)–R1 (heading) period marks the beginning of the critical phase of grain number definition; from R1 to R3, seed set is consolidated and filling begins. This interval is simultaneously the most sensitive to water and heat stress.

Current hybrids exhibit a more restrained size, more upright leaves, and better tolerance to high densities, favoring effective leaf area index (LAI) and greater fraction of absorbed PAR (fPAR). In erect architecture materials, effective LAI values for high yield tend to range from ~3.5–5.5,

although environments and hybrids can shift the optimum; studies report maximum LAI close to 5–5.5 and operational optima between ~4.5 and ~6, depending on density and N.

Because it is C4, corn has lower photosaturation and lower photorespiration, which increases radiation use efficiency (RUE) under favorable conditions. In the field, meta-analyses and trial series report RUE of ~3.5–4.0 g DM MJ⁻¹ of APAR (varying by N, density, microclimate, and health).

LAI: frequent target between 3.5 and 5.5 for high yield; optimization depends on architecture (upright leaf) and stand uniformity.

NDVI/NDRE and SPAD: optical indices useful for tracking vigor, N status, and senescence, supporting nitrogen coverage decisions and canopy limitation diagnostics. Brazilian trials validate SPAD for N in corn and tactical applications with NDRE in the reproductive stage to infer yield.

The number of grains is predominantly defined between VT–R2/R3 and responds to canopy growth in the critical period; grain mass depends on the rate and duration of filling, conditioned by the supply of assimilates and nitrogen. (Integration of corn yield studies.)

The seasonal water demand of corn is typically ~500–800 mm per cycle, with peak ET_c from VT to R3. The most widespread operational estimate uses ETo (Penman–Monteith parameterized FAO-56) and crop coefficients (K_c) in a simple curve, with widely used reference values: K_{c_ini} ≈ 0.40; K_{c_mid} ≈ 1.15–1.20; K_{c_end} ≈ 0.35–0.60 (adjustable for climate, cultivar, and senescence).

The “least limiting water range” (LLWR) integrates water, aeration, and penetration resistance (PR) into a single indicator. PR values > ~2.0 MPa are classically associated with root elongation limitation; the LLWR defines the moisture range in which root growth is minimally restricted by lack of air (in wet conditions) and by mechanical resistance (in dry conditions). In SPD, mulching and controlled traffic increase the LLWR; gypsum application and deeper roots help to exploit subsurface water.

The higher the fraction of transpiration (T) in evapotranspiration (ET), the greater the water use efficiency (WUE_g) tends to be. In corn crops, partitioning studies report T/ET around 0.60–0.65 in the growing season,

with a positive correlation with LAI and canopy closure—objectives that also guide densification and straw management.

Corn vegetative growth and physiology are favored at temperatures of ~20–32/35 °C, with a higher risk of reproductive disorders above that. Heat at VT–R2 reduces pollen viability/germination, floral synchronism, and pollen tube growth, directly affecting grain number; higher relative humidity (lower VPD) can mitigate seed set losses.

Sowing on cold soil (low heat sum) delays emergence and can reduce effective stand and initial leaf area, compromising light interception at the critical stage. In SPD, soil cover and date selection mitigate part of the problem (consolidated principles).

In Latosols, a target V% of ~50–60 and pH(CaCl₂) of ~5.2–5.8 are recommended as operational ranges for corn; gypsum application does not replace liming, but is complementary for subsurface acidity, increasing Ca²⁺ in the subsoil and reducing Al³⁺, favoring root deepening where indicated by diagnosis (texture/CTC/content).

N demand accelerates from V6 to VT, a period in which cover (or fertigation) contributes most to productivity, provided that the canopy is healthy and the water at the critical point is adequate. Absorption curves and physiological studies reinforce this peak and the advantages of synchronizing supply (installment/fertigation) with this window.

Phosphorus is often limiting in Cerrado soils; it is recommended to build availability in the profile (correction and band/plot management) and strategically position the fertilizer according to texture and history (Embrapa summaries and Cerrado management literature).

The grain exports a small fraction of the absorbed K; a significant part remains in the stalks/straw. In silage or residue removal systems, K export increases significantly, and the fertilization plan must take this additional output into account. (Embrapa trials detail the low export via grains and the retention of K in straw.)

Sandy soils and environments with high removal/low OM require attention to S; Zn and Mn can become limiting at high pH and B in dry environments (leaf/soil diagnosis and targeted corrections).

Combined stresses (water + heat; water + N deficiency) are not additive: the damage may be less, equal, or greater than the sum of the

isolated stresses because they share signaling pathways and physiological targets (e.g., stomatal closure reduces internal C and increases leaf temperature, amplifying thermal damage). Recent reviews emphasize this interactive nature and the importance of integrated management and genetic approaches.

In densification, gains in light capture and increases in T/ET accumulate up to limits imposed by water/N and the architecture of the hybrid. In water-limited conditions, excessive densities penalize growth in the critical period and reduce WUE at the grain level; in high-potential environments, high densities with erect leaves sustain functional LAI and extend the duration of the green canopy after heading.

ZARC (MAPA): Updated ordinances publish sowing windows by municipality, soil type, and cycle (1st and 2nd crops). For second-crop corn, Embrapa defines cultivation as rainfed, extemporaneous, from January to April, usually after early soybeans; complying with ZARC reduces VT–R3 exposure to dry spells and heat waves.

Practical calendar: in the Midwest and Southeast, the 1st harvest tends to occur from September to December; the 2nd, from January to March, immediately after soybeans. In the South, windows shift a little later. Industry and extension sources indicate similar windows, but always subject to the current Ordinance and local forecast.

The operational range is wide ($\sim 45\text{--}90$ thousand plants ha^{-1}). In limited rainfed areas (water/N), optimal densities of $\sim 50\text{--}65$ thousand are common; in high-potential/irrigated areas, $70\text{--}85$ thousand with narrow rows ($0.45\text{--}0.50$ m) and erect hybrids are common, always respecting the hybrid recommendation and the water capacity of the system. Embrapa documents indicate $55\text{--}65$ thousand plants ha^{-1} as typical operational density and signal an increase under modern technologies and densification-tolerant materials.

Avoiding deficits between VT–R3 is a priority. In supplemental irrigation, anticipate blades based on $\text{ET}_0 \times \text{Kc}$ (FAO-56) and the system's application capacity, remembering that Kc_{mid} reaches $\sim 1.15\text{--}1.20$.

In the Cerrado, building a profile (deep liming when possible, gypsum application based on diagnosis), reducing traffic on wet soil, and maintaining abundant mulch are pillars for expanding LLWR and

stabilizing water supply during VT–R3.

Gas exchange/porometry: measuring A, gs, E in V8–V12 and R1–R3 helps interpret microclimate and limitations (water/compaction/heat).

Fluorescence (Fv/Fm) and SPAD: Fv/Fm signals photochemical integrity; SPAD informs N status and senescence; persistent drops indicate a need to reevaluate N/water.

Temperatures around or above ~35 °C near anthesis impair pollen viability and pollen tube growth.

Agronomic losses tend to be greater when high DPV and water deficit occur together.

Compaction narrows LLWR: in wet conditions, there is a lack of air; in dry conditions, PR > 2 MPa limits root elongation. In SPD, mulch reduces soil E and increases the T/ET fraction; controlled traffic and operating windows prevent the generation of critical PR in active layers. (Syntheses of LLWR and PR in agricultural soils.)

Nutrition: N, P, K, and S from an ecophysiological perspective

N: synchronizing V6–VT coverage with adequate water increases RUE and prevents early canopy senescence (functional stay-green).

P: very common restriction in Latosols; work on profile construction and positioning.

K: grains export little K; removing straw (silage) changes the K balance and requires compatible replacement.

S: essential in sandy soils and environments with high removal.

Integration with contemporary systems and practices

Safrinha as a system

The second crop has established itself as the main corn season in many regions; its success depends on the speed of the soybean → corn transition (early soybean performance and harvest), respecting ZARC windows to escape autumn droughts and thermal peaks during flowering. Technologies such as early sowing (Antecipe system) make it possible to advance the planting of the second corn crop by up to ~20 days before the

full soybean harvest, provided that agronomic and legal criteria are met, mitigating the climatic risk of VT–R3.

Plant arrangements, architecture

In rainfed areas, closing the canopy early (thickening to the optimum point for the environment and hybrid) increases the transpiration fraction, reduces evaporation losses (E), and sustains productive LAI in the critical phase; in high potential areas, narrow rows and erect hybrids increase radiation efficiency in the canopy profile.

Sensing and adaptive management

UAV/spectral indices: prioritize VT, R1, R2–R3 for yield prediction and stress detection; NDRE/GNDVI in post-flowering are strong predictors; integrate with SPAD at key points.

Infrared thermometry: apply CWSI to define irrigation on pivots and adjust blades in near real time.

Practical guidelines by macroenvironment

Cerrado/MATOPIBA

Sowing: immediately after early soybeans, within the municipal ZARC; avoid delays that push VT–R3 into drier/hotter April–May.

Soil: V% 50–60, pH(CaCl₂) 5.2–5.8; gypsum application by diagnosis for acidic subsoil (Ca²⁺/Al³⁺ reduction); robust mulching and controlled traffic increase LLWR and water resilience.

Density: 60–80 thousand plants ha⁻¹ for tolerant hybrids and good supply; reduce to 50–65 thousand with water risk and high Kc_{mid} without irrigation.

N and PGPB: align N V6–VT;

South/Southeast

1st crop: plant from Sept.–Dec. (depending on region), avoiding cold during establishment and heat/drought during the reproductive phase

using ZARC.

2nd crop: align soybean harvest and sowing until Feb.–Mar. to protect VT–R3; density defined by the water potential of the year.

Soil: correct acidity (liming) and use gypsum when there is subsurface acidity/ Al^{3+} ; maintain SPD and mulch for water and thermal stability.

– CHAPTER 3 –

Ecophysiology of Coffee Trees **(*Coffea arabica* and *C. canephora*)**

The coffee tree is a C3 perennial that is notoriously sensitive to the environment: water availability in the soil and air (via vapor pressure deficit, VPD), temperature, and radiation govern the coupling between sources (leaves and, to a lesser extent, green fruits) and sinks (flowers, expanding fruits, vegetative growth), determining productivity, interannual stability, and quality. In Brazilian systems, from the South/Southeast to the Cerrado and north of Espírito Santo/Rondônia, long-term success comes from aligning ecophysiological processes with management decisions: spatial arrangement/LAI, nutrition, shading when indicated, irrigation and flowering synchronization, as well as pruning to modulate the load. Reviews of references show that, although coffee trees are vulnerable to drought/high VPD and heat, they have a great capacity for acclimatization when well nourished and managed, and can benefit from high CO₂ by maintaining functional photochemical apparatus even under moderate heat.

The recent climate situation reinforces the need for a dynamic risk assessment: heat waves, dry spells, and frost events have gained operational relevance, and the Agricultural Climate Risk Zoning (ZARC) underwent updates for canephora coffee in 2024, with national ordinances for irrigated and rainfed cultivation. For arabica, the 2021 ordinances defined periods/areas by state and are the regulatory basis until further revisions.

Coffee trees have an orthotropic axis (trunk) and productive plagiotropic branches, with a root system concentrated in the first 30–40 cm, although with plasticity according to texture, structure, and management. Field and shaded system studies show a predominance of fine roots at the top of the profile (0–30 cm), with a more uniform distribution up to ~40

cm, and sensitivity to compaction, which affects hydraulic conductance and, consequently, stomatal control.

Under tropical/seasonal conditions, vegetative pulses alternate with reproductive ones. A short dry period ($\approx 2\text{--}4$ months) induces floral differentiation; the return of rains (or strategic irrigation) “unlocks” anthesis, and multiple blooms under sparse rains generate uneven maturation. Biennialization emerges when high loads depress vegetative renewal and increase maintenance respiration; management via pruning (skeletoning, zero harvest in conilon) and nutritional balancing modulates this cycle. Classic reviews and physiological studies relate source–sink competition to dieback and crop alternation.

Process physiology

Gas exchange, DPV, photosynthesis (A), stomatal conductance (gs)

In the field, A is typically higher in the morning, when stomatal conductance is high and DPV is moderate; as the air warms, the increase in DPV induces stomatal closure and afternoon depression of A. In exposed leaves, this pattern is almost always stomatal, with little evidence of photoinhibition when nutrition is adequate. The A–gs coupling tends to be stronger in *C. arabica* than in *C. canephora*; in hot-dry conditions, moderate shading reduces leaf DPV and alleviates stomatal limitation. Operational indicators such as iWUE (A/gs) and WUE (A/E) are useful for comparing genotypes and environments and for in-season water decisions.

Photoprotection, radiation, and leaf temperature

Under high light, coffee plants activate dissipative pathways (xanthophyll cycle, alternative electron transport, and photorespiration) and antioxidants (SOD, APX, catalase, carotenoids, tocopherols), protecting PSII. This explains why Fv/Fm rarely falls persistently in adequate plants, even in full sun, as long as water and nutrition are not limiting; however, high DPV + low gs raise leaf temperature and can precipitate burning, leaf fall, and fruit damage. In hot, dry sites, moderate shading (20–40%) is a physiological tool for maintaining canopy energy balance and reducing

heat stress. In micrometeorological analyses, coffee leaves can heat up several degrees above the air on dry, radiative afternoons; the effect is mitigated by higher g_s and shading.

Source–sink, load, and the role of fruits

Yield results from (i) productive branches per plant, (ii) fruits per node/branch, and (iii) grain mass. Load manipulations (thinning, pruning) alter the water status and g_s through stomatal pathways (via assimilate demand), helping to contain dieback and bienniality. As for the fruits, there is photosynthesis in the pericarp; estimates suggest a relevant contribution to the daily respiration of fruits and, at high loads, fruits can represent up to 20–30% of the photosynthetic area of the plant + fruit ensemble. However, the net contribution to grain growth is context-dependent (light, position in the canopy, load). The current consensus is that this photosynthesis recycles respiratory CO_2 and contributes occasionally to the local balance, without replacing the need for a robust foliar source.

Soil and climate requirements and suitability in Brazil

Temperature and precipitation

For Arabica, the optimal average annual range is $\approx 18\text{--}23\text{ }^\circ\text{C}$; above this, maturation accelerates (potentially affecting quality), and below $17\text{--}18\text{ }^\circ\text{C}$, growth slows down. For canephora, the optimum is $\approx 22\text{--}26\text{ }^\circ\text{C}$, with a relative advantage under warming conditions. Recent projections for Brazil point to an altitudinal shift of suitable areas and greater risk in already hot/semi-arid zones, reinforcing the importance of shading, irrigation, and adapted materials. Annual precipitation $\approx 1,200\text{--}1,800\text{ mm}$, with a short drought (2–4 months) to induce flowering, is a classic suitability target; year-round rainfall hinders the concentration of flowering and harvesting.

Wind, radiation, and frost risk

Winds intensify ETo and increase DPV in the canopy, aggravating hydrothermal stress; windbreaks and row design reduce losses. As for

frost, recent studies with sensing show great spatial variability in damage; technical references indicate that temperatures around -2°C (trunk) to -3°C (leaf) are sufficient to kill young leaves/branches. In new crops, the risk is even greater, and relief arrangements, windbreaks, and the choice of more tolerant cultivars are decisive.

Soil, chemistry, and physics: where ecophysiology meets management

Chemistry: pH, V%, and gypsum

In Brazilian systems, usual targets of $\text{pH}(\text{CaCl}_2) \sim 5.2\text{--}5.8$ and V% 60–70% balance Ca/Mg availability, mitigate toxic Al^{3+} , and favor root activity in the topsoil; gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) complements liming for subsurface acidity, deepening roots when indicated (texture/CTC and levels in the profile). Recent recommendations highlight that the target V% depends on CTC: low CTC soils require a higher V% for adequate Ca/Mg supply, while high CTC soils operate well with a more modest V%.

Physics: LLWR, compaction, and water in the profile

The Least Limiting Water Range (LLWR) integrates available water, aeration, and penetration resistance (PR). In coffee plants, $\text{PR} > \approx 2\text{ MPa}$ already restricts root growth; compacted layers increase the risk of “physiological drought” even with normal rainfall, as the hydraulic conductance of the soil-root-xylem falls and stomatal control is anticipated. Controlled trials confirm that compaction reduces g_s , A , and growth, in addition to altering root anatomy. In the field, SPD with abundant mulch and controlled traffic are key to stabilizing LLWR.

Light, shading, and canopy architecture

When and why to shade

In mild, well-watered environments, full sun tends to maximize annual production. In hot/dry environments or under high DPV, moderate shading (20–40%) reduces leaf temperature, stabilizes g_s , and decreases the afternoon depression of A , with gains in crop stability and, in several

cases, improvements in beverage quality (effects on sugars and precursors). The primary mechanism is microclimatic: a decrease in DPV and radiative load on the leaf, with photoprotection maintained within less costly limits.

LAI and interception

The operational LAI in low-growing Arabica tends to fluctuate between ~ 3 and 6 in the stages of greatest interception, reaching higher levels in dense/irrigated crops; the goal is to close the canopy without exaggerating self-covering, which accelerates basal senescence and increases air humidity in the canopy (pests/diseases). Empirical K_c –LAI relationships show that as LAI increases, K_c increases (higher transpiration), but with decreasing marginal gains, which is valuable information for designing density and timing irrigation.

Water, irrigation, and flowering synchronization

Water demand and crop coefficients

Typical seasonal demand is around ≈ 900 – $1,200$ mm year⁻¹ in productive coffee plantations (rain + irrigation), varying with LAI, climate, and age. For practical management, ETo is used with crop-specific K_c . Under Brazilian conditions, measurements and models relate K_c to LAI and stage: average “mid-season” K_c values in mature coffee often approach 1.0–1.2, varying with soil cover, weed management, and canopy architecture. The dual approach ($K_{cb} + K_e$) allows canopy transpiration and soil evaporation to be separated, increasing accuracy under active mulch/inter-row.

Strategic irrigation and “controlled drought”

In rainfed arabica, a brief dry period synchronizes floral differentiation; in irrigated canephora, “controlled water stress” practices (reducing leaves to a target soil moisture) followed by rehydration are used to concentrate flowering and harvesting, reducing unevenness. National technical literature and field practice support this strategy, as long as stress is not extended during berry setting–filling, when water sensitivity is at its highest.

Dynamic diagnostics

In addition to water balances, thermography (leaf temperature), porometry (g_s), and fluorescence ($\Phi PSII/NPQ$) help adjust leaf area in real time, especially on afternoons with high DPV and wind. Thermography has been applied to coffee trees to infer stomatal conductance and anticipate stress before the drop in A is visible to the naked eye.

Heat, cold, and combined stresses

Heat $\times$ drought $\times$ high light

Under heat and high DPV, stomatal limitations dominate the drop in A ; if photoprotection mechanisms become overloaded, scalding appears and senescence accelerates. Adding moderate shading, mulch, and timely irrigation reduces the risk. Elevated $[CO_2]$ tends to increase thermal resilience, sustaining A and the integrity of the photochemical apparatus under 37/30 °C (day/night) regimes when water stress is controlled. FACE trials in *C. arabica* show sustained increases in A without biochemical downregulation, signaling the potential for partial mitigation of warming via CO_2 , provided there is no water deficit.

Cold and frost

Cold tolerance sets limits on suitability at lower altitudes/latitudes; frosts can cause severe losses and even plant death, especially in young plots. Recent studies with UAVs show that spectral indices can map damage and guide localized interventions after the event. In terms of thresholds, values in the order of -2 °C (trunk) and -3 °C (leaf) are already critical.

Soil nutrition and biology: N and K at the center, with S, Ca, and Mg “driving” resilience

N and K dominate annual demand; installment payments/fertigation increase efficiency (especially in irrigated *canephora*), and K is crucial in high DPV environments due to its osmotic/stomatal role. S, Ca, and Mg need to be monitored by leaf/soil analysis, and micronutrients (B, Zn, Mn) should be given attention in soils with high pH or very sandy

soils. Soil biology (OM, cover, microbial diversity) improves infiltration and buffers moisture and temperature variations, resulting in more stable gs throughout the day. Regional guides and fertilization manuals from public research support these principles.

Guidelines by environment

South of Minas/Mogiana/Caparaó — *C. arabica*

Risks: cold autumn-winter and heat/drought during filling.

Arrangement: medium densities aiming for LAI ~3–5 with good aeration; regular pruning to contain bienniality.

Soil: liming for V% 60–70% and pH(CaCl₂) 5.2–5.8, gypsum application if there is subsurface acidity; permanent cover.

Water: in rainfed areas, use ZARC to position planting and manage “short dry” pre-flowering; supplemental irrigation (when available) with Kc×ETo and Tfolha/g_s reading.

Cerrado Mineiro/Goiás/Western BA — *C. arabica*

Risks: high spring-summer DPV and dry spells; heat during filling.

Arrangement: slightly higher densities to close canopy early, without aeration deficit; abundant mulch.

Moderate shade (20–30%) as an ecophysiological tool where the thermal load is high, weighing possible peak yield losses vs. stability/quality.

Water: support irrigation at ETo peaks; use Kc–LAI to refine blades, preferring a dual approach when there is active mulch/inter-row.

Northern ES/RO/southern BA — *C. canephora* (*conilon/robusta*)

Modern system basis: irrigation + densification + stem management (multi-stem) and flowering synchronization through water control (controlled dry + rehydration).

Nutrition: high responses to K; staggered fertigation.

Soil: attention to subsurface acidity (gypsum) and PR under mechanization; permanent cover.

ZARC: follow ordinances 6 and 7/2024 (rainfed/irrigated) by state/DF.

Ecophysiological monitoring and diagnosis

Gas exchange/porometry: A , g_s , and E in the morning vs. afternoon (exposed leaves) reveal stomatal restrictions due to DPV/water.

Fluorescence: F_v/F_m , $\Phi PSII$, and NPQ signal photoinhibition/recovery; persistent drops require nutritional/water investigation.

Infrared thermography: Tleaf as a proxy for g_s and thermal stress, sensitive to rapid PVD variations.

Remote sensing (UAV): spectral indices for intra-plot uniformity and post-event frost/stress mapping.

Combined stresses and management trade-offs

Drought + heat + high light rarely add up to linear effects; they can be synergistic (i.e., low g_s + high DPV → leaf heating, requiring more photoprotection). Densification improves the fraction of radiation used (higher transpiration/shading evaporation of the canopy), but under water-limiting conditions, very high densities penalize growth at the critical point and WUE_g, in addition to increasing the risk of disease if aeration falls. Effective mitigations combine: functional soil profile (chemical + physical), mulch/straw, shade cloth or trees when the site is hot/dry, N and K rates adjusted to growth and, if possible, precision irrigation. The increase in $[CO_2]$ mitigates some of the heat damage in *C. arabica* when water is not limiting, but does not compensate for prolonged water deficits.

– CHAPTER 4 –

Ecophysiology of sugarcane (*Saccharum* spp.) in Brazil

Sugarcane is a semi-perennial C₄ grass grown in a wide range of climates in Brazil for the production of sugar, ethanol, and bioelectricity. Its remarkable photosynthetic efficiency and ability to form large leaf area and sucrose-rich culms allow for biomass yields higher than those of most annual crops. However, this physiological ceiling only translates into yield when the soil-plant-atmosphere system is well coupled: active roots at depth, canopy that intercepts and uses radiation efficiently, water available without critical restrictions, and nutritional management tuned to source-sink partitioning (leaves/stalks). The objective of this chapter is to integrate the ecophysiological fundamentals, C₄ photosynthesis, radiation interception and use, water relations, root growth, assimilate partitioning, and maturation with agronomic decisions regarding planting, fertilization, irrigation, mulch management, and harvesting, with an emphasis on Brazilian conditions (rainfed and irrigated, plant cane and stumps).

Morphophenology and stages

Architecture and organs

The crop forms clumps of cylindrical culms with nodes/internodes, alternate leaves (sheath + blade), and a fasciculated root system, with roots originating from the “set” (culm-seed buds) and, later, adventitious roots (“shoot roots”) that support the crop and stubble. The classical literature describes systems with high surface root density, downward-oriented roots and, in some materials, deep bundles, with documented water activity beyond 2 m and historical reports of depths greater than 6 m when the environment allows. Distribution with depth declines exponentially and is strongly modulated by texture, structure, compaction, and management.

Operational stages (sugarcane plant) — (i) Germination/sprouting (0–45 d): dependent on soil temperature and moisture in the furrow; (ii) Tillering (up to ~120 d): defines effective culm population; (iii) Rapid growth (~120–300 d): expansion of LAI and culm elongation; (iv) Maturation: deceleration of vegetative growth, increase in °Brix/Pol and juice purity. In stubble, the cycle is shorter, with strong sensitivity to damage to the base/cutting height, compaction by traffic, and post-harvest stalk reserves that feed the source–drain imbalance.

Cycle duration — In Brazilian tropical environments, “one-year cane” (≈ 12 months) and “one-and-a-half-year cane” (≈ 15 –18 months) predominate. Thermal time (degree days) and water availability determine the speed of canopy closure and the rate of stalk elongation. In cases of high potential (unlimited water/nutrition and high temperatures, but not excessive), the canopy can close ~70–80 days after planting, explaining the exceptional biomass yields observed in high-input studies in northeastern Brazil.

C4 photosynthesis, radiation interception, and efficiency

Via C4 — Sugarcane has Kranz anatomy and a C4 pathway, with pepcase activity detected at different intensities, which gives it a high photosynthetic rate under intense radiation and high temperatures, with low photorespiration. This biochemistry sustains high assimilation rates (A) in closed and luminous canopies, as long as water and nitrogen do not limit stomatal conductance and associated biochemical reactions.

Light interception — The fraction of absorbed PAR (fPAR) increases as the leaf area index (LAI) increases; high-vigor sugarcane reaches LAI > 4–5, with a light extinction coefficient (k) of around 0.45–0.50 in common arrangements. In the field, radiation use efficiency (RUE) for dry matter tends to vary, in well-managed crops, approximately between 1.5 and 2.8 g DM MJ⁻¹ of intercepted PAR, with variations in density, architecture, and microclimate. Trials in northeastern Brazil estimated $k \approx 0.48$ –0.51 and quantified the energy conversion of the canopy under two spacings, demonstrating that the row arrangement modulates light distribution and effective RUE.

Source–drain and sucrose accumulation — During tillering, partitioning favors culms (structural growth). Maturation involves adjusting drains and metabolism to accumulate sucrose in the stalk parenchyma; milder nights and a slight benign water deficit shift the source–sink balance in favor of sugar accumulation, provided that stalk mass is not lost due to excessive stress. The use of chemical maturers (e.g., glyphosate in sublethal doses, etefom, sulfometuron) is a specific tool to anticipate and concentrate maturation in specific scenarios, always subject to the environment and legislation.

Water relations, water demand, and crop coefficients

Seasonal demand and sensitive phases — Water consumption throughout the cycle varies widely (≈ 900 – $2,500$ mm), depending on cycle length, climate, and management (rainfed vs. irrigated). The phases most sensitive to deficits are: establishment/sprouting, initial tillering, and stalk elongation. Near harvest, moderate deficits may favor sucrose, but severe deficits reduce stalk mass and total recoverable sugar (ATR). In humid/sub-humid tropics, peak ET_c occurs during the period of maximum IAF, with daily evapotranspiration often above 5–6 mm when water is not limiting. Recent Brazilian syntheses consolidate regional ET values and irrigation requirements in different climates.

Kc — Reference crop coefficients (K_c) (FAO-56 standard condition) for sugarcane are typically $K_{c_ini} \approx 0.4$; $K_{c_mid} \approx 1.20$ – 1.25 ; $K_{c_end} \approx 0.7$ – 0.8 , with variations depending on climate and management. In environments with high evaporative demand (high DPV, winds), the effective K_c may be < 1.0 even with a closed canopy, because stomatal closure in the face of high DPV reduces the transpiration fraction of ET_c . The dual approach ($K_{cb} + K_e$), which separates canopy transpiration (K_{cb}) from soil evaporation (K_e), is especially useful in drip/fertigation and in areas with mulch.

ETo and operational criteria — Estimating leaf area from ET_o (Penman–Monteith FAO-56) and K_c/K_{cb} is a well-established practice for supplemental irrigation. In Brazilian regions, agrometeorological integrations and field observations help define irrigation schedules and

potentials by micro-regions. Remote sensing tools, such as geeSEBAL (SEBAL in GEE), have been validated in irrigated sugarcane to estimate ETa and qualify management at the field scale.

Straw and ET fractions — In mechanized harvesting systems without fire clearing, straw reduces Ke (soil evaporation), increases water storage in the profile, and can maintain ETc for longer during droughts because it slows surface water loss and protects the soil-atmosphere interface; these effects favor inter-crop stability, with trade-offs discussed below.

Temperature, photoperiod, and thermal limits

Thermal ranges by process — Sugarcane germinates/sprouts best at 25–32 °C (variable thermal base ~12–16 °C). Culm elongation and leaf growth perform at ~28–32/35 °C; below 20 °C it slows down, and above 35 °C heat losses occur. At maturity, sunny days and mild nights (~18–22 °C) favor sucrose accumulation. Detailed physiological studies demonstrate changes in sugar allocation and storage when grown below or above the optimum, highlighting the importance of temperature in sugarcane production. °C) favor sucrose accumulation. Detailed physiological studies demonstrate changes in sugar allocation and storage when grown below or above the optimum, highlighting the importance of combining local climate and harvest calendar. Photoperiod has a secondary effect compared to thermal time.

Canopy closure as a thermal target — In tropical conditions with unlimited inputs, closing the canopy up to ~70 days after planting (high LAI/fPAR) explains some of the cases of very high yields; this “target” results from the combination of high, but not excessive, temperatures and a water/nutrient regime that sustains continuous growth.

Root system, soil physics, and structural quality

Root as bottleneck/insurance — In sugarcane, water and nutrient uptake depends on a vigorous and deep root system. Reviews show great plasticity, but a recurring pattern of high density in the surface layers and detectable water activity below 2 m when the soil allows it. Compacted

layers and high resistance to penetration (> 2 MPa) limit root elongation, delay canopy closure, and reduce water resilience. Planning controlled traffic, managing harvest moisture, and performing diagnosis-driven subsoiling are key strategies for preserving the least limiting water range (LLWR) and exploitable soil volume.

Planting and renewal — In area renewal (sugarcane), site preparation strongly affects the root environment and the yield of the first harvest, with evidence in the Cerrado that systems that relieve compaction and optimize structure increase rooting and productivity. In Brazilian cultivars under subsurface fertigation, studies with mini-rootstools estimated effective rooting depth and distribution profile, useful for calibrating Kcb per layer.

Mineral nutrition, liming/gypsum application, and organic recycling

Liming and gypsum application — In many Latossols, working with a pH (H_2O) close to 6.0 and $V\% \approx 60$ is a frequent operational target. Gypsum application complements liming when there is subsurface acidity/excess Al^{3+} , increasing Ca^{2+} at depth and favoring root deepening; its dose depends on texture/CTC and diagnosis. The relationship between liming and potassium is sensitive: over-liming can affect the availability of K and micronutrients, requiring careful management.

Macronutrients

Nitrogen (N): the response depends on organic matter, mulch, and history; doses and installments are adjusted to the system (plant vs. stump) and the goal (sugar vs. biomass). Phosphorus (P): focus on planting (in the furrow), with strategic maintenance in soils with low availability. Potassium (K): high requirement and intense recycling via mulch and vinasse; positioned fertilization (furrow, broadcast, fertigation) and source/dose compatible with texture and rainfall regime. Reviews on vinasse show gains in fertility and soil quality when well managed (including as a source of K), while pointing out risks and the need for environmental criteria (dose, area, distance from watercourses, monitoring).

Organic sources and circular economy — Vinasse and filter cake are part of nutrient and water recycling strategies in the sugarcane system;

technical-scientific syntheses report improvements in the chemical, physical, and biological attributes of the soil and a significant contribution of K and water to crops when used with environmental governance (load tracking, application limits, risk of localized salinization). There has been recent innovation in ultrafiltration/conditioning of vinasse to increase efficiency and reduce logistics costs.

Fertilization guidelines — Brazilian fertility manuals for sugarcane detail soil/leaf analysis targets, export balances, and recommendations by texture and environment; frequent updating of these guides and integration with productivity/quality data are essential for decision-making by field.

Straw, harvest, and carbon balance

Raw harvest deposits $\approx 8\text{--}20 \text{ t DM ha}^{-1}$ of straw (varies by cultivar/environment), reduces direct evaporation from the soil, decreases surface temperature range, and contributes to carbon storage. On the other hand, it can immobilize N (high C:N ratio), harbor pests/diseases, and require fine adjustments in N and K doses/timing. Reviews of straw decomposition in Brazil quantify mineralization rates and scenarios in which partial removals (for energy purposes) reduce soil C and stored water, penalizing water resilience.

Abiotic stresses: drought, heat, cold, and combinations

Water deficit and DPV — At high DPV, sugarcane regulates stomatal conductance (gs), anticipating a drop in transpiration and effective Kc, even without immediate water limitation in the soil; the effect protects the photosynthetic apparatus, but reduces the transpiration fraction of ET and can limit A and stalk elongation when persistent. This behavior explains the $Kc_{mid} < 1$ observed in hot and dry climates despite closed canopy.

Heat — Temperatures above the optimum ($\geq 35 \text{ }^{\circ}\text{C}$) increase the risk of disturbances in growth and sucrose balance, especially when they coincide with high DPV and dry winds. Management with mulch, strategic irrigation, and varietal selection helps to cushion thermal peaks in the canopy.

Cold and frost — Temperatures $< 8\text{--}12 \text{ }^{\circ}\text{C}$ drastically slow down

physiological processes; Frosts define suitability limits at risky altitudes/latitudes, requiring adjustments to the calendar (planting/harvesting), choice of adapted materials, and landscape planning (windbreaks, topography). ZARC guidelines consolidate thermal risk by decadal period and soil type/cycle.

Combined stresses — Late droughts + heat + high radiation tend to accelerate senescence and reduce the useful life of the sugarcane field. On the other hand, moderate and short-term deficits at the end of the cycle can intensify maturation (increase °Brix/Pol) if management prioritizes ATR per unit of water (water productivity for sugar), and not just stalk mass.

Spatial arrangement, architecture, and rapid canopy closure

The time to closure is one of the major determinants of yield. In high-potential environments, closing the canopy in ~10 weeks (≈ 73 days, on average) explains productivity gains because it increases the fraction of absorbed radiation (fPAR) early on, reduces weed growth, and maximizes the RUE of the cycle. Density adjustments, spacing (single/double rows, 1.5–1.8 m, or combined arrangements) and architecture (more upright leaves) contribute to achieving the target LAI without compromising mechanized harvesting.

Irrigation and water management (rainfed and irrigated)

Rainfed planning — In south-central Brazil, staggering plantings so that tillering and the onset of grand growth coincide with the rainy season is a key strategy. The ZARC by state/municipality/cycle, fed by historical series and water balance and thermal limit models, indicates windows of lower risk (20–30–40%), guiding decisions on timing and, consequently, harvesting.

Supplementary irrigation — Where available, use $ET_o \times K_c / K_{cb}$ with triggers per phase (soil moisture by θ /tension) and prioritize sugar per water during the maturation period. In high evaporative demand, consider effective $K_c < FAO-56$ due to stomatal closure by DPV; calibrating by plot reduces blade errors. The adoption of remote sensing (geeSEBAL),

combined with soil observations, has shown efficiency gains in the management of irrigated sugarcane in Brazil.

Maturation: climate, “controlled dry” and ripeners

Maturation is favored by sunny days and mild nights; mild and transient water stress can concentrate sugars without significant loss of stalk biomass, as long as the “controlled dry” does not trigger premature senescence. In specific contexts, ripeners (e.g., sublethal doses of glyphosate, etefom, sulfometuron-methyl) advance and standardize harvest, but their performance and varietal response are conditioned by climate and canopy physiology, requiring local validation and regulatory compliance.

Technological quality and trade-offs

Indicators — °Brix, Pol, purity, and ATR guide harvesting. In irrigation and nutrition planning, it is prudent to pursue water productivity for sugar (and not just for stalk mass). Mulching improves ATR stability between harvests by cushioning water stress, but may require N adjustments to mitigate immobilization.

– CHAPTER 5 –

Ecophysiology of Cotton (*Gossypium hirsutum*) in Brazil

The herbaceous cotton plant (*G. hirsutum*) is a C3 species, perennial and cultivated as an annual, with indeterminate growth habit and high phenotypic plasticity. Its ecophysiology is strongly modulated by the microclimate of the canopy (radiation, leaf temperature, and DPV), soil water (profile, LLWR), and nutrition (especially N and K), with direct effects on the retention of reproductive structures, boll/capsule mass, and fiber quality. This chapter integrates processes (gas exchange, photoprotection, source–sink), phenological stages, and Brazilian edaphoclimatic factors (Cerrado, MATOPIBA, MS/GO/MT/BA) into practical management guidelines.

Functional morphology and phenology

Architecture — main axis with vegetative and fruiting branches; cordate leaves with trichomes (pubescence) that influence energy/thermal threshold; taproot with deep lateral roots when the profile is not dense/acidic.

Practical stages — (i) emergence; (ii) flower bud; (iii) flowering; (iv) fruiting/apple filling; (v) boll opening and maturation. Growth is indeterminate: vegetative and reproductive coexist, requiring balance via densification, N/K, and growth regulator (mepiquat chloride) when necessary.

Thermal time (DD60) — development is well described by degree days based on 15.6 °C (60°F). Operational targets: 1st square ~425–475 DD60; 1st flower ~775–850 DD60; boll opening ~>1,600 DD60 after flowering; harvest ~2,200–2,600 DD60 (varies by environment/cultivar).

Growth and production physiology

C3 photosynthesis, stomata, and DPV

A (assimilation) is strongly coupled to g_s (stomatal conductance) and DPV; there is typical afternoon depression of A on dry/hot days. Pubescence and leaf angle modulate leaf temperature.

iWUE (A/g_s) and WUE (A/E) are useful metrics for comparing materials/sites; adequate N and K balance sustains source (leaf) and sink (apple/fiber) under high DPV.

Source–sink and yield definition

Number of apples/caps and retention in basal/primary positions define potential; the key period → flowering → 3 weeks post-flower is critical for retention.

Excessive vegetative growth (high N/water + wide spacing) shifts assimilates to leaves/branches → increased abortion and delayed ripening; mepiquat helps restore the source–sink relationship.

Temperature and heat

Optimal growth/setting close to 30 °C; peaks > 35–36 °C during flowering/filling reduce pollen viability, pollen tube elongation, and apple retention; nights above 24–26 °C increase respiration and worsen the source–drain balance.

Water, evaporative demand, and Kc

Demand

Water requirement for the cycle (rainfed/irrigated): ~600–1,000+ mm, varying with cycle length, climate, and management. ET_c peaks from flowering to filling.

Phases most sensitive to deficit: establishment, budding (squares), flowering, and early apple filling phase.

Crop coefficients

K_c (simple, reference): initial ≈ 0.35 – 0.40 ; middle ≈ 1.15 ; final ≈ 0.50 – 0.60 (before leaf fall). At high demand (high VPD/wind), the effective K_c may be < 1.0 even with a closed canopy.

A dual approach (K_{cb} + K_e) is recommended for drip/fertigation and SPD with mulch, separating canopy transpiration and soil evaporation.

Strategies

In rainfed areas, time sowing to coincide with budding–flowering during the rainy season (ZARC) and close the canopy early (density/rows). In irrigation, manage by ETo $\times$ K_c/K_{cb}, moisture/tension in the profile, and limits per phase; aim for high WP (kg of fiber per mm).

Soil, liming, and nutrition

Reaction — in the Cerrado, aim for pH(CaCl₂) ~ 5.5 – 6.0 and V% ~ 50 – 60 , correcting subsurface acidity (gypsum) when indicated.

Nitrogen (N) — high response, but excesses increase leaf area and reduce retention/precocity; split applications according to rainfall/irrigation.

Phosphorus (P) — focus on the furrow (planting) and maintenance through soil/condition analysis; PP limits initial/root growth.

Potassium (K) — most demanded by the crop; calibrate dose according to K in the soil and production target; pay attention to maintenance in intensive systems and fiber quality (micronaire/maturity) sensitive to K supply.

Sulfur and micronutrients — S in sandy soils/oxysoils; monitor B/Zn/Mn/Fe (fiber and glue).

Spatial arrangement, density, and regulators

Population and spacing — operational reference for conventional system: 0.80 – 0.90 m between rows with ~ 80 – 120 thousand plants ha⁻¹ (≈ 8 – 12 plants m⁻¹); in dense planting (0.45 – 0.50 m), reduce plants per meter to maintain LAI without excessive vegetation.

Canopy architecture — narrower rows and moderate densities reduce the critical period of competition with weeds, close the canopy earlier, and increase the T/ET fraction. Adjust to the cultivar/environment.

Growth regulators (mepiquat) — tool to contain height and branch elongation, improve retention in the first positions, and uniform maturation, especially in high N/water environments.

Cavitation, embolism, and hydraulic safety

Key concepts — Cavitation is the formation of bubbles in xylem sap under high tension; when the vessels are filled with air, embolism occurs, reducing hydraulic conductance and water supply to the canopy.

Cotton plant strategy — In *Gossypium hirsutum*, the crop avoids hydraulic failure via early stomatal closure and, in prolonged droughts, leaf abscission, preserving the integrity of the stem and root xylem. Leaves are more vulnerable to embolism than stems and roots, and stomatal closure (g_s) precedes the onset of embolism, providing a positive hydraulic safety margin. Acoustic cavitation signals accompany the decline in assimilation (A) and stomatal conductance (g_s) in controlled drought.

Hydraulic segmentation and reproductive organs — The system is segmented: peripheral organs (leaves and young reproductive structures) yield first, protecting the stem. Recent studies describe the hydraulic properties of the pedicel/apple and fruit transpiration, which are useful for reducing apple abortion under stress

Practical implications

Water planning: position pre-flowering and flowering in the ZARC windows and avoid dry spells at this stage.

Irrigation triggers: use leaf water potential (Ψ_{leaf} , pressure chamber) or stem water potential (Ψ_{stem} , microtensiometer or bagging method) to intervene before the material's typical g_s is reached.

Canopy and DPV: close the canopy early (density/spacing) to reduce leaf temperature and DPV; monitor with infrared thermometry.

Soil and nutrition: maintain an uncompacted profile, adequate K and Ca (wall/xylem), cover/mulch, and gypsum when indicated.

Dry-wet cycles: avoid “on-off” regimes that cause repeated cavitation-refill cycles (possible cavitation fatigue); prefer stable blades in the reproductive stage.

Field procedure (summary): measure Ψ_{leaf} at noon (sun leaf) and at dawn; record A, g_s , and leaf temperature on representative days; monitor NDVI/NDRE and LAI to anticipate a drop in hydraulic conductance. In irrigated conditions, integrate $E_{\text{To}} \times K_c / K_{cb}$ with Ψ .

Abiotic stresses and responses

Heat + drought (combined stresses): reduce g_s and A; thermal peaks during reproduction cause apple/capulho retention to drop and shorten fibers. Measures: ZARC windows, density/architecture to close canopy, K management and use of mepiquat; in irrigated areas, cool the canopy via timely spraying.

Waterlogging/low aeration: limits roots and increases abortions; avoid compaction and poorly drained furrows.

Regional guidelines (Brazil)

Mato Grosso/GO/MS (Cerrado) — prioritize sowing of 1st crop in ZARC windows; in 2nd crop (post-soybean), pay attention to dry spells and lower water/temperature potential. Moderate densities and mepiquat according to vigor/cultivar.

Bahia (West)/MATOPIBA — High DPV and winds: close canopy early; consider narrower arrangements; supplemental irrigation where available.

South/Southeast — risk of cold weather during planting; adjust sowing, cultivars, and regulators to ensure early maturity and avoid harvest rains.

Eco-physiological monitoring (field)

Gas exchange/porometry (A, g_s , E) and iWUE at budding and flowering.

Chlorophyll/SPAD and $F_v/F_m/\Phi PSII$ for N status and photoinhibition in heat waves.

Canopy climate — DPV, T_{leaf} (IR thermometry), PAR, and NDVI/NDRE for uniformity; seasonal K_c/K_{cb} adjusted to LAI.

– CHAPTER 6 –

Ecophysiology of Winter Crops in Brazil (Wheat, Barley, Oats, and Canola)

Winter crops play a central role in the sustainability of Brazilian rainfed and irrigated systems, especially in the South, Southeast, and Central-West at high altitudes. As C3 species, they share ecophysiological principles: (i) photosynthesis sensitive to temperature and vapor pressure deficit (VPD); (ii) source–sink modulating the number of reproductive structures and grain/silique filling; (iii) strong influence of vernalization (exposure to cold) and photoperiod on the vegetative→reproductive transition; (iv) marked responses to cold/frost, heat, and water deficit in critical windows. Integrating sowing time (ZARC), plant arrangement, water (ETc), and nutrition places sensitive stages (anthesis/flowering and initial filling) in less stressful conditions, increasing yield and quality.

Common ecophysiological bases

C3 photosynthesis, stomata, and DPV

CO₂ assimilation (A) in C3 increases with PAR until saturation and is modulated by temperature and stomatal conductance (g_s). On dry/windy afternoons, high DPV induces stomatal closure (drop in g_s) and afternoon depression of A. The A–g_s coupling explains part of the intra-plot and inter-environment variability; iWUE = A/g_s and WUE = A/E (or yield/ET) are useful for comparing materials and management practices, especially when water is limited.

Source–sink and yield definition

In winter cereals, the number of grains m^{-2} (NGM) results from the number of ears/spikelets and the fertility of flowers at anthesis; grain mass depends on the duration and rate of filling. In canola, yield is given by panicles $\text{m}^{-2} \times$ grains per panicle $\times$ thousand-grain weight; well-synchronized flowering and stable canopy improve the vertical distribution of panicles. Stomatal (water/heat/wind) and thermal (cold, frost, heat) limitations in the critical window (rubberization→anthesis→beginning of filling) have the greatest impact.

Vernalization and photoperiod

Wheat, barley, and oats have different levels of vernalization requirements and sensitivity to photoperiod (long days) that regulate the transition to reproductive and the duration of the phases (tillering, elongation, heading). In spring canola, vernalization is low; mild temperatures during planting and flowering are decisive for setting and initial filling.

Temperature, degree days, and windows

Thermal time (GDD) organizes phenological progress. Typical optimal ranges for winter C3 vegetative growth are between 15–22°C; below ~5°C, growth slows sharply; above ~28–30°C, there is a shortening of phases and a decrease in functional leaf area. At anthesis, light frosts can sterilize flowers; heat peaks reduce pollen viability, fertilization, and seed set. °C, there is a shortening of phases and a decrease in functional leaf area. At anthesis, light to moderate frosts can sterilize flowers; heat peaks reduce pollen viability, fertilization, and shorten filling.

Phenology and morphology by crop

Wheat (*Triticum aestivum*)

Architecture: culm with nodes/internodes, alternate leaves, fasciculated root system; tillers determine part of the NGM. BBCH/Feekes scales: tillering (Feekes 2–4), elongation (5–7), rubberization (10),

heading (10.1–10.5), anthesis (10.5.1), milky grain (11.1), doughy grain (11.2), hard grain (11.3), and physiological maturity.

Vernalization/photoperiod: spring cultivars predominate. In warmer regions, materials that are less sensitive to day length and have low vernalization requirements anticipate heading/anthesis.

Critical window: from rubberization to anthesis and 10–15 days after; frosts ($\approx -2\text{ }^{\circ}\text{C}$ to $-4\text{ }^{\circ}\text{C}$) can sterilize spikelets; heat at anthesis/initial filling reduces NGM and mass.

Barley (*Hordeum vulgare*)

Architecture: similar to wheat, with well-defined spikelets; malt quality requires moderate protein and uniformity of maturation. Anthesis is sensitive to frost and heat; branching/tillering should be adjusted to avoid excessive vegetative growth that increases lodging.

Oats (*Avena sativa* / *A. strigosa*)

Architecture: panicle, high plasticity (grains, forage, and cover). In grains, stability depends on positioning anthesis outside of frosts and heat waves. *A. strigosa* is used as cover/grazing, generating high-quality straw (benefits to SPD and nutrient cycling).

Canola (*Brassica napus* ssp. *oleifera*)

Architecture: main stem and lateral branches; LAI peaking at flowering; yellow flowers (autogamous, occasionally allogamous); siliques along the canopy. In mild environments, full sun maximizes productivity; in waves of dry wind/high DPV and heat, there is a greater risk of flower abortion and spikelet drop. Boron (B) is critical in flowering (pollen tube growth) and sulfur (S) in oil/protein synthesis.

Water, ET_c, and crop coefficients (K_c)

Water demand and sensitivity by phase

Wheat/barley/oats (rainfed): seasonal requirement ~300–550 mm, with peak ET_c from elongation to the beginning of filling. In irrigated conditions, the total increases according to duration and climate.

Canola: continuous demand from vegetative growth to flowering and early filling; deficits during this period reduce spikelets × grains, the main driver of yield.

Reference K_c

Winter cereals: K_{c_ini} ≈ 0.30–0.40; K_{c_mid} ≈ 1.10–1.15; K_{c_end} ≈ 0.25–0.40 (before total senescence).

Canola: K_{c_ini} ≈ 0.35–0.45; K_{c_mid} ≈ 1.05–1.15; K_{c_end} ≈ 0.25–0.45.

Note: in dry/windy climates (high DPV/wind), the effective K_{c_mid} may be < 1.0, due to stomatal reduction of transpiration and lower soil evaporation under mulch.

Dual K_c (K_{cb}+K_e) and dynamics by stage

The dual approach separates canopy transpiration (K_{cb}) and soil evaporation (K_e), useful in drip/fertigation and under mulch. In wheat/barley/oats, K_{cb} rises from tillering to flowering and falls in senescence; in canola, it peaks at flowering (maximum LAI) and decreases with leaf fall. Series by days after emergence show peaks close to anthesis/beginning of filling, useful for scheduling irrigation.

Practical water strategies

In rainfed areas, use ZARC to position rubberization→anthesis with a higher probability of rain; avoid late sowing that exposes anthesis to heat.

In irrigated fields, manage by ET_o×K_c/K_{cb} and soil moisture/tension; reduce replenishment at the end to preserve quality (wheat/barley/oats) and avoid dehiscence in canola.

Temperature, cold, frost, and heat

Establishment and vegetative

Germination/emergence favored by 10–20°C and good moisture. Early frosts can reduce stand (seedling necrosis). Optimal vegetative growth at 15–22°C; below >28–30°C, phenology accelerates and functional leaf area tends to decrease.

Anthesis, flowering, and initial filling (critical window)

Wheat/barley/oats: frosts during heading/anthesis cause sterility; heat near anthesis and at the beginning of filling reduces pollen viability, shortens filling duration, and decreases grain mass. In controlled and field evaluations, heat stress during this period explains much of the variation in yield between crops.

Canola: intense cold during flowering and heat > ~30 °C with dry wind increase flower abortion/silique drop; initial filling requires continuous water and available S/B.

Soil, liming, and nutrition

Soil reaction and profile

Performance is maximized with a decompressed profile, good structure, and adjusted reaction (pH in CaCl₂ or H₂O, according to local recommendations). In clay soils and under SPD, take care of compacted layers (controlled traffic, rotation with aggressive roots), as waterlogging reduces O₂ diffusion, limits absorption, and increases N losses.

Macronutrients

Nitrogen (N): in cereals, it defines tillering, spikelet fertility, and grain protein (technological quality); fractioning into coverings during elongation and pre-anthesis reduces the risk of losses and improves efficiency. In canola, N sustains LAI and number of siliques; excess very late delays maturation and can increase lodging.

Phosphorus (P): critical in establishment and tillering (roots/

meristems).

Potassium (K): regulates water/stomatal balance, sugar transport, and quality (hectoliter weight/protein in cereals; oil in canola).

Sulfur (S): essential for protein/oil synthesis; in canola, requirements are higher than in winter cereals.

Micronutrients

Boron (B): critical in canola (flowering/setting; pollen tube growth); deficiency leads to flower abortion and fewer grains/siliqua.

Zinc (Zn), Manganese (Mn), Copper (Cu): influence tillering, stress resistance, and health in winter cereals; adjustments according to leaf/soil analysis.

Abiotic stresses and management

Cold and frost

Wheat/barley/oats: frosts during heading/anthesis can cause partial/total sterility; during filling, they reduce the rate of starch deposition and result in empty grains.

Canola: reproductive frosts cause abortion and significant drops in siliques; prior acclimatization mitigates damage but does not eliminate risks.

Regional guidelines

South (RS/SC/PR)

Risks: late frosts, rain during harvest (quality), and periods of wind/high DPV in the spring. Wheat/barley: align anthesis outside cold spells; in malting barley, control protein with calibrated N and avoid lodging (density/arrangement/cultivar). Canola: flowering in dry wind requires water and S/B management. Oats: excellent option for rotation/mulch; in grains, avoid late heat.

Southeast (SP/MG at altitude)

Shorter windows; wheat and oats at medium altitudes; canola in colder/higher locations. In irrigated areas, pay attention to quality (hectoliter weight, protein/oil content) and health.

Midwest (MS/GO/DF)

Irrigated wheat/barley: risk of heat during reproduction and dry spells; manage by Kc/Kcb and soil moisture/tension, positioning anthesis to avoid heat peaks. Canola at higher altitudes/irrigated requires continuous water until the beginning of filling and adequate S/B.

ZARC — Agricultural Zoning of Climate Risk

Consult the current ordinances by state/municipality/crop/system (rainfed/irrigated; including dual purpose in wheat). Use windows $\leq 20\text{--}30\%$ risk, adjusted by soil type and cycle, to position anthesis/flowering outside of frosts/heat waves and maximize the chance of effective rainfall in the phases of highest ETc.

– Chapter 7 –

Ecophysiology of Tomato, Onion, Garlic, and Carrot Crops

The most economically important vegetables in Brazil, such as tomato (*Solanum lycopersicum*), onion (*Allium cepa*), garlic (*Allium sativum*), and carrot (*Daucus carota* subsp. *sativus*), share common ecophysiological principles, but exhibit striking differences in terms of photoperiod, temperature, water requirements, and management strategies. This chapter integrates ecophysiological bases with practical recommendations for Brazilian environments (South, Southeast, Midwest/Cerrado, Northeast, and MATOPIBA), covering open-field cultivation and protected systems (tunnels, greenhouses), with a focus on: (i) canopy structure and light capture; (ii) water relations and use of crop coefficients (K_c); (iii) phenological development and critical stages; (iv) mineral nutrition and physiological disorders; (v) edaphoclimatic adaptations.

Cross-cutting ecophysiological axes

Photosynthesis and gas exchange (C3): all species discussed here are C3, with A (assimilation) to DPV, leaf temperature, and stomatal closure. Instantaneous water use efficiency ($iWUE = A/gs$) is a good comparative indicator between cultivars and management practices.

Evapotranspiration and K_c : irrigation management via $ET_c = K_c \times ET_o$ (FAO-56 methods, simple or dual coefficient) is the bridge between microclimate and field physiology. K_c varies by phenological stage, canopy architecture, soil cover, and surface wetting frequency.

Assimilate partitioning: the source-sink relationship changes rapidly during reproductive periods (fruiting or bulb/root formation), which are the stages most sensitive to water, thermal, and nutritional stresses.

Product quality: Attributes such as soluble solids content (tomatoes), pungency and dry matter (onions/garlic), and carotenoid accumulation (carrots) respond to microclimate, nutrition, and water availability.

Useful general parameters

Operating DPV: 0.8–1.8 kPa on cool mornings and 2.0–3.5 kPa on hot summer afternoons; above ~2.5–3.0 kPa, g_s tends to drop sharply, reducing A.

Functional LAI: LAI 2.5–3.5 usually maximizes the fraction of photosynthetically active radiation intercepted (fPAR) without penalizing canopy ventilation in the field; in protected conditions, the target LAI may be slightly lower in summer to prevent fruit/leaf heating.

Post-stress recovery: after short drought events, prioritize small and frequent watering, avoiding “water shocks” that aggravate root cracks (carrots) and BER (tomatoes).

Tomato (*Solanum lycopersicum*)

Phenology, architecture, and environment

Tomato plants have a variable cycle (90–140 days after transplanting, depending on the cultivar and environment) and great architectural plasticity under staked (1–2 stems) or creeping (industrial) training. In tropical/subtropical environments, moderate nighttime temperatures and days that are not excessively hot favor fruit setting and development. In protected cultivation, ventilation and shading management reduce leaf temperature and DPV at dusk.

Temperature, fruiting, and quality

Reference temperature ranges

Germination/establishment: 15–25 °C (optimal), with accelerated emergence in 7–10 days and a more uniform stand.

Vegetative growth: 18–25 °C favors leaf expansion and inflorescence formation with moderate internodes.

Fruiting/filling: nights between 16–20 °C and days 22–29 °C are favorable; nights ≥ 21 °C for several days reduce pollen viability and setting.

Flower setting and pollination

Very high daytime temperatures ($> 32\text{--}35$ °C) disrupt microsporogenesis, thicken the pollen wall, and shorten the receptive phase; in protected conditions, ventilation and light shading (20–30%) reduce fruit/leaf temperature and improve setting.

Industrial and table quality

Lycopene: maximized in mild fruit temperature ranges; extreme heat suppresses biosynthesis and increases alternative carotenoids, altering coloration.

Soluble solids (°Brix) and acidity: K and water management during fruit filling shapes the sugar/acid balance. Controlled water deficit at the end of the cycle can increase Brix, but the risk of cracking requires caution.

Water relations and Kc

Practical approach: use FAO-56 (simple Kc) or dual method (Kcb + Ke) adjusted to the microclimate and irrigation system (drip reduces Ke). In the field, typical Kc values: initial ≈ 0.6 ; intermediate $\approx 1.10\text{--}1.15$; final $\approx 0.70\text{--}0.90$. In protected cultivation, Kc is sensitive to ventilation, density, and plastic covers.

Irrigation protocols:

- Estimate daily ETo (Penman–Monteith/local station).
- Apply Kc for the stage (or Kcb and Ke in dual, reducing Ke under drip).
- Correct for system efficiency (e.g., 0.92 under drip; 0.70–0.85 under sprinkler, depending on wind/uniformity).
- Convert to mm/plot and schedule short shifts in the early morning.

Critical stages: flower bud→flowering→setting and beginning of filling. Interrupt strong fluctuations in soil moisture (to prevent cracking and BER). Real-time indicators: tensiometer (–10 to –25 kPa in loamy soils), SPAD (N), Tleaf–Tair (IR thermometer), and Fv/Fm (photoinhibition).

Nutrition and physiological disorders

- Calcium: apical rot is linked to low Ca availability in the fruit combined with irregular transpiration flows. Strategies: maintain stable soil moisture (without stress peaks), ensure Ca in the root system (proper liming; calcium sources in fertigation when applicable), manage the canopy to avoid excessive transpiration of leaves to the detriment of the fruit, and avoid excess N and K in the early stages of fruiting; avoid excessive leaf pruning that exposes the fruit to direct sunlight and increases fruit temperature.

- Potassium: adjusts Brix and coloration, but very high doses at the beginning of fruiting can compete with Ca in the xylem. N–K–Ca balance is key to productivity and quality.

- Magnesium and micronutrients: Mg supports chlorophyll and response to high irradiance; Zn/B influence fruiting and flower health.

Ecophysiological management

Density and pruning: more open training in hot seasons to reduce temperature and improve aeration; higher density in mild seasons to capture light without excessive shading of the fruit layer.

Irrigation: prioritize drip irrigation with short cycles; during heat peaks, start irrigation early in the morning to lower leaf temperature, supplementing in the afternoon only if necessary (avoiding nighttime wetting in sprinkler systems). Monitoring by tensiometry (–10 to –25 kPa in loamy soils) and daily water balance by ET_c provides predictability.

Protected cultivation: cross ventilation, 20–30% shade screens in summer, and DPV control to contain flower abortion and fruit hail

Practical checklist (tomato)

- Plan the planting window to avoid peak heat during fruiting.
- Use K_c per stage and adjust per system (low K_e in drip irrigation).
- Maintain stable humidity to avoid BER; calibrate N–K–Ca.
- Ventilate/shade in protected areas and adopt pruning/density compatible with the season.

Onion (*Allium cepa*)

Photoperiod and adaptation classes

Onions are long-day plants for bulb formation, but cultivars are distributed into three photoperiod classes:

- Short days (SD): bulb formation begins with ~11–12 hours of light;
- Intermediate days (ID): 12–14 hours;
- Long days (LD): > 14 hours.

In Brazil, SD and ID are mainly used, adjusting sowing/transplanting dates to coincide with the onset of bulb formation with suitable days and temperatures. Prolonged exposure to low temperatures ($\approx 5\text{--}13\text{ }^{\circ}\text{C}$ for weeks) can induce bolting, which is undesirable for commercial bulb production.

Root system and water sensitivity

The root system of onions is shallow and shallow, with a low density of fine roots compared to other crops; this makes it very sensitive to compaction, waterlogging, and occasional deficits. Irrigation should be low-depth and high-frequency in light soils; during bulking (bulb thickening), maintain regular depths without prolonged excesses.

Water, Kc, and critical stages

- Total water requirement: approximately 350–650 mm per cycle, depending on climate, cycle, and irrigation system.

- Kc by stage: reference values depend on the method and system; in sprinkler irrigation, the initial Kc is higher due to Ke (soil evaporation). In drip irrigation, Ke is reduced and effective Kc decreases in the initial phase; in bulbing (phase III), Kc returns to high levels.

- Critical stages: establishment (seedling/seedbed), vegetative transition→bulb and filling; deficits here reduce size and dry matter. Excess water during maturation impairs curing and health.

Nutrition and quality: sulfur and dry matter

- Sulfur (S): key to pungency (thiosulfates) and dry matter. Adequate doses increase solids and firm bulbs; interactions with N determine pungency and conservation. Avoid excess late N, which delays maturation and reduces solids.

- pH and liming: onions are sensitive to acidity, performing best at pH 6.0–6.5 and low Al^{3+} saturation. In acidic soils, liming should be done in advance.

- Micronutrients: Zn and B participate in cell division and elongation, affecting bulb uniformity and leaf emission.

Ecophysiological management

- Varietal choice x latitude/season: align photoperiod class with the local window so that the photoperiod reaches the threshold when the plant already has sufficient leaf mass. Early bulb formation (long photoperiod before full leaf area) produces small bulbs; late bulb formation lengthens the cycle and exposes the plant to climatic risks.

- Irrigation: frequent and uniform shifts; reduce blades and suspend at the end to facilitate curing. In drip irrigation, double lines per row improve uniformity.

- Soil: avoid compacted layers; ensure macro and microporosity for root oxygenation.

Practical checklist

1. Position the correct DC/DI class at the latitude/season; avoid bolting.
2. Keep shifts short and uniform; attenuate blades at maturity.
3. Ensure S and pH 6.0–6.5; adjust N for solids and conservation.

Garlic (*Allium sativum*)

Ecophysiological phases, vernalization, and photoperiod

Garlic development can be outlined in two major stages:

1. Inductive phase: requires short photoperiod and low temperatures (e.g., pre-planting/bulb chilling) for bulbils differentiation and bulb growth induction;

2. Morphogenic phase: requires a longer photoperiod and moderate temperatures for effective bulbils growth. In subtropical/tropical regions, pre-planting vernalization (0–10 °C for several weeks) standardizes and anticipates the cycle, reducing pseudopollination and heterogeneity.

Water, Kc, and critical stages

- Water requirement: commonly 400–850 mm throughout the cycle, varying with climate and cultivar duration. Water deficit strongly impacts size and uniformity.

- Kc by stages: moderate initial, high intermediate during leaf expansion and bulb filling, and low final at maturity, when leaf/skin drying is induced. The dual method ($K_{cb}+K_e$) is useful for separating transpiration and evaporation in sprinkler-irrigated beds.

Nutrition and quality: sulfur and bioactive compounds

- S is decisive for allicin and thiosulfates, also interfering with productivity; the balance with N and the availability of micronutrients (B, Zn) influences vigor and health.

- Soil pH: general ideal range 5.5–6.5 (with practical preference for 6.0–6.8 in many soils), with liming recommended in high acidity. Avoid salinization in fertigation.

- Post-harvest quality: adequate physiological maturation and curing reduce losses due to pathogens and maintain the integrity of layers/bulbs

Ecophysiological management

- Bulb seed: use virus-free material, uniform size, adequate maturation point, and refrigeration according to the cultivar and region.

- Irrigation: frequent and moderate watering in light soils; reduce and suspend irrigation close to harvest to facilitate curing and storage quality. In hot and dry phases, short intervals prevent leaf stress and loss

of photosynthetic area.

- Soil: fine preparation, well-drained beds, and no compaction; garlic is sensitive to waterlogging.

Carrot (*Daucus carota* subsp. *sativa*)

Temperature, vernalization, and bolting

Carrots are a mild climate species, with better root quality when the cycle occurs at moderate temperatures. In cultivars adapted to the Brazilian summer (Brasília Group), there is greater heat tolerance, but high temperatures shorten the cycle and impair color and shape. Exposure to low temperatures followed by long days can induce bolting (undesirable for root production). Winter cultivars (Nantes group and related) maintain superior shape and color in colder ranges, but are more susceptible to bolting if sown out of season.

Reference temperature ranges

- Germination/emergence: 20–30 °C accelerates and standardizes; below 10–12 °C, emergence is delayed.

- Vegetative growth: 15–22 °C favors leaf area and reserve accumulation.

- Root thickening: 15–21 °C optimizes quality (color/carotenoids) and reduces deformities; > 30 °C shortens the cycle and worsens quality.

Water relations, Kc, and root quality

Irrigation: generally by sprinkler (conventional or pivot), but drip irrigation is growing in popularity because it allows for smaller leaf areas and reduces leaf diseases. Short shifts in sandy soils prevent transient water stress that causes cracking and deformations.

Kc: in tropical/subtropical conditions, reference values per phase indicate moderate initial Kc (≈ 0.45 – 0.50), high intermediate (≈ 1.3), and final close to 1.0. Adjustments are necessary according to density, soil cover, and irrigation frequency.

Quality: blade management at the end of the cycle influences soluble

solids; excessive irrigation reduces sugars and can increase discards due to defects (green shoulders, cracks, and unevenness).

Nutrition and disorders

Boron and calcium: deficiencies favor cracking and cell wall disorders. Avoid excessively high pH due to excessive liming; apply B at the recommended dose and time, preferably by broadcast before sowing or via fertigation.

Micronutrients: Zn and Mn support enzymatic metabolism and coloration; mild deficiencies reduce vigor and uniformity.

pH and soil: ideal 6.0–6.5; uneven structure (clods, compaction) and dense layers generate forked and twisted roots. Loamy to light, deep, and well-drained textures are preferable.

Ecophysiological management

Season: time sowing so that the root thickening phase occurs in moderate temperatures; in very hot summers, use summer cultivars and light shading when necessary.

Density: fine spacing and early thinning establish a uniform population, avoiding competition and thin roots.

Health: canopy aeration and irrigation shifts that avoid nighttime leaf wetting reduce leaf burn.

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