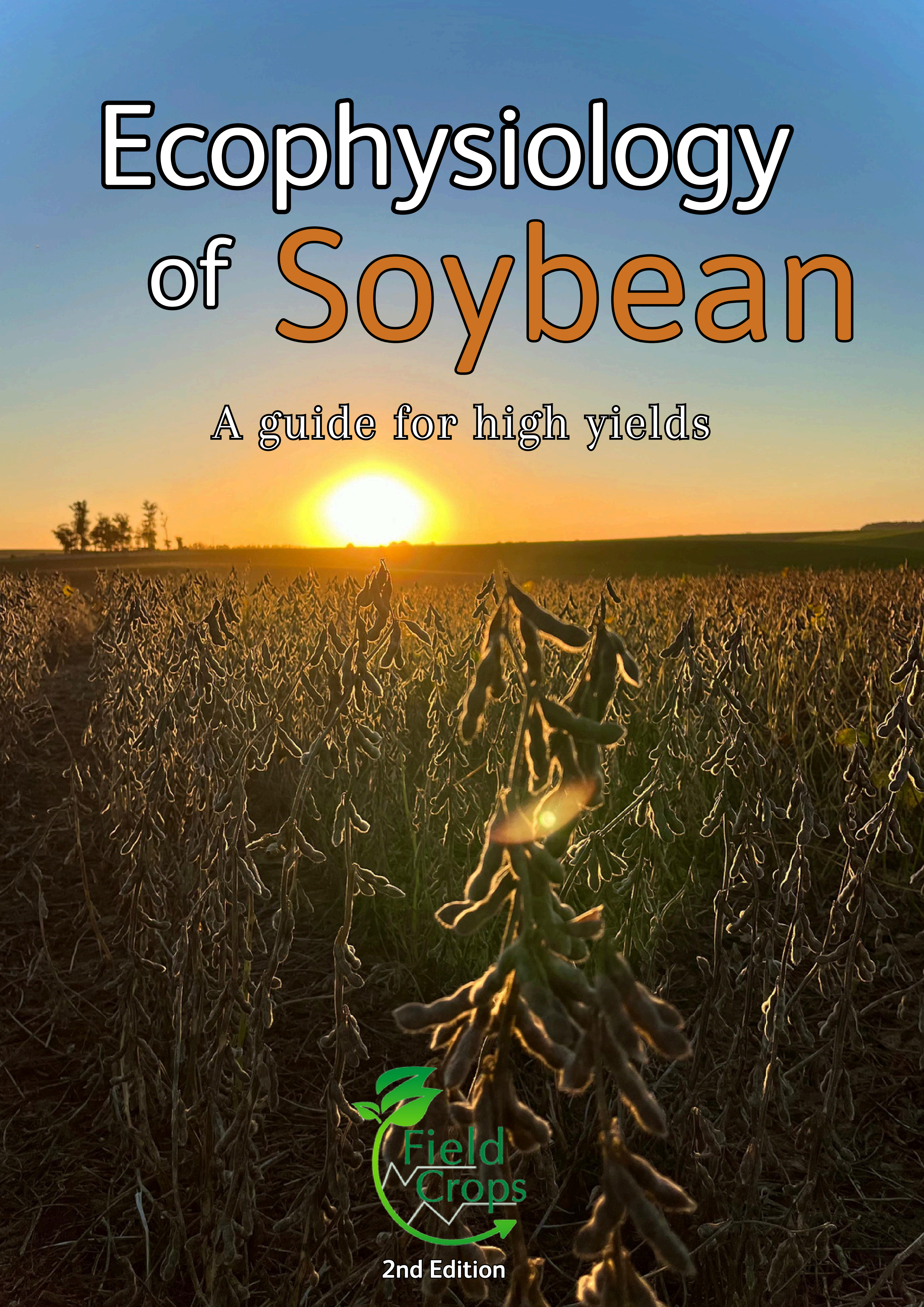
Ecophysiology of Soybean

A guide for high yields



Field Crops

2nd Edition

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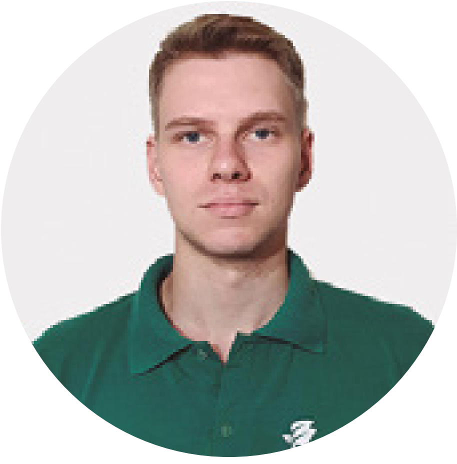

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02/27/1987 - 01/27/2013
* Kiss Nightclub tragedy in Santa Maria, Rio Grande do Sul, Brazil.

Equipe FieldCrops is a multidisciplinary and multi-institutional research and extension team for soybeans, rice, cassava, maize, wheat and cover crops that strives for a sustainable intensification of agriculture. The name FieldCrops comes from the English word for “field crops”. The FieldCrops team develops research and extension work in the grower's field through inquiry, also focusing on the sustainability of agriculture at a global level by being a partner in international projects such as the Global Yield Gap Atlas (www.yieldgap.org). The knowledge generation and technology transfer activities led by the FieldCrops team are based on the interaction GxExMxF (genotype x environment x management x producer).

The FieldCrops team shares technical information for growers via the official social networks (Instagram, X, Youtube, Facebook and Linkedin):

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Contents

Preface

South America plays a significant role in meeting the growing global demand for food. Among these foods, soybean cultivation stands out due to its importance in the global supply of protein and oil and its contribution to the gross domestic product of countries in the region.

The achievements of agriculture over the centuries have been remarkable and deserving of recognition. However, increases in production have been associated with environmental degradation. The environmental impact resulting from current agricultural activity clearly highlights the need to find more efficient and sustainable ways to meet the demand for agricultural products. The challenge facing agriculture is to satisfy the growing demand for food while reducing the adverse environmental effects of its activities—decoupling production from environmental impact—while also ensuring the income and well-being of farmers.

In the international literature, experts today agree that the necessary production increases must be achieved through higher and more stable yields within existing agricultural areas and by intensifying cropping sequences, all while minimizing and reversing environmental impacts and using resources and inputs more efficiently. This aligns with the concept of sustainable intensification, a strategy that enables increased production and profitability while simultaneously improving environmental conditions.

Available and emerging technologies, integrated into a common strategy, can contribute to achieving these goals. Among these, process-based knowledge technologies are particularly noteworthy. Understanding the environment, crop functioning, pest biology, and interactions between system components is fundamental for the development, selection, and application of appropriate process technologies for soil, crop, and pasture management, as well as for addressing biotic adversities. These advancements also contribute to progress in genetic improvement, biotechnology, and the optimized use of other technologies. Such technologies are low-cost, accessible to producers, and enhance the utility of more advanced technologies. However, they require significant research and extension efforts and greater dedication from producers.

Among the essential areas of knowledge for sustainable intensification, Crop Ecophysiology stands out. This discipline focuses on studying the processes and mechanisms that determine crop growth, development, and yield in interaction with the environment. These concepts are critical for designing knowledge-intensive management strategies aimed at increasing agricultural production, enhancing the productivity of resources and inputs, and reducing environmental impact. Understanding how crops function in their environmental context also aids in guiding genetic improvement and developing crop growth simulation models.

This book is an important contribution in this regard, as it presents an organized and up-to-date overview of the phenological, physiological, and morphological foundations of soybeans, a crop of great importance for the country.

The book includes a botanical and morphological description of soybeans and their various phenological stages, emphasizing the significance of each phase in determining yield. It discusses growth types and maturity groups and their implications for production. Additionally, it analyzes the foundations of development and growth, identifying the most critical periods for determining yield and its numerical components. The book also details the crop's climatic (radiation, temperature, and photoperiod), nutritional (including macro- and micronutrients), and water (addressing both deficiencies and excesses) requirements. Based on this knowledge, the book discusses key crop management practices, such as plant density, planting date, row spacing, cultivar selection, plant stand uniformity, fertilization, pH correction, use of bio-inputs, and more. Furthermore, it addresses considerations regarding productivity and stability, yield potential, yield gaps, and their causes.

In summary, the book provides updated knowledge on how soybeans function in interaction with the environment, which is invaluable for refining crop management to achieve greater adaptation to specific production conditions and climate change, increasing resource and input productivity, and reducing environmental impact. This ultimately leads to increased production and sustainability.

Finally, the challenges we face require collaboration and an interdisciplinary approach. This work is a clear example of the remarkable and valuable outcomes that dedication and collaboration can bring.

I congratulate the authors and encourage them to continue on this virtuous path of understanding soybean ecophysiology, which will undoubtedly continue to bring significant benefits to agricultural production in Brazil and the region.

Prof. PhD. Fernando Héctor Andrade

Agricultural Engineer from the Faculty of Agronomy at the University of Buenos Aires (Argentina), with a master's and a doctorate from Iowa State University (USA). Currently, he is a professor of Crop Ecophysiology at the Faculty of Agricultural Sciences at the National University of Mar del Plata (Argentina), a researcher and national coordinator of the strategic area of Plant Ecophysiology at the National Institute of Agricultural Technology (INTA), and a researcher at the National Scientific and Technical Research Council (CONICET).

Brazil: The Story of the World's Biggest Soybean Producer

Originally native to Asia's east coast, soybeans originated from creeping plants that grew along the Yangtze River in China (Figure 1). Chinese scientists began the process of selecting and breeding plants through natural crossings between two soybean wild species, marking the first instances of this crop appearing between 2883 and 2838 BC. The introduction of soybeans to the European continent only took place in the late 15th century, specifically in the botanical gardens of England, France and Germany. This introduction was primarily driven by curiosity and lacked commercial purposes (Gazzoni & Dall'agnol, 2018).

Due to its high levels of oil and protein, soybean gained significance in the United States during the early 20th century. During this time, certain cultivars were selected to carry specific genes that would allow the crop to adapt to the North American agricultural system, which until then had primarily consisted of wheat and corn (Bonetti, 1981). In the meantime, attempts to introduce soybeans into the production systems of certain European countries like Russia, England, and Germany were not successful, largely due to the unfavorable climate for crop establishment (Gazzoni & Dall'agnol, 2018).

Figure 1. Huazhong Agricultural University, China (2019), on the banks of the Yangtze River (the cradle of soybeans in the world).

There are historical records of soybean usage as fodder in Bahia State (BA) dating back to the mid-1880s and in São Paulo State (SP) around 1890s. In 1914, the first recorded soybean cultivation for commercial grain production took place in the northwest of Rio Grande do Sul State (RS), where the municipality of Tuparendi is located today. The genetic material used for this cultivation was imported from the southern United States, and due to climatic similarities, including latitude and temperature, it proved to be well-adapted for RS (Bonetti, 1981). In 1930, soybeans begun to be cultivated at the Alfredo Chaves Experimental Station[1] in Veranópolis (RS), where collections of various cultivars were maintained, including Laredo, Tokio, Biloxi, Prolific and Mammouth (Rubin & Santos, 1996).

In the early 1940s, the first soybean experiment was conducted with the aim of examining the relationship between yield and row spacing. In 1960, Orlando Mello, through a series of genetic crosses, introduced the first commercial soybean cultivar developed in RS, known as "Pioneira" (Feres et al., 1982). Simultaneously, the Ministry of Agriculture of Brazil, through the Instituto Agronômico do Sul, started research on soybean cultivation by introducing American cultivars and quantifying the production of green matter and grain yield.

Starting from the 1950s, an incipient production system[2] for soy cultivation indirectly gained momentum due tonational incentive policies for wheat farming[3]. This policy prioritized

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[1] The Estação de Seleção de Semantes Alfredo Chaves was founded on May 30, 1919, in the municipality of Veranópolis, Rio Grande do Sul, where Fepagro Serra is located today. This agro research station marked the first research with wheat in Brazil, leading to the development of the Alfredo Chaves genotypes, a crucial step in the country's first wheat genetic breeding crossing. In 1970, the station also became the first to evaluate the effects of inoculating soybeans with nitrogen-fixing bacteria compared to using mineral nitrogen fertilizers.

[2] Brazil's soybean production reached 25 thousand tons, making it an international statistics figure for the first time as a soybean-producing country.

[3] The 1st incentive was provided by Decree-Law No. 29299 on January 26th, 1951, which required all mills operating within the national territory to purchase wheat produced in Brazil. The 2nd incentive came from Banco do Brasil SA, which became the sole entity for importing wheat and supplying it to the mills, effectively establishing state control to stimulate domestic production.

wheat cultivation in Brazil and provided an ideal environment for integrating soybeans, especially from a technical perspective, as a legume-based crop following wheat, thereby optimizing the productive and economic system. This integration improved land use, machinery, farm implements, and increased income for farmers (Medina, 1981). During the 1940s and 1950s, the soybean cultivar “Amarela Comum” dominated more than 80% of the soybeans sowing area in RS (Santos, 1975).

Throughout the 1960s, a second public policy aimed at encouraging the application of lime and soil correction, known a “Operação Tatu”[4] made it possible to increase the area under soybean cultivation in the state of Rio Grande do Sul (RS). Over the course of this decade, soybean production increased five-fold, rising from 200 thousand tons to 1 million tons (Embrapa, 2003). In the 1970s, this growth continued, and the Brazilian soybean production, which had started at 1.5 million tons in the early 1970s, achieved a historic milestone by reaching 15 million tons by late 1970s, a ten-fold increase, equivalent to 1.5 million tons annually. This success was attributed to the expansion of cultivated areas, which grew from 1.3 to 8.8 million hectares. Additionally, there was an increase in yield from 1.1 ton to 1.5 ton ha^{-1}, driven by cultivars such as Bragg, IAS 4, IAS 5, and Cobb, which covered more than 70% of the commercial area (Rubin & Santos, 1996). Up until that time, soybean fields were almost exclusively found in the southern region of Brazil, primarily in Rio Grande do Sul.

By the beginning of the 1980s, the introduction of new cultivars and genetic breeding targeted at extending the juvenile growth period of soybean plants allowed for increased vegetative growth and delayed flowering under short-day conditions. This

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[4] Program established in the state of Rio Grande do Sul to correct soil pH and fertility. The program’s foundation included: a) soil sampling for chemical analysis conducted by UFRGS students on experimental model farms; b) expanding the management of these model farms to other municipalities in Rio Grande do Sul through the Associação Sulina de Crédito e Assistência Rural (ASCAR); and c) Banco do Brasil acepted initial installment of limestone and fertilizer as an investment, allowing for payments to be made in installments over three to five years.

innovation enabled the expansion of soybean crops into the Midwest region of Brazil (Hartwig & Kiihl, 1979; Kiihl et al., 1985; Hinson, 1989; Sinclair et al., 2005). In addition to the juvenile gene, other traits, including plant height and first pod insertion, were also improved through the development of adapted cultivars for lower latitudes. The first Brazilian cultivars recommended for tropical areas were Timbira, Tropical, BR-10, and BR-11 (Kiihl et al., 1985).

The genetic advancements that facilitated soybean cultivation in the Brazilian Midwest led to a significant increase in the soybean cultivation area in Brazil. Until the early 1970s, it is estimated that only 2% of Brazilian soybean production came from the Midwest. By the1980s, this estimate had risen to 20%, and by around 1990, it had already exceeded 40% (IBGE, 2015). In the 2000s, for the first time, the Midwest region outpaced the Brazil Southern region in soybean production. for the 2020/21 season, 45% of the total soybean grains were produced in the Brazilian Midwest, while the southern region harvested only 32%. Factors such as tax incentives for agricultural expansion, a landscape conducive to large-scale mechanization, and a favorable rainfall regime justify the expansion of the soybean cultivation area in the Brazilian Midwest.

The enactment of Law Nº 9456 for Cultivar Protection in 1997 enabled and stimulated private breeding programs in Brazil, resulting in the release of a significant number of new soybean cultivars each agricultural year. Consequently, there was a reduction in the cultivar development cycle, the adoption of the maturity group (MG) system to represent the duration of the development cycle in each region, and an increase in the use of cultivars with indeterminate growth types, as well as transgenic cultivars with resistance to herbicides and caterpillars.

In the current soybean crop scenario, where cultivars adapted to the main farming regions of Brazil are available, breeding programs are now focusing on cultivars with greater yield potential and/or resistance to abiotic factors (such as HB4®, AREB) and biotic factors (including Inox®, TF®, Intacta®, Xtend®, Conkesta®, Enlist®, Liberty Link®, Block).

Courtesy: Darlan Scapini Balest

1. Soybean growth and development

Eduardo Lago Tagliapietra; José Eduardo Minussi Winck; Michel Rocha da Silva; Alexandre Ferigolo Alves; Guilherme Guerin Munareto; Anderson Haas Poersch; Bruna San Martin Rolim Ribeiro; César Eugênio Quintero; Gean Leonardo Richter; Darlan Scapini Balest; Victória Brittes Inklman; Renan Augusto Schneider; Kelin Pribs Bexaira; Cristian Savegnago; Leonardo Silva Paula; Marcos Dalla Nora; Edgardo Santiago Arevalo; María Soledad Armoa Báez; Luciano Zucuni Pes; Nereu Augusto Streck; Kaleb Emanoel Ferreira do Amaral; Ijésica Luana Streck; Thiago Schmitz Marques da Rocha; Solon Lemos da Rosa; Patric Scolari Webber; Fabricio Vendruscolo Pinto Filho; Felipe Andrade Tardetti; Guilhermi Penteado Simões; Felipe Schmidt Dalla Porta; Bruna Pinto Ramos; Heitor Santos Bitencourt; João Bernardo de Abreu; Lorenzo Dalcin Meus; Enrico Fleck Tura; Cintia Piovesan Pegoraro; Patrícia Carine Hüller Goergen; Isabel Lago; Leandro do Prado Ribeiro; André da Rosa Ulguim; Daniel Debona; Jerson Vanderlei Carús Guedes; Luís Henrique Loose; Dilson Antônio Bisognin; Cleber Maus Alberto; Paulo Arbex Silva; Alencar Junior Zanon

Plant development and growth are distinct yet related processes that can occur simultaneously during the plant cycle (Figure 1.1). Development encompasses the organogenic and morphogenic processes that the soybean plant undergoes throughout its life cycle, from cell differentiation and the formation of new tissues to the appearance of new organs, extending to the senescence of organs or the entire plant. Development can be quantified by the number of leaves, branches, and the appearance of flowers, pods and grains. On the other hand, growth is defined as the irreversible physical increase in the size of a specific part or the entire plant. This increase can be quantified through measurements such as length, width, height, mass, volume, or diameter of organs or the entire soybean plant (McMaster, 1997). The development and growth of soybean plants are influenced by genetic factors (type of growth, relative maturity group, hormones, and the juvenile gene presence), climatic factors (photoperiod, solar radiation, temperature, and water availability), and farming management (fertilization, plant density, plant spacing and pest, disease and weed control).

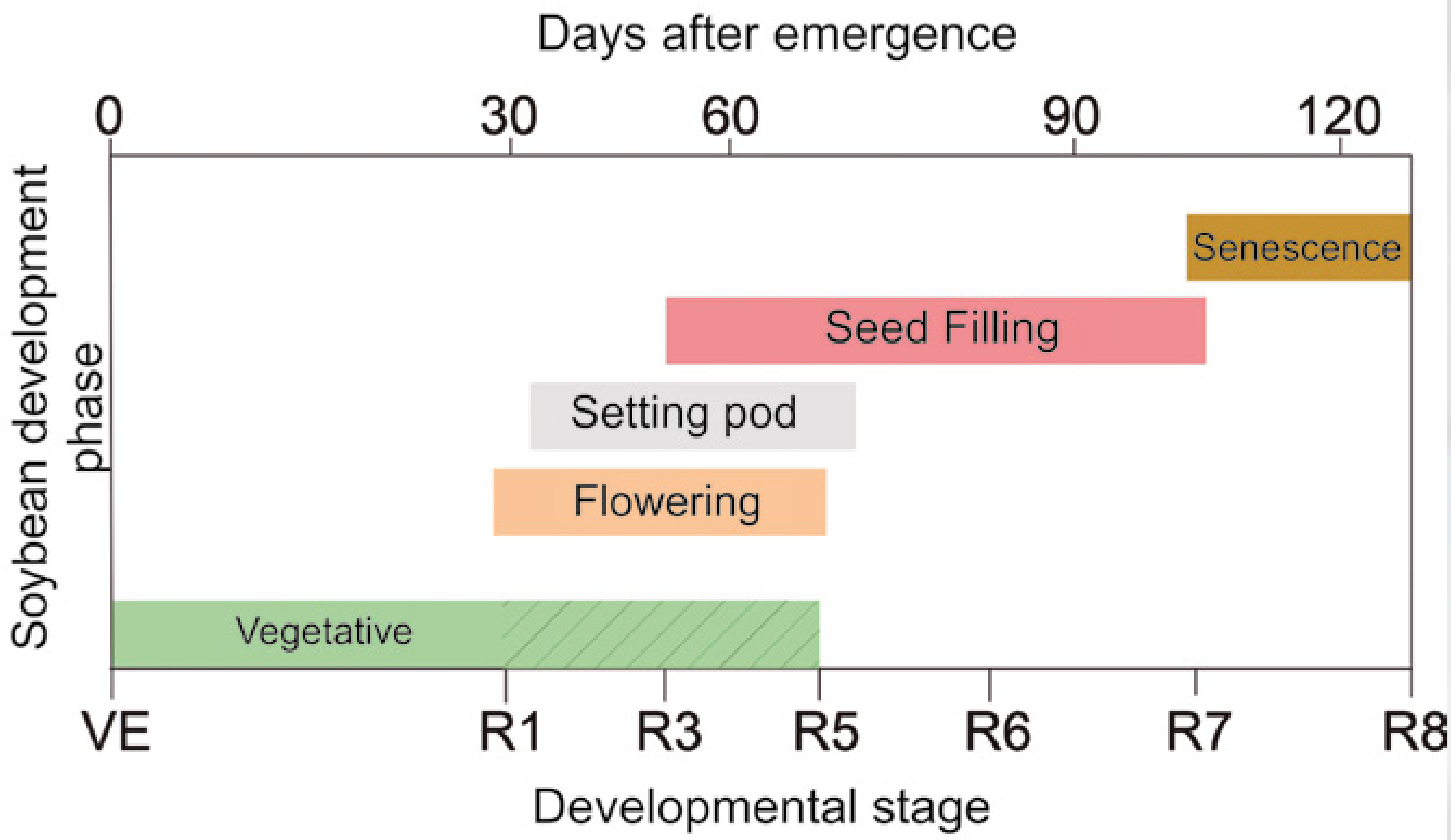


Figure 1.1. Soybean development, from emergence (EM) to harvest (R8).

In line with high-impact international scientific literature, this book employs the term "developmental stage" to denote a morphological moment for the plant or some organ, while the "phase of development" is defined as the interval between two successive developmental stages during the plant's life. Each phase can be further divided into sub-phases for practical application in ecophysiological knowledge. The terms "stage" and "phase" in many literatures correspond to the terms "stadio" and "subperiod," respectively, influenced by the Spanish language. "Development sequence" is the term used to define the sequence in which developmental stages occur during the soybean plant development cycle. The "development cycle" represents the life course of the soybean plant, from the seed placed in the soil to harvest.

1.1. Botany and morphology

Soybean is a diploid species (2n) with 40 chromosomes, self-pollinated, herbaceous, and annual (Kiang & Gorman, 1983). Its taxonomic position places it in the *Angiospermae* subdivision, *Dicotyledoneae* class, *Rosales* order, *Fabaceae* family, *Papilionaceae* subfamily, *Phaseoleae* tribe, Glycine *L.* genus, *Glycine max* (*L.*) *Merrill* species (Carlson, 1973).

During germination and emergence, the cotyledons are raised above the soil surface by the hypocotyl (epigeal emergence), distinguishing them from true leaves by their elliptical oval shape. The soybean stem develops from the embryonal axis after germination, being an herbaceous erect, pubescent, and branched type. The soybean root system consists of a main taproot and secondary roots. Throughout the development cycle, the soybean plant has two types of leaves: unifoliolate and trifoliolate. The size, shape, and positioning of these leaves may vary between cultivars and sowing dates. The two unifoliolate leaves are the first true leaves with a single leaflet, set oppositely at the first node above the cotyledonary node. Trifoliolate leaves (leaves with three leaflets) are the next true leaves that appear on the stem, emanating from main stem nodes above the unifoliolate leaves or from branch nodes, arranged alternately in a distichous manner (Figure 1.1.1).

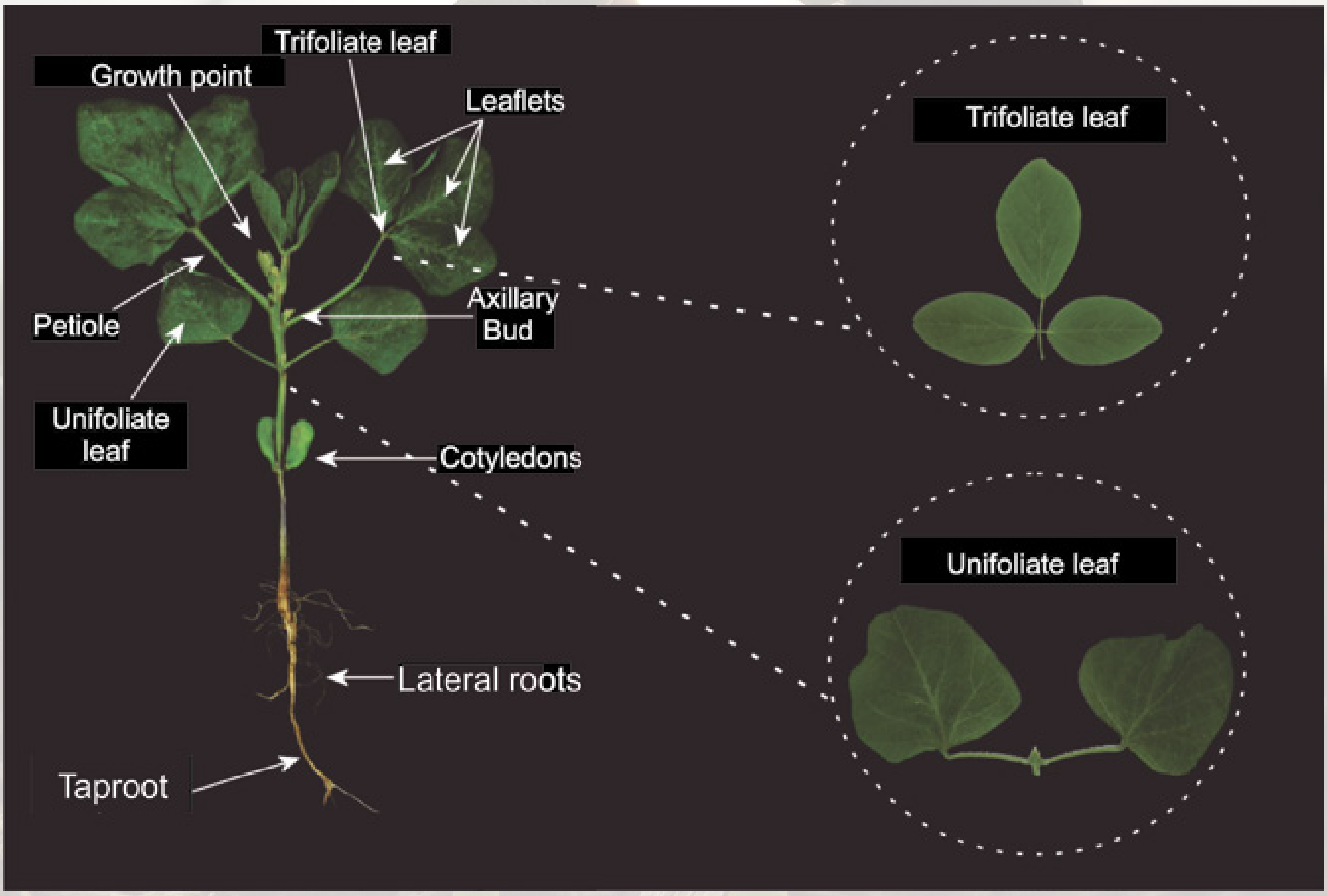


Figure 1.1.1. Soybean plant and its morphological structures before flowering.

Soybean flowers are complete, white, or purple (Figure 1.1.2), and located in terminal or axillary racemes (Figure 1.1.3, panels A and B). The raceme is an indefinite inflorescence in a bunch form, where the flowers' pedicels are inserted at different levels on the rachis. The number of flowers per raceme ranges from 2 to 35 (Carlson, 1973). The soybean fruit comes from two valves of a simple carpel, called a pod. The pod is flat, straight to slightly curved, pubescent, and dehiscent, usually 2 to 7 cm long, depending on the cultivar and edaphoclimatic conditions. The pod contains one to five seeds (Figure 1.1.4 and Figure 1.1.5); however, most cultivars have pods with two or three seeds (Figure 1.1.4). The color of the ripe pod can vary from straw yellow to brown, depending on the cultivar.

Figure 1.1.2. Two soybean plants, where the left is a white flower plant and the right is a purple color plant.

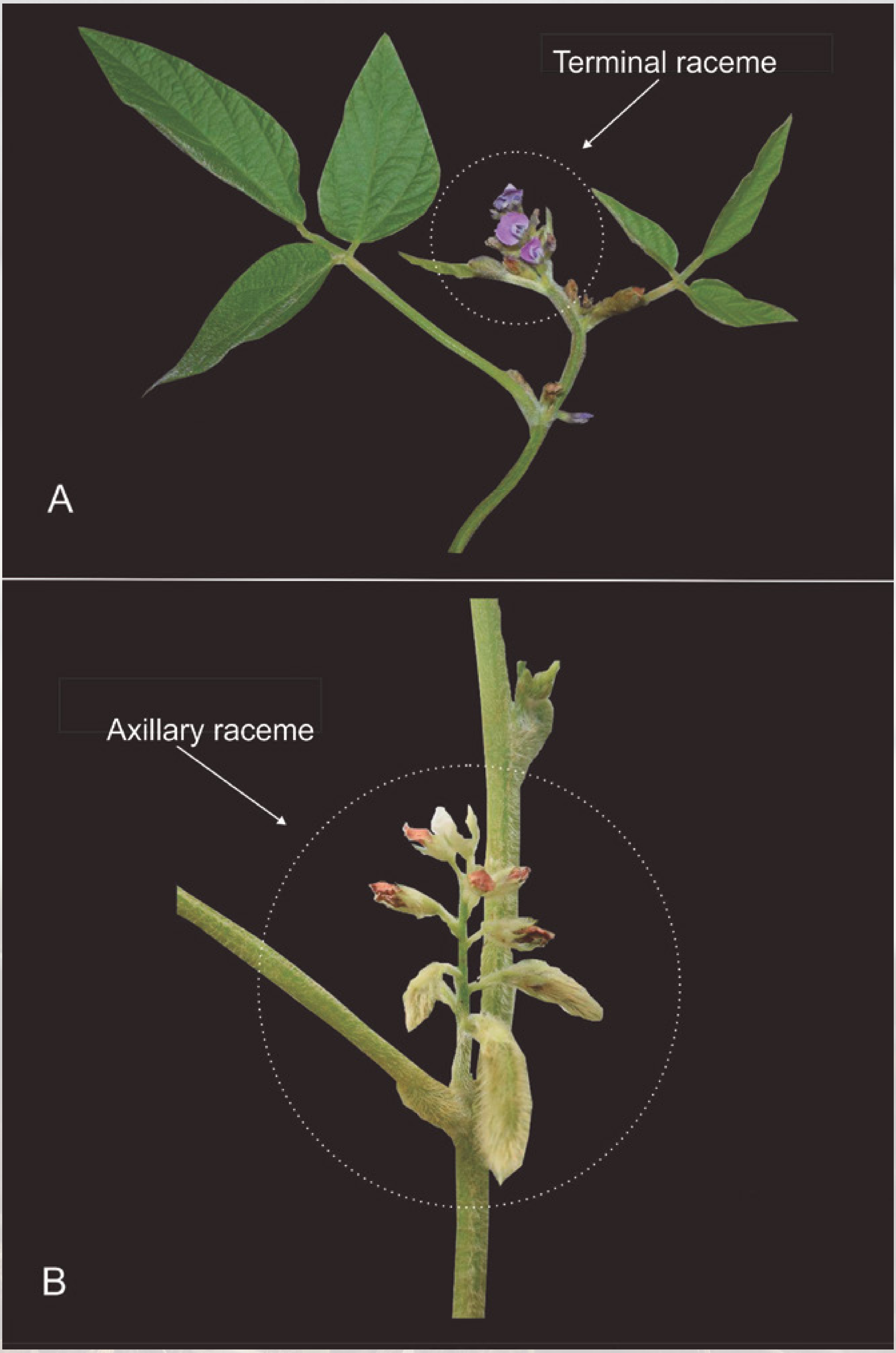


Figure 1.1.3. Terminal raceme (A) and axillary raceme (B) on the soybean plant.

Figure 1.1.4. Grain number of per pod in soy.

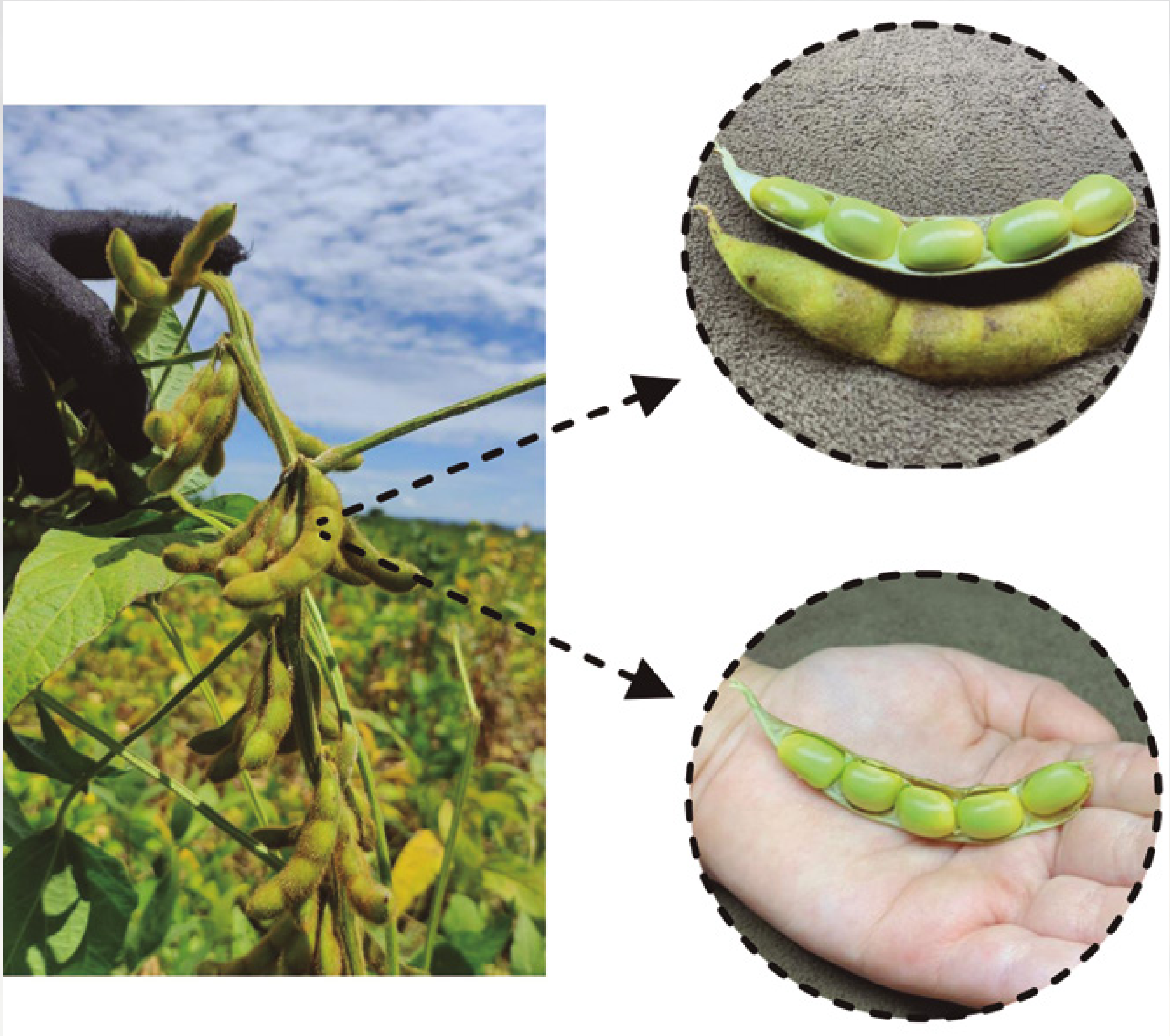


Figure 1.1.5. Soy pod with 5 grains. Photo by Cleiton Renato Casagrande, Porto Nacional, Tocantins, Brazil.

The soybean seed is composed of a seed coat wrap, exhibiting variations in shape, size, seed coat color, hilum color, and cotyledon color. The seed's shape can be globose, ellipsoidal, or oval. The seed coat contains the hilum and, at the vertex, the micropyle, and, below this, the hypocotyl.

1.2. Phenological scale

Phenology is the study of how plants develop. Monitoring phenology in a soybean field involves considering the "physiological age" of the plant rather than its "chronological age." This approach more accurately reflects the current stage of the plant and precisely defines the favorable environmental and crop conditions for each developmental stage. A phenological scale, or developmental scale, characterizes phenological stages and standardizes terminology objectively and precisely. Agricultural crop phenological scales are crucial for communication among researchers, extensionists, technical assistants, and farmers, as management practices are defined according to crop phenology. Throughout the entire development cycle, phenology is influenced by various factors that can either delay or expedite the soybean development cycle, subsequently affecting final productivity. Recognizing the importance of phenology in managing and defining the yield potential of soybean crops, section 1.2.1 describes the primary worldwide soybean crop phenological scale proposed by Fehr & Caviness (1977).

1.2.1. The Fehr & Caviness phenological scale (1977)

The Fehr & Caviness (1977) scale is divided into two phases: the vegetative stage and the reproductive stage. The vegetative phase is described by the letters V, E (VE), and C (VC), representing emergence and cotyledonary stages, respectively. Subsequently, the letter V followed by a number ranging from 1 to “n” indicates the fully developed number of leaves on the plant at a given time. A leaf is considered fully developed when the edges of each leaflet no longer touch the leaf right above the main stem. The reproductive phase is denoted by the letter R, followed by a number ranging from 1 to 8, indicating the formation stage of flowers, vegetables, or grains. The development stage of a soybean field is determined when at least 50% of the plants exhibit the characteristics defining that stage.

1.2.1.1. Vegetative phase

VE: Emergence of crop. This stage is reached when 50% of the plants have cotyledons above the ground, forming a 45° angle or more (Figure 1.2.1.1.1).

Figure 1.2.1.1.1. Emergence stage (EV) on the Fehr & Caviness soybean scale (1977).

VC: Cotyledonary stage. The unifoliate leaves are sufficiently extended so that the edges do not touch (Figure 1.2.1.1.2).

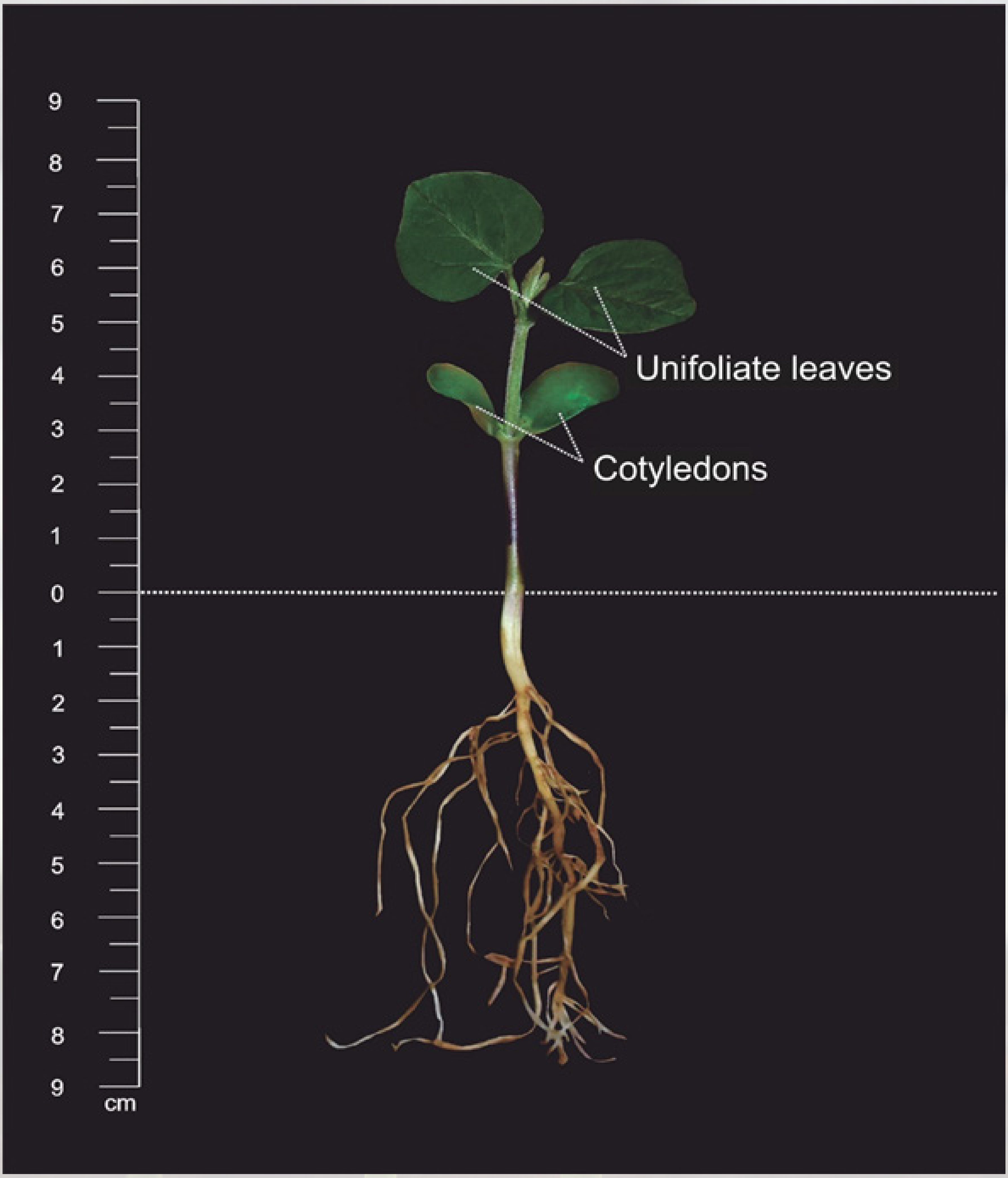


Figure 1.2.1.1.2. Cotyledonary stage (EV) on the Fehr & Caviness soybean scale (1977).

V1: Fully developed unifoliate leaf (Figure 1.2.1.1.3). The unifoliate leaf is only counted or called developed if the leaf right above it does not have leaflets edges touching each other.

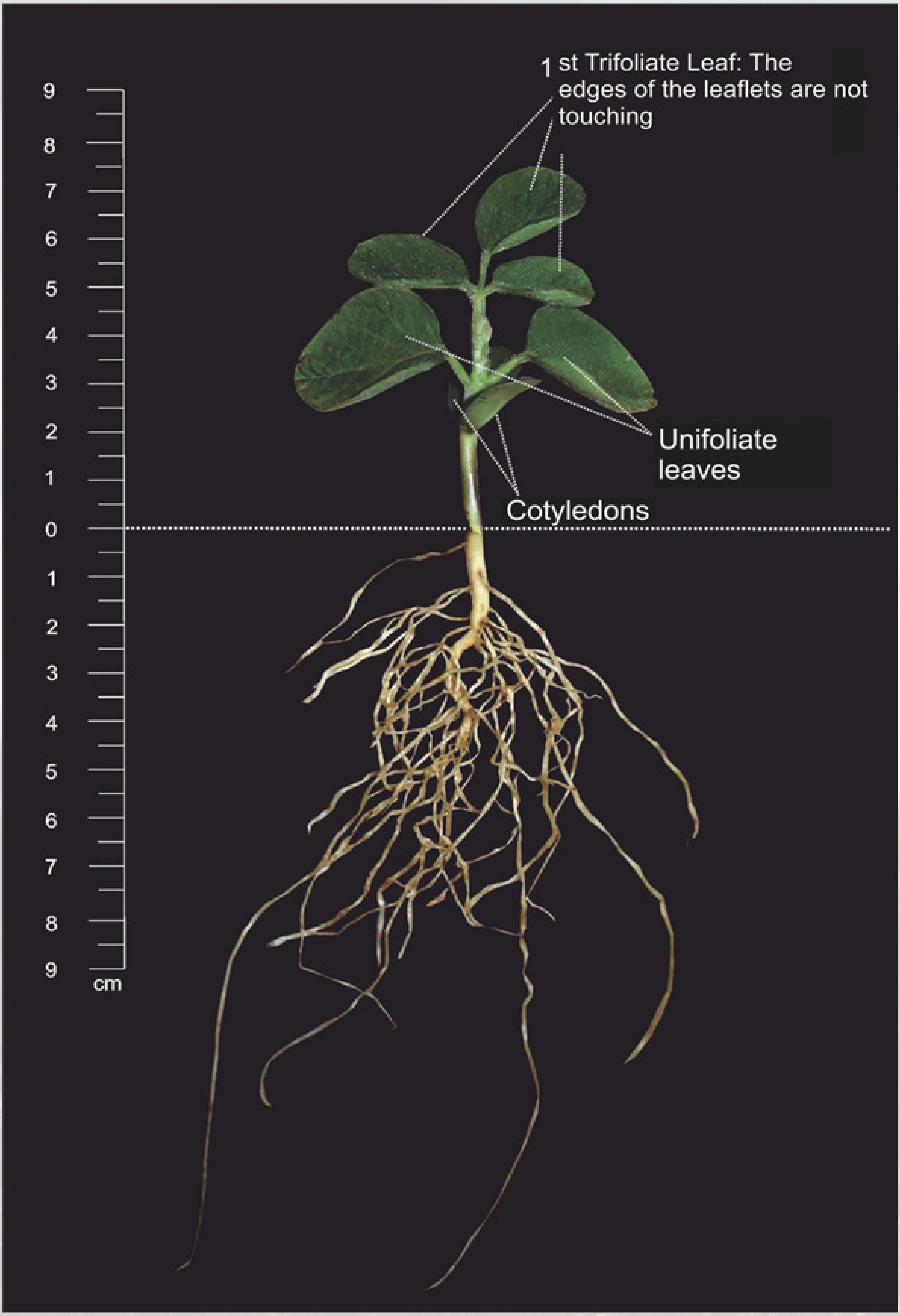


Figure 1.2.1.1.3. V1 stage on the Fehr & Caviness soybean scale (1977).

V2: First fully developed trifoliate leaf (Figure 1.2.1.1.4). This leaf is considered developed only if the leaf right above it does not have leaflet edges touching each other.

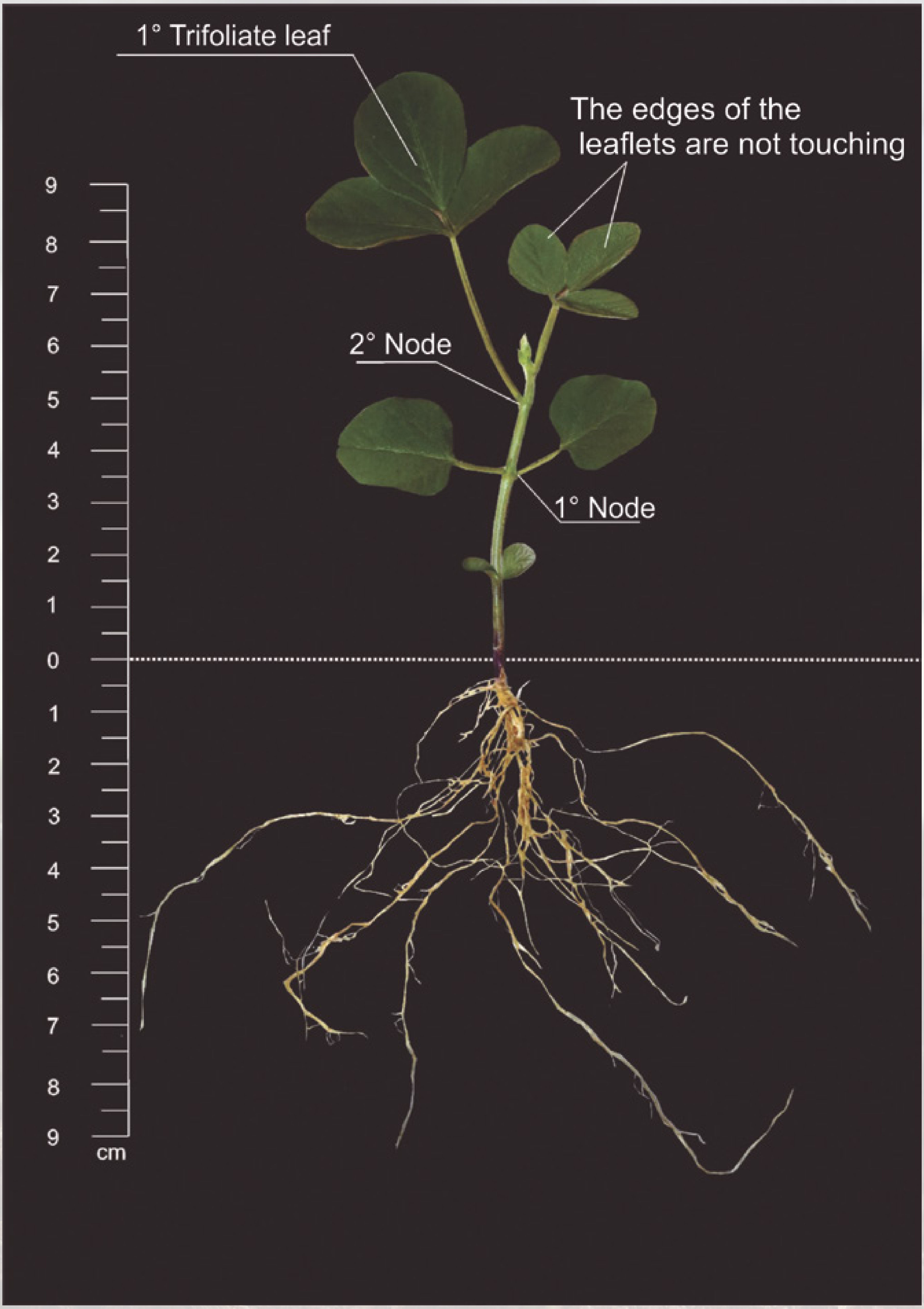


Figure 1.2.1.1.4. V2 stage on the Fehr & Caviness soybean scale (1977).

V3: Second fully developed trifoliate leaf (Figure 1.2.1.1.4). This leaf is counted or called developed only if the leaf right above it does not have leaflet edges touching each other.

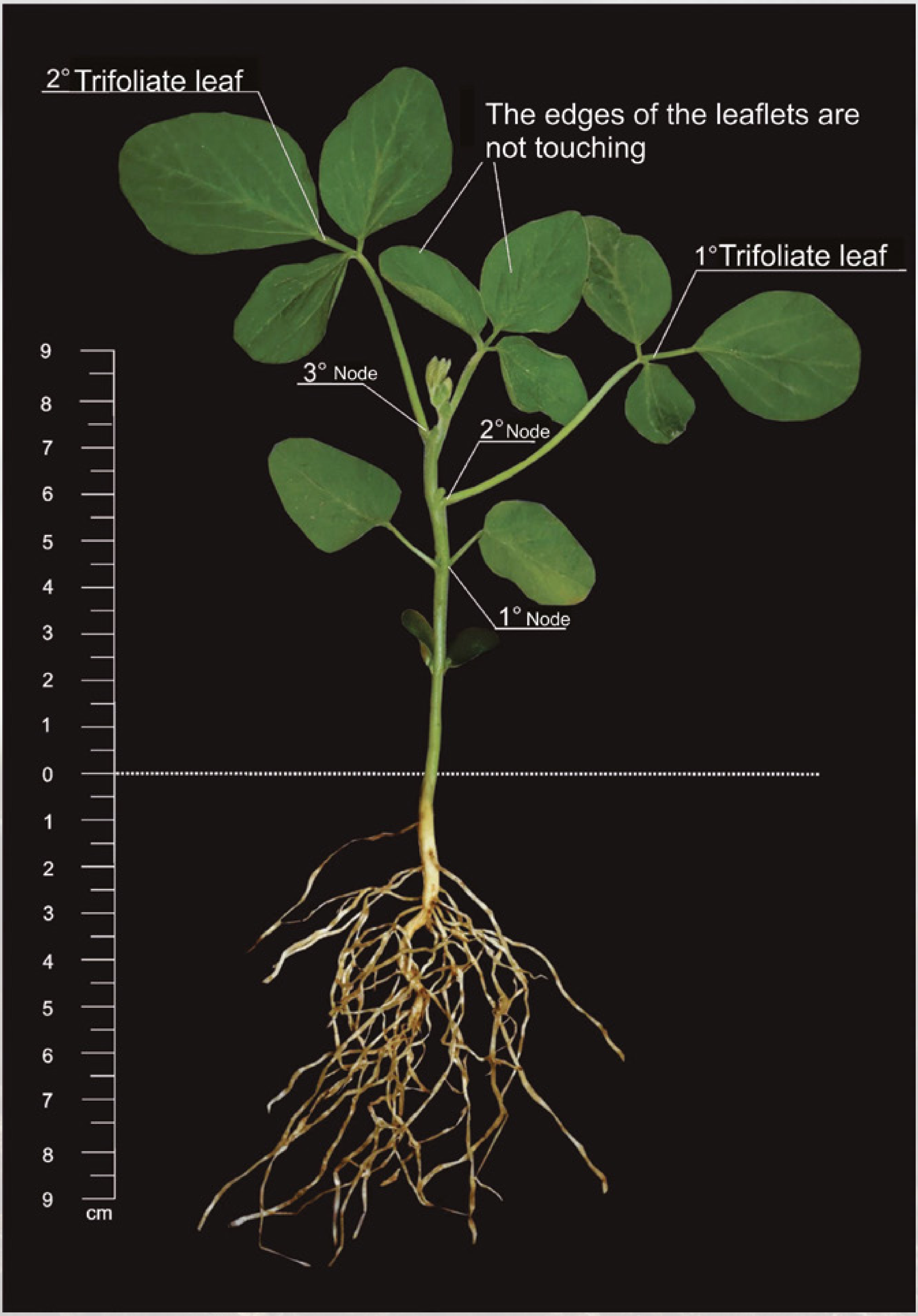


Figure 1.2.1.1.5. V3 stage on the Fehr & Caviness soybean scale (1977).

Vn: “N” fully developed trifoliate leaves on the main stem, starting the count from the unifoliolate leaves. The last leaf is considered developed when it reaches more than 75% of the final size and exhibits the same color as the leaves inserted below the main stem (see Figure 1.2.1.1.6). For determinate growth type plants, this occurs between the R1 and R3 stages, while for indeterminate growth type plants, it happens at the R5 stage (Zanon et al., 2015).

Figure 1.2.1.1.6. Vn (final number of leaves) of soybean cultivars from determined growth type (A) and indeterminate growth type (B) (see item 1.4).

1.2.1.2. Reproductive phase

R1: Beginning of flowering. An open flower at any node on the main stem (Figure 1.2.1.2.1).

Figure 1.2.1.2.1. R1 soybean stage on Fehr & Caviness soybean scale (1977), showing the first open flower on the main stem.

R2: Full blossoming. An open flower at one of the last 2 nodes of the main stem with a fully developed leaf (Figure 1.2.1.2.2).

Figure 1.2.1.2.2. R2 soybean stage on Fehr & Caviness soybean scale (1977), featuring an open flower at one of the last 2 nodes with a fully developed leaf.

R3: Pods formation beginning. Pods 0.5 cm size at any of the last 4 nodes of the main stem with fully developed leaves. Stage called “canivete” by the farmers in Brazil (Figure 1.2.1.2.3).

Figure 1.2.1.2.3. R3 soybean stage on Fehr & Caviness soybean scale (1977), showing the 0.5 cm pod.

R4: Pods formation. Pods 2.0 cm size at any of the last 4 nodes of the main stem with fully developed leaves (Figure 1.2.1.2.4).

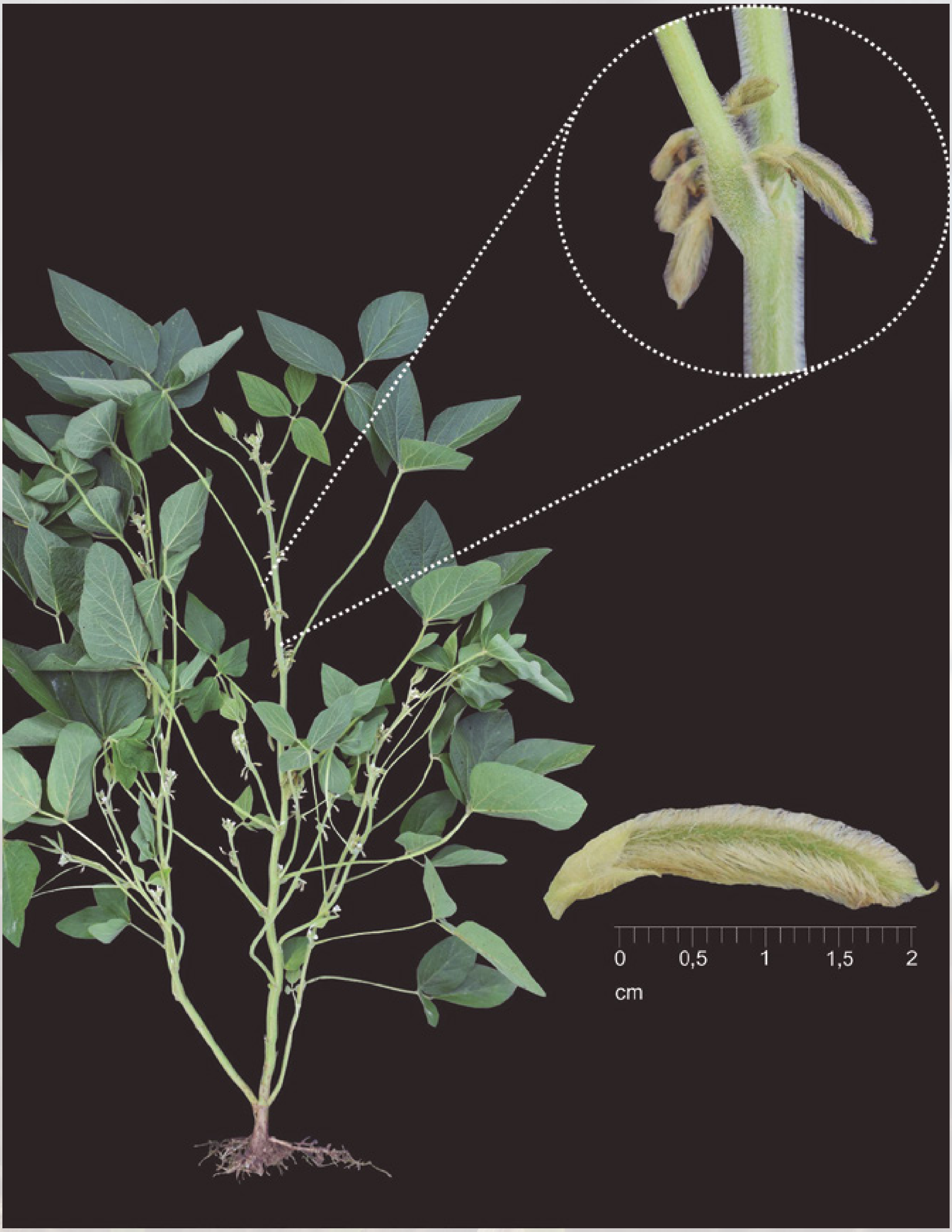


Figure 1.2.1.2.4. R4 soybean stage on Fehr & Caviness soybean scale (1977), showing the 2.0 cm pod.

R5: Grain development beginning. Presence of 3 mm grains on the pod, at one of the last 4 nodes of the main stem with a full developed leaf (Figure 1.2.1.2.5).

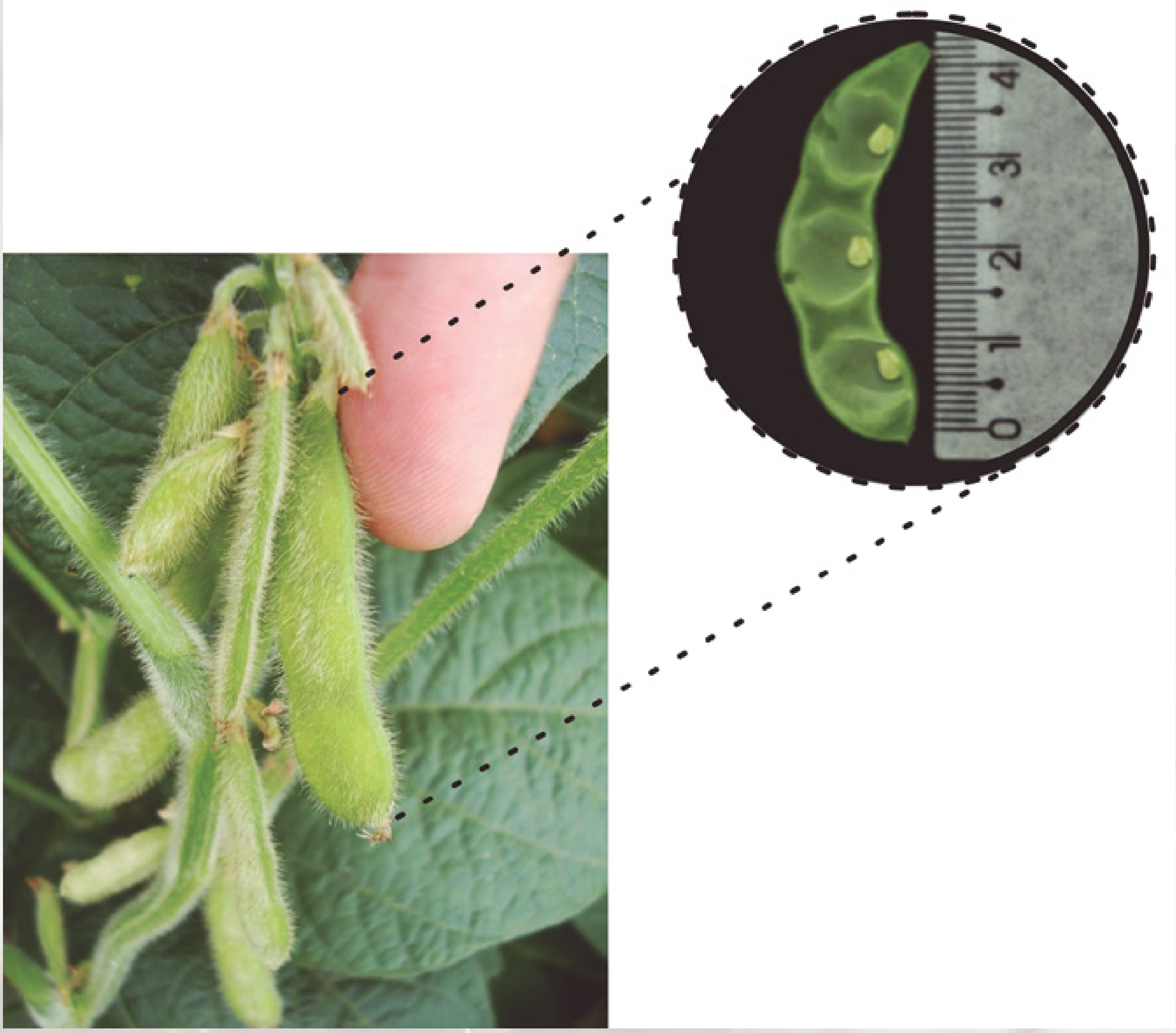


Figure 1.2.1.2.5. R4 soybean stage on Fehr & Caviness soybean scale (1977), showing the presence of 3 mm grains lenght. Photo: Bruno Kräulich (*in memoriam*).

Yorinori (1996) adapted the phenological scale proposed by Fehr & Caviness (1977), introducing sub-stages for the R5 stage (Figure 1.2.1.2.6).

R5.1: Grains perceptible on tact (equivalent to 10% grain-filling);

R5.2: Grain-filling of 11% to 25%;

R5.3: Grain-filling of 26% to 50%;

R5.4: Grain-filling of 51% to 75%;

R5.5: Grain-filling of 76% to 100%;

Figure 1.2.1.2.6. R5 stage on Fehr & Caviness soybean scale (1977) rescaled by Yorinori (1996).

R6: Complete (or full) grain. Green grains fill the pod cavities at one of the last 4 nodes of the main stem with fully developed leaves (Figure 1.2.1.2.7).

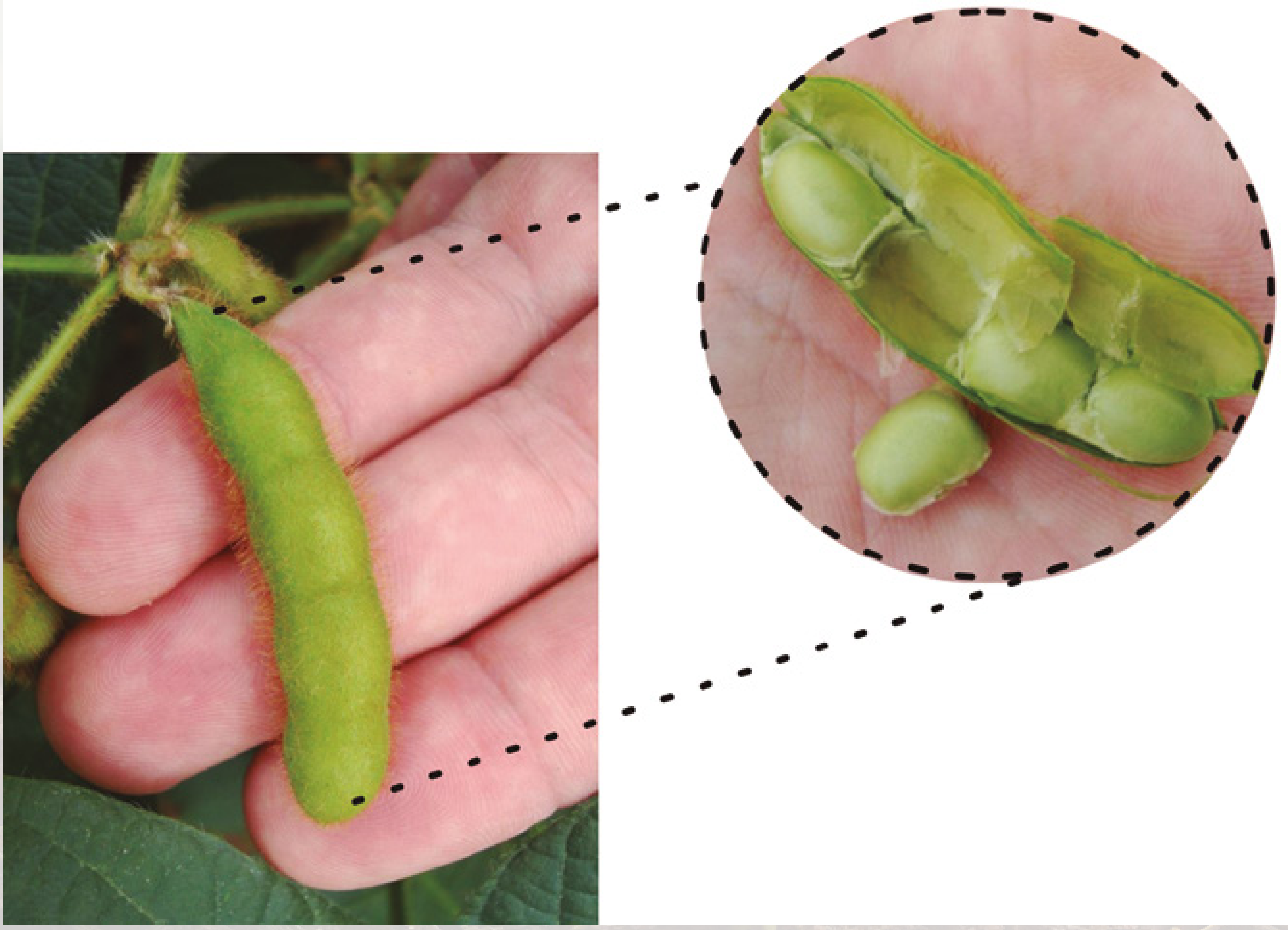


Figure 1.2.1.2.7. R6 soybean stage on the Fehr & Caviness soybean scale (1977), demonstrating filled pod cavities Photo: Bruno Kräulich (in memoriam).

R7: Maturation initiation – Physiological maturation marked by the presence of a mature color pod on the main stem (Figure 1.2.1.2.8).

Figure 1.2.1.2.8. R7 soybean stage on the Fehr & Caviness soybean scale (1977), showing the presence of a mature color pod on the main stem.

R8: Harvest maturity. Presence of 95% of mature color pods on the main stem (Figure 1.2.1.2.9).

Figure 1.2.1.2.9. R8 soybean stage on the Fehr & Caviness soybean scale (1977), showing the presence of 95% of mature color pods on the main stem.

1.3. Ecophysiology and management

In addition to dividing soybean development into two phases (vegetative and reproductive) and characterizing each development stage using the Fehr & Caviness scale (1977), another approach to delineating the soybean development cycle involves considering crop requirements. Six crucial phases have been identified, taking into account the plant's organ needs and the allocation of photoassimilates during the development cycle. This approach aims to enhance resource utilization efficiency and optimize management practices for achieving high yields.

1.3.1. Seeding - emergency phase (Planting - VE)

The planting-emergence phase begins when the seed contacts the soil and continues until cotyledons appear above the top-soil level. Although this phase is short in terms of days, it plays a vital role in determining the initial establishment and distribution of plants in the field. The soil surface layer is the starting point of this phase, and it must be properly prepared to provide optimal conditions for seed germination, including adequate moisture content, temperature, and aeration. Once these conditions are met, the germination process initiates through water absorption by the seed. Subsequently, there is a reduction in the mechanical resistance of the seed coat, initiating a series of metabolic and enzymatic activities that convert and translocate reserve substances from the cotyledons to the meristematic differentiation region. In this region, the elongation of the radicle or primary root begins (the first structure to break the seed coat and contact the soil) and that of the hypocotyl (located between the cotyledonary node and the radicle) (see Figure 1.3.1.1). From the primary root, the growth of secondary roots commences, and through hypocotyl elongation, the cotyledons rise toward the soil surface, a phenomenon known as epigeal germination (see Figure 1.3.1.1).

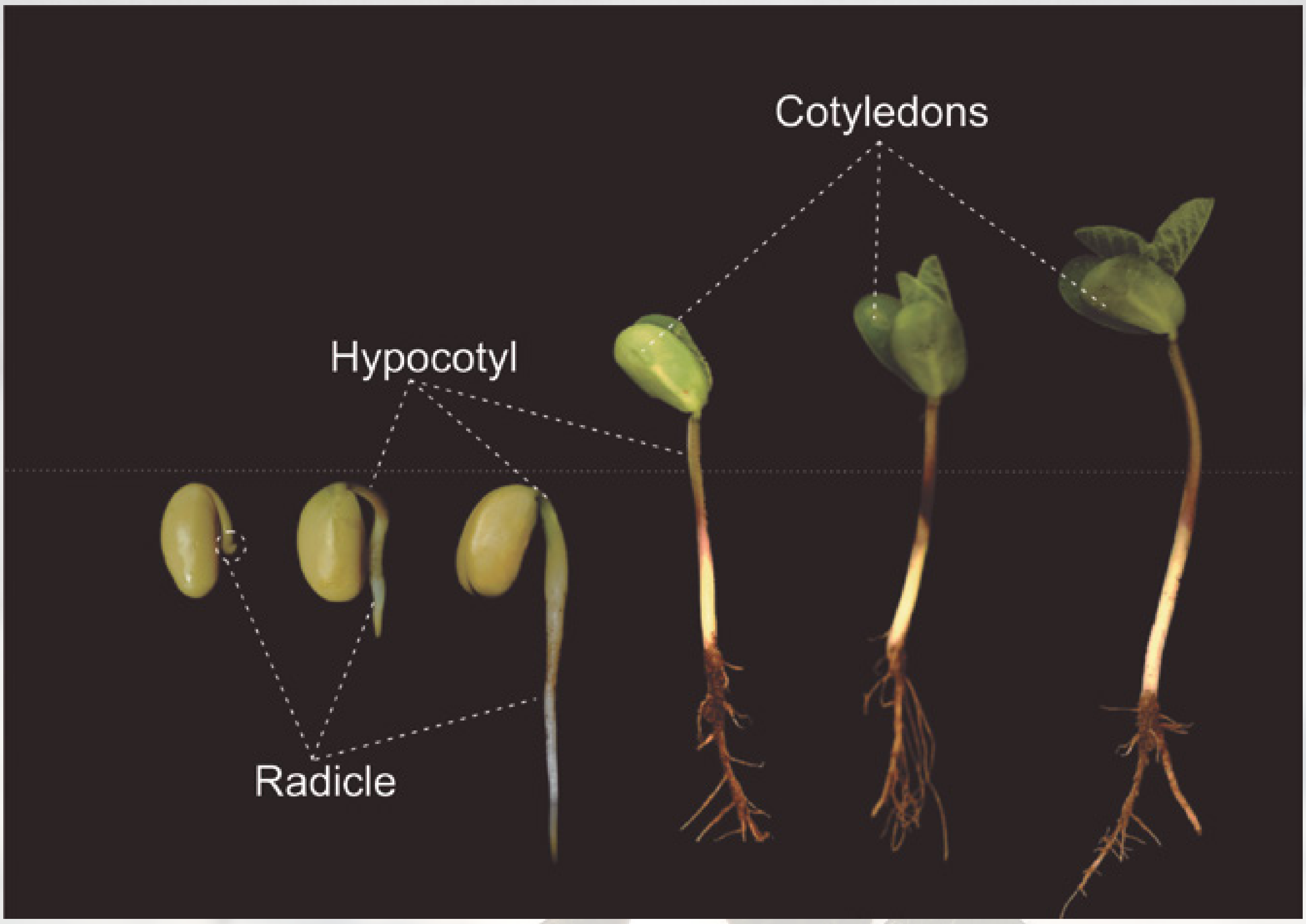


Figure 1.3.1.1. Seed germination process and soybean seedling emergence.

The greater the sowing depth, the greater the energetic cost for seedling emergence (Figure 1.3.1.2). When solar radiation falls on the cotyledons, the formation of photosynthetic pigments at the plastids is stimulated, giving the cotyledons a greenish color.

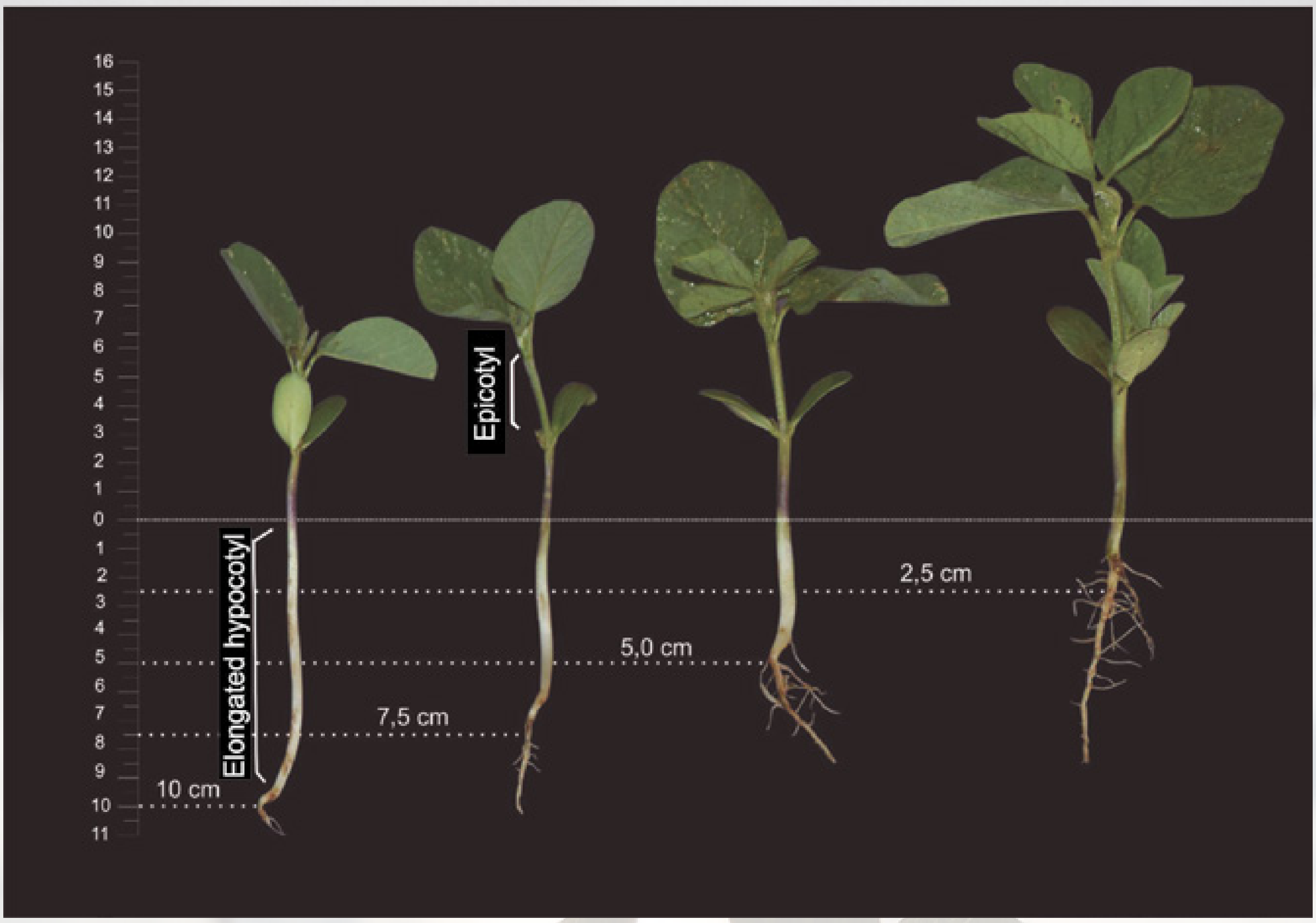


Figure 1.3.1.2. Soybean seedlings from the same sown day, with different sowing depths.

At the seeding-emergency phase, one of the main components of productivity is defined: the density of field plants. Preliminary monitoring of sowing factors, such as analyzing historical data on area pests and diseases, as well as conducting seed pathogen analyses, serves as crucial decision-making tools for determining the management strategies to be adopted. Inoculants based on *Bradyrhizobium* are recommended for seed treatment and/or in-furrow application to enhance soybean biological nitrogen fixation. It is important to note that in fields where soybeans are newly introduced or experiencing issues throughout the crop cycle (such as excess water or water stress), higher application rates than recommended should be considered.

Both abiotic and biotic issues, such as water shortage or excess and pathogen attacks, can result in seed rotting, pre- or post-emergence seedling damping-off, or even root rotting. In terms of managing pest arthropods, especially for soybean crops established after cover crops (mostly grasses), preceding species have an impact on pest occurrence in the early stages of soybean growth. Therefore, the incidence of pests, particularly remaining caterpillars, should be analyzed in the preceding crop to plan effective control actions. Depending on the type of pest and the level of infestation, pre-seeding treatments and emergency management may be necessary to ensure an adequate plant population. Insecticides can be used for seed treatment, flight spraying, often associated with desiccant herbicides, or possibly in post-emergence spraying. Additionally, early desiccation of the preceding crop could be employed for the management of some pests.

Soil compaction, excess moisture, and low temperatures generally support pathogens attacks due to the lag in soybean tissue differentiation, prolonging the emergence process. In poorly drained environments, a common issue is plant damping-off (*Phytophthora sp*). The oomycete causing this disease can also attack plants at any development stage, leading to stem rot. Seed treatment (ST) is a crucial preventive management practice against pests and diseases affecting soybean crop cycles. To position ST effectively, it is necessary to identify the pests and diseases present in the field and/or on the seeds.

Seed treatment technology has advanced significantly in recent years, especially with the emergence of industrial seed treatment (IST). IST provides uniform coverage of phytosanitary products (insecticides and/or fungicides) on seeds, preventing over- or underdosing and ensuring the desired protection for the beginning phase (control effectiveness and protective action persistence) and the maintenance of the seeds physiological quality. Systemic fungicides, used in seed treatment, act on pathogen fungi in seeds and soil offering protective, curative, and eradicating effects. They create a protection zone around the seed and can be absorbed by the roots, translocating through the xylem to other plant parts, providing protection against early cycle diseases. Combining protective and systemic ST products has shown the highest emergence percentages. Biologically-based treatment products, like *Trichoderma*, have also gained prominence in seed and seedling protection management, offering an alternative for disease control. However, caution is needed, especially with *Trichoderma*, to avoid exposing these microorganisms to certain active ingredients.

Weed management must be based on a set of agronomic practices, including the introduction of a no-tillage system, soil disturbance only in the sowing line, and other farming operations (Embrapa, 2014). The importance of soybean emergence in a 'clean field,' without the presence of weeds, is emphasized to prevent yield losses due to weed interference. The losses depend on the weed species, emergence time, and the phenological stage of the competing plants (Rizzardi et al., 2003; Agostinetto et al., 2014).

The pre- and post-sowing management, involving desiccation and pre-emergent herbicides before soybean seedlings and weeds emerge, are strategies used by farmers. Desiccation aims to control preceding soybeans and those tolerant to glyphosate, such as horseweed (*Conyza spp*.), red amaranth (*Amaranthus hybridus*), sourgrass (*Digitaria insularis*), white-eye plant (*Richardia brasiliensis*), among others species. desiccation is the only opportunity to control these species, which lack efficient chemical alternatives for post-emergence soybean management. To achieve effective desiccation, it is crucial to carry out this operation preferably on weeds smaller than 15 cm (with a maximum of 4 leaves) and at a low weed density.

Regarding pre-emergent herbicide use, careful consideration should be given to soil moisture. Applying pre-emergent herbicides in dry soils can reduce weed control effectiveness. Pre-emergent herbicides become particularly important for fields with herbicide-resistant weeds, mainly glyphosate-resistant ones. In many cases, pre-emergent products have different action mechanisms than those used for post-emergence herbicides. This type of weed management ensures soybean emergence in a 'clean field,' preventing competition for water, light, and nutrients between weeds and the soybean crop at the beginning of the cycle.

1.3.2. Vegetative development phase (VC - Vn)

The vegetative development phase begins when the cotyledons emerge above the soil surface continues until the last node of the main stem is emitted. The duration of the vegetative phase varies depending on the cultivar (MG and growth type), along with local conditions and planting time factors such as temperature, precipitation, and photoperiod. Node emission serves as the primary morphological parameter for characterizing soybean vegetative development, and it can be determined through the plastochron, which represents the time[2] required for two successive nodes to appear on the main stem (Sinclair, 1984). The soybean plastochron ranges from 45 °C day^{-1} $node^{-1}$ to 70 °C day^{-1} $node^{-1}$, depending on the cultivar and sowing time (Martins et al., 2011). Integrating the node emission rate over time provides the total number of accumulated nodes (NN) on the main stem (Streck et al., 2005). NN is used to characterize vegetative development and is associated with the evolution of the plant's leaf area (Streck et al., 2008). Typically, the number of nodes on a soybean plant can vary from 12 to 35. Indeterminate growth type cultivars cease node emission at the beginning of grain filling (R5,) regardless of MG and local conditions, while determinate growth type cultivars have the last node emission between R1 and R3, varying from different sowing times and cultivars. This topic will be discussed in detail in chapter 1.4.

During the first days after emergence, soybean seedlings still rely on cotyledon reserves for growth. Starting from the V1 stage, plants begin to be supplied by the photoassimilates produced in the leaves. Close to V1 stage, there is an infection by atmospheric nitrogen-fixing bacteria from *Bradyrhizobium* genus (commonly known as rhizobia) and nodules formation, visible between five and twelve days after crop emergence (Hungary et.al., 2001) (Figure 1.3.2.1). Rhizobia utilize the nitrogenase enzyme to break the atmospheric N_2 triple bond and reduce it to ammonia (NH_3), fixing N_2. The synthesized ammonia in the plant is rapidly incorporated into hydrogen ions (H+), leading to the transformation into ammonium ions (NH4+), which, through ureides, are distributed in organic N form within the plant (Hungary, et.al., 2001).

Biological nitrogen fixation (BNF), under favorable conditions, normally meets up to 65% of the crop's N requirement, but issues such as high temperatures, deficits and/or water excess, low fertility and soil acidity disturb the symbiosis between plant roots and *Bradyrhizobium*, reducing BNF (Ciampitti & Salvagiotti 2018).

Figure 1.3.2.1. Cross-section showing the rosy color nodulation, which indicates the activity of nitrogen-fixing bacteria in the roots of the soybean plant.

From V4/V5 onwards, the emission of ramifications in soybeans begins (Zanon et al., 2015a). These ramifications, commonly known as twigs, emerge from the meristematic axillary bud located at the leaf petiole insertion (cotyledonary, unifoliolate, and trifoliolate) on the main stem. The axillary bud can become dormant or give rise to vegetative (ramification) or reproductive (flowers, vegetables, or raceme) structures. This capacity to develop new structures grants significant regenerative capability or plasticity to the soybean plant. The number of ramifications varies according to the cultivar and sunlight incidence on the lower plant stratum (greater spacing between lines or lower plant density induces ramification), with each plant capable of emitting more than eight ramifications. Each ramification develops nodes, trifoliate leaves, and axillary meristems that can differentiate into tertiary ramifications or floral racemes, producing flowers and pods as well as the main stem. In Figure 1.3.2.2, two plants in full bloom are depicted, one without ramifications (1.3.2.2 A and 1.3.2.2 C) and one with ramifications (1.3.2.2 B and 1.3.2.2 D).

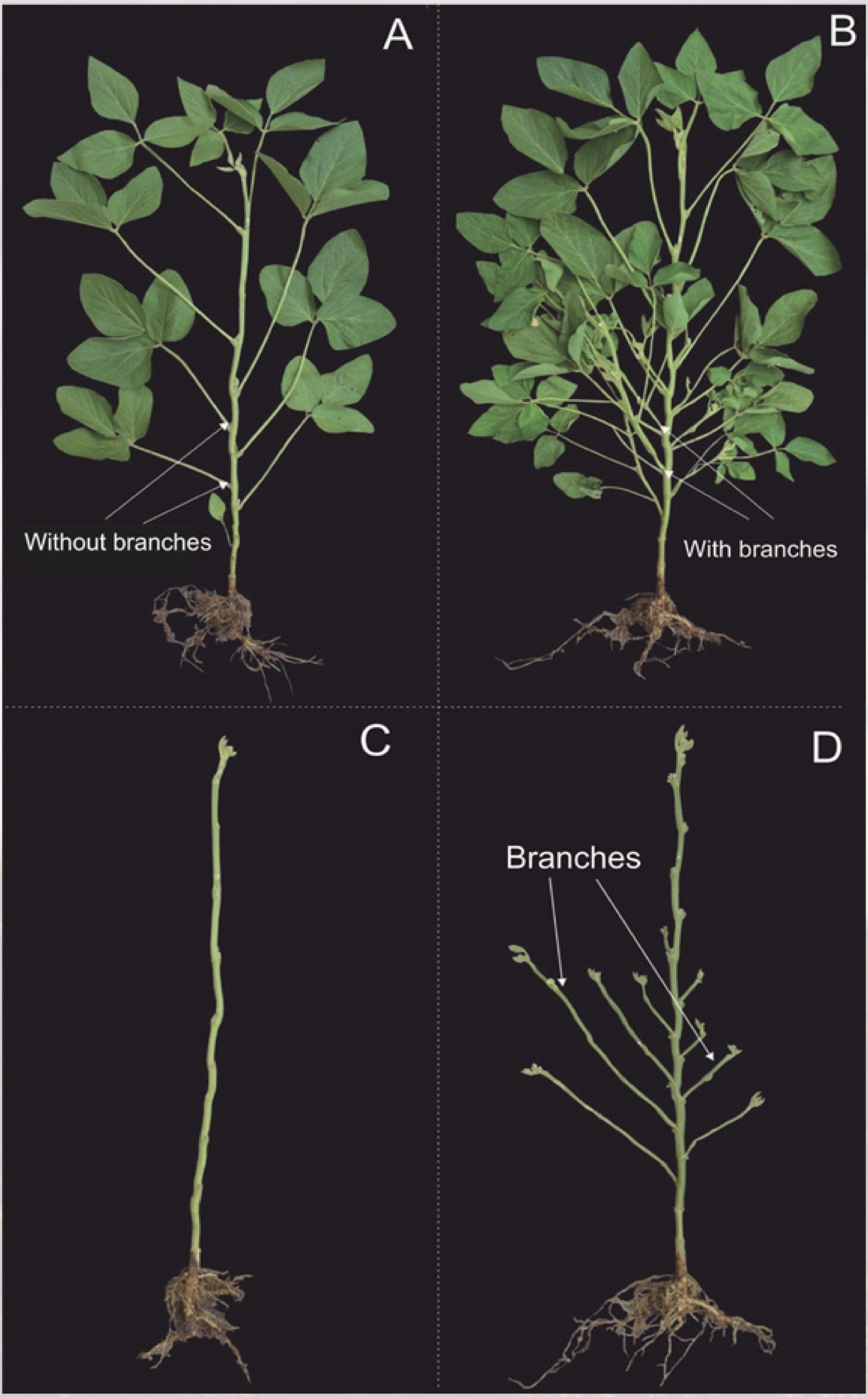


Figure 1.3.2.2. Soybean plant without branches (A) and with branches (B). Soybean plant without petioles, leaves, and branches (C) only with branches (D).

During the vegetative phase, photoassimilates are directed towards leaf area growth, node emission and root growth. Protection of the leaves is carried out to defend against pests and diseases, safeguarding the leaf area index (LAI). The LAI can be considered a “plant solar radiation pane”, responsible for capturing solar radiation—the energy source for the photosynthesis process, crucial for grain production. To ensure high yields, it is imperative to avoid competition with weeds, pests, and diseases, thereby preventing the limitation of LAI (Tagliapietra et al., 2018).

Regarding soybean diseases during this stage, the primary focus is on leaf spots, such as brown spot, target spot, *Cercospora* leaf blight, and anthracnose. Periods of frequent rainfall favor the onset of diseases, with pathogens surviving in seeds or plant remains. Conversely, years with less rainfall and mild temperatures increase the likelihood of powdery mildew. Delayed sowing may lead to soybean rust during the vegetative phase. Farmers must consider the area’s disease history, sowing time, meteorological conditions, crop cycle, and cultivar resistance when managing diseases. It is important to note that fungicides applied for disease control have limited mobility within plant tissues. Therefore, effective mechanical spraying is essential for good droplet penetration into the crop canopy, ensuring uniform coverage of soybean leaves, especially those in the lower third of the plant, where foliar diseases often begin.

At this stage, the management of defoliating insects should be defined through daily crop monitoring, preferably using a vertical beating cloth (Stürmer et al., 2012). In addition, special attention should be given to the emergence of bugs and other soybean secondary pests, such as the soybean stalk weevil, whitefly, and stem fly. Although this phase is not the critical period for pest infestation, even low-density occurrences in some areas, without proper monitoring, can lead to pest population growth, resulting in serious issues during the end of the vegetative phase or the beginning/reproductive phase of soybean. Thus, while this period represents a lower-risk stage, fields closing the vegetative stage with low pest activity may achieve better management results during the soybean reproductive stage.

Regarding weed interference in soybean crops, the cycle can be divided into three periods: before the interference period (BIP), interference prevention total period (IPTP), and interference prevention critical period (IPCP). BIP is the period where weed presence does not interfere with crop growth because the environment can provide necessary resources for both weed and crop growth. This period lasts about 11 to 34 days from emergence, being shorter with a greater weed population (Meschede et al., 2002; Nepomuceno et al., 2007; Silva et al., 2009). The IPTP is the phase during which soybean crops must grow free from weeds to avoid yield reduction; by the end of this period, new emerging weeds will not significantly reduce soybean yield due to the crop's ability to suppress competing plants, coinciding with canopy closing time (Brighenti et al., 2004; Radosevich et al., 2007). The IPCP is the phase in which weeds cause irreversible yield losses, requiring effective management practices to prevent their presence and damage (Radosevich et al., 2007).

In general, the ideal time to adopt control strategies is as soon as possible at the end of the BIP, as yield losses are already occurring in the IPCP. These periods may vary based on sowing time, soybean growth type, relative maturity groups, environmental conditions, and weed emergence (Zandoná et al., 2018). For southern Brazil conditions and cultivar relative maturity groups ranging between 5.0 and 6.8, the average BIP is around 20 days from emergence for October and November sowings and approximately 15 days for December sowings (Pigatto et al., 2021; unpublished data). Based on this, management practices related to desiccation, pre- and post-emergence weed control can be planned to avoid yield losses. However, it's important to note that the BIP is the period in which the soybean plant has the greatest capacity to recover from setbacks, such as hailstorms and pest defoliation, which can cause a decrease in leaf area index, dry mass, and/or apical growth meristem breakage (Cera et al., 2016).

1.3.3. Flowering phase (R1 – R2)

This phase begins with the appearance of one open flower and ends at full bloom on the main stem. During flowering, there is a fast increase in the N fixation rate by the nitrogen-fixing bacteria present in the nodules, as well as for the dry matter accumulation rate and nutrients to vegetative parts. For this phase, some changes in photoassimilate translocation begin, where, in addition to photoassimilate translocations to leaves and stems development, the plant starts driving photoassimilates towards flower development.

The flowering stage is one of the most susceptible phases to water deficit issues. Water deficit can lead to the abortion of leaves, flowers, and unborn pods (Figure 1.3.3.1 and Figure 1.3.3.2), causing a reduction in one of the main yield components—the number of pods per plant. Therefore, sowing must be planned to align with the period of greater water availability within the flowering and grain-filling period, especially in fields without irrigation systems.

Figure 1.3.3.1. Soybean raceme showing flower abortion caused by soil water deficit.

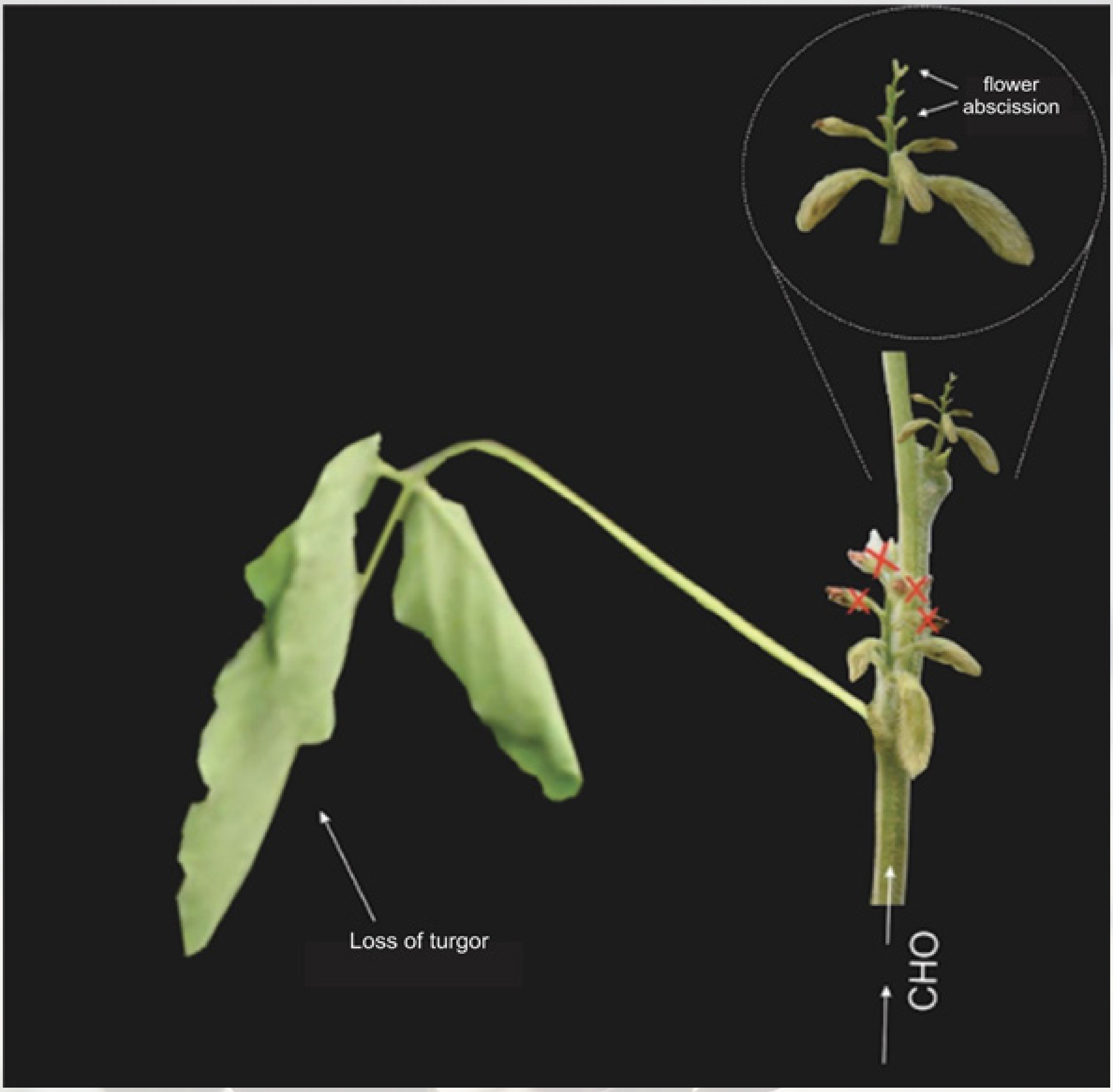


Figure 1.3.3.2. Soybean raceme showing flower abortion caused by soil water deficit.

From the perspective of solar radiation absorption, it is essential that all plant leaves remain green during flowering to maximize solar radiation interception. Mistakes in cultivar choice, seeding density, and row spacing can cause early leaf senescence at the canopy bottom, leading to a phenomenon known by local farmers as "shin," where the decrease in leaf surface reduces sunlight interception in soybean plants (Figure 1.3.3.3).

There is an interdependence between the reproductive leaf axil organs (sink) and the leaf (source). With a decrease in stomatal conductance caused by drought, salinity, or high temperatures at this stage, the flowers and pods of the raceme start to experience photoassimilate restrictions. This induces the synthesis of stress hormones in the plant, such as abscisic acid and ethylene, responsible for some reproductive structure abortion in favor of others, aiming to ensure the self-propagation of the species.

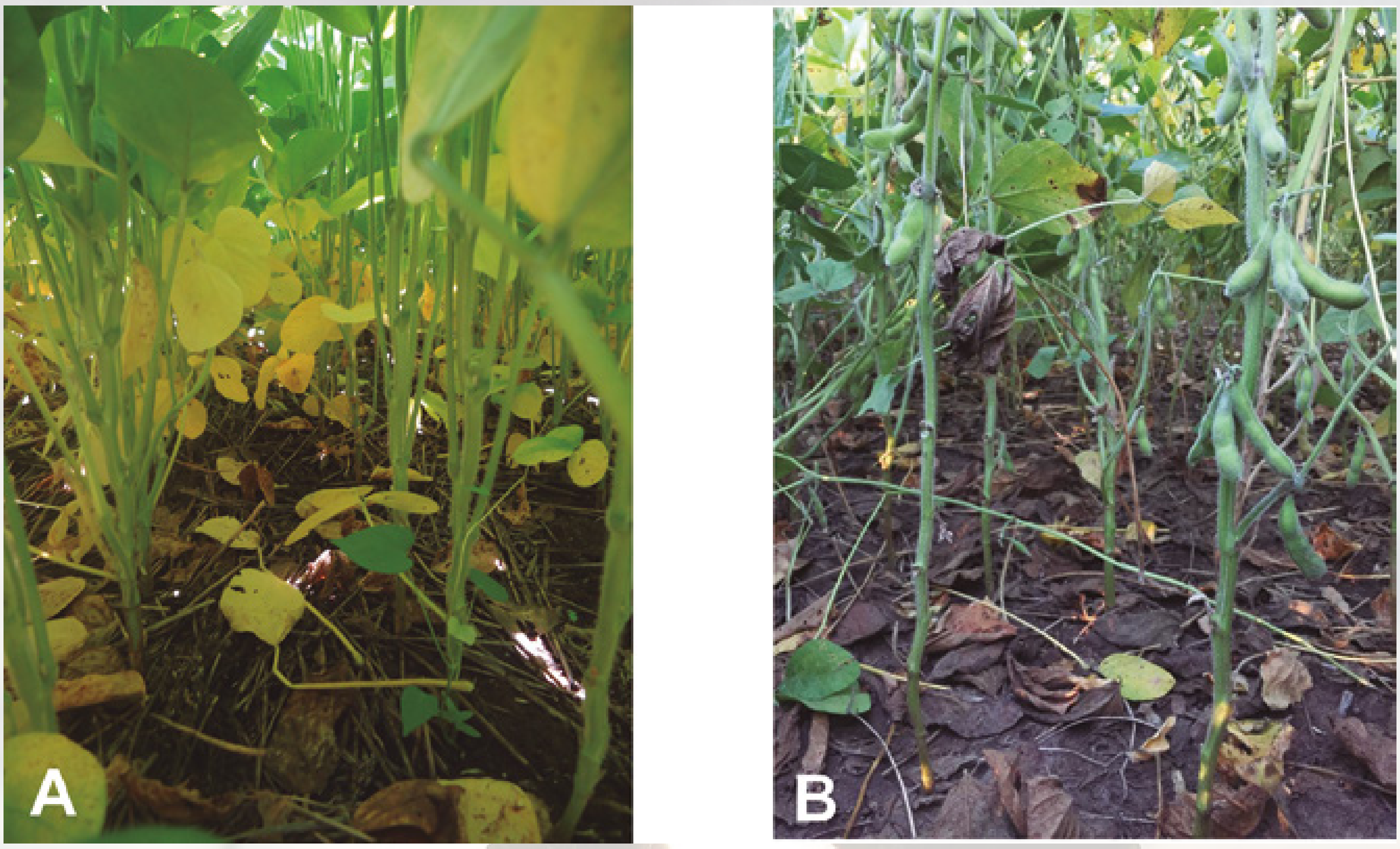


Figure 1.3.3.3. Early leaf senescence in soybean (A) causes reduced on pod fixation on the plant's lower tercile, that is, forming "shin" in the soybean plant (B).

The modification in plant physiology makes it more sensitive to attacks by pests and diseases. Therefore, it is necessary to monitor and prevent diseases and pests under favorable conditions, especially for species that infest flowers (thrips) and can cause their abortion.

In addition, the full flowering phase (R2) is most vulnerable to white mold incidence, a disease caused by *Sclerotinia sclerotiorum*, since the flower is used as the primary energy and food source by the fungus (Campos et al., 2010). Despite being a disease more frequent at altitudes above 600 meters and dependent on favorable conditions (high humidity and temperatures ranging between 10 and 21°C), its occurrence and impact have been increasing in almost all growing regions in the South and Midwest of Brazil (Meyer et al., 2018). In such cases, specific products are recommended for disease control, including fluazinam, procymidone, or dimoxystrobin.

From the flowering stage, there is a reduction in the plant's natural defense capacity, which leads to diseases initiated in the vegetative phase having an increased progression rate. Anthracnose is a critical disease at this stage, as the pathogen obstructs flower fertilization, resulting in gnarled and grainless pods. Additionally, diseases that may not have established themselves yet, such as Asian rust (in the case of early sowing), are more likely to occur after flowering due to greater host susceptibility (Figure 1.3.3.4). In such situations, a mix of carboxamides and strobilurins may be advised for a lower disease pressure scenario, or a mix containing triazoles or triazolinthione for a higher disease pressure scenario.

Similarly, this decrease in natural defenses allows the rise of pest infestations, including caterpillars, stink bugs, and whiteflies, as well as the presence of spider mites and especially thrips, which are often period-related. Specific control measures are generally required for these pests and an integrated management approach that addresses both traditional pests and those gaining importance for soybean crop.

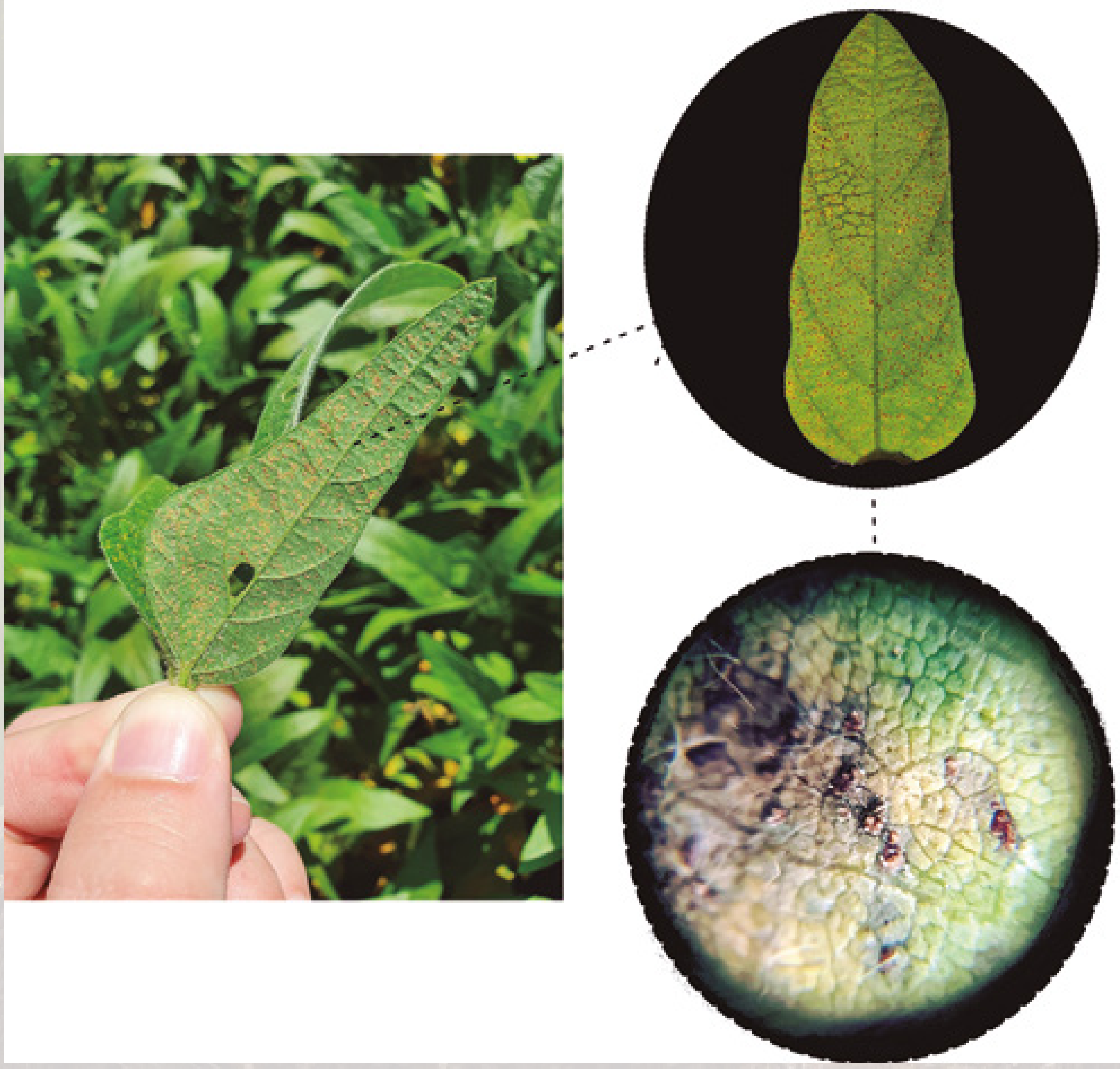


Figure 1.3.3.4. Asian rust symptoms (*Phakopsora pachyrhizi*) in soybean after flowering. Photo by: Felipe Ferri Michelon, Torres, Rio Grande do Sul, Brazil.

1.3.4. Pod formation phase (R3-R4)

This phase begins with the appearance of a pod with 0.5 cm in length (popularly known as “pocket knife”) and ends when a pod reaches 2 cm in length, located in one of the last 4 nodes with leaves developed on the main stem. At this moment, the number of pods per plant is being defined, as their fixation and development take place (Mundstock & Thomas, 2005). The plant starts directing photoassimilates to pod production. Therefore, it is crucial that there is neither water deficiency nor excess at this time, as the pod can be aborted if there is not enough water for its development. Long periods of under-soil water saturation, common in lowland soybean crops (in rotation with irrigated rice), can also lead to pod abortion. Pods’ abortion at this stage can cause an imbalance in the source-sink relationship, resulting in foliar retention in the soybeans’ maturation stage (see Figure 1.3.4.1). This occurs because pod drop prevents the translocation of stored photoassimilates in the leaves and stems to the grains, causing uneven plant maturation. Stink bug attacks at the beginning of pod formation (R3 and R4) can cause abortion and lead to gnarled pods that dry up and fall off.

However, other factors may be related to green stem disorders and leaf retention (see Figure 1.3.4.1), such as the use of certain fungicides for foliar disease management, especially rust, anthracnose, and late-season soybean diseases (LSSDs), potassium deficiency, nutritional imbalance, water stress (excess or restriction), high temperatures, and pest attacks, mainly from the stink bug - biotic agents associated with the soybean ‘greening effect’ (Silva et al., 2013). More recently, the occurrence of this disorder (called ‘green stem’) has been associated with the presence of the green-stemmed soybean nematode, *Aphelenchoides besseyi*. This nematode infects the aerial part of plants, leading not only to the green stem and leaf retention syndrome but also causing deformation of younger leaves, such as distortions, blistering, strapping, and vein thickening. Additionally, it results in flower and pod abortion (Meyer et al., 2017; Leme et al., 2019).

Figure 1.3.4.1. Green stem and leaf retention syndrome in the soybean plant after maturation. Photo by: Ioran Guedes Rossato and Emerson José Goin.

1.3.5. Grain filling phase (R5-R6)

It begins when the grains of a pod are 3 mm long and ends when a pod has fully developed grains filling the pod cavity at one of the last four nodes of the main stem with developed leaves, rain filling is a phase of rapid storage of dry matter and nutrients in the grains. In the R5 phase, there is the maximum leaf area index, root development, and nitrogen fixation by the bacteria present in the nodules. During this phase, plants have a high water requirement (5 to 7 mm day^{-1}) as the translocation of photoassimilates to the grains begins, which occurs through sap flow (water). Water deficit during this time can shorten the phase duration and injure grain filling, leading to the formation of "aborted" grains, thereby reducing grain weight and crop yield.

During grain filling, it is necessary to monitor pests and diseases, paying particular attention to stink bug attacks (Figure

1.3.5.1), end-of-cycle diseases (EOCDs), and soybean Asian rust. Due to their direct impact on grain quality, stink bug monitoring should occur more frequently, preferably through the use of the vertical beat-cloth, advising chemical management when the pest population reaches control levels (2 and 1 stink bug m^{-2} for grains and seed production, respectively) (Stürmer et al., 2012). Attacks at the beginning of the R5 stage cause grain abortion, reducing the number of grains per pod, while attacks at the end of this stage (R5.4 - R5.5) have the most significant impact on the thousand-grain mass and, consequently, on seed physiological quality (Figure 1.3.5.2.B).

In addition to stink bugs, attention should also be paid to the occurrence of mites and thrips, especially in seasons, regions, or locations with rain or humidity shortages. Recently, caterpillars have gained increased importance for the crop, particularly black caterpillars (*Spodoptera* species) and the *Helicoverpa* caterpillar (*Helicoverpa armigera*), which can cut and damage formed pods (Figure 1.3.5.2.A) or pods in formation. The soybean looper, of the Plusiinae species, is also noteworthy. *Chrysodeixis includens* was previously the most important among these species until the advent of Bt soybeans (*Bacillus thuringiensis* - Bt Cry1Ac). However, recent seasons have witnessed a change in this pattern, with the survival of the *Rachiplusia nu* looper (Figure 1.3.5.3) in some Bt soybean fields in different locations in Brazil, showing resistance to the toxin and necessitating control by insecticides, even in cultivars with the Cry1Ac gene. Nevertheless, with the new generation of biotechnologies for pest control, involving the addition of two more Bt proteins to soybeans (Cry1A.105 and Cry2Ab2), the complex of caterpillars Helicoverpa *armigera* and *Spodoptera cosmioides* has also started to be controlled by Bt technology, which is also effective in protection against *Anticarsia gemmatalis*, *Chrysodeixis includens*, *Crocidosema aporema*, *Chloridea virescens*.

Figure 1.3.5.1. Stink bug attack during the soybean grain-filling phase.

Figure 1.3.5.2. Soybean damage caused by caterpillar attack (A), pod and grain damage caused by stink bug attack (B).

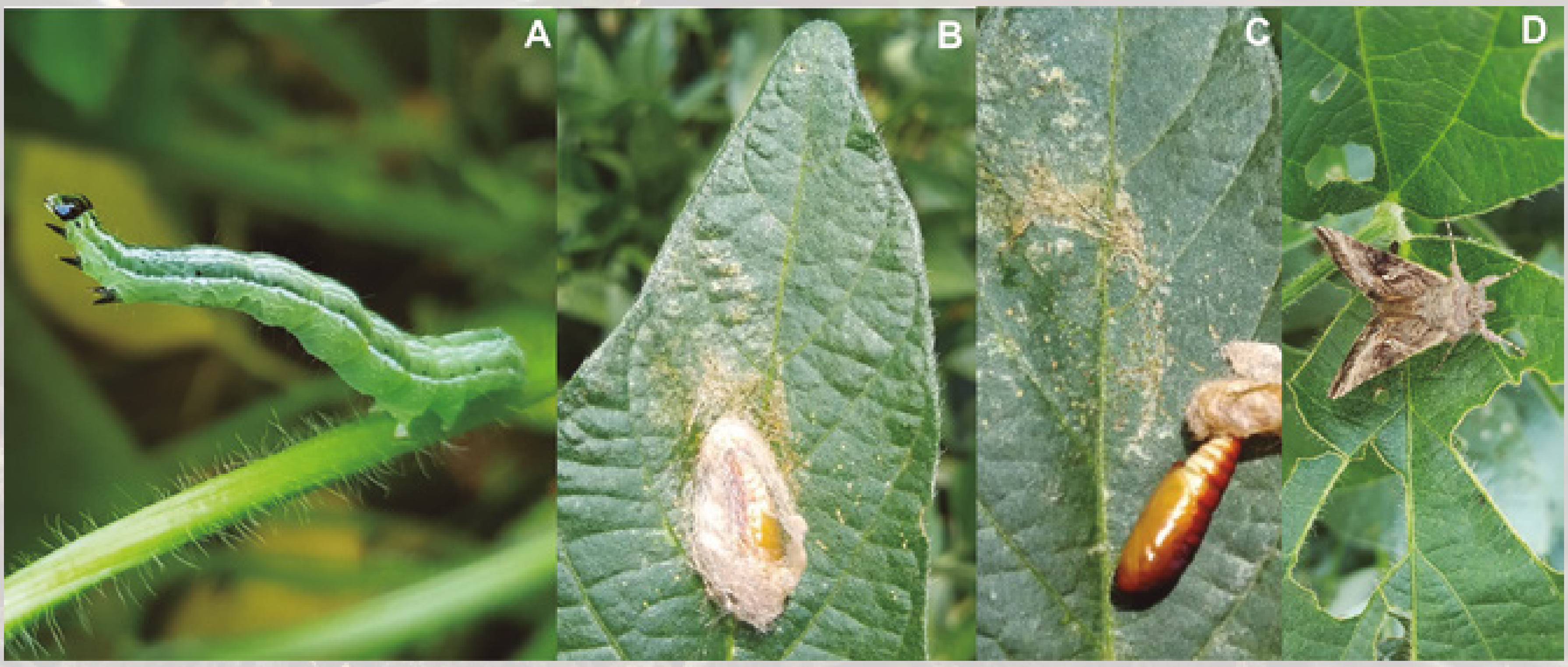


Figure 1.3.5.3. Caterpillar stage of *Rachiplusia nu* (A), pupa under the web on the soybean leaflet (B), dark brown pupa (C) and adult moth (D). Photo by: Marcelo da Silva and Elderson Ruthes.

During the grain-filling phase, the final fungicide applications are typically carried out, as diseases do not significantly impact yield after the end of grain filling (R5.5). With the availability of inoculum and favorable environmental conditions, particularly frequent rainfall, “end-of-cycle diseases” have their progress accelerated during grain filling. It should be noted that these diseases are established during the vegetative phase, but symptoms intensify during the grain-filling phase, leading to the mistaken classification of “end-of-cycle diseases.” Therefore, reducing inoculum through fungicide application during the vegetative phase is essential in regions or areas where there is a history of these diseases, provided there is a conducive pathogenic environment. Additionally, much of the pathogen inoculum causing leaf spot and anthracnose migrates from leaves, stems, and petioles to the pods during this phase, reaching the seeds. This can reduce germination and vigor while increasing the inoculum of these pathogens or introducing them in the next growing season.

Asian rust also progresses more rapidly during this phase. However, sanitary practices and crop management, such as sowing early cultivars at the beginning of the recommended period, can delay the onset of this disease. This reduces the interaction time between the pathogen and host, which is crucial for disease management. Regarding chemical control, it is important to consider that grain filling usually represents the phase of the greatest pressure and diversity of diseases that could be controlled. To alleviate disease pressure in the grain-filling phase, chemical control programs against leaf spot and rust can be implemented. Carboxamides should be avoided during this phase due to their low curative performance and fungi resistance to this chemical group. Mixtures of triazoles and strobilurins are good alternatives during this phase. Fenpropimorph morpholine is also an excellent option, as it has good curative action and acts at a different site of action than triazoles. Regardless of the systemic fungicide used, the inclusion of multisite fungicides in the chemical control program is an alternative during this period due to increased disease pressure.

During the grain-filling phase, photoassimilates are primarily directed to the grains, including those stored in reserve organs (leaves, petioles, and stem). This high flow to the drain structures increases the risk of phytotoxicity caused by some pesticides, such as the fungicide prothioconazole, necessitating additional care with combinations of products in mixture and consideration of environmental conditions at the time of application.

1.3.6. Physiological maturation phase (R7-R8)

The process initiates when a pod on the main stem attains mature color (which varies depending on the cultivar) and concludes when 95% of the pods on the main stem display mature color. During this period, the plants reach physiological maturity, signifying the maximum accumulation of dry matter in the grains. At this stage, plants cease to absorb water and nutrients. The pods start losing their green color, and the physical process of water loss continues until the ideal humidity for harvest (13 to 15% humidity) is achieved.

While the plants already harbor fully formed grains and key crop yield components, such as the number of pods per plant and the thousand-grain mass, are already defined, stink bug attacks at the full grain stage (R6) may lead to a reduction in the viability and vigor of the seeds (Scopel et al., 2017). Therefore, monitoring and managing stink bugs from this stage is justified only for seed production fields, aiming to maintain the physiological quality (germination and vigor) of the seeds to be produced.

In cropping systems where cover crops are cultivated during the inter-season, sowing over the yet-to-be-harvested soybean of certain crops such as oats, ryegrass, vetch, forage radish, clover, or intercropping of species (crop mix), among others, can be carried out. This management practice is implemented with the goal of promoting nutrient cycling and reducing the duration of bare soil, as the cover plants will be establishing themselves in the field after the soybean harvest.

For cropping systems in regions experiencing a well-defined drought season, where two summer crops are cultivated, there is a high risk of water shortages at the end of the second crop development cycle (corn or cotton). Consequently, many farmers perform soybean crop desiccation in the physiological maturation phase (after R7), aiming to shorten the soybean cycle and consequently extend the growth season for the second crop. In regions with water excess at this development stage, cultivars with tolerance to excess humidity are strongly recommended to prevent germination and/or rotting before harvesting the grains (Figure 1.3.6.1).

Figure 1.3.6.1. Soybean germination in the field before harvest.

Sementes Aurora field, in Cruz Alta, Rio Grande do Sul, Brazil, with yield of 6180 kg ha^{-1} in the 2018/2019 harvest. Courtesy: Maurício de Bortoli.

1.4. Soybean growth types

The type of soybean growth is defined by the overlap of the vegetative and reproductive phases. This overlap is determined by the period between the beginning of flowering and the emission of the last node on the main stem. The main factor that determines the type of growth in soybeans is the cultivar genetics (Setiyono et al., 2007). Bernard (1972) defined soybean growth type as the moment when the main stem ceases growth after the beginning of flowering (R1). This period is influenced by genotype, temperature, and photoperiod. Soybean cultivars can exhibit determinate, semi-determinate, and indeterminate growth types (Figure 1.4.1).

Figure 1.4.1. Soybean cultivar with a determined growth type (A) and a soybean cultivar with an indeterminate growth type (B). Note that in determinate growth type cultivars, the pods' stage is the same throughout the main stem, while in indeterminate growth type cultivars, there are pods at different formation stages.

Using datasets from the US Department of Agriculture Soybean Germplasm Collection, Bernard et al. (1998) classified cultivars on a scale ranging from "1" (very determined) to "5" (very indeterminate), according to the period in which vegetative growth ceases after the beginning of flowering. Cultivars with a value lower than 2.0 were classified as determined growth type, characterized by null or small stature growth after flowering. Cultivars of indeterminate growth type received a score higher than 2.5 due to nodes' emission and stem elongation until close to grain filling. Those with values between 2.0 and 2.5 were classified as semi-determined growth type (Bernard, 1972; Heatherly & Smith, 2004).

However, for soybean cultivars sown in subtropical environments before or after the recommended period, the length of the overlapping period over the vegetative and reproductive phases changes according to weather conditions. This can garble the types of growth characteristics described above (Zanon et al., 2016b). Determined growth type cultivars have a higher growth rate until the R1 stage, resulting in greater plant stature and a greater number of nodes (NN) at the beginning of flowering. In contrast, indeterminate type cultivars show slower initial growth but stop growing close to grain filling beginning (Zanon et al., 2016b). In Figure 1.4.2, it can be seen that the lowest NN in R8 occurs for soybean determined growth cultivars sown in September (before the preferential season) because plants exposed to a short photoperiod in late September and early October are induced to flower early and, consequently, cease nodes emission a few days after R1. On the other hand, indeterminate growth type cultivars, despite being induced to flowering, still emit nodes until the grain filling beginning (Figure 1.4.2).

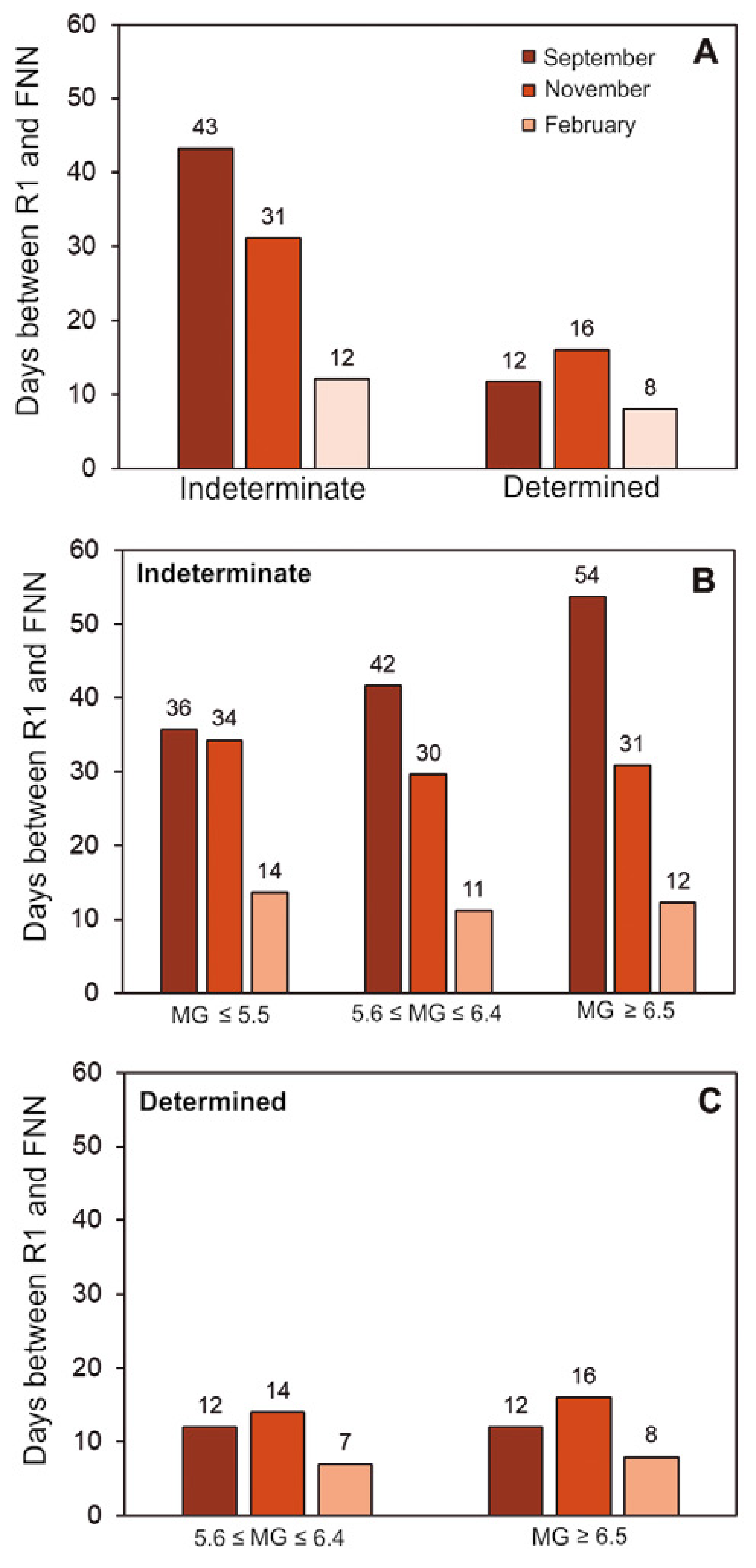


Figure 1.4.2. Overlap, in days, between flowering beginning (R1) and the final nodes number (FNN) in soybean cultivars sown in September, November, and February in Santa Maria, Rio Grande do Sul, Brazil. Adapted from Zanon et al. (2016b).

In short, growth in stature, the number of nodes emitted between R1 and R8, and the duration of overlap between vegetative and reproductive phases are greater for indeterminate growth type cultivars compared to determined growth type cultivars. In southern Brazil, the magnitude of the overlap decreases with a delay in sowing time for indeterminate cultivars and practically does not vary for determined cultivars (Figure 1.4.3 and Figure 1.4.4). In tropical environments, the overlap period between vegetative and reproductive phases, height, and the emission of nodes between R1 and R8 show little variability under different sowing schedules.

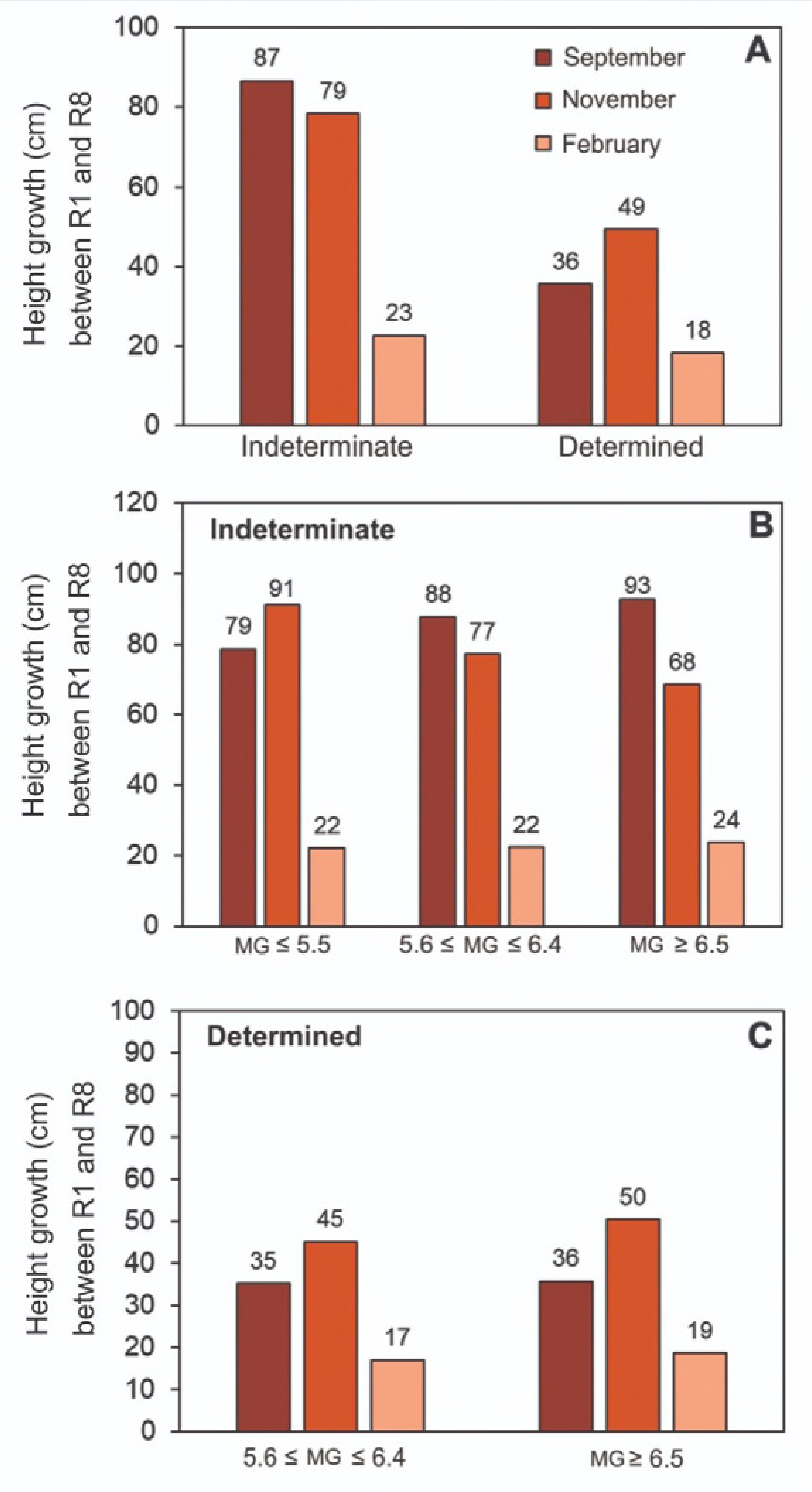


Figure 1.4.3. Difference in height growth (cm) between R1 and R8 in soybean cultivars sown in September, November and February in Santa Maria, Rio Grande do Sul, Brazil. Adapted from Zanon et al. (2016b).

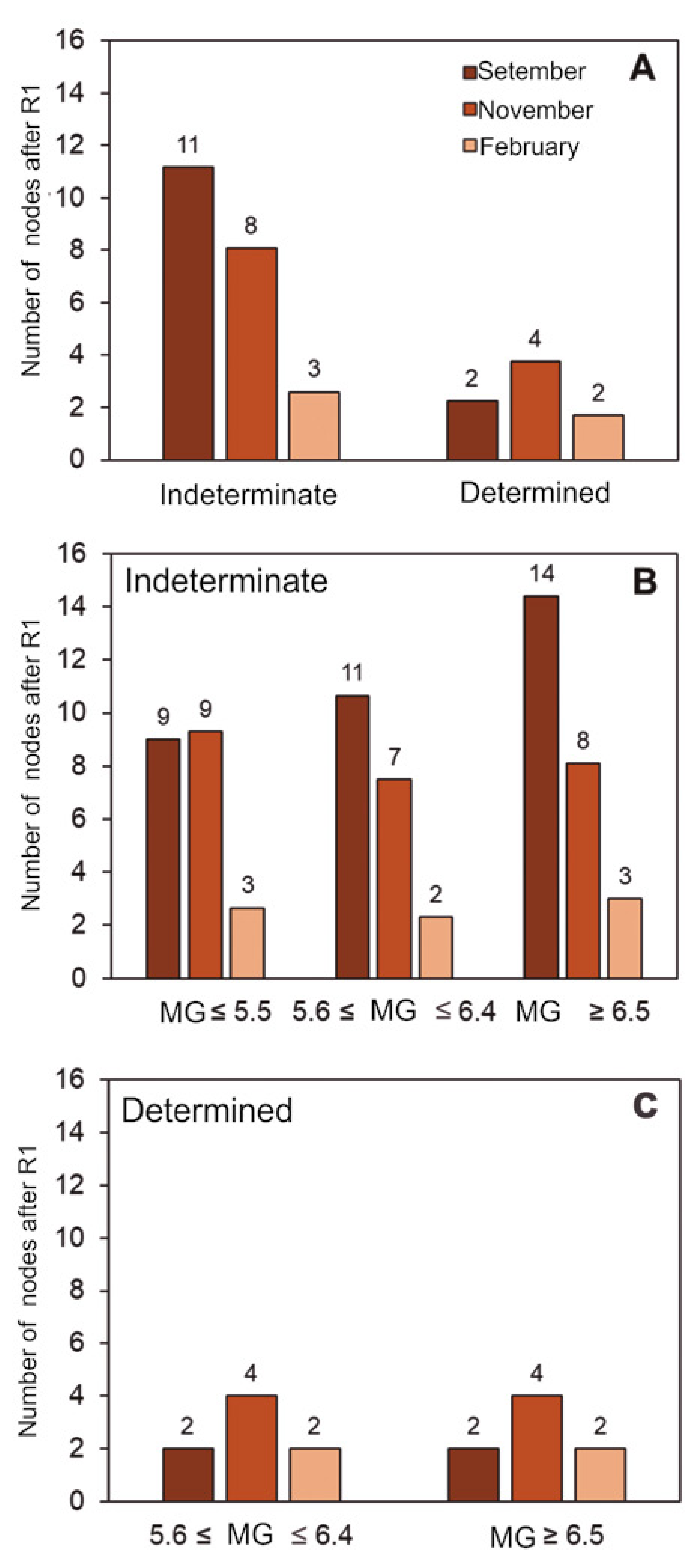


Figure 1.4.4. Difference in the nodes number between R1 and R8 in soybean cultivars sown in September, November and February in Santa Maria, Rio Grande do Sul, Brazil. Adapted from Zanon et al. (2016b).

The wide range in soybean growth and development in southern Brazil after the beginning of flowering is linked to the wide range of MG (4.7 to 8.2), sowing dates (September to February), and growth types that can be used (Figure 1.4.5). Results found at higher latitudes (38°N) by Egli & Leggett (1973) or close to them (33°N) by Heatherly & Smith (2004) demonstrate that determined growth type cultivars present more than 70% of the final height and emit more than 80% of the total nodes from the main stem up to R1. In contrast, cultivars of indeterminate growth type present less than 50% of the final height and less than 60% of the final number of nodes up to R1. Thus, there is clear importance in adapting management practices, such as choosing the type of growth and MG depending on the sowing time and farming region.

Figure 1.4.5. soybean growth types at sowing carried out in September, in southern Brazil, showing Indeterminate growth type cultivar (left) and determined growth type cultivar (right).

When early or late sowings are carried out in subtropical regions, knowledge of the variability between growth types is essential to achieve maximum yields, as height and NN characteristics are determining factors for cultivar adaptation, management operations, and consequent yield potential expression. For subtropical environments, such as southern Brazil, indeterminate growth type cultivars cease nodes production around the R5 stage (Figure 1.4.6). On the other hand, for determined growth type cultivars, the final number of nodes comes closer to the R2 stage in sowings from September to November and to the R3 stage in sowings from December to February, showing that there is variation in development according to the sowing tim (Figure 1.4.7).

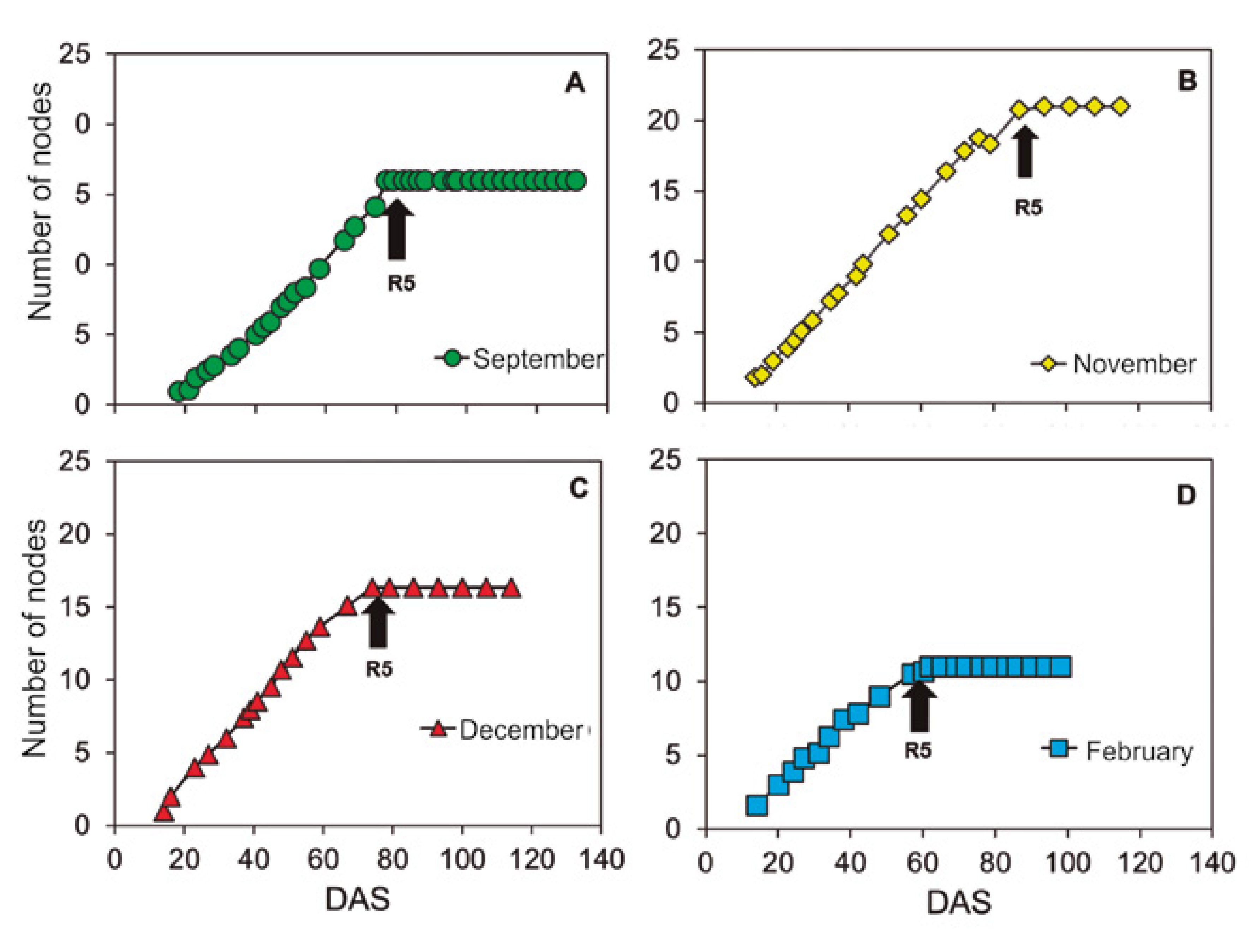


Figure 1.4.6. Evolution of nodes number at the soybean main stem as a function of days after sowing (DAS) for an indeterminate growth type cultivar sown in September (A), November (B), December (C) and February (D) in Santa Maria, Rio Grande do Sul, Brazil.

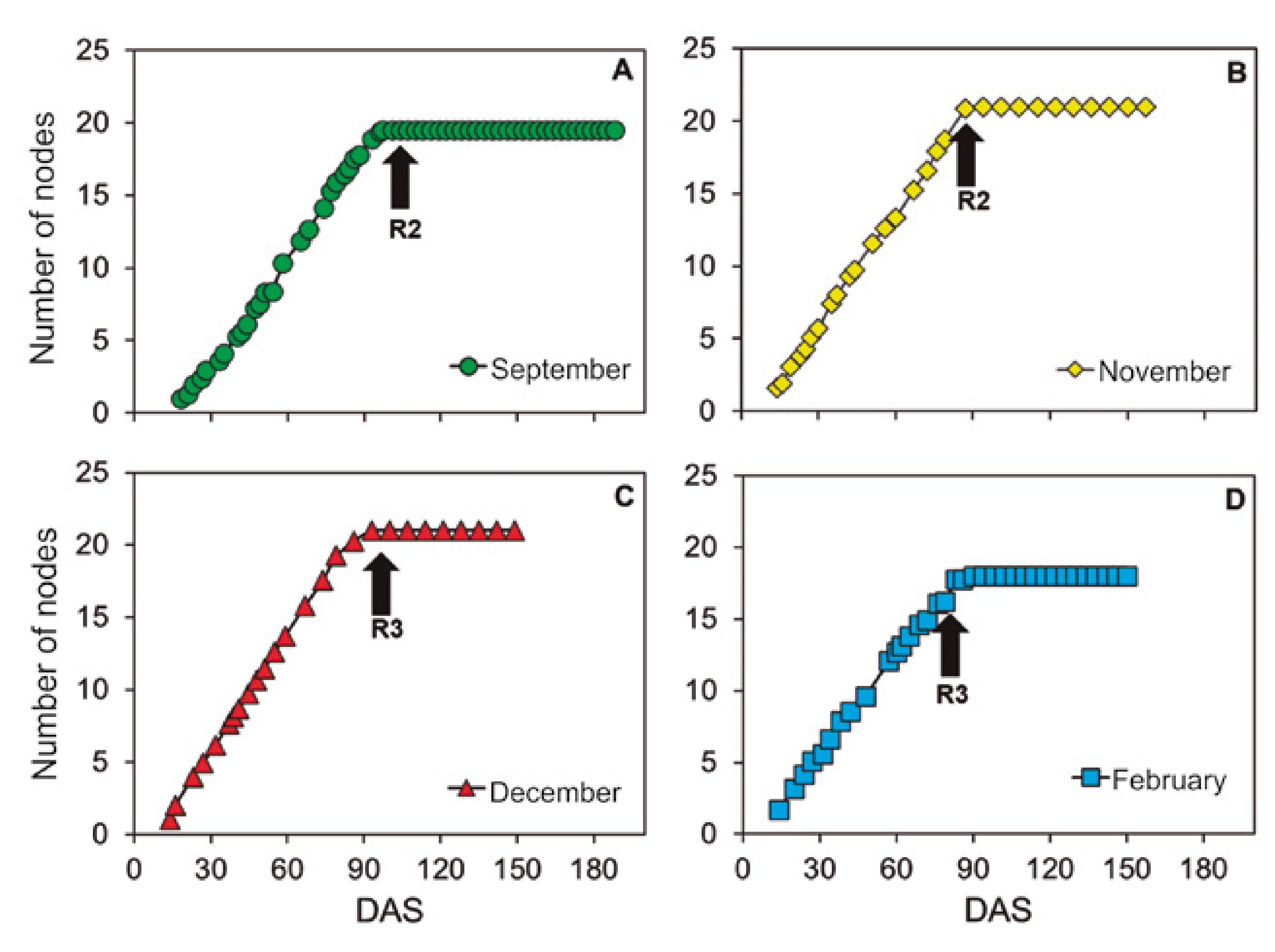


Figure 1.4.7. Evolution of nodes number at the soybean main stem as a function of days after sowing (DAS) for a determinate growth type cultivar sown in September (A), November (B), December (C) and February (D) in Santa Maria, Rio Grande do Sul, Brazil.

The emission of new leaves after R1 for indeterminate growth type cultivars causes strong competition for the drain of photoassimilates between the leaves emitted after R1 (upper stratum) and the fixation and growth of the plant's reproductive structures. For this reason, indeterminate growth type cultivars have leaves with a shorter lifespan and size in the upper tercile compared to the other leaves (Figure 1.4.8) (Winck et al., 2020). This differentiation of the upper leaves of indeterminate growth type cultivars gives the plants a more accentuated pyramid shape, allowing solar radiation penetration and the penetration of phytosanitary products into the middle stratum leaves of the canopy.

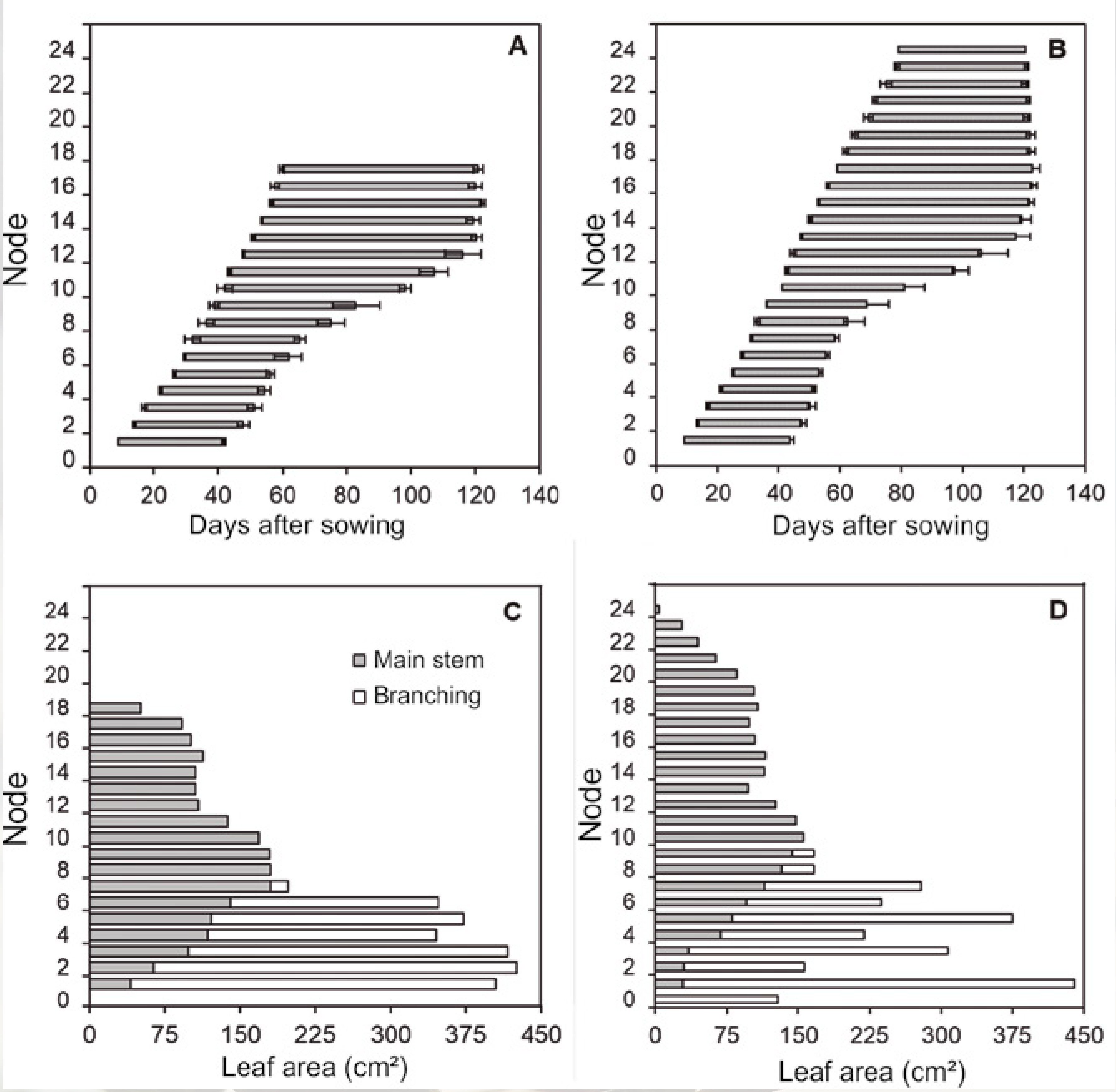


Figure 1.4.8. Lifespan of each main stem trifoliate leaf of a determined growth type soybean cultivar with MG 6.2 (A) and indeterminate growth type soybean cultivar with MG 6.3 (B) and leaf size of a determined growth type cultivar (C) and indeterminate growth type (D). Adapted from Winck et al. (2020).

As indeterminate growth type cultivars have a longer flowering and grain-filling period (Figure 1.4.9), an early beginning of grain dry matter accumulation in the lower parts of the soybean plants and less abrupt grain accumulation (Figure 1.4.10), in the lower parts of the plants, and less abrupt grain accumulation (Figure 1.4.10) than cultivars with the determined growth type, it can be deduced that these cultivars have greater stability, with a greater capacity to adapt to adverse growing conditions, such as anticipation or delay in the sowing date, as well as short periods of water stress caused by the absence of rain or water excess in the soil. These characteristics allow us to understand why, in the last 20 years, there has been an inversion of the adoption of indeterminate growth type cultivars of soybeans sown in Brazil. In southern Brazil, where droughts are frequent, the use of soybean indeterminate growth type cultivars has increased since the 2000s, and currently, they represent more than 90% of the cultivars sown by farmers. In the Brazilian Central-West Region, indeterminate growth type cultivars occupy more than 50% of the cultivated area, while in the North Region, determined growth type cultivars predominate.

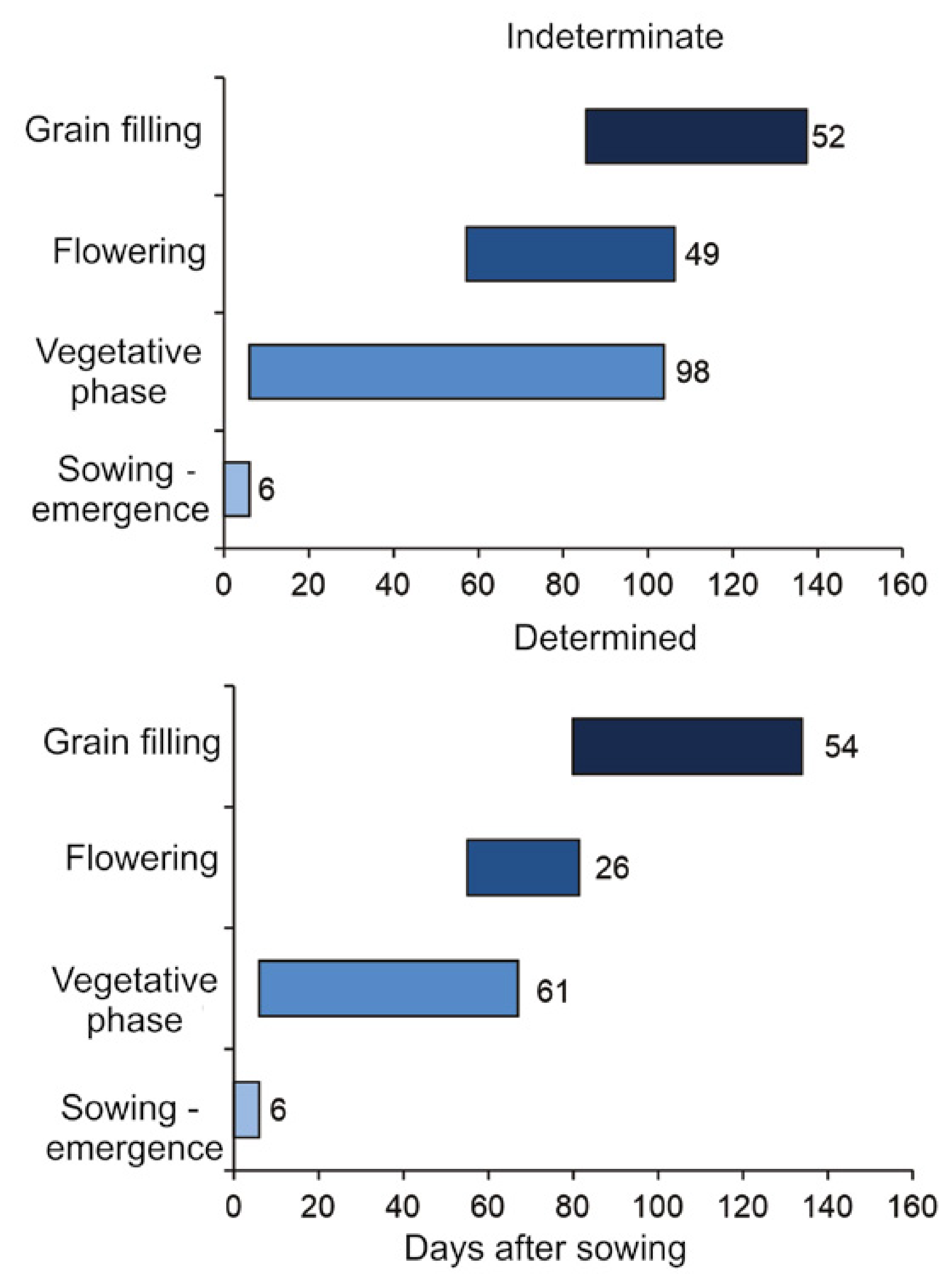


Figure 1.4.9. Phases duration of an indeterminate growth type soybean cultivar and a determined growth type soybean cultivar. Adapted from Rocha et al. (2017).

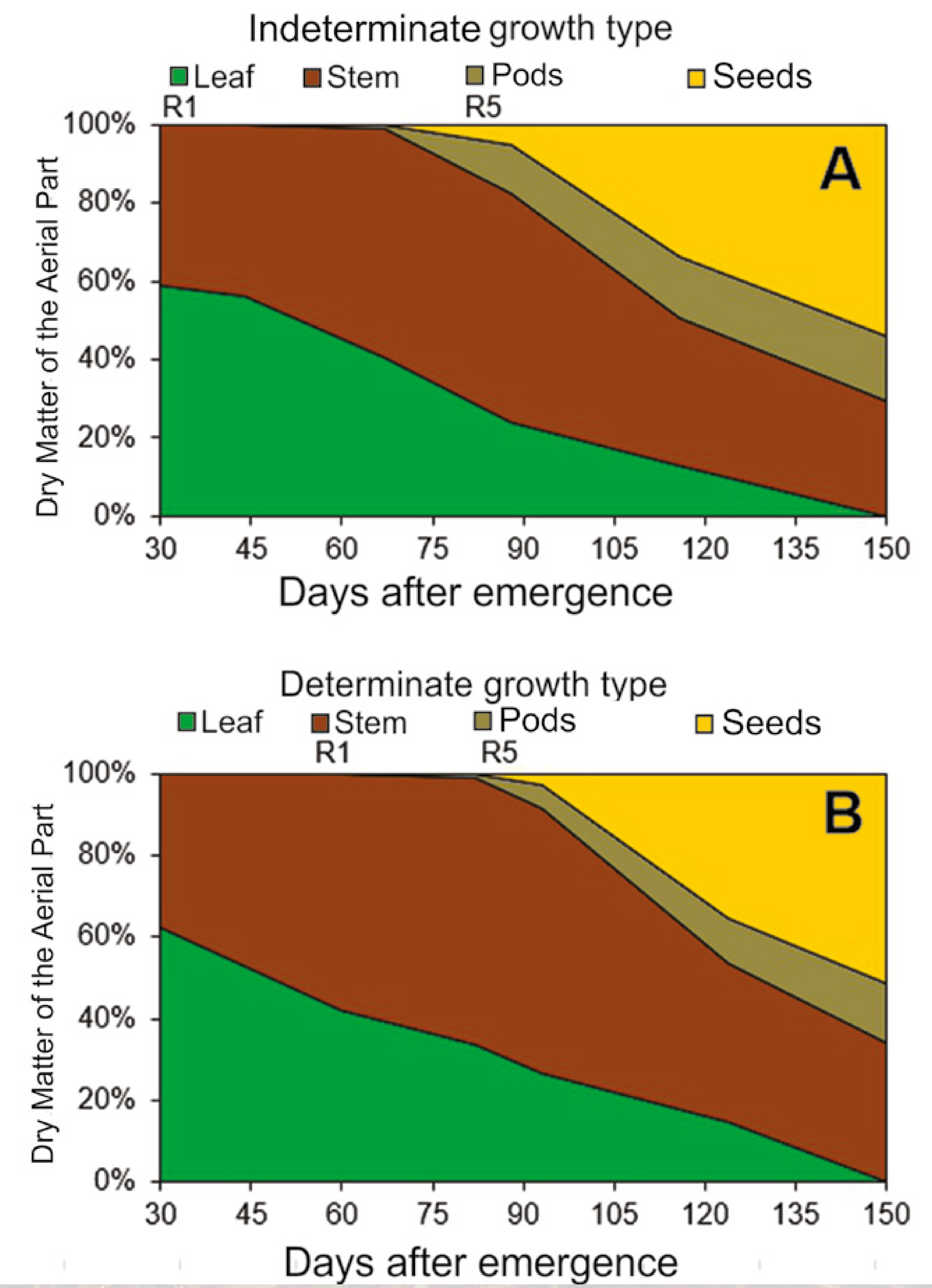


Figure 1.4.10. Shoot plant partition of dry matter in an indeterminate growth type soybean cultivar (A) and in determinate growth type soybean cultivar (B).

Courtesy: Michel Rocha da Silva

1.5. Maturity Group (MG)

Since the enactment of the Cultivar Protection Law in 1997, soybean breeding programs have been established by private companies in Brazil. These programs have begun releasing a substantial number of cultivars each new agricultural season and have proposed a new classification for the soybean development cycle duration (Alliprandini et al., 2009). Subsequently, the traditional approach used in Brazil to describe soybean relative maturity—categorized as super-early, early, medium, semi-late, and late cycles (Alliprandini et al., 1994)—started to give way to the new classification into relative maturity groups (MG), similar to that developed and used in the United States of America (Poehlman, 1987). This shift was prompted by the realization that the cycle's classification could not effectively describe relative maturity across the diverse environments and latitudes found in the soybean cultivation areas of Brazil (Alliprandini et al., 2009).

The relative maturity group represents the duration of the soybean development cycle (from sowing to physiological maturity, in days). It is mainly determined by the photoperiod cultivar response, crop management practices, and the general area of adaptation for soybean cultivars. The new MG classification provides a more realistic representation of the factors influencing the duration of the development cycle in soybean plants. In the first scientific work employing the MG approach in Brazil, Alliprandini et al. (2009) evaluated a commercial cultivars group across various locations (different latitudes and altitudes). The goal was to quantify genotype/environment interactions and classify them into different MGs based on the development cycle duration (Figure 1.5.1). This commercial cultivars group was termed "standard cultivars," and soybean breeding programs in Brazil now use these cultivars to classify releases in the annual soybean crop chain. In this classification, the lowest MG cultivars (from 4.5 to 7.0) are recommended for the subtropical region of Brazil, while the highest MG cultivars (from 6.5 to 10.0) are indicated for tropical regions near the equator.

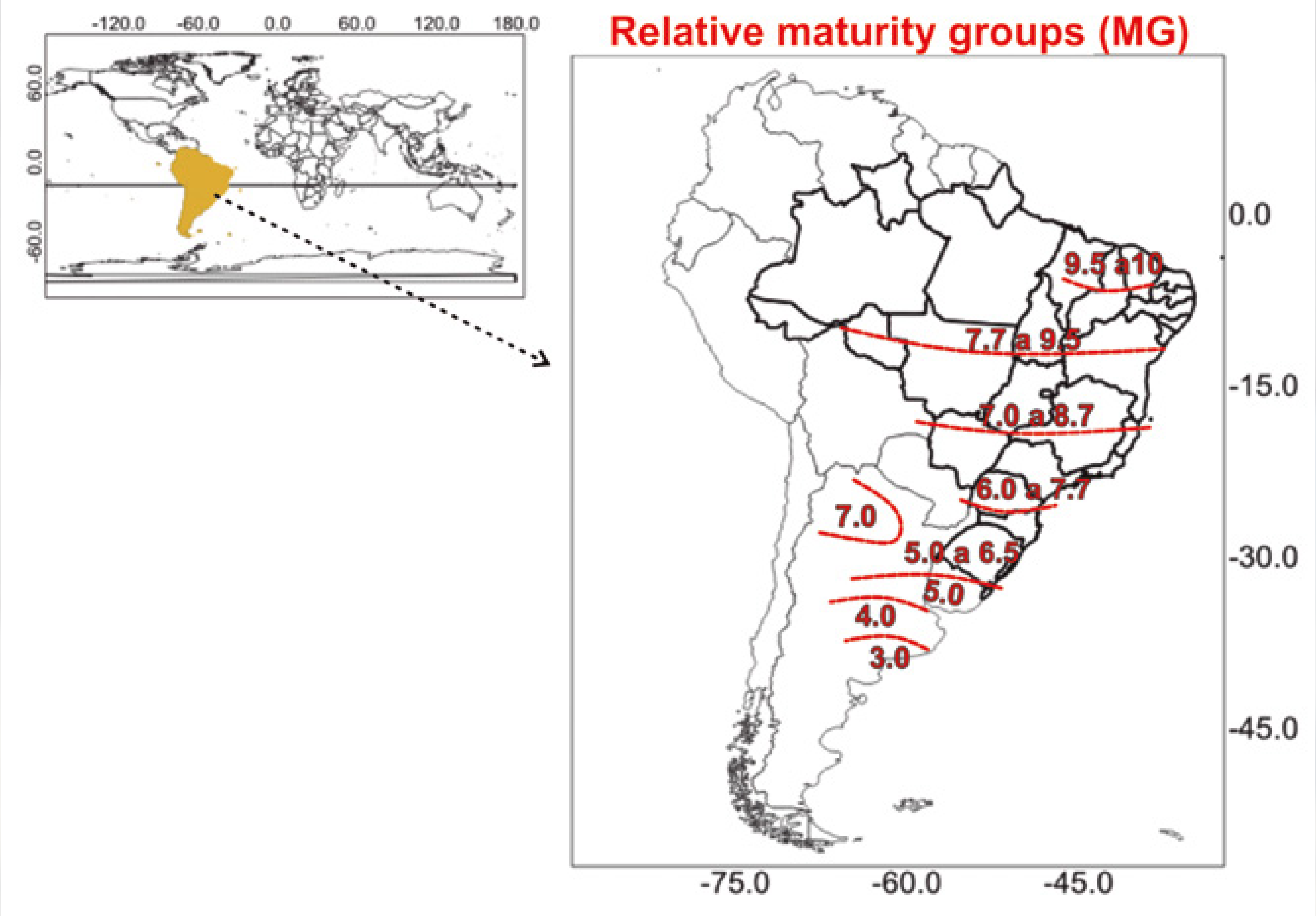


Figure 1.5.1. Soybean cultivars maturity groups distribution at Latin America. Adapted from Grassini et al. (2021).

When different MG cultivars are sown in the same region, it is expected that for higher MGs, the cultivar development cycle will be longer (Figure 1.5.2) (Zanon et al., 2015b).

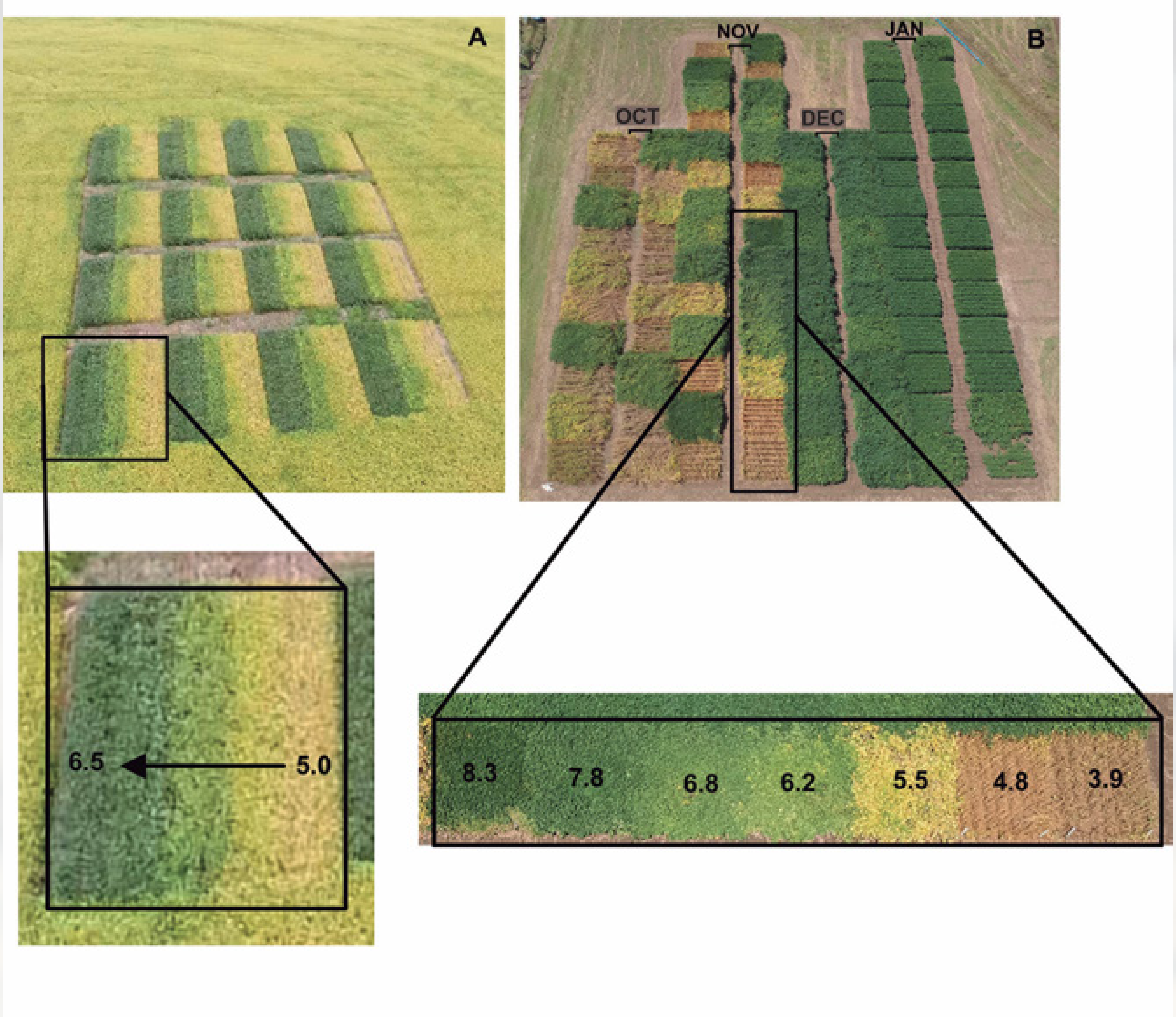


Figure 1.5.2. Evolution of the soybean cultivars development cycle for different maturity groups (MG) at October sowing on Coxilha, Rio Grande do Sul, Brazil (A) and at different sowing times (October, November, December and January) on Santa Maria, Rio Grande do Sul, Brazil (B).

In cases of delayed sowing compared to the ideal time, a reduction in development cycle duration is observed, irrespective of the cultivar's MG (Figure 1.5.3). However, the extent of cycle reduction varies by region, with greater variation in southern Brazil influenced by a broader photoperiod amplitude and a more extended sowing season (September to February). In the Central-West region of Brazil, the cycle reduction is smaller due to a more consistent photoperiod throughout the growing season (September to November), influenced by off-season production systems and the Sanitary Void Law.

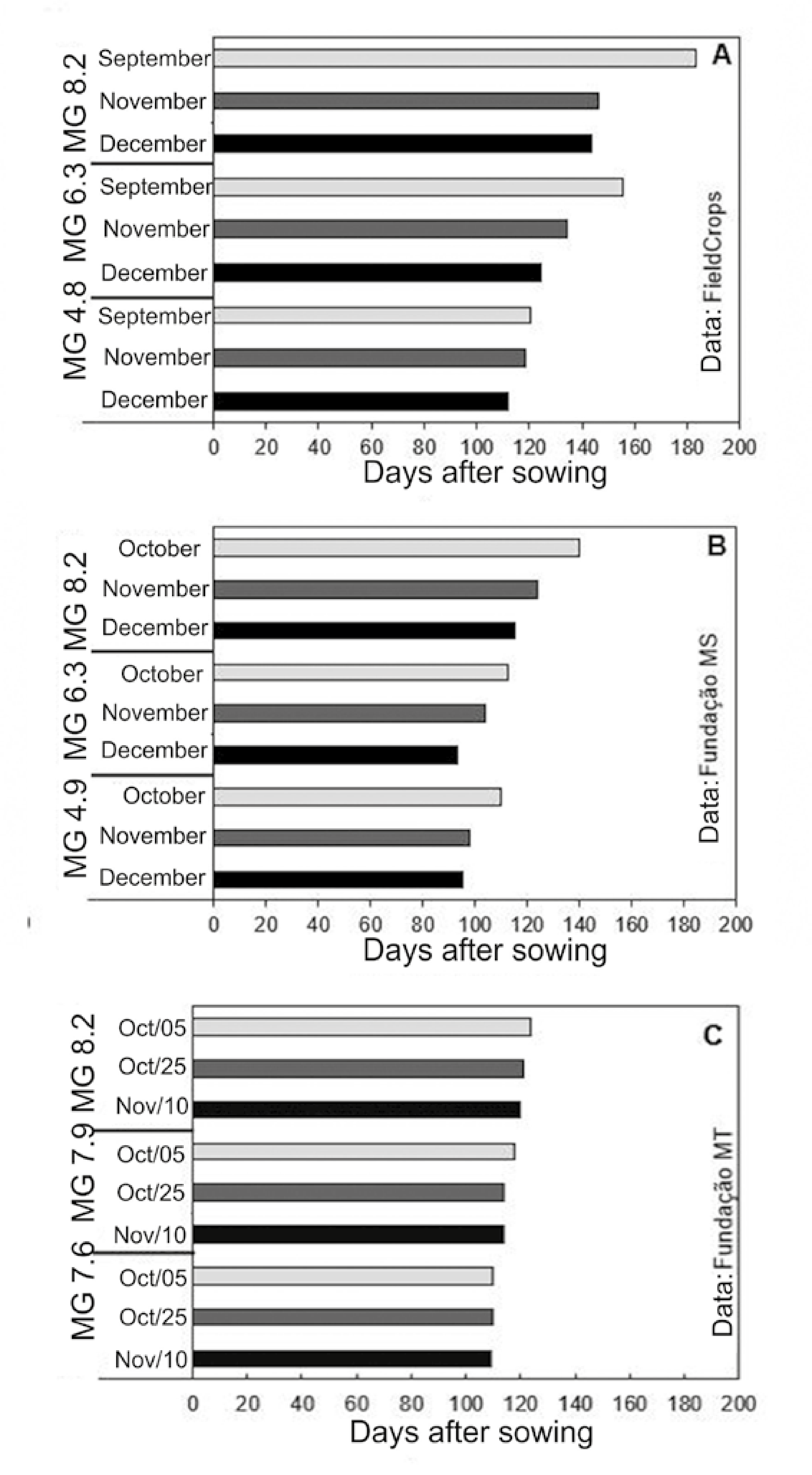


Figure 1.5.3. Development cycle duration, in days, of three soybeans maturity groups (MG) sown in Santa Maria, Rio Grande do Sul, Brazil (A), Maracaju, Mato Grosso do Sul, Brazil (B) and Sorriso, Mato Grosso, Brazil (C), at different sowing times.

Despite the maturity group (MG), there was a reduction in the soybean cultivar development cycle resulting from delayed sowing. This cycle reduction occurs by shortening the durations of various phases, starting with emergence, which happens more rapidly with delayed sowing due to increased soil temperature. In the vegetative phase (VC - Vn), influenced by photoperiod and temperature, there is a reduction in phase duration with an increase in photoperiod induction from September to January (Figure 1.5.4). The pod formation phase (R1 - R5) experiences the most significant reduction with delayed sowing, decreasing by 48 days in September, 25 days in November, and 15 days in January for MG 6.8. For MG 5.5, the reduction is 28, 24, and 16 days, respectively. The grain-filling phase (R5 - R8) exhibits the least variation across sowing seasons (Figure 1.5.4), as it is primarily controlled by the genetic characteristics of the cultivars.

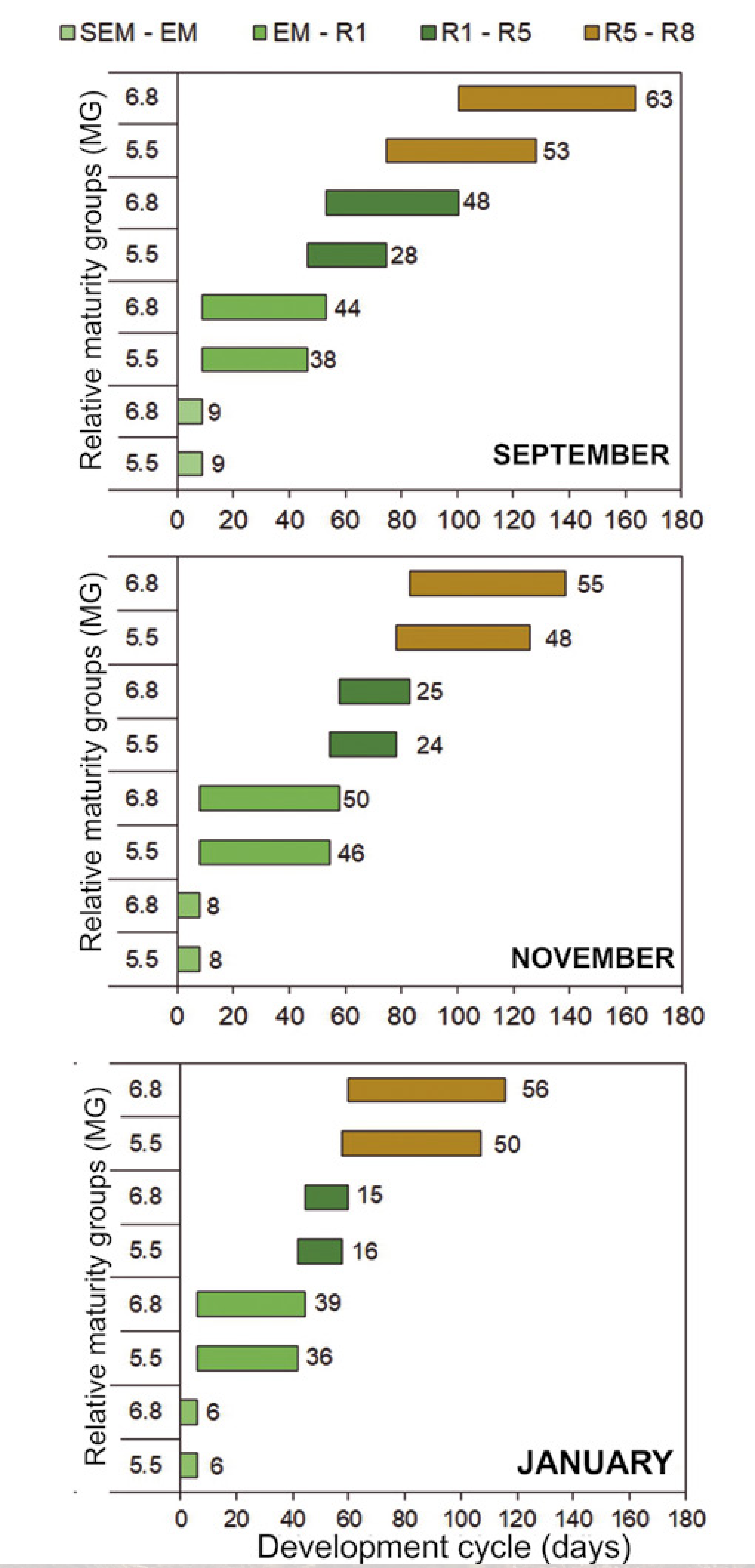


Figure 1.5.4. Developmental stages duration, in days, of soybean MG 5.5 and 6.8 cultivars at different sowing dates in Santa Maria, Rio Grande do Sul, Brazil. Source: Field Crops Team.

The MG classification significantly enhances the accuracy of estimating the development cycle duration for soybean cultivars when sown near the first half of November (Alliprandini et al., 2009). However, the accuracy diminishes for sowings conducted in late September and early October or after the second half of December in the subtropical latitudes of southern Brazil. This reduced accuracy results from temperature and photoperiod variations due to extreme (early or late) sowing schedules and cultivar genetic characteristics (juvenility) (Zanon et al., 2015b).

Observations from sowing time experiments and fields where sowings occurred before or after the first half of November indicate that the development cycle increases for early sowings and decreases for late sowings, regardless of the MG of the sown cultivar (Figure 1.5.5). The magnitude of this cycle variation varies among MGs, with greater differences observed in sowings before the first half of November, diminishing with sowing delay (Figure 1.5.5).

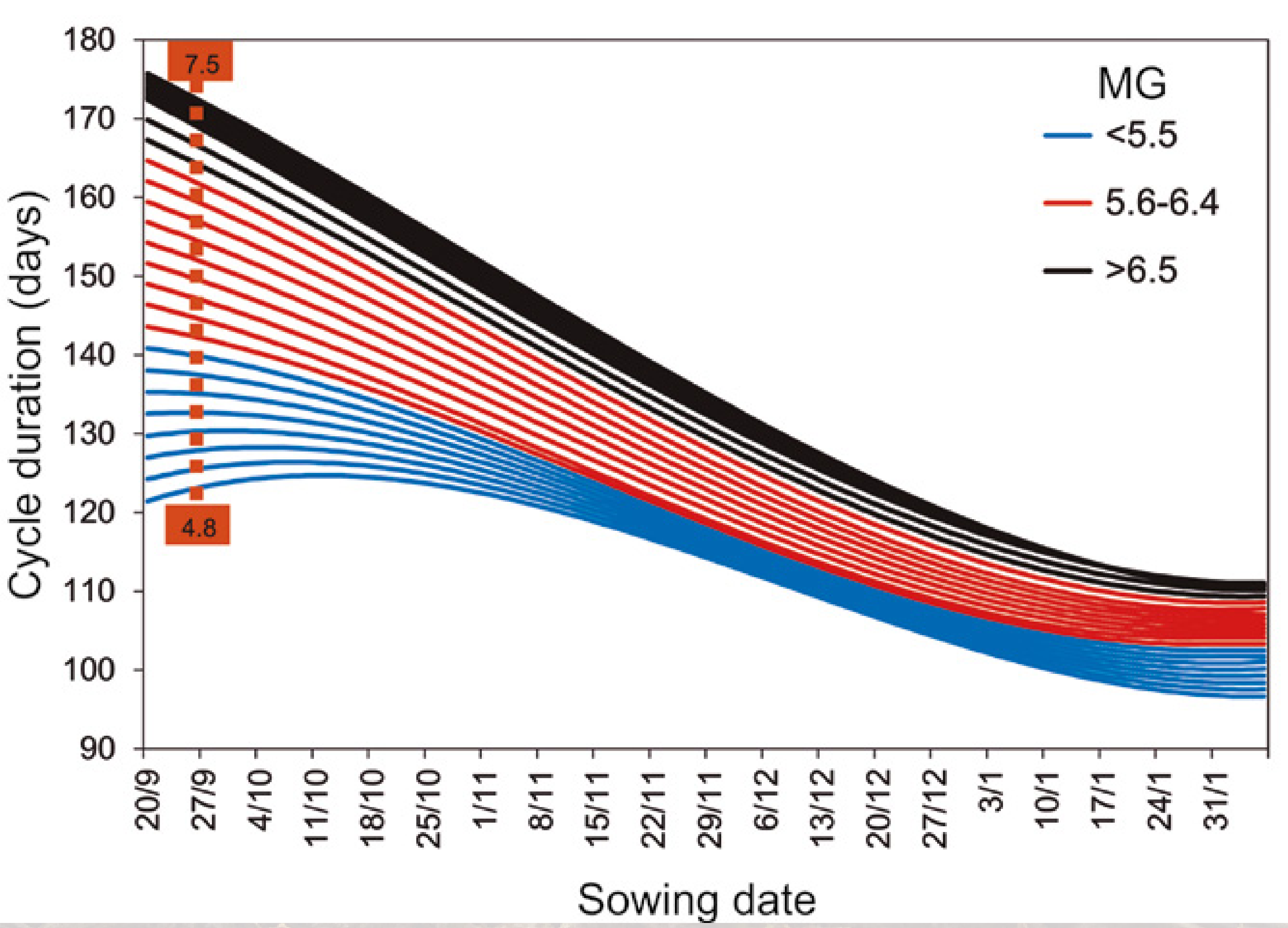
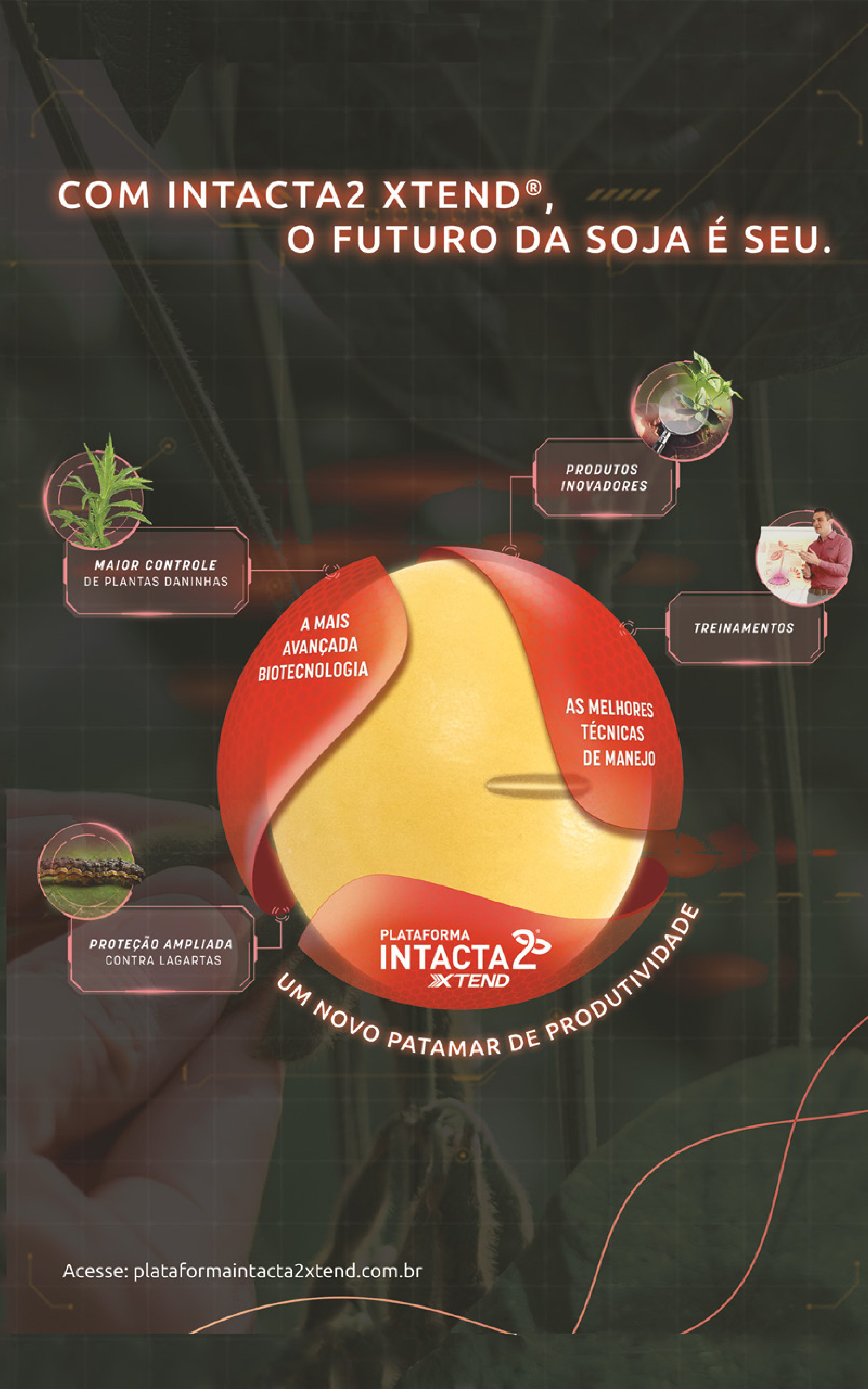


Figure 1.5.5. Duration, in days, of development cycle of the maturity groups 4.8 to 7.5 at different sowing times for southern Brazil.

Therefore, for a soybean field sown outside the first half of November (which defines the MG of a new cultivar), Table 1.5.1 provides values to estimate the development cycle duration in southern Brazil.

Table 1.5.1. Soybean development cycle duration of the, in days, with different MGs sown in October, November, December and January in southern Brazil (cycle estimated for the 15th of each month).

	Cycle duration (days)			
MG	**October**	**November**	**December**	**January**
4.6-5.0	126	119	109	100
5.1-5.5	132	122	111	103
5.6-6.0	140	126	114	106
6.1-6.5	148	132	118	109
6.6-7.0	157	139	124	113
> 7.0	160	142	125	114



1.6. Cultivars - Adaptability and Stability

The increase in soybean yield can be attributed to the development of more productive cultivars, environmental changes resulting from climate change, or improvements in crop management by farmers. In this context, the choice of cultivar stands as a fundamental step toward the success and profitability of the crop.

The cultivar grain yield is only known in comparison to other cultivars. This is because the yield has at least three main components: genetic (cultivar), environmental (site conditions and year of cultivation), and the interaction between genotype (cultivar) and the cultivation environment (GxE). The GxE interaction implies that the yield of a cultivar varies in different growing environments and, therefore, should be determined for a large number of environments. These environments are categorized by their average and considered favorable, with a higher average, and unfavorable, with a lower average than the general average of all evaluation environments.

A linear regression model between the release year of cultivars and crop yield, based on information from 854 crops, 5 harvests, and 86 cultivars recorded in MAPA[3] between 2008 and 2019 (Figure 1.6.1), showed a yield increase of 41.4 kg ha^{-1} yr^{-1} ttributed to genetic improvement in soybeans grown in Rio Grande do Sul State (BR). Similar yield increases, close to 40 kg ha^{-1} yr^{-1} due to genetic improvement, were found for Brazil in data analysis from 1965 to 2011 (Todeschini et al., 2019). In Argentina, between 1980 and 2015, the yield improvements due to genetic enhancement were approximately 43 kg ha^{-1} yr^{-1} (Felipe; Gerde; Rotundo, 2014) while for the United States, the gains are approximately 29 kg ha^{-1} yr $^{-1}$ (Specht et al., 2014).

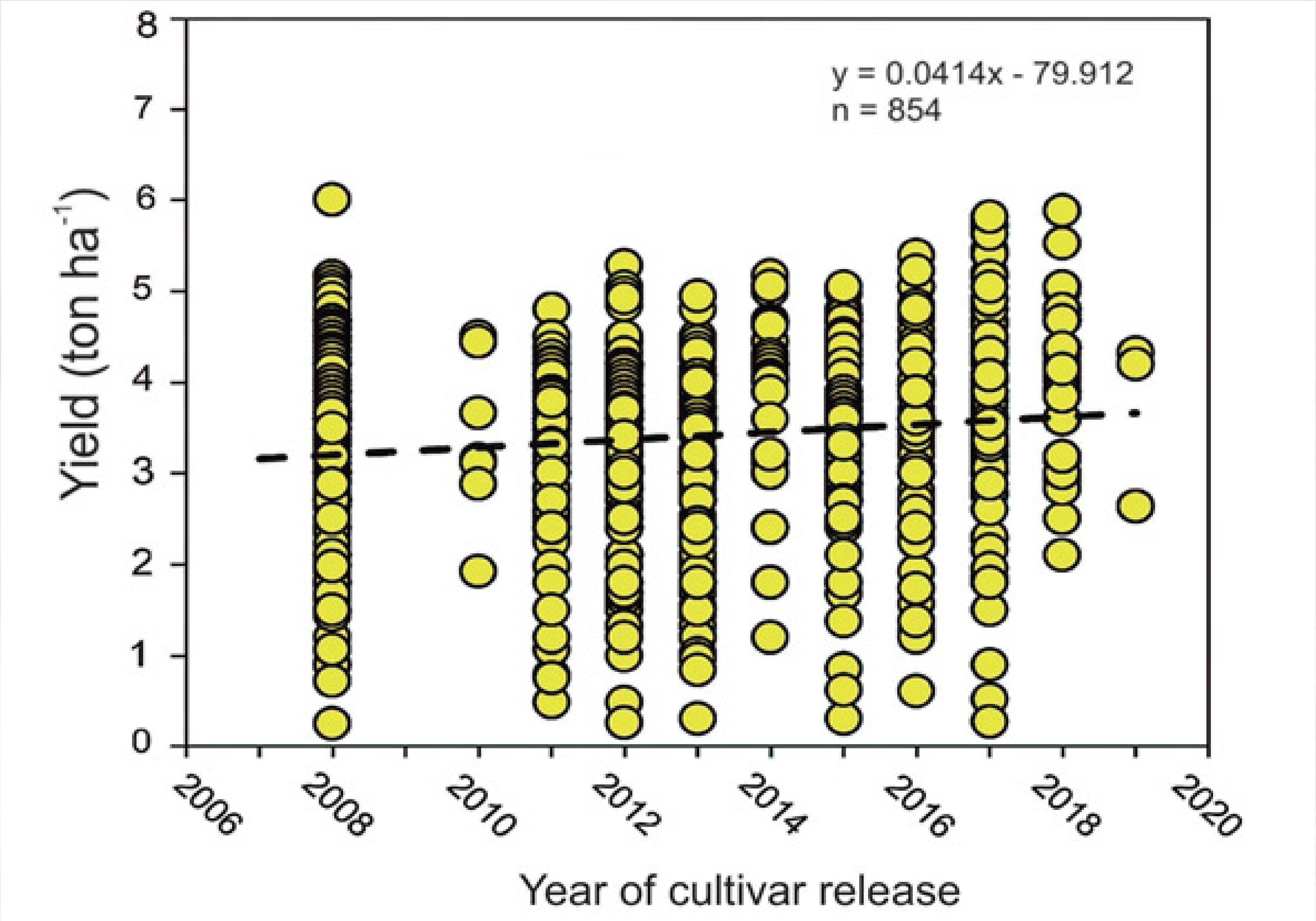


Figure 1.6.1. Yield increase by genetic improvement estimated by 854 fields regarding the soybean cultivars release year.

From 2019 to 2022, Brazil increased the number of registered cultivars in the National Registry of Cultivars from 2042 cultivars in 2019 to 4033 cultivars in February 2022 (MAPA, 2022). This increase is mainly due to the emergence of new breeding companies and new biotechnological programs in Brazil (INTACTA2 XTEND®, HB4®, Libert Link®, Enlist®, and Conkesta®). With the release of such a large number of cultivars, the expected yield increase from genetic improvement in the coming years may reduce, as commercial competition between companies could lead to the release of cultivars with new biotechnologies and lower genetic gains.

The proliferation of cultivars raises concerns and uncertainties for producers when deciding which one to use for their crops. Results from the FieldCrops team demonstrated that there might be differences of more than 100% in yield between the best and worst cultivar for a given production environment (Ribeiro et. Al., 2021; Winck et al., 2021).

Soybean cultivars differ in terms of adaptability and stability (Figure 1.6.2). Adaptability of a cultivar is defined as its capacity to respond advantageously to the local environment. High adaptability means that a cultivar responds well to improvements or management of the environment. Cultivars with high adaptability approach their productive potential in a favorable environment; however, when grown in an unfavorable environment, the reduction in yield can be higher (Eberhart & Russell, 1966). The concept of stability is related to the predictability of behavior in different environments. Cultivars with high stability show smaller variations in yield when grown under different environmental conditions, indicating that a cultivar is considered stable if the yield is relatively constant in different environments.

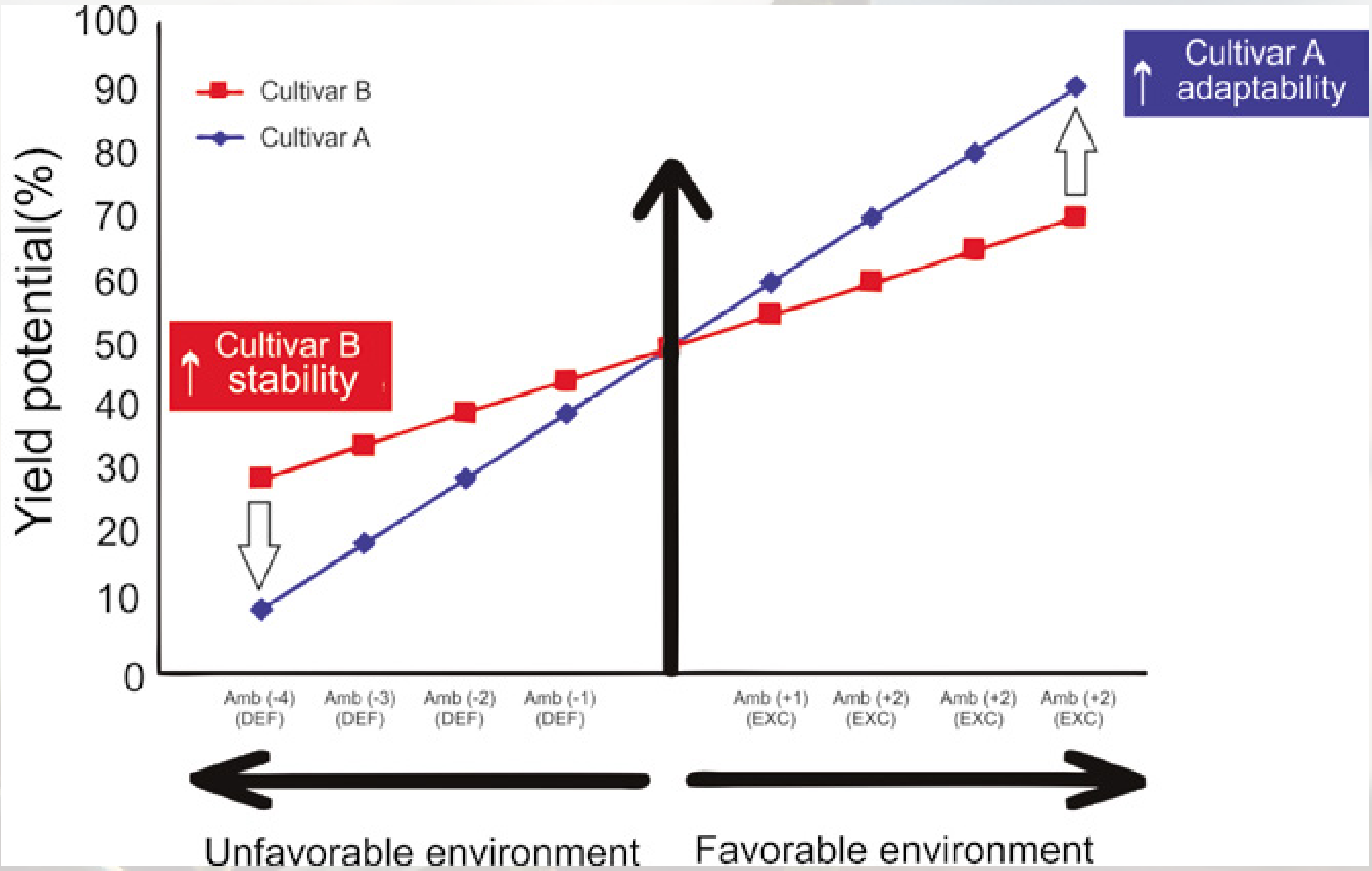


Figure 1.6.2. Relationship between yield potential and favorable or unfavorable environments according to adaptability and stability in soybean culture, which is represented in the figure for cultivars A and B, respectively. Cortesy: José Salvador Foloni – Embrapa Soja.

Enhancement programs continuously integrate modern methods over time to select superior genotypes (Jorasch, 2020). A superior cultivar can be selected for high yield, high bean quality (oil and protein), tolerance to abiotic stress (dryness, excess water, high temperature, salinity), and resistance to herbicides and biotic stress (insects and diseases).

The interaction of genotype x environment x management is complex. The first step to better comprehend this interaction is understanding the phenological behavior of each cultivar in different sowing times, latitudes, and altitudes. Soybean is a short-day plant (induced to flower with a short day length), and the plant's response to the photoperiod differs according to its cultivar maturity group (MG) and the presence of juvenile genes (the more expressed the juvenile gene, the longer the non-induced flowering period). Therefore, the same cultivar sowed in different latitudes, altitudes, or sowing times can show differences in its cycle duration. Additionally, two cultivars of the same MG sowed on the same date can show differences in cycle duration due to juvenile gene expression.

The different responses of cultivars MG to sowing seasons make this the first criterion to be considered when choosing a cultivar. In the south of Brazil, for example, to approach the productive potential of each crop, producers recommend the use of smaller MG cultivars (<6.0) in early seedings of the sowing period (October) and higher MG (>6.3) in sowings at the end of the sowing period (December) (see item 1.6.1). In the Center-West of Brazil, producers choose to adjust the MG of cultivars focused on harvesting crops in the months of January and February to adapt the soy/corn or soy/cotton production system, sowing the second crop in the rainy season.

With the definition of the MG to be used according to the sowing time, the second criterion to be considered when choosing the cultivar is the production environment, whether irrigated or rainfed. Cultivars with the same MG may show differences related to the efficiency of water use, drought tolerance, root architecture, and stomatal control. However, the characterization of drought-tolerant cultivars has been continuously studied in recent years, but with the approach of increasing plant survival, which is often seen as not promising if the tolerant cultivar does not present higher grain production in a stressful environment than a non-tolerant cultivar (Winck et al., 2021).

The third criterion for choosing a cultivar is the analysis of the qualitative characteristics of the cultivars (such as drought tolerance, water excess, salinity, resistance to herbicides, insect resistance, disease tolerance, etc.) according to the peculiarities of each crop. Therefore, it is extremely important that producers and technicians have a good diagnosis of climatic predictability season, soil compaction, chemical analysis of the soil, presence of soil diseases, and operational capability for efficient pests and diseases control. Based on these criteria, they should choose a cultivar group that might adapt to these conditions.

In a mannerly way, it is necessary for producers and technicians to comprehend the interaction between genotype x environment x management, seeking information generated by research, technical assistance, seed production companies, and overall on-farm experiments. The FieldCrops team coordinates the project “The Best Soybean Cultivar for Your Crop,” and annually, results are published in e-books (https://www.ufsm.br/app/uploads/2021/06/AMELHOR-CULTIVAR-DE-SOJA-PARA-SUA-LAVOURA.pdf) that can be accessed at no cost by producers and consultants to assist in decision-making regarding the adaptability of each soybean cultivar for a specific region. Digital tools such as Plantio Certo and Best Cultivar applications can also be used to help producers choose a cultivar based on the sowing season and desired characteristics. Furthermore, it is recommended that producers conduct annual experiments in their local area with the main soybean cultivars used to be more assertive when choosing a new cultivar.

1.6.1. Optimal Agronomic Cycle

The complex interaction effects of photoperiod, air temperature, maturity groups, and soybean growth types make the positioning and selection of cultivars for different locations and production systems challenging. In this context, the concept of the Optimal Agronomic Cycle (OAC) emerges. The OAC is a new approach that will help producers determine the most suitable cultivars for their fields for each sowing period. The OAC is defined as the soybean cycle that provides the best environmental utilization for each sowing period and is determined by optimizing the interaction between the sowing period, cultivar, latitude, and altitude of the field.

Estimates of the OAC are only available for Southern Brazil as of the publication of this book. The OAC varies from 112 to 141 days (Figure 1.6.1.1) for sowing from September 20th to January 31st. With the OAC, it is possible to choose the Maturity Group (MG) that will provide the highest productivity for each sowing date. Recently, digital solutions based on the OAC concept have been developed, such as Best Cultivar (more information in Chapter 7 - Digital Ecophysiology), which offers two functionalities developed with agronomic intelligence:

- Identification of the best cultivar(s) for a sowing period.
- Identification of the best sowing period for a specific cultivar.

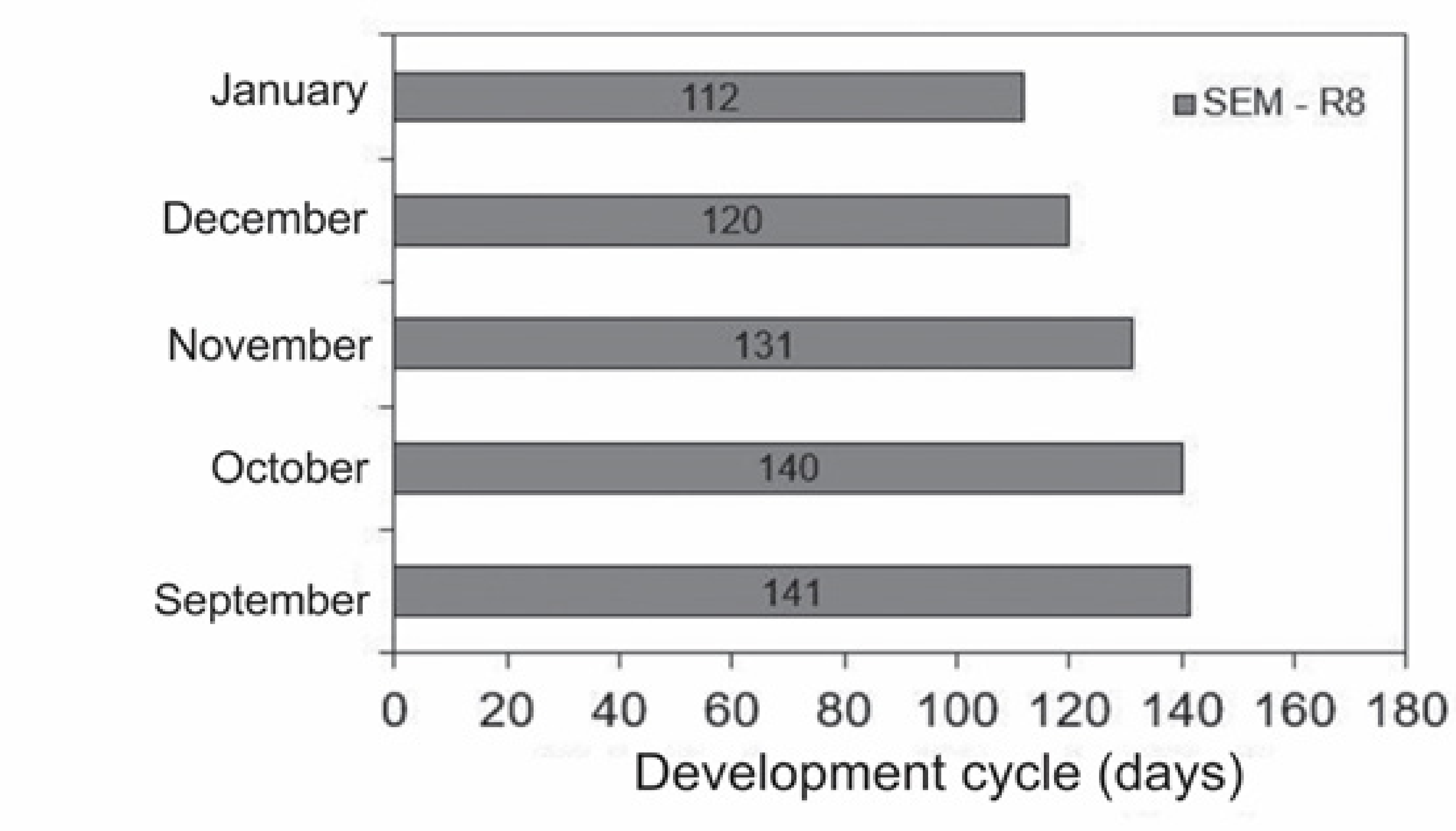


Figure 1.6.1.1. Optimal agronomic cycle (days) for the sowing period from September to January in Southern Brazil (value refers to sowing on the 15th of each month).

From this study, technical consultants and farmers will be able to make more assertive decisions regarding the positioning of cultivars based on the sowing period. The total cycle estimate presented in item 1.5 (Table 1.5.1) allows an understanding of the actual duration of the total development cycle according to the sowing period. The OAC allows for identifying the best cycle duration to maximize the utilization of environmental conditions during the crop's critical periods. Therefore, understanding and using the OAC is fundamental for reducing the productivity gap, increasing resource efficiency, reducing environmental impact, and increasing soybean field productivity.

Courtesy: Cristian Savegnago

1.7. Leaf Area Index (LAI)

The Leaf Area Index (LAI) is the ratio between the leaf area and the ground area occupied by the crop. By linear measurements of the leaves, the main photosynthetic organs of the plants, the leaf area of a trifoliate leaf (AF_t) can be estimated by the following formula (Richter et al., 2014):

$$AF_t\ (cm^2) = 2{,}0185*(C*L)$$

where *C* is the maximum length of the central leaflet, and *L* is the maximum width of the central leaflet.

By summing the leaf area of a plant, the total leaf area (AF_p) of the plant can be estimated:

$$AF_p = \Sigma\ AF_t$$

Using the average area occupied by each plant (A_p) (estimated from the plant population per linear meter and the row spacing), the LAI can be calculated:

$$A_p\ (cm^2) = \text{row spacing (cm)/population per linear meter}$$

$$LAI = AF_p\ /\ A_p$$

The LAI can be used to represent photosynthetic efficiency, for growth analysis, and as a conditioning factor for productivity. The LAI defines the canopy's ability to intercept solar radiation, convert it into dry matter through photosynthesis, and determine the crop's productive potential (Setiyono et al., 2008; Zanon et al., 2015a; Tagliapietra et al., 2018).

The evolution of the LAI throughout the soybean development cycle depends on the interaction between genotype, environment, and management, which can alter foliar growth on the main stem and the number of branches (Zanon et al., 2015a). The contribution of branches to the LAI begins when soybean plants have between 4 and 6 leaves on the main stem, marking the point when branching starts (between stages V3 and V5, depending on the cultivar and environment) (Zanon et al., 2015a). On average, branches contribute 16% to the LAI, although there is significant genetic variation and, especially, variation between sowing periods (Figures 1.7.1 and 1.7.2). In addition to the cultivar and sowing period, plant density can alter the contribution of branches to the total LAI in soybeans. Therefore, plant density should be managed according to information provided by the companies owning each cultivar, the sowing period, and the expected productivity level of the field.

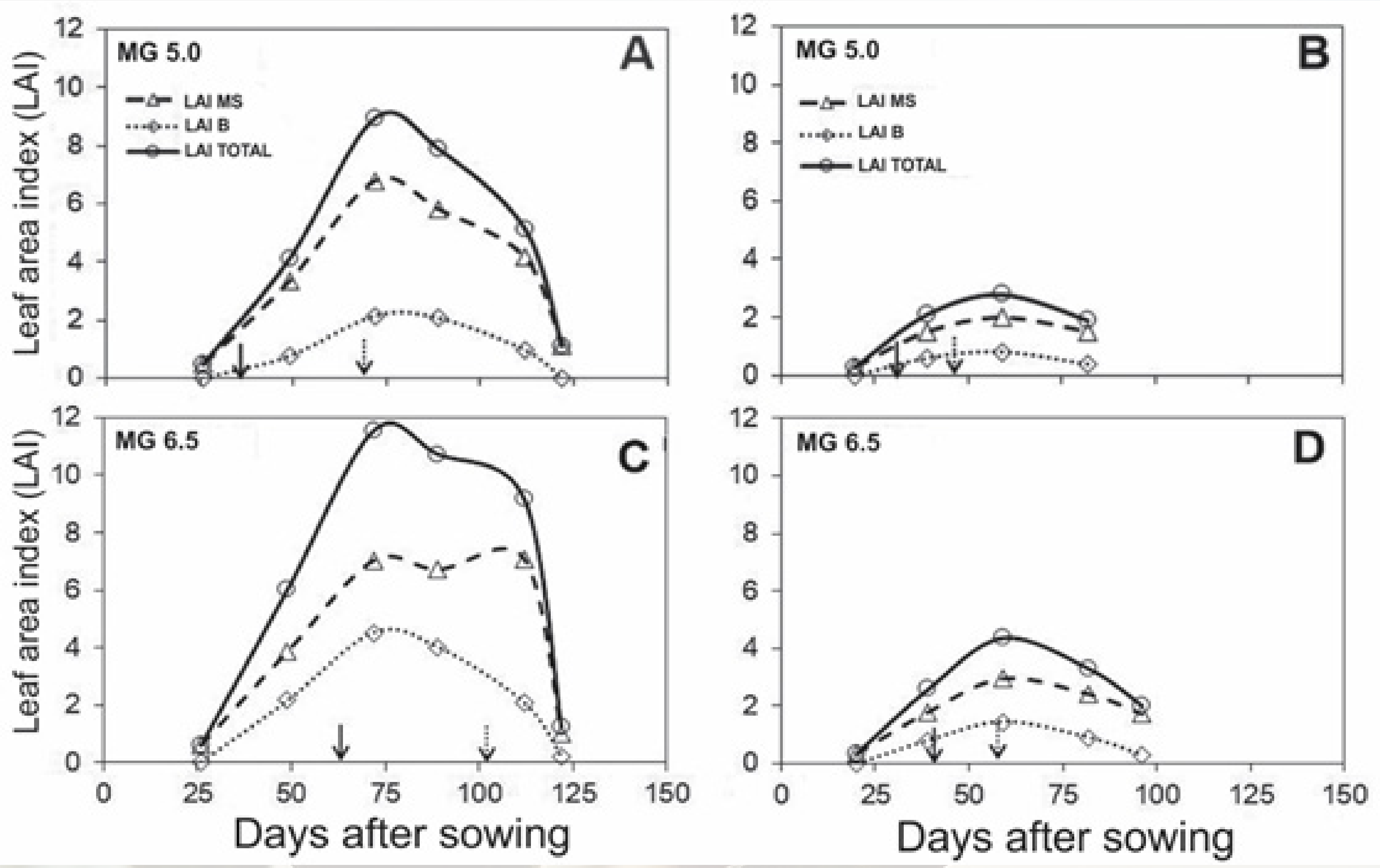


Figure 1.7.1. Evolution of total leaf area index (LAI TOTAL) on the main stem (LAI MS) and branches (LAI B) during the development cycle of soybean cultivars with MG 5.0 (A) and MG 6.5 (C), sown in October in Santa Maria, Rio Grande do Sul, Brazil. Evolution of total leaf area index (LAI TOTAL) on the main stem (LAI MS) and branches (LAI B) during the development cycle of soybean cultivars with MG 5.0 (B) and MG 6.5 (D), sown in February in Santa Maria, Rio Grande do Sul, Brazil. The solid arrow indicates stage R1 and the dashed arrow indicates stage R5.

The three factors that most affect the number of branches and, consequently, their contribution to the total LAI are:

1. Cultivar: the genetics of the cultivar determine the branching capacity (Figure 1.7.1), making it important to know the genetic material to determine plant density and, consequently, the LAI;

2. Plant density (Figure 1.7.2): many of the cultivars used today tend to increase the number of branches and, consequently, their contribution to the total LAI as plant density decreases. However, the characteristics of each cultivar should always be known;
3. Sowing period: the later the sowing period, the lower the contribution of branches to the total LAI (Figures 1.7.1 and 1.7.2).

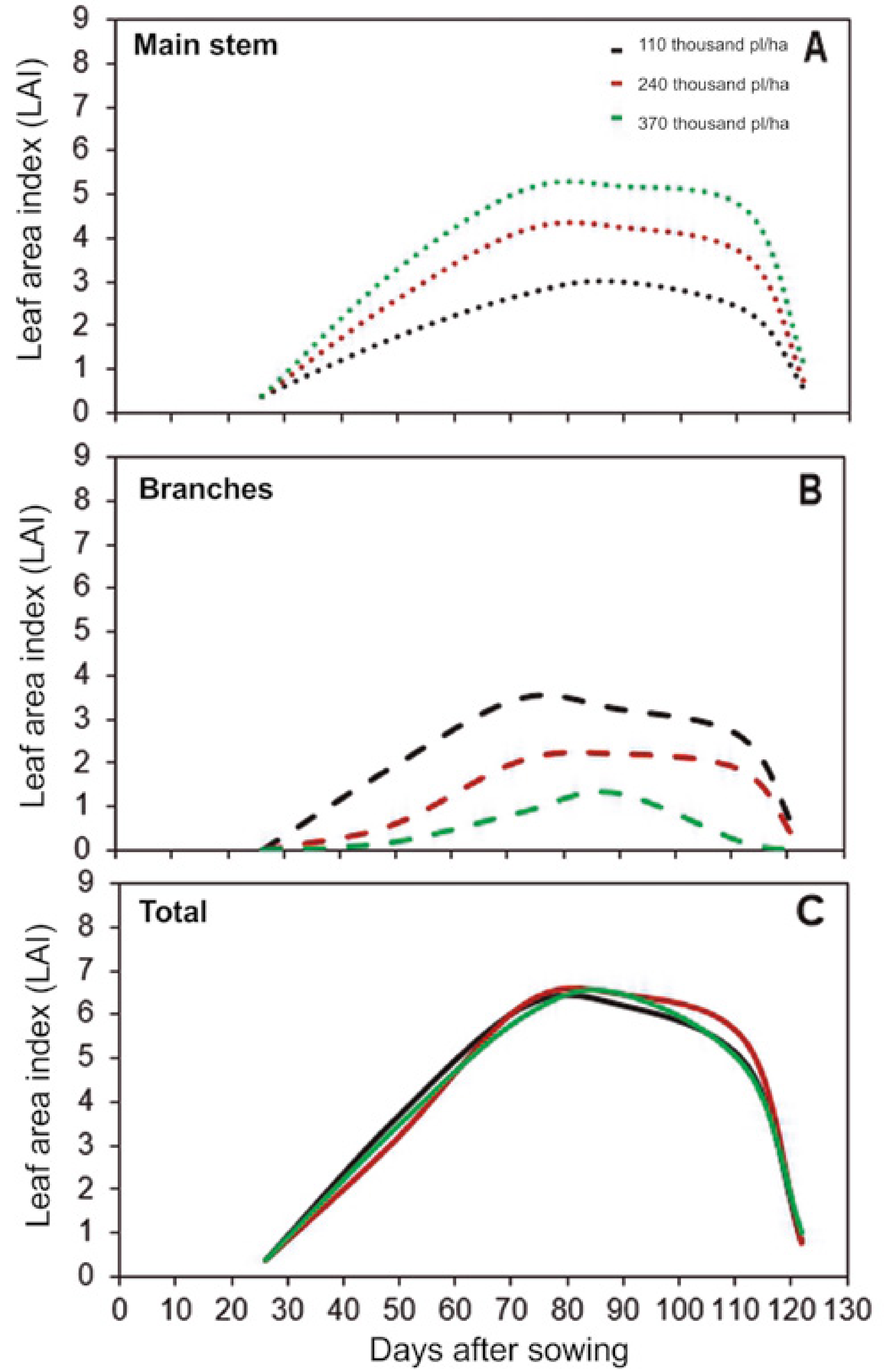


Figure 1.7.2. Evolution of the leaf area index on the main stem (A), branches (B), and total (C) at three sowing densities during the development cycle of a soybean cultivar with MG 5.7, sown in October in Santa Maria, Rio Grande do Sul, Brazil.

Although the contribution of branches is important in constituting the total LAI, the main stem is the major source of LAI in soybeans, contributing on average more than 85% of the total LAI, which can vary from 50% to 100% of the total LAI composition (Zanon et al., 2015a). On the main stem, the contribution of each leaf to the total LAI varies according to the node considered on the plant. For example, a leaf from the 4th node contributes approximately 90 cm² of leaf area, while a leaf from the 9th node contributes 167 cm² of leaf area (Figure 1.7.3).

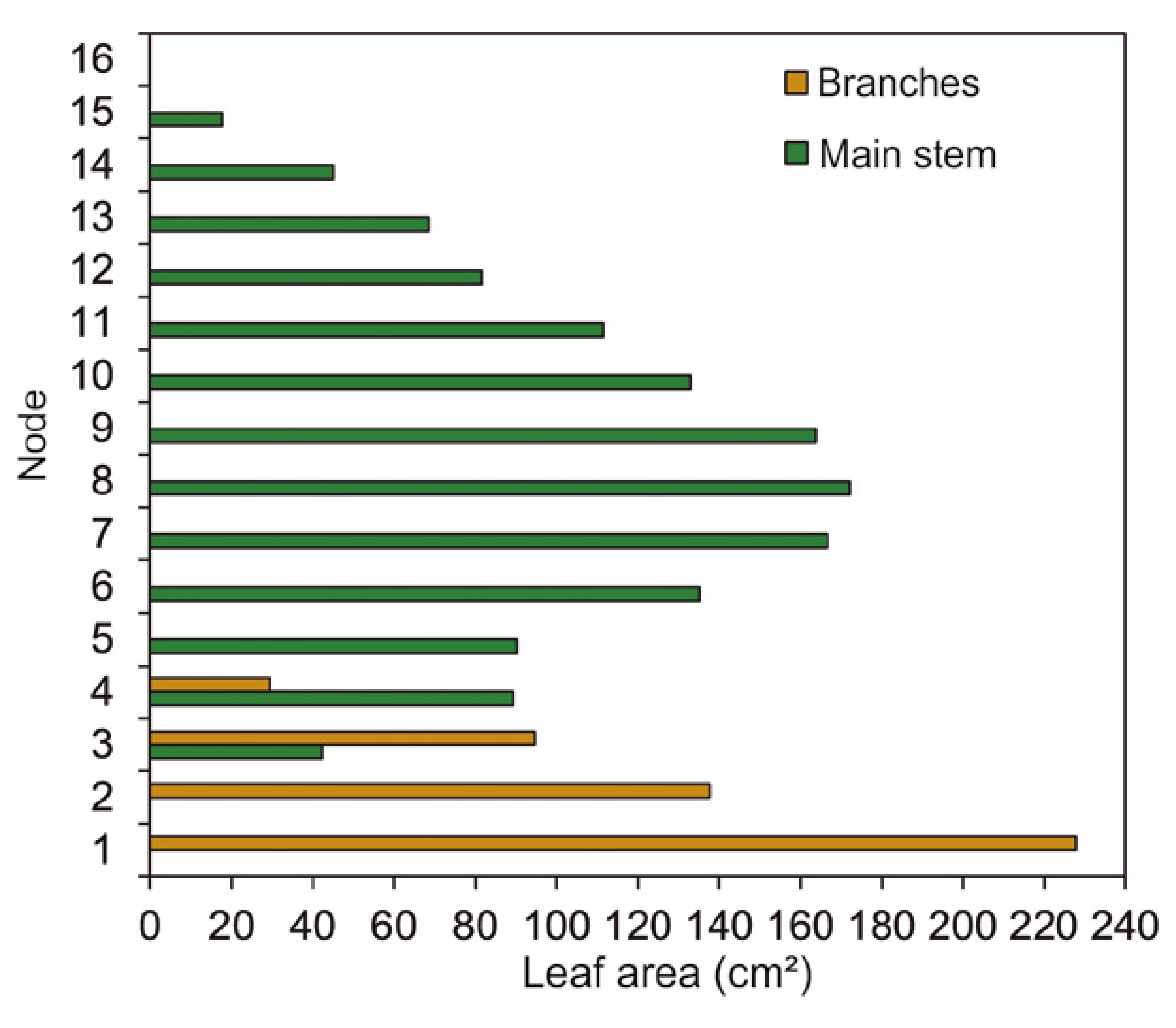


Figure 1.7.3. Contribution of each leaf of the main stem and the branch to the total leaf area of the soybean plant in a cultivar with MG 5.5 and indeterminate growth type at stage R5.

To understand the relationship between LAI and grain yield, it is important to know two basic ecophysiological concepts: critical LAI and optimal LAI. The critical LAI is defined as the number of leaves needed to intercept 95% of solar radiation, usually occurring when row closure happens. In some cultivars, row closure coincides with flowering (R1). The optimal LAI occurs when net photosynthesis stops increasing, meaning that the increase in solar radiation interception no longer enhances net photosynthesis (Hay & Porter, 2006). Therefore, the optimal LAI will always be higher than the critical LAI.

According to the classical concept, under ideal conditions, the critical LAI is sufficient to reach productive potential. From the optimal LAI concept, considering the production environment and the negative impacts of various biotic and abiotic factors on productivity, a more representative and applicable relationship between LAI and productivity can be established for agronomic management. This is because LAI is directly related to grain yield (Tagliapietra et al., 2018). To achieve yields close to 6.0 ton ha^{-1}, Tagliapietra et al. (2018) defined the necessary LAI values during the critical development stages for soybeans: a critical LAI of 3.5 (Figure 1.7.4 A) at the beginning of flowering (LAIR1) and an optimal LAI of 6.2 (Figure 1.7.5 B) at the beginning of grain filling, considered the optimal maximum LAI (LAI_{max}), using a boundary function. As an advancement to Tagliapietra et al.'s study (2018), the FieldCrops Team related LAI to productivity considering different relative maturity groups (MG).

Figure 1.7.4. Illustration of a field with LAIR1 of 3.5 (A) and a field with an optimal maximum LAI of 6.0 (B).

For high productivity in MGs less than 5.5, between 5.6 and 6.4, and greater than 6.5, an LAI in R1 of 1.8, 3.7, and 3.9, and a maximum LAI (in R5) of 5.0, 5.6, and 6.7, respectively, is necessary (Figure 1.7.5). $\mathrm{LAI}_{\mathrm{max}}$ values greater than 8.0 tend to reduce grain yield due to excess leaf area, causing shading between plants, less solar radiation in the lower third of the vegetative canopy, higher energy expenditure for vegetative growth, and creating a favorable environment for the proliferation of pests and diseases, consequently increasing control costs (Salvagiotti et al., 2008; Taiz & Zeiger, 2013).

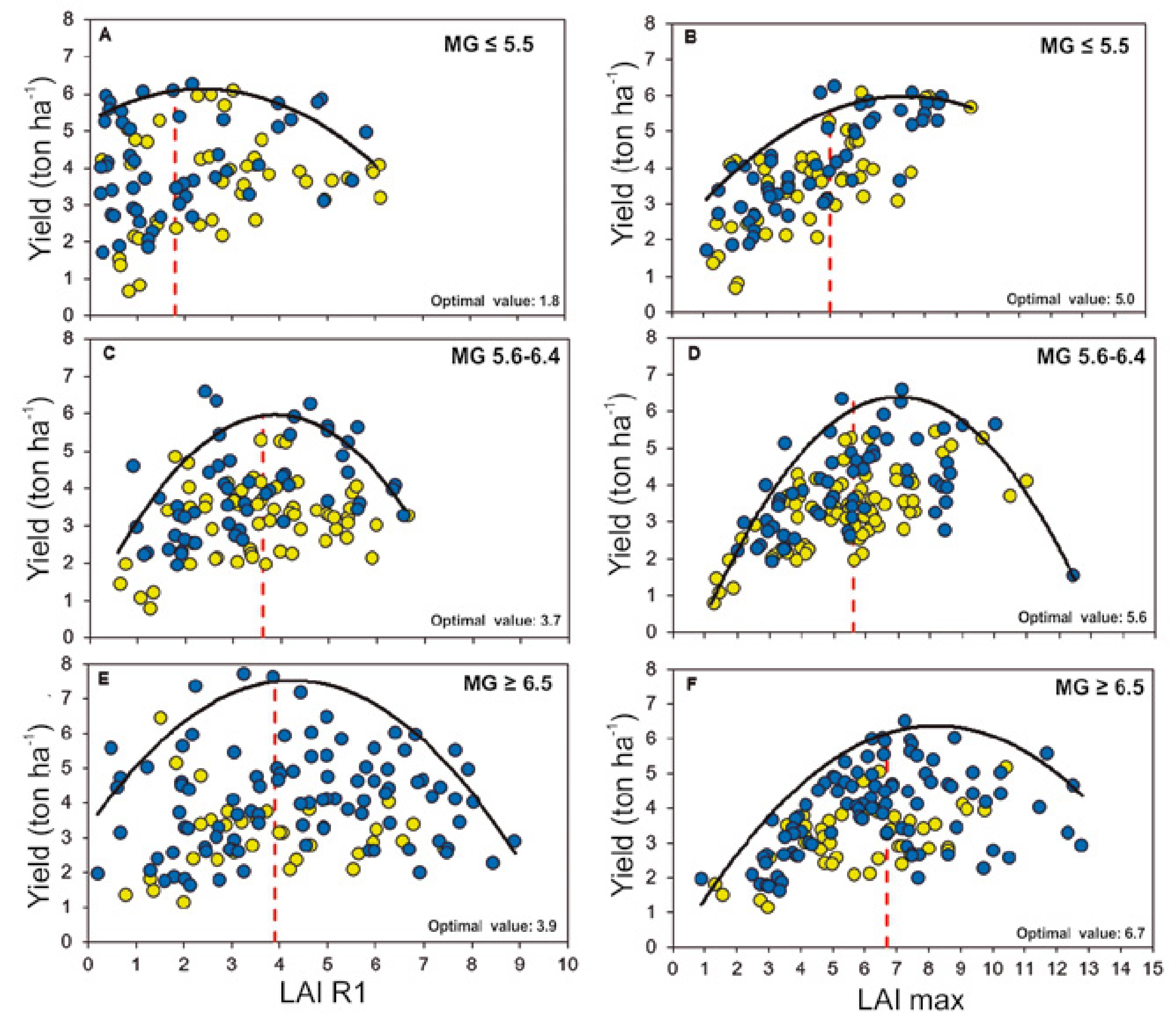


Figure 1.7.5. Relationship between grain yield (ton ha^{-1}) as a function of leaf area index at flowering (LAIR1): MG ≤ 5.5 (A); 5.6 ≤ MG ≥ 6.4 (C) and MG ≥ 6.5 (E); and grain yield (ton ha^{-1}) as a function of maximum leaf area index ($\mathrm{LAI}_{\mathrm{max}}$): MG ≤ 5.5 (B); 5.6 ≤ MG ≥ 6.4 (D) and MG ≥ 6.5 (F) in soybeans for irrigated (blue circles) and rainfed (yellow circles) crops. The solid red line indicates the LAIR1 and $\mathrm{LAI}_{\mathrm{max}}$ values that maximize grain yield.

According to Tagliapietra et al. (2018), with an LAI close to 4.0, it is possible to achieve yields close to 4.0 tons ha^{-1}, which is higher than the average yield in Brazil, the United States, and Argentina. However, with genetic and management advancements, yields in high-tech fields reach 6.0 tons ha^{-1}, making it necessary to achieve an LAI of 6.0 during grain filling so that this is not a limiting factor for productivity (Tagliapietra et al., 2018).

With the estimate of a linear relationship between the optimal LAI for high yields (close to 6.0 tons ha^{-1}) as a function of sowing time for three MG ranges (Figure 1.7.6), it is observed that cultivars with MG ≤ 5.5 reach the optimal LAI for high yields when sown from mid-October to late November. However, these values are very close to the limit, meaning any loss of leaf area results in a loss of productivity. On the other hand, cultivars with MG > 5.5 and early sowing maintain the LAI above the optimum, meaning it is possible to tolerate some loss of leaf area due to biotic factors and still achieve high yields.

Comparing cultivars with high MG (greater than 6.5) with cultivars with intermediate MG (between 5.6 and 6.4), a greater difference in LAI$_{max}$ is observed in early sowings (September), less difference during the preferred sowing period (November), and little difference in late sowings (from December onwards). From this LAI$_{max}$ relationship, it is possible to adjust levels of LAI losses according to the sowing time and MG.

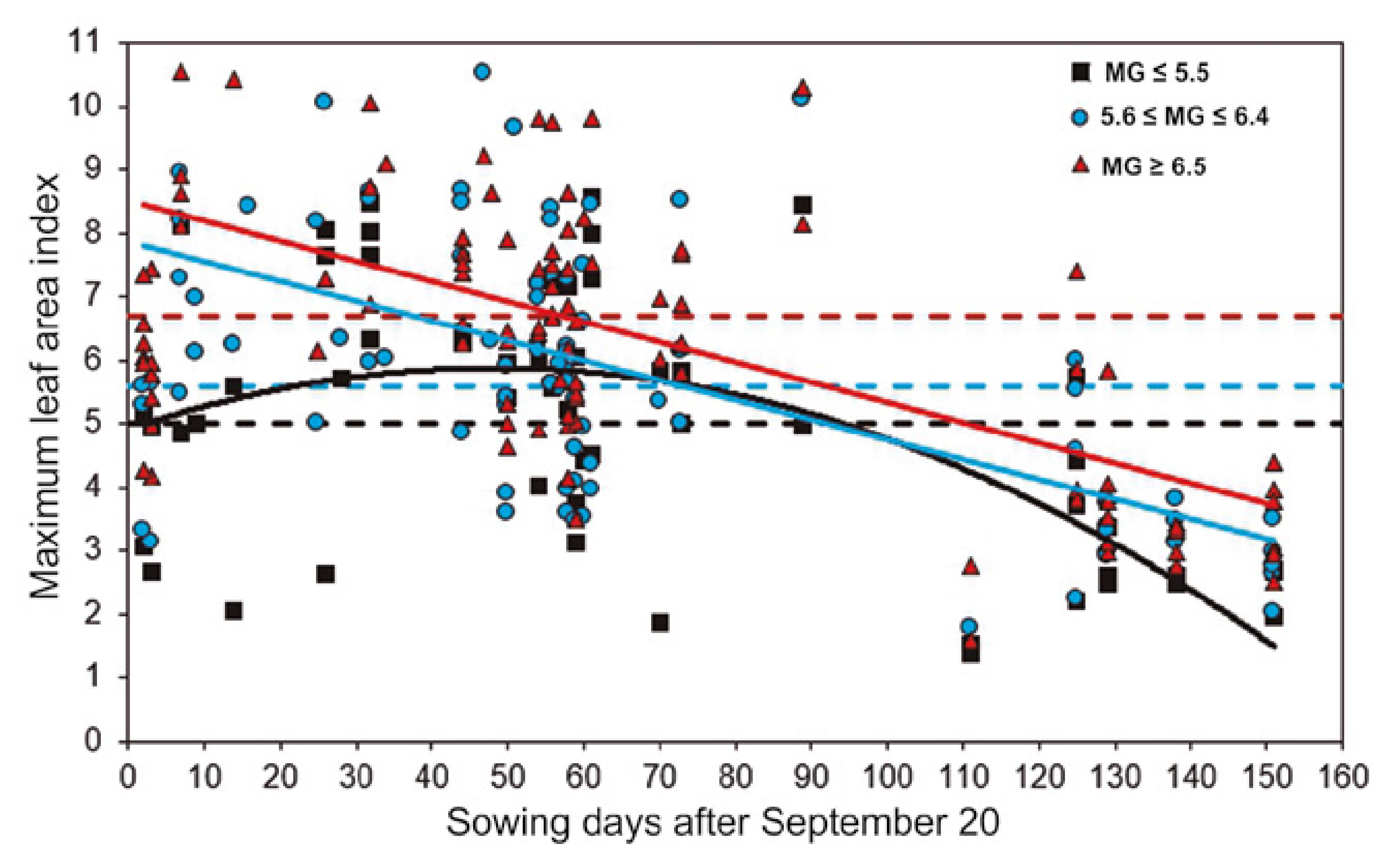


Figure 1.7.6. Relationship between the maximum leaf area index (LAI_{max}) and the sowing date (expressed as days after September 20th), for different groups of relative maturity (MG) in soybeans in Southern Brazil. The solid black line shows the second-degree function adjusted for MG ≤ 5.5, the solid blue line shows the first-degree function adjusted for MG between 5.6 and 6.4, and the solid red line shows the first-degree function adjusted for MG ≥ 6.5. The dashed black line represents the optimal LAI for MG ≤ 5.5, the dashed blue line represents the optimal LAI for 5.6 ≤ MG ≤ 6.4, and the dashed red line represents the optimal LAI for MG ≥ 6.5, above which the yield gain is less than 0.5%. Source: Tagliapietra et al., 2018 and FieldCrops Team, 2021.

For fields with high yield potential, there is a direct relationship between the increase in yield and the increase in LAIR1 and LAI_{max} (Figures 1.7.7 A and B). The relationship expressed in the slope of the equations in Figures 1.7.7 A and B shows a yield increase of 0.41 to 0.47 tons ha^{-1} for each 1.0 increase in LAIR1 and LAI_{max}, respectively. Therefore, the LAI_{max} for high-yield fields (above 4.5 tons ha^{-1}) should be greater than the LAI values cited in the literature as optimal (3.5 to 4.0) for soybeans (Specht et al., 1999). For fields with expected yields below 3.0 tons ha^{-1}, there is no direct relationship between the increase in LAIR1 and LAI_{max} with yield (Figures 1.7.7 C and D). In other words, for areas with high yield potential, where the soil has been corrected to pH 6.0 and the levels of essential nutrients are high, without water deficiency and with good control of biotic factors (weeds, insects, and diseases), the sowing time and cultivar should be chosen aiming to reach an LAI_{max} close to 6.0 and, consequently, yields close to 6.0 tons ha^{-1}. For fields with yields lower than 4.5 tons ha^{-1}, the management factor limiting yield increase should be identified, whether due to abiotic and/or biotic factors, before considering reaching an LAI_{max} of 6.0. For these areas, the LAI values of 3.5 to 4.0, cited as optimal for soybeans by Specht et al. (1999) and other authors, are still valid.

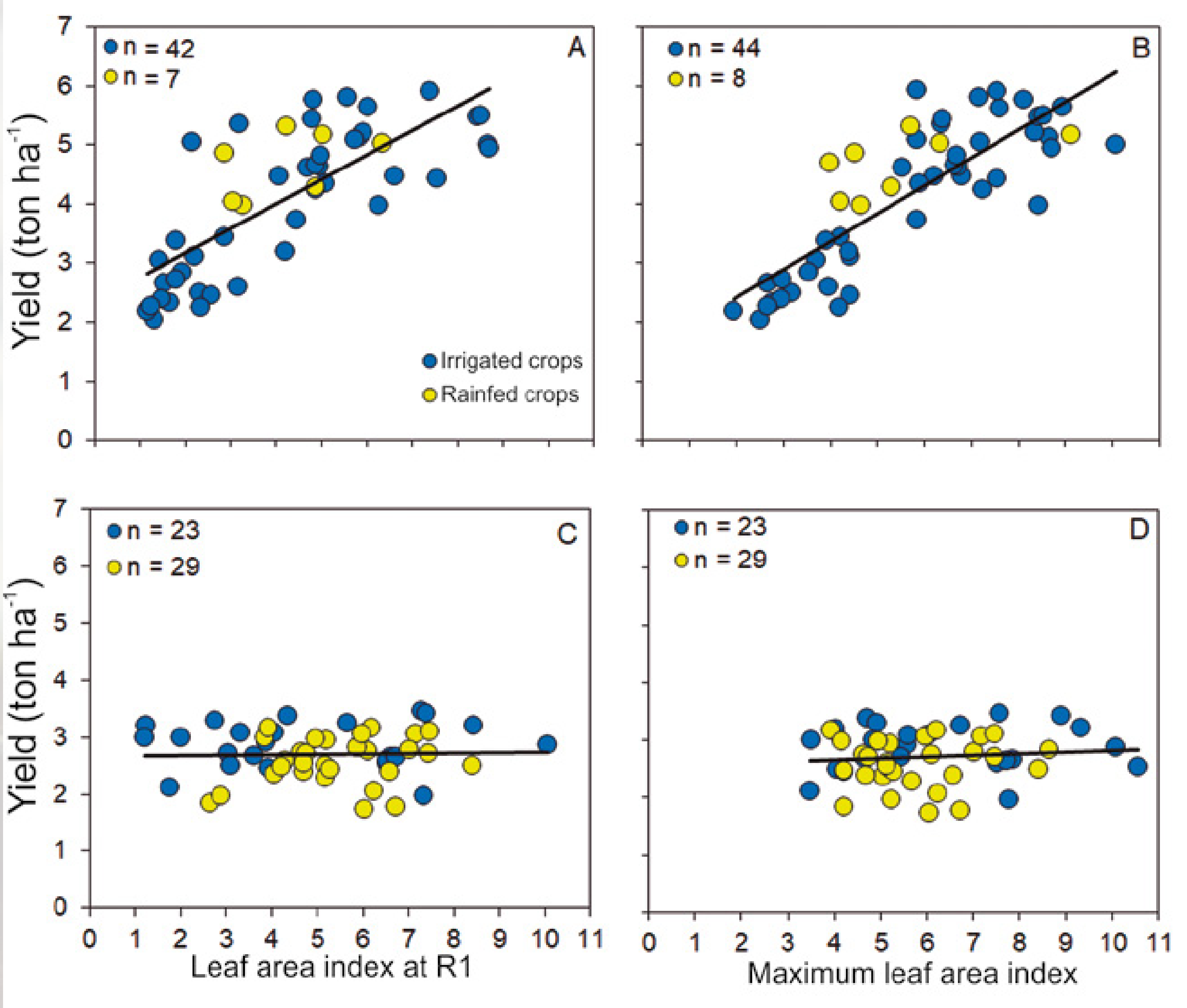


Figure 1.7.7. Relationship between soybean grain yield (tons ha^{-1}) and LAI in R1 for high-yield fields (A) and low-yield fields (C) and relationship between soybean grain yield (tons ha^{-1}) and maximum LAI in high-yield fields (B) and low-yield fields (D). Yellow circles represent rainfed crops and blue circles represent irrigated crops. Source adapted: Tagliapietra et al. (2018).

Courtesy: José Eduardo Minussi Winck

1.8. Optimal agronomic components

The grain yield of a soybean crop is built through productivity components (or yield components) (Figure 1.8.1). Agronomic optimal components are values of productivity components that maximize yield. To define the optimal values of yield components, experiments conducted by the FieldCrops Team in crops throughout Brazil since 2010 were evaluated. These values were derived from nonparametric statistics of the function limit (French & Schultz, 1984). It is worthy to mention that the values of optimal agronomic components presented are not just mathematical values that, when multiplied, allow achieving high productivity but are the result of the genetic interaction x environment x management that should serve as a reference for producers and consultants seeking sustainable and profitable soy crops.

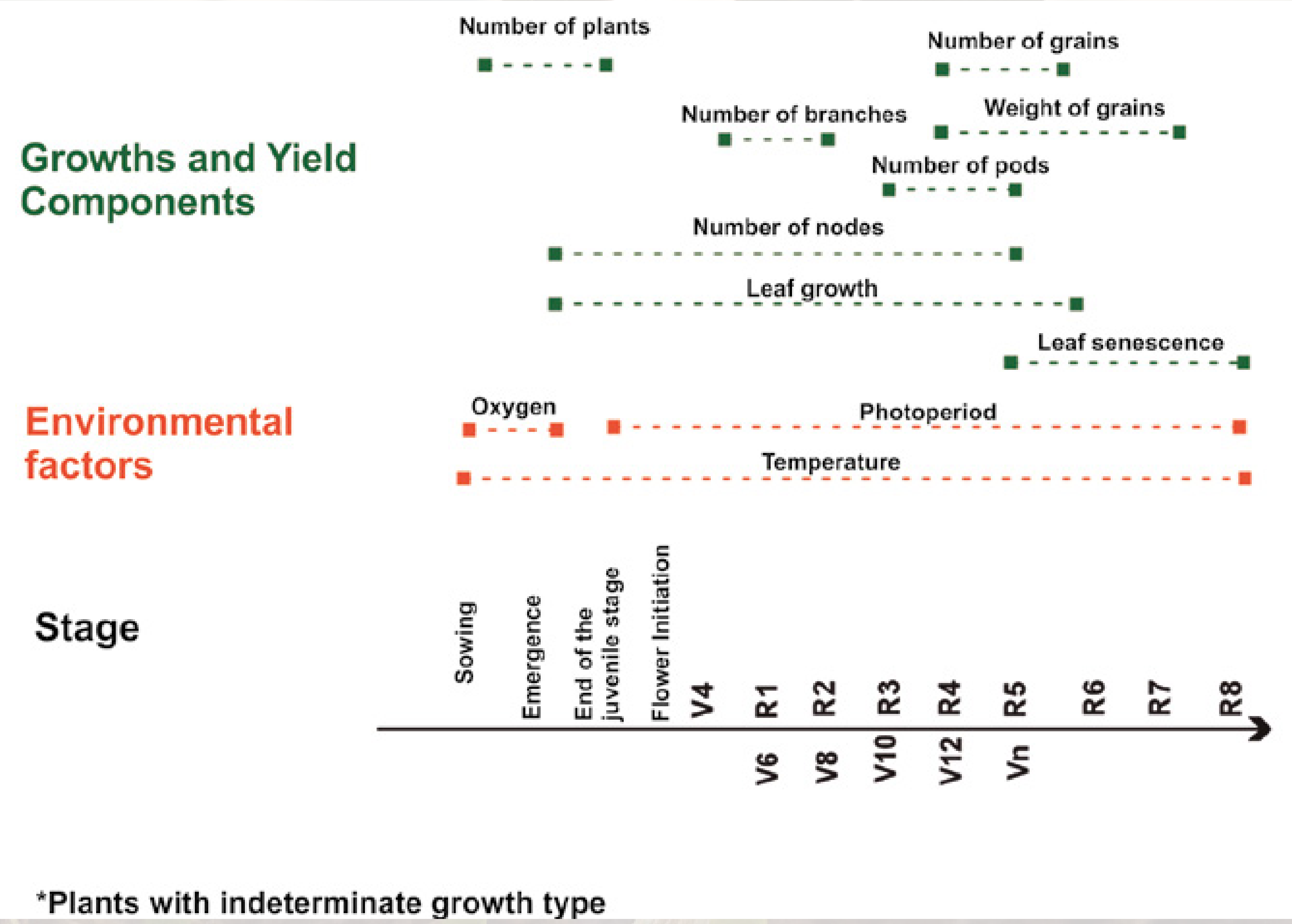


Figure 1.8.1. Relationship between development stages, environmental factors, and yield components of soybean. Adapted of Andrade et al., (2000).

The first yield component, the number of plants per area, is defined at sowing and in the initial establishment of seedlings. The optimal value of the number of plants per area must be defined from the genetic characteristics of the cultivar, sowing date, and resources available in the production environment (farming). Some management practices are important to define this yield component's behavior, such as the use of seeds of good quality, combined with good plantability and protection of seeds (Item 1.9.1).

The number of pods per plant (or area) is the most variable yield component with the modification of the plant arrangement (plant density and spacing between lines). To isolate the effect of plant density on the number of pods per plant, the FieldCrops Team quantified the number of pods per m². In a study conducted with almost a thousand crops, the ideal values found were 1836 pods per m² (Figure 1.8.2). To reach 1836 pods per m², it is necessary to adjust the plant density in the field according to the genetic characteristics of the cultivars and sowing date, to stimulate the increase in the number of nodes per area, and without radiation restriction solar in the middle and lower third of the canopy, necessary for the fixation of flowers and pods.

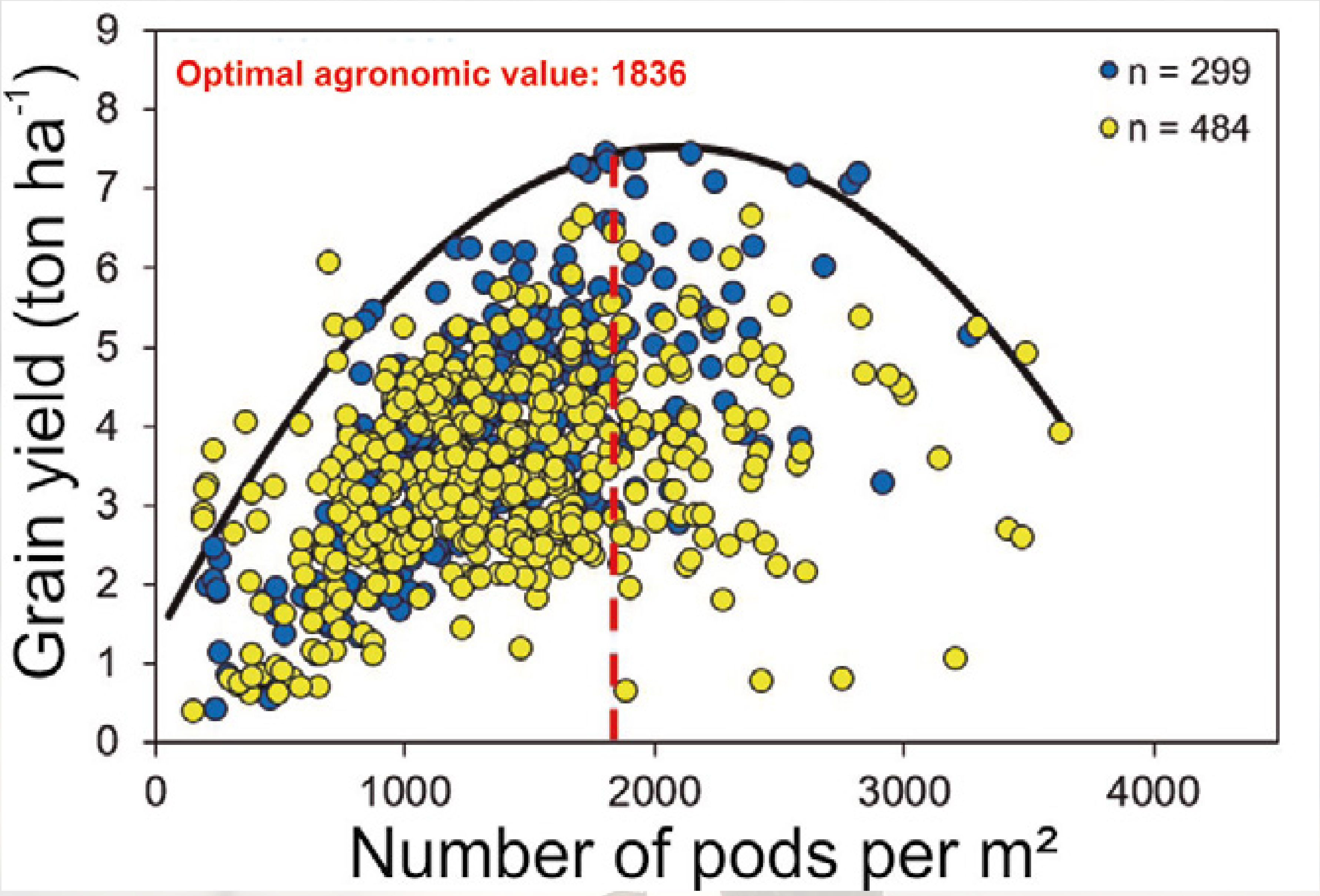


Figure 1.8.2. Relationship between grain yield (ton ha^{-1}) and the number of nods per m² in soybean for irrigated cultivation (blue circles) and rainfed ones (yellow circles). The solid black line represents an estimated limit function, and the dashed red line indicates the value of nods number per m² that maximizes grain yield.

The optimal value of grains per nod was 2.2 to reach high yields (Figure 1.8.3). The number of grains per nod is defined genetically (depends on the cultivar) and is directly affected by hydric stresses between R2 and R5 and by the presence of sucking insects (stink-bugs) (Mundstock & Thomas, 2005).

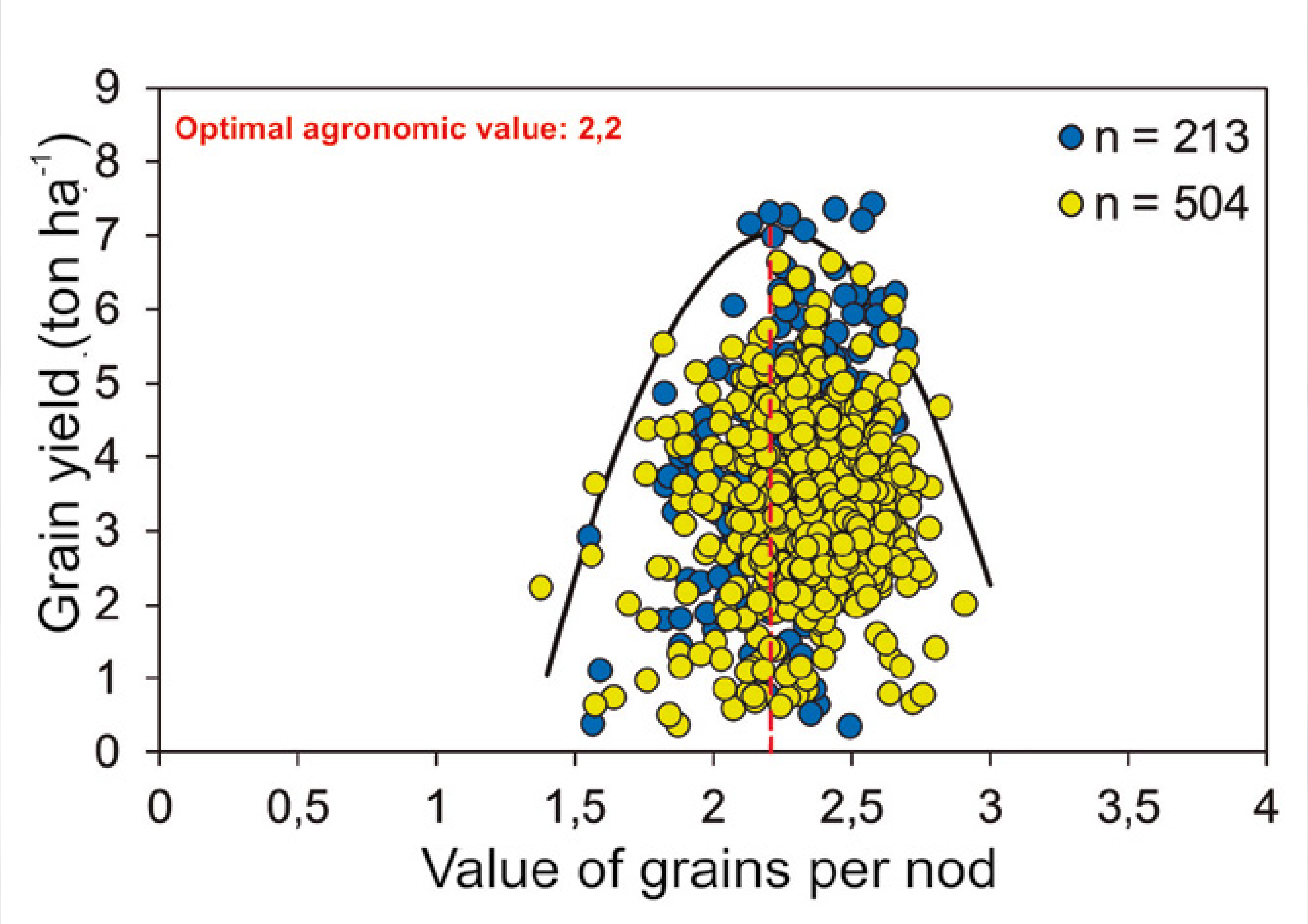


Figure 1.8.3. Relation between grain yield (ton ha^{-1}) and the number of grains per nods in soybean for irrigated (blue circles) and rainfed crops (yellow circles). The solid black line represents an estimated limit function, and the dashed red line indicates the number of grains per nods that maximizes grain yield.

Grain weight is a characteristic determined by genetics but deeply influenced by the environment (rainfall) and management (seeding density, soil fertility, and protection against attacks of sucking insects and diseases) (Pandey & Torrie, 1973). The optimal agronomic value of a thousand grain weight is 207 g (Figure 1.8.4).

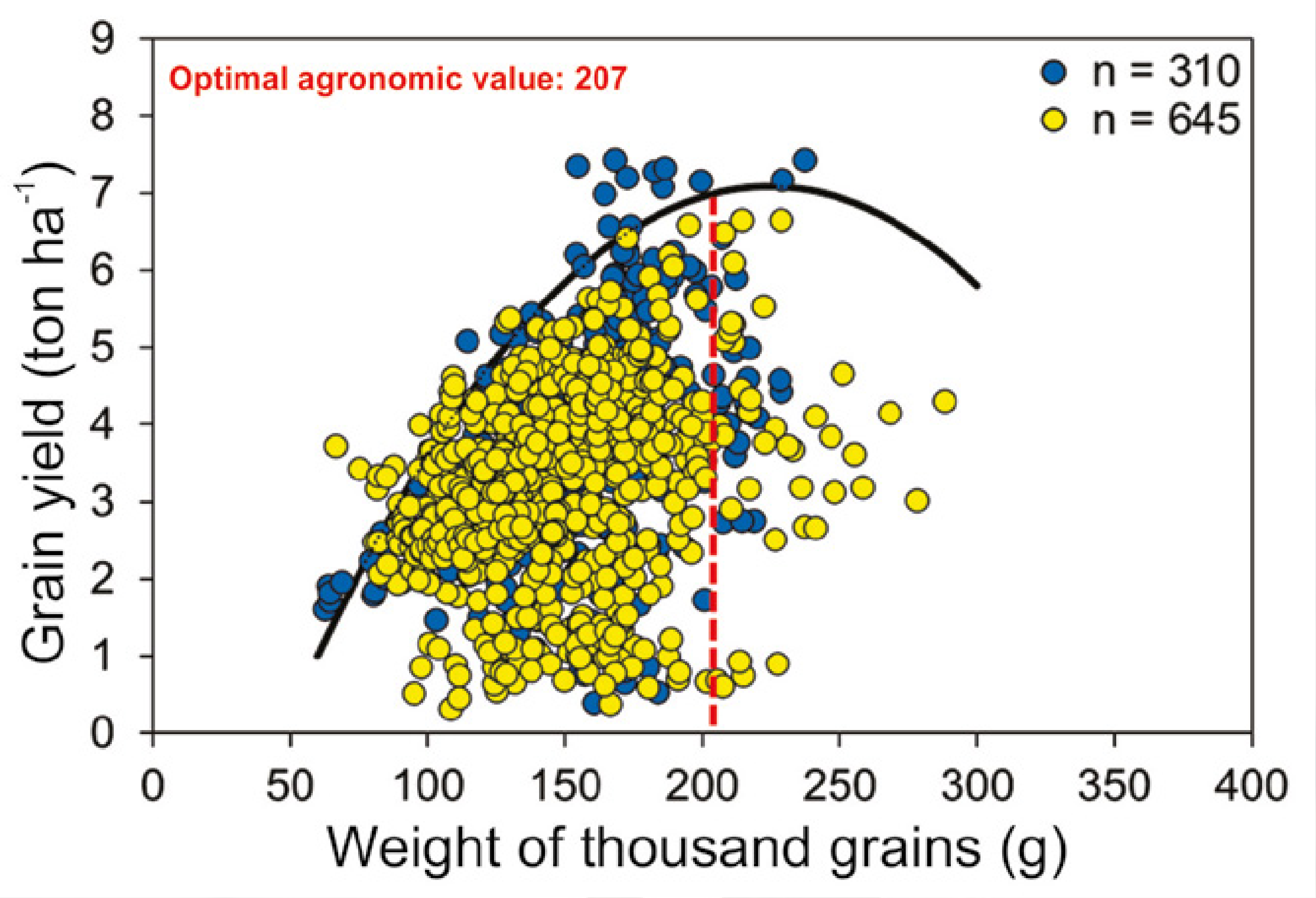


Figure 1.8.4. Relationship between grain yield (ton ha^{-1}) and weight of thousand grains (g) in soybean for irrigated (blue circles) and rainfed crops (yellow circles). The solid black line represents the limit function estimated and the red dashed line indicates the value of the thousand grain weight which maximizes grain yield.

Plant height is a key attribute when choosing the cultivar to be introduced in a crop, as it is related to the leaf area index, efficiency using solar radiation, and tolerance to lodge. Variations in plant height can be influenced by the cultivar, sowing date, spacing between lines, plant density, rainfall, and irrigation during the vegetative growth (V1 to R5), temperature, soil fertility, and photoperiodic response of the cultivar (Rocha et al., 2012). The ideal height found to achieve high yield was 104 cm (Figure 1.8.5). If there is excessive growth in height (>120 cm) up to R2, the leaves of the lower stratum of the plant (basseiro) the leaves begin to senesce due to a lack of solar radiation, failing to differentiate the meristems present in the armpits of the senescent leaves, in flowers and nods causing yield losses (Figure 1.3.3.3). In contrast, the low plant height reflects a low number of nodes (and consequently low number of nods per plant) and low insertion of the first nod, which may result in losses during harvest.

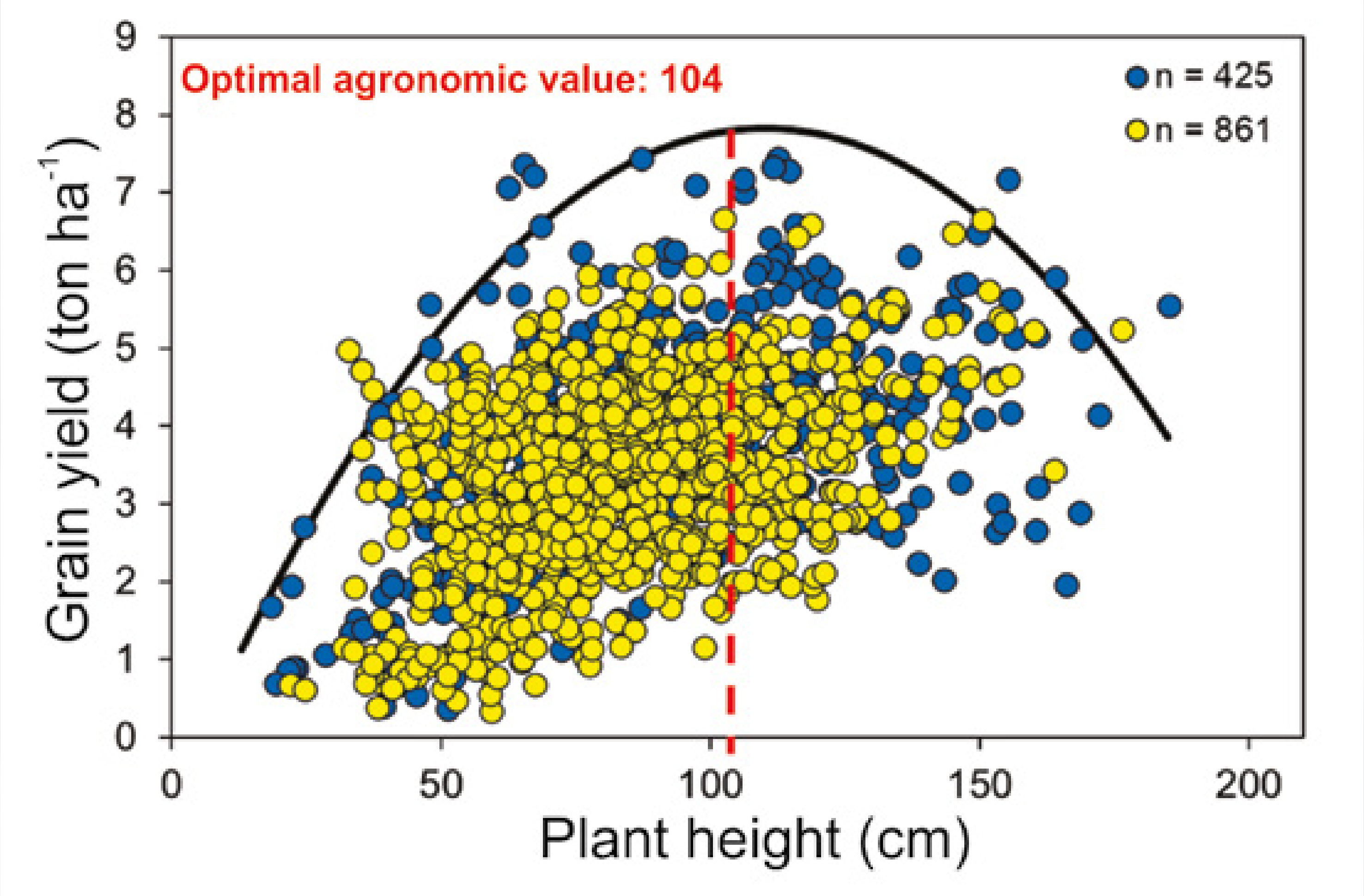


Figure 1.8.5. Relationship between grain yield (ton ha^{-1}) and plant height (cm) in soybean for irrigated (blue circles) and rainfed crops (yellow circles). The solid black line represents the estimated limit function, while the red dashed line indicates the plant height value that maximizes grain yield. The final number of nodes (NFN) in soybean is determined by the interaction between temperature and photoperiod during the development cycle, as well as the absence of abiotic stresses, such as drought (Setiyono et al., 2007). The optimal agronomic value is 18 nodes per plant (Figure 1.8.6).

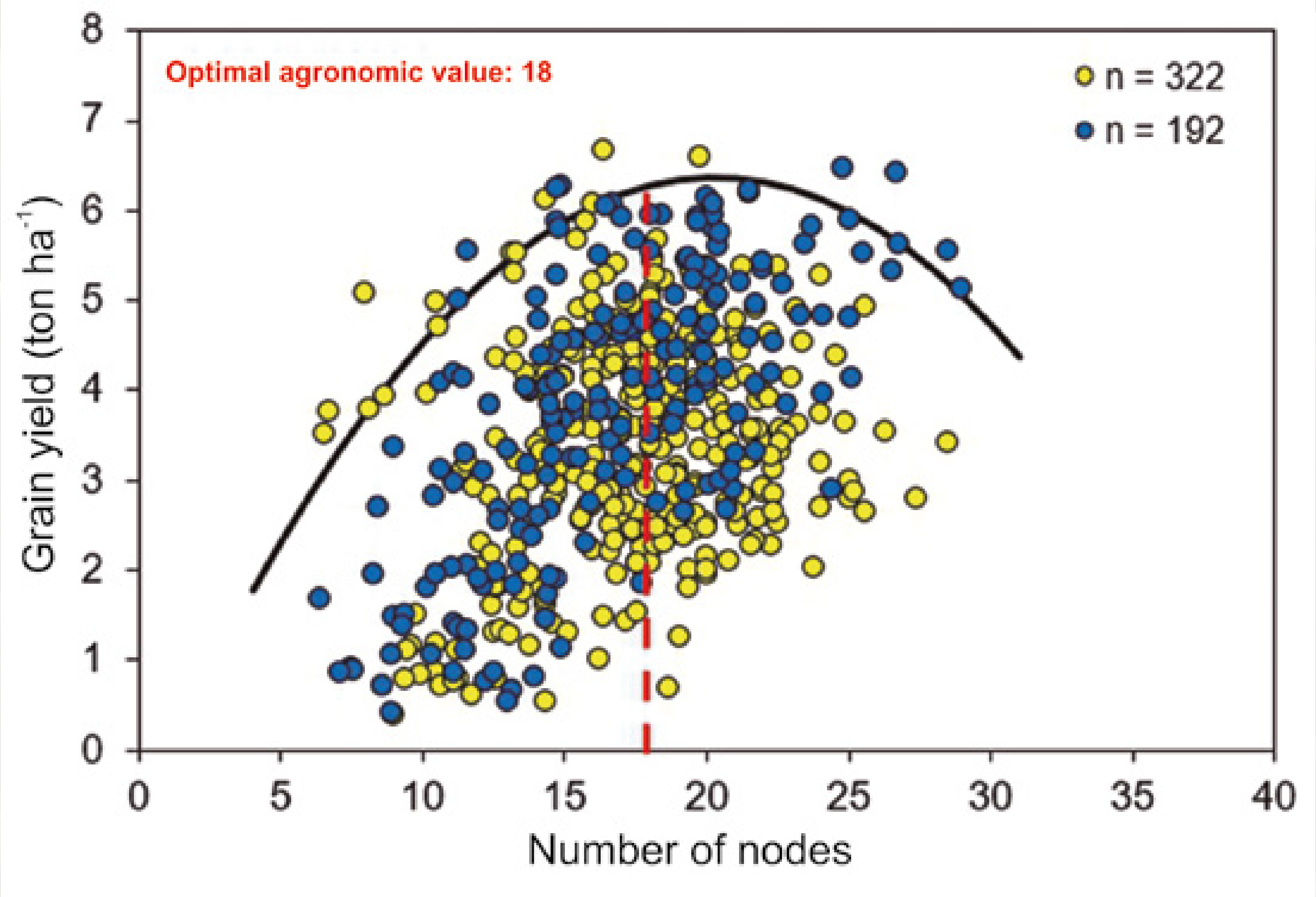


Figure 1.8.6. Relationship between grain yield (ton ha^{-1}) and the final number of plant nodes in soybean for irrigated crops (blue circles) and dryland (yellow circles). The solid black line represents the estimated limit function, and the red dashed line indicates the value of the final number of plant nodes that maximizes grain yield.

These values of optimal agronomic components of yield can be used by the programs of genetic enhancement as a criterion for the selection of superior genotypes, which means cultivars with greater yield potentials. In addition, at the farm level, the optimal agronomic components are values referenced for farmers and consultants to identify what were the biophysical and management factors that prevented the realization of these values in farming and by that, plan strategies to seek these agronomic components and achieve high yields.

Given these "optimal" values of the components of yield, it can be inferred that in a crop with 1836 nods per m^2, 2.2 grains per nod, and a thousand weight grains of 207 g, there is potential to produce 8.3 ton ha^{-1}, which corresponds to 139.3 bags of soybeans per hectare.

1.8.1. The Reality of Yield Components in Soybean Fields

The analysis of the yield components of 1305 fields monitored over 10 years by the FieldCrops Team identified the order of importance of yield components at the field level. The main yield component of soybeans is the number of pods per m^2. Fields with yields exceeding 3.3 tons ha^{-1} have more than 939 pods per m^2, while low-yield fields (less than 2.4 tons ha^{-1}) that have "gaps in the field" (spaces without plants) have fewer than 939 pods per m^2. The second most important yield component is the weight of a thousand grains, with high-yield fields having values above 174g. Although most cultivars have potential values above 174g, it is observed at the field level that a significant portion of productivity is lost due to errors in plant nutrition, plant protection, and especially due to water deficiency during the grain filling phase (Figure 1.8.1.1).

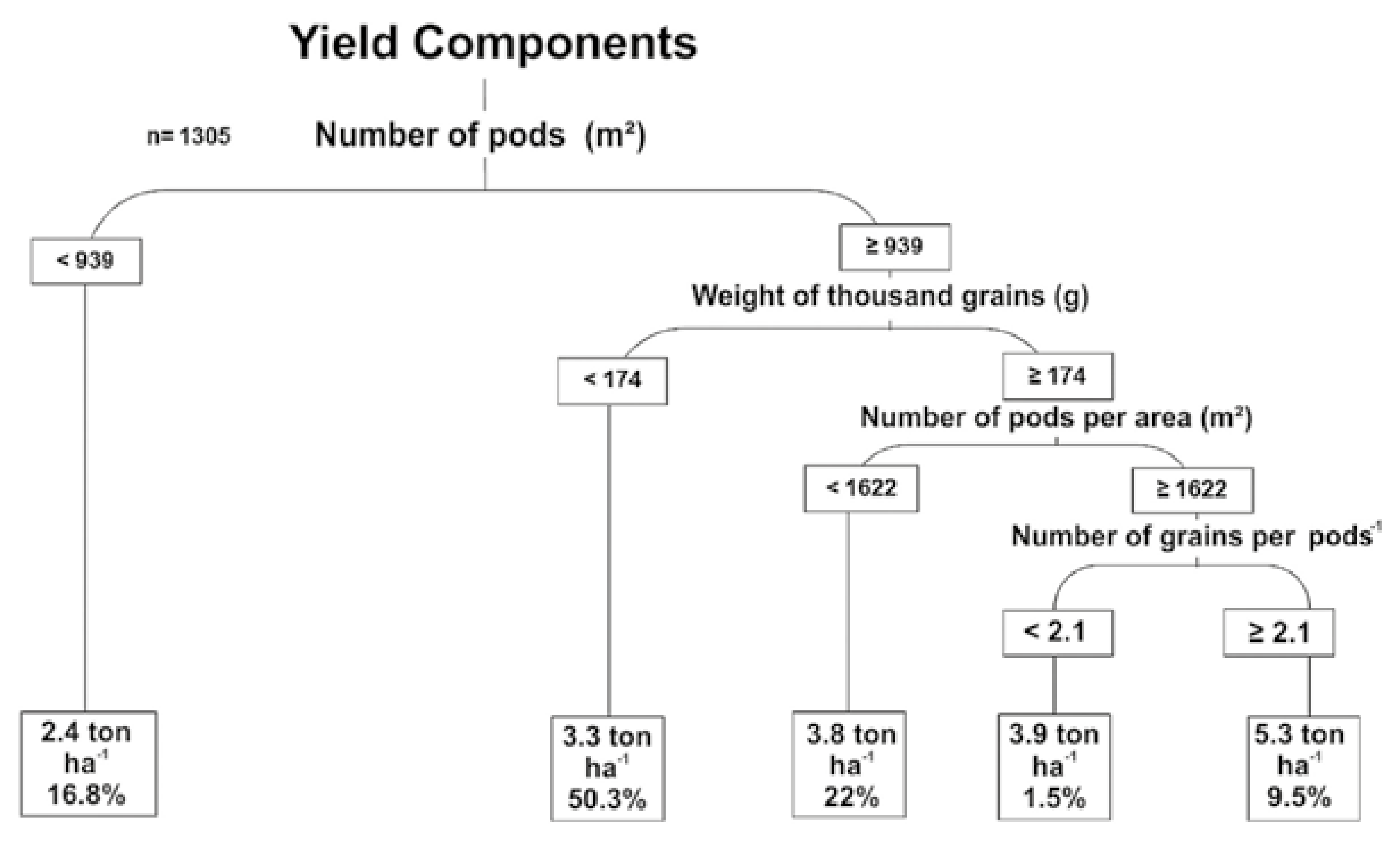


Figure 1.8.1.1. Regression tree showing soybean primary components recommended for increasing yield at crop level.

1.9. Plantabillity

The selection of the soybean sowing date stands out as one of the most crucial operations influencing the yield process. Moreover, with advancements in technology on a large scale, it becomes imperative to approach this stage with meticulous care. Achieving a correct distribution and uniformity of plants is the initial factor essential for cultivating high-yield crops. Plantability refers to the spatial arrangement, encompassing the space between lines and plants, and the proper seeding of seedlings. The sower must ensure a longitudinal disposition where the spacings between seeds within the row and seed depth are as homogeneous as possible (see Figure 1.9.1). Successful plantability relies on various factors, including environmental conditions (such as soil and climate), the equipment (seeder), and the operator. The operator should consider the soil condition at the time of sowing, the weather forecast for the days following sowing, seed density (dependent on seed vigor), and specific recommendations for the cultivar based on the potential yield area and sowing time.

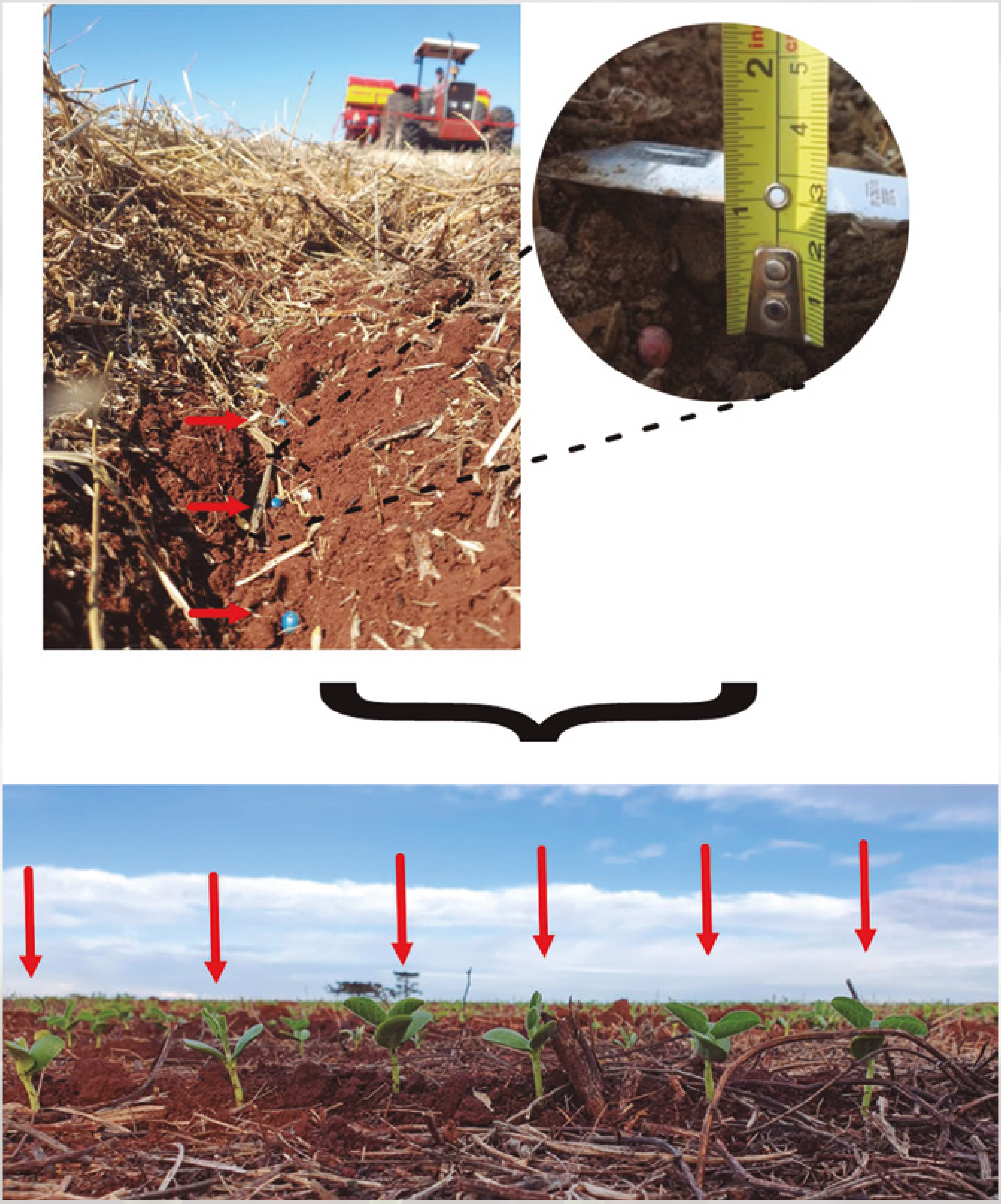


Figure 1.9.1. Sowing uniformity and final plantability of the crop. Courtesy: João Julio Schneider - Ibirubá, Rio Grande do Sul, Brazil.

The initial step towards achieving optimal plantability is determining the desired plant population. To achieve this, it is crucial to understand the quality attributes of seeds that can impact the final plant population. Seed quality can be assessed through four attributes:

Genetic quality: The seeds must express the genetic characteristics of the chosen cultivar without showing genetic segregation or varietal mixture;

Physical Quality: Seed packages must contain only seeds, without the presence of cultural remains or other grains that may interfere with the seed metering system;

Sanitary quality: Seeds can carry diseases and act as a vehicle for introducing pathogens into the area, potentially affecting plant health and reducing crop yield;

Physiological quality: Seeds must exhibit a high percentage of germination and vigor. The germination percentage is the ability of seeds to germinate and emerge under suitable cultivation conditions. Vigor refers to the capacity of seeds to germinate and emerge quickly and uniformly under a wide range of conditions (Figure 1.9.2 B).

To determine the seed density at sowing, one should consider the percentage of vigor along with on-farm emergency tests. For on-farm emergency testing, it is recommended to sow 300 seeds at a depth of 3 cm within a fenced area in the field, with plant counts after 8, 7, or 6 days (for sowings in September, October, and November, respectively), followed by a second plant count at 15 days after sowing. The calculation of the percentage of on-farm emergency is performed using the formula: (Number of plants in the 2nd count/300) * 100. To calculate the emergency vigor on the farm, use the formula: (Number of plants at the 1st count/300) * 100.

Another critical aspect for good plantability is the soil condition and the weather forecast for the days following sowing. Soil conditions, such as the presence of straw, texture, and moisture, directly affect the sowing operational process and the favorability of the environment for seed germination. Excessive hot days (temperatures >35°C) immediately after sowing, combined with soils without straw, can lead to soil temperatures close to 50°C, causing denaturation of membranes, seed death, strangulation of the hypocotyl in newly emerged plants, and consequent plant death (see Figure 1.9.2 A). Furthermore, monitoring the weather forecast is essential to avoid sowing immediately preceding heavy rains (above 30 mm) because excess soil moisture can cause “damage by imbibition” in the seeds (see Figure 1.9.2 C). Imbibition damage occurs due to the rapid absorption of water by the seeds, especially when the humidity is below 12%, in the first hours after sowing. This damage happens due to the difference between the water potential of the soil and the seed, leading to the rupture of cell membranes of the seeds, resulting in abnormal plants with low vigor or seed deterioration. Low soil humidity can, in some cases, induce seed germination without sufficient moisture for complete plant emergence or cause surface crusting of the soil, making it difficult for plants to emerge. At sowing, it is recommended that the soil contains moisture between 50% to 85% of the available water capacity (AWC) to provide a suitable environment for the seed to absorb 50% of its weight in water and complete germination and emergence. The sowing process involves cutting the straw, opening the furrow, depositing the fertilizer at a greater depth than the seed, depositing the seed with a longitudinal distribution density of seeds, and a vertical depth of 3 to 5 cm. Closing and compacting the sowing furrow are also integral steps. The sowing depth depends on soil type and moisture, the amount of straw, and seed vigor, directly affecting the expression of seed vigor and emergence speed, while the longitudinal distribution of seeds depends on the cultivar characteristics, crop yield potential (sowing date and soil fertility), and seed vigor.

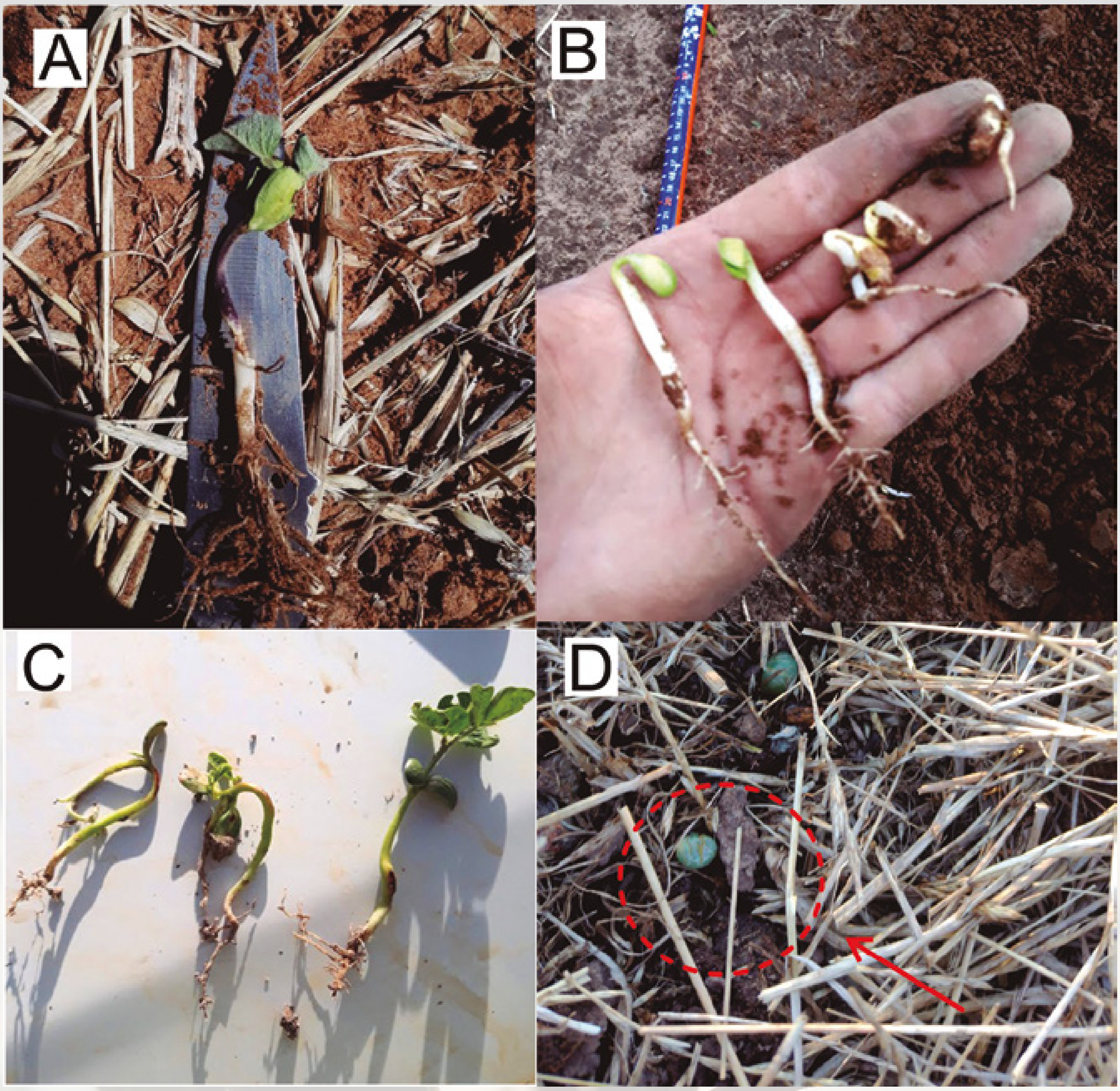


Figure 1.9.2. Death of plants by high temperatures after emergence (A), low seed vigor (B), damage by seed imbibition (C) and seed on the surface due to lack of pressure in the seeder line (D).

For the entire sowing process to occur with quality, the maintenance of the seeder and the actions of the operator are crucial factors to avoid harming the vertical and longitudinal distribution of seeds. An example of an issue is when good singulation occurs (longitudinal distribution of the seed) without problems in the metering system. However, when passing through the conductive tube, the seeds are deposited at different depths due to the lack of pressure on the seeder line (downforce) (see Figure 1.9.2 D). The result of this issue is that the seeds can remain at different depths, compromising the plant stand due to irregular emergence of seedlings. The vertical distribution of the seeds is also affected by the presence of “clods” (non-uniformity of the depth of the sowing), excess soil moisture (causes mirroring of the furrow and the deposition of the seed at high depth), and low cut-off wheel pressure in areas with a high amount of straw (causes the seed to envelop, preventing seed--soil contact). Some adaptations in seeders can be carried out to minimize these problems (Santos et al., 2019). The longitudinal distribution of seeds can be affected by incorrect use of the seed metering disc or by the sowing speed. The determination of the seed doser disc depends on the seed diameter. Discs with large alveoli might cause the deposition of two double seeds, while small alveoli can cause a seedless space due to failure or clogging of the alveolus. The seeding speed affects the distribution of seeds due to errors in the dosing system or ricochet of the seeds in the conductive tube to the furrow of sowing. Additionally, speeding reduces the acceptable spacing between seeds, increases the number of double seeds or faulty spacing, and causes greater soil turning. The ideal speed for sowing is the maximum speed at which there is no loss of quality during the operation. In general, pneumatic seeders allow a higher sowing speed compared to mechanical seeders. Acceptable spacing is defined when seed deposition occurs uniformly, meaning with longitudinal spacing within the recommended (number of seeds per desired linear meter) (Figure 1.9.3). “Double seeds” are defined when the deposition of seeds in the soil is less than 50% of the recommended spacing length. “Double seeds” lead to dominance among plants, competition for light, a lower number of ramifications, reduced production per plant, a smaller stem diameter, and greater plant height, increasing the propensity of plants to lodging. The “spacing flaw” occurs when the longitudinal spacing between seeds is 150% higher than recommended. Plant failure reduces the use of resources such as light, water, and nutrients and allows for greater weed growth.

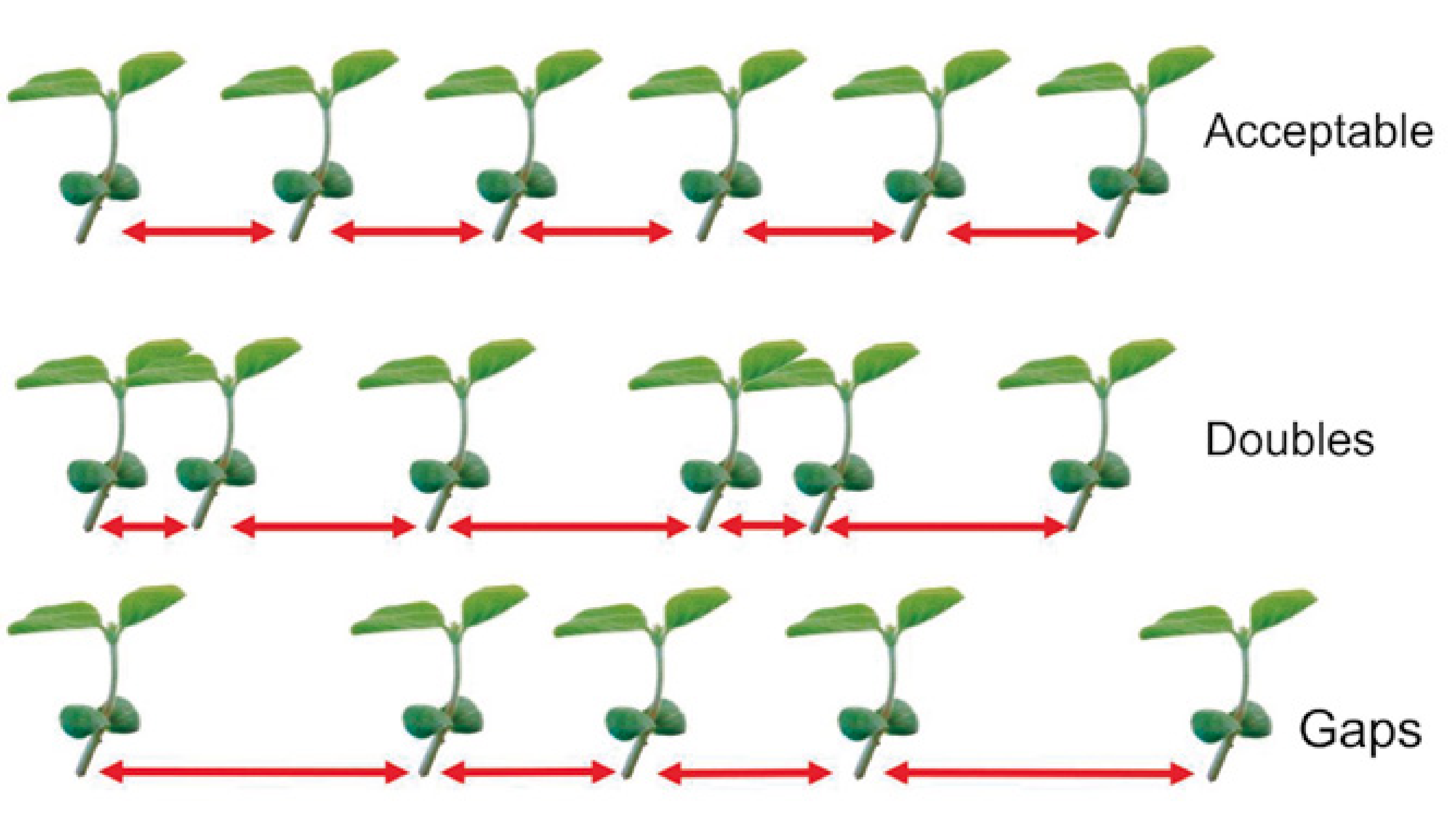


Figure 1.9.3. Representation of acceptable spacings, doubles, and bracks. Courtesy: Paulo Arbex, 2022.

To assess the quality of the vertical distribution of seeds, the Coefficient of Variation method is used (CV) (Table 1.9.1). The first step to calculate the CV is to set the desired spacing between seeds, note in 1 linear meter the distance between the seeds, and after calculating the standard deviation (SD) between spacings:

SD = $(\sqrt{(M1-X)^2 + (M2-X)^2 .....})/N$ where M1, M2... are the distances between a seed and another, X is the desired space between plants, and N is the number of plant spaces between seeds in one linear meter;

The second step is to calculate the CV by the following formula:

$$CV (\%) = (SD * 100)/X$$

where X is the desired seed spacing.

Table 1.9.1. Classification of sowing quality through the coefficient of variation. Source: adapted from Tourino & Klingensteiner (1983).

Result CV (%)			
< 10	10-25	25-50	>50
Great	Good	Regular	Unsatisfactory

Good plantability, with uniformity in sowing depth and CV close to zero in seed distribution, is the first step in obtaining high yields (Figure 1.9.4).

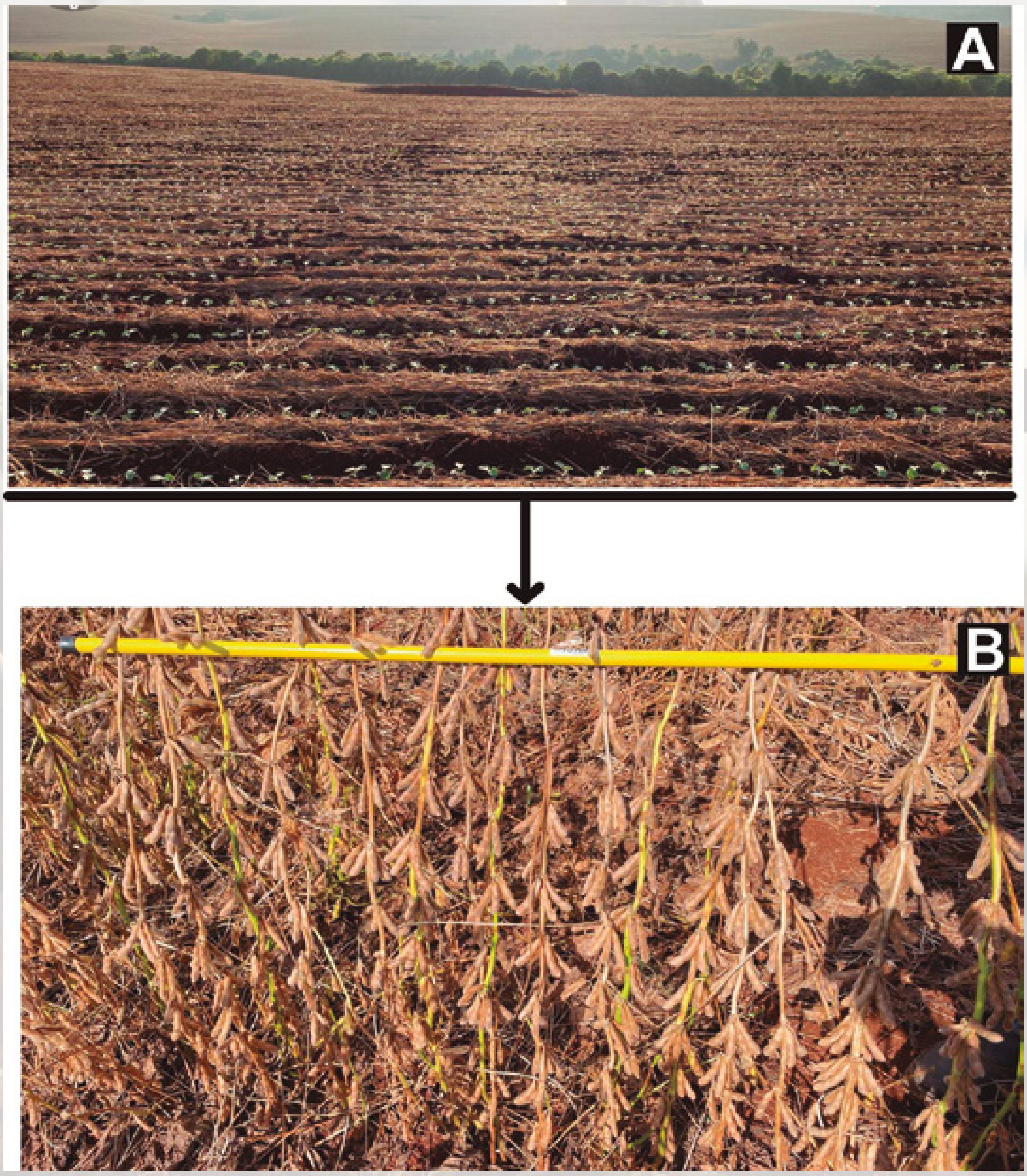


Figure 1.9.4. Crop with good plantability and uniformity in the emergence of plants at the beginning of development (A) and, in the same crop, maintaining the plant stand and consequently, high yield (6540 kg ha^{-1}) (B). Strobel Farming, in Dois Irmãos das Missões, Rio Grande do Sul, Brazil, 2021/2022 harvest.

1.9.1. Optimal Agronomic Density

The optimal agronomic plant density (OAPD) is defined as the number of plants per area that minimizes intra-specific competition and maximizes efficiency in the use of environmental resources (solar radiation, temperature, and water) and nutrients. Therefore, the OAPD indicates the number of emerged and healthy plants for a given sowing season, MG, and production environment, representing a strategy to reduce costs and increase yield (Balest, 2021). To define OAPD, the density of plants at the time of harvest was used, not during initial establishment. Over six agricultural years (2015-2021), more than a thousand soybean crops were monitored to identify the OAPD. During this period, it was found that OAPD is 29 plants m-^{2} to achieve high yield. This value represents the final number of plants m-^{2} that maximized the genotype (cultivar) x environment (sowing time) interaction x management (nutrition). In addition to OAPD, there is a range of plant density that allows high yields to be achieved according to the duration of the development cycle. From this range, the reduction of a plant m-^{2} results in losses of 78 kg ha^{-1} in soybean crops with a cycle of up to 133 days (Figure 1.9.1.1 A) and 59 kg ha^{-1} in soybean crops with a cycle longer than 133 days (Figure 1.9.1.1 B). It is also necessary to be aware of the equidistant distribution of plants during seeding. Low density and poor plant distribution cause a reduction in the yield potential of the crop, even if the cultivar has plasticity.

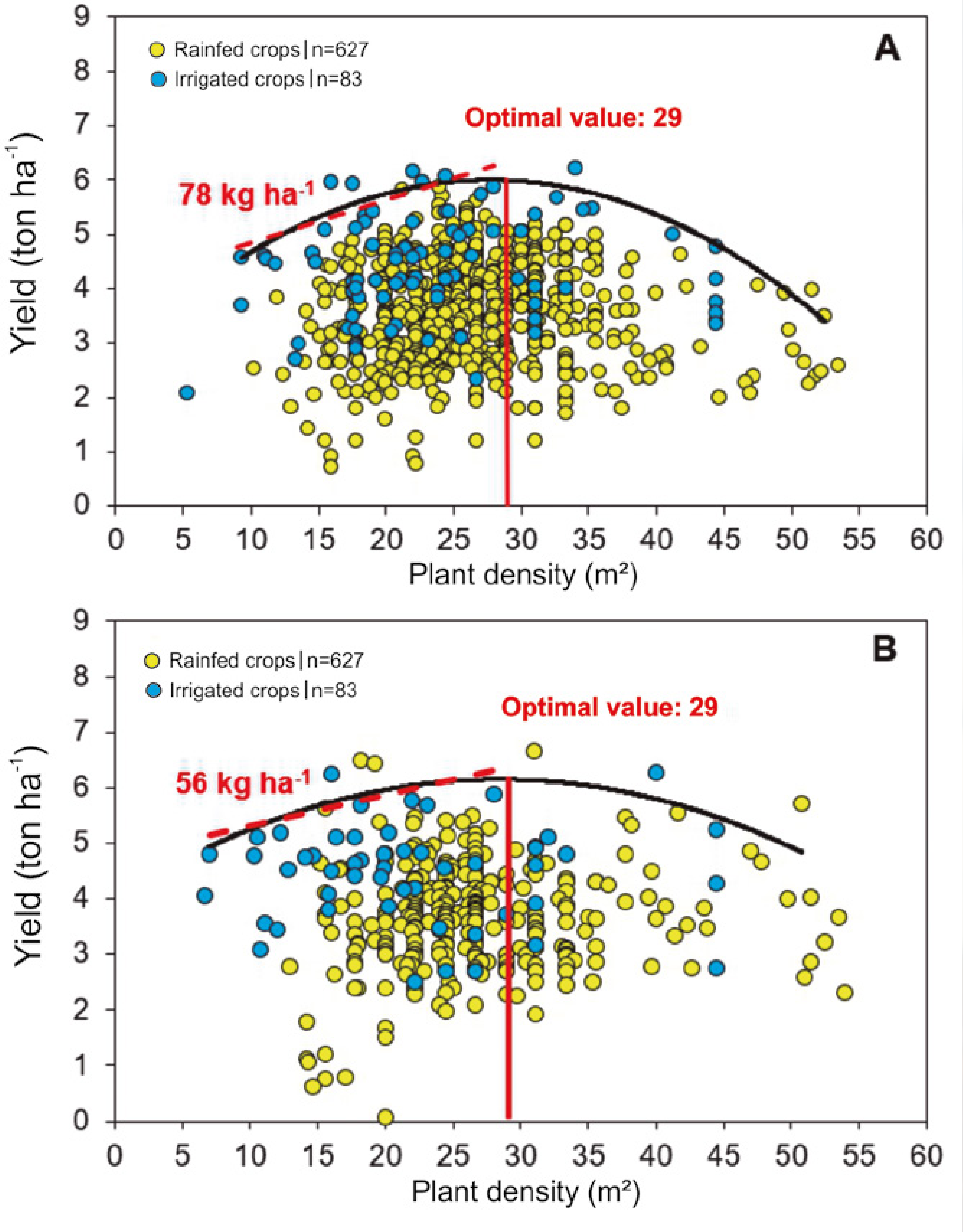


Figure 1.9.1.1. Relationship between grain yield (ton ha^{-1}) and the number of plants per m² for cultivars with a full cycle duration less than 133 days (A) and greater than 133 days (B) for soybean in irrigated (blue circles) and rainfed (yellow circles) crops. The solid black line represents the limit function, and the solid red line indicates the value of optimal agronomic plant density that maximizes the productivity of grain. The red dashed line indicates yield loss (kg ha^{-1}) for each plant less per m².

The plasticity is a genetic trait that allows the soybean plant to compensate for uneven distribution of plants through the issuance of branches (Toyota et al., 2017, Agudamu & Shiraiwab, 2016). Each branch can produce knots, leaves, flowers, vegetables, and grains, increasing yield stability at different densities (Zanon et al., 2015b; Zhang et al., 2016). In Figure 1.9.1.2, it is observed that the smaller the number of plants per area, the greater the number of branches needed to reach high yields (Figure 1.9.1.2 A and 1.9.1.2 B). On the other hand, crops with high plant density have fewer branches per plant to reach high yields (Figure 1.9.1.2 C and 1.9.1.2 D). Thus, even if the cultivar has a high potential for branching and compensation for plasticity, producers must be aware of the adjustment (increase/decrease) in density recommended by the holders to capture the maximum solar radiation during the development cycle (Suhre et al., 2014; Salmeron et al., 2016; Santachiara et al., 2017).

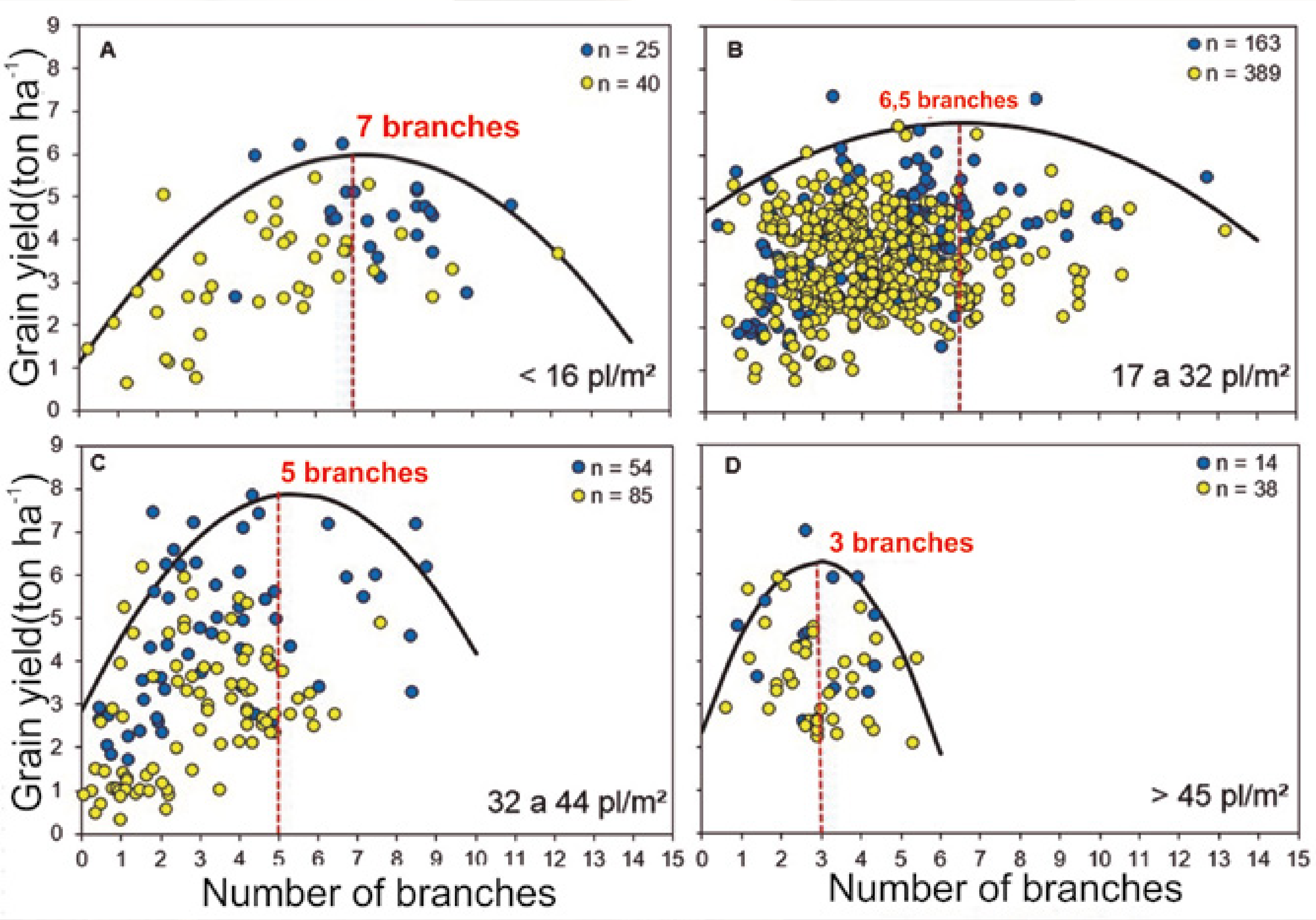


Figure 1.9.1.2. Relationship between soybean grain yield (ton ha^{-1}) and the number of branches per plant for density < 16 pl/m² (A), between 17 and 32 pl/m² (B), between 32 and 44 pl/m² (C) and > 45 pl/m² (D) plants m-² in irrigated (blue circles) and rainfed (yellow circles) soybeans. The dashed red line indicates the value of branches that maximize the grain yield.

OAPD is cultivar/crop-specific, as the interaction between cultivar (MG, ability to branch, tolerance to lodging) and tillage (supply of water and nutrients) will determine the ideal number of plants per hectare for each production environment. The goal is to distribute the plants according to the supply of nutrients and water from the soil, taking into account the specific characteristics of a given cultivar. For instance, high-tech crops have already implemented variable-rate sowing and fertilization based on the production environment of a crop (Figure 1.9.1.3). Recent studies suggest a potential seed density reduction of 18 to 24% in high-yield (> 5 ton ha^{-1}) compared to low-yield (< 4 ton ha^{-1}) scenarios (Carciochi et al., 2019; Corassa et al., 2018). Research conducted in 13 commercial crops of high technological level in 2021 in Rio Grande do Sul, Tocantins, Paraná, and Mato Grosso states by the FieldCrops team and partners demonstrated a yield increase of +3 to +6% with variable seed rates, with greater gains observed in low-yield areas. One challenge with this management approach is linked to the machinery used during sowing (year/brand of sowing machines), which, coupled with the relief of the area and sowing depth/speed, may or may not ensure good plantability. This study revealed a variation between target plants versus achieved plants ranging from 0% to 30% (acceptable values up to +/- 15%), making it challenging to measure the gain in management in some cases where the ideal stand cannot be reached or there is little difference in plant numbers between managed areas. Additionally, the study identified that a minimum yield difference of 500 kg between zones is necessary to justify variable-rate seeding, highlighting the potential for the greatest yield gains.

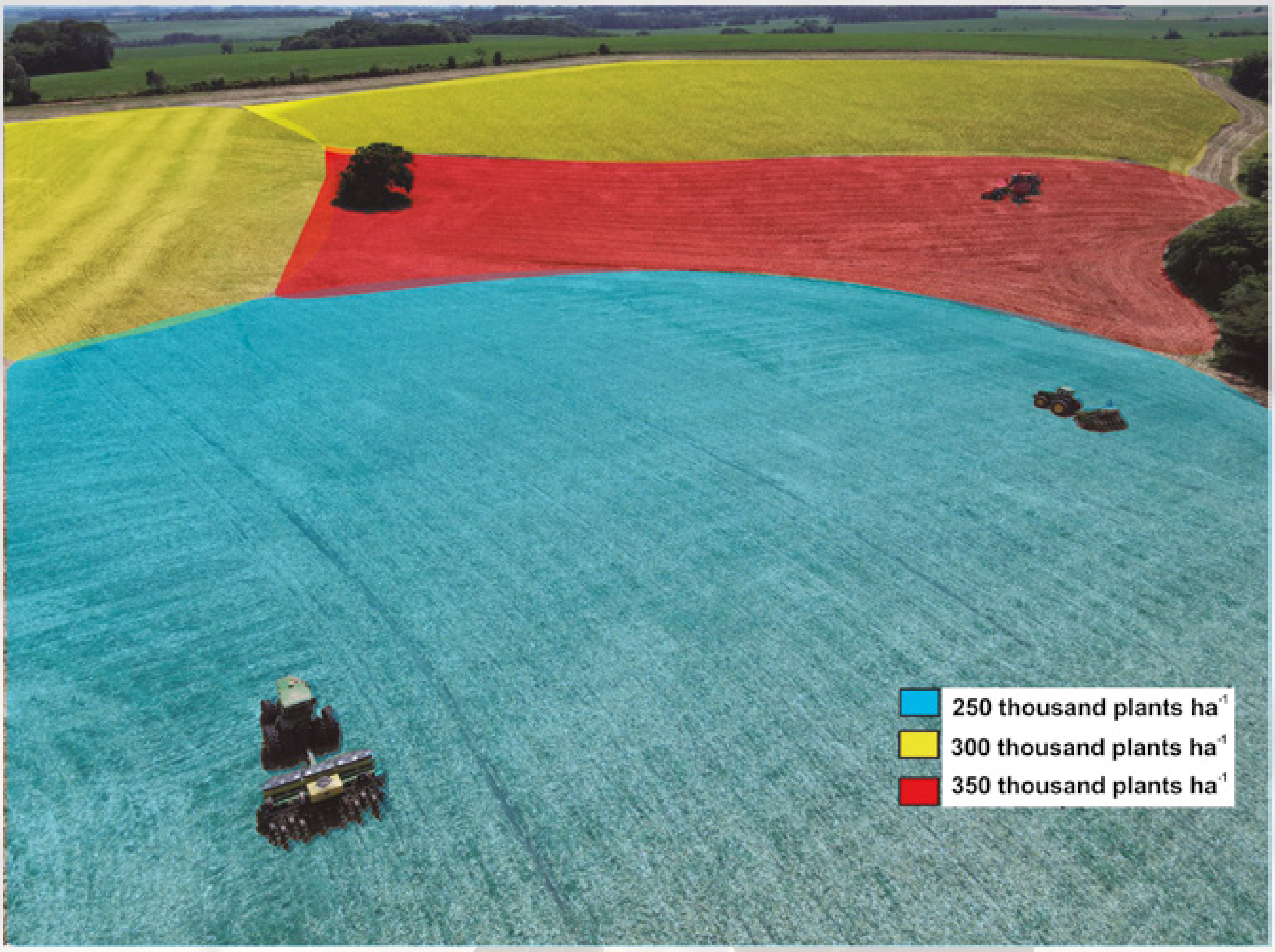


Figure 1.9.1.3. Variable rate seeding per production environment (low, medium and high yield). Blue represents an environment of high yield, yellow for medium and red for low. Courtesy: Gabriel Caye - Cachoeira do Sul, Rio Grande do Sul, Brazil.

Determining a universal plant density allows producers to adjust plant density according to their specific production environment (Corassa et al., 2018; Tagliapietra et al., 2021). The highest suggested densification of plants (31 plants m-^{2}) is recommended in production environments with a low yield history, where factors such as soil fertility, water deficit, sowing time, planting failures, and soil diseases can restrict plant growth. These restrictions result in plants with reduced growth, low compensatory capacity, and grain production concentrated on the main stem, allowing densification without the risk of lodging. For environments with a history of high yield, the ideal density is 24 plants m^2, which minimizes intra-specific competition between plants, maximizing the use of water, nutrients, and light while ensuring seed economy. High densities in high-yield environments can lead to plant lodging, causing senescence of older leaves due to insufficient light and resulting in yield losses (Winck et al., 2020).

1.9.2. Row spacing

The most commonly used row spacing in soybean crops in South America ranges from 40 to 60 cm. Adjusting the row spacing does not incur costs for the producer, and if done appropriately for the characteristics of each farm, it increases the interception of solar radiation and reduces issues related to diseases and weeds. Modifications to the plant arrangement alter the relationship between source and drain, affecting crop yield due to the interdependence between the leaf (source of photoassimilates) and the reproductive organs of the leaf axil (photoassimilate drain) (Zhou et al., 2011). The smallest internodal translocation of products from photosynthesis affects the number of flowers and vegetables that can be fixed on each inflorescence, depending on factors limiting the production of photoassimilates, especially light (Winck et al., 2020).

There are two ecophysiological purposes for changing row spacing: 1) to achieve parameters R1 and R3 during phenological stages, ensuring that 95% of solar radiation is absorbed, and all canopy leaves intercept solar radiation at this stage of development (Figure 1.9.2.1); 2) at the beginning of grain filling (R5), the leaves of the lower tertile of the plant remain green, allowing the fixation of vegetables and the filling of grains.

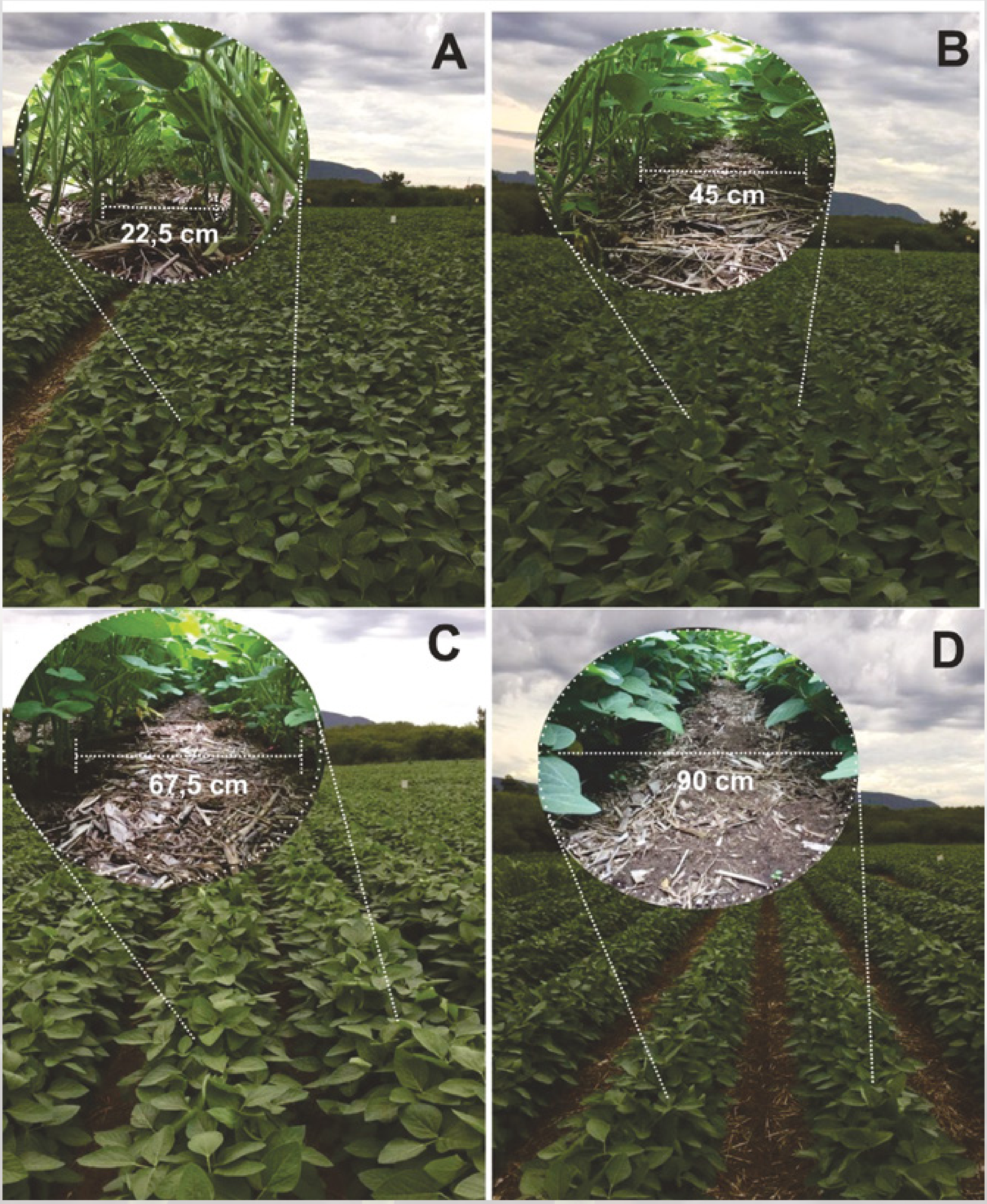


Figure 1.9.2.1. Row spacing of 22.5 cm (H), 45 cm (B), 67.5 cm (C) and 90 cm (D) in soybean in Santa Maria, Rio Grande do Sul, Brazil.

An experiment conducted in Santa Maria/RS by the Field-Crops team, with three soybean cultivars, early (August) and late (January) sowings, different plant densities, and spacing between rows (30 and 45 cm), showed an increase in yield with reduced spacing between lines, regardless of plant density and MG used (Figure 1.9.2.2). Similar results were observed by Andrade et al. (2019), who also found increased yield in US soybeans with reduced spacing from 78 to 36 cm. The magnitude of the difference between the smallest and the greatest spacing between lines depends on the region and management practices.

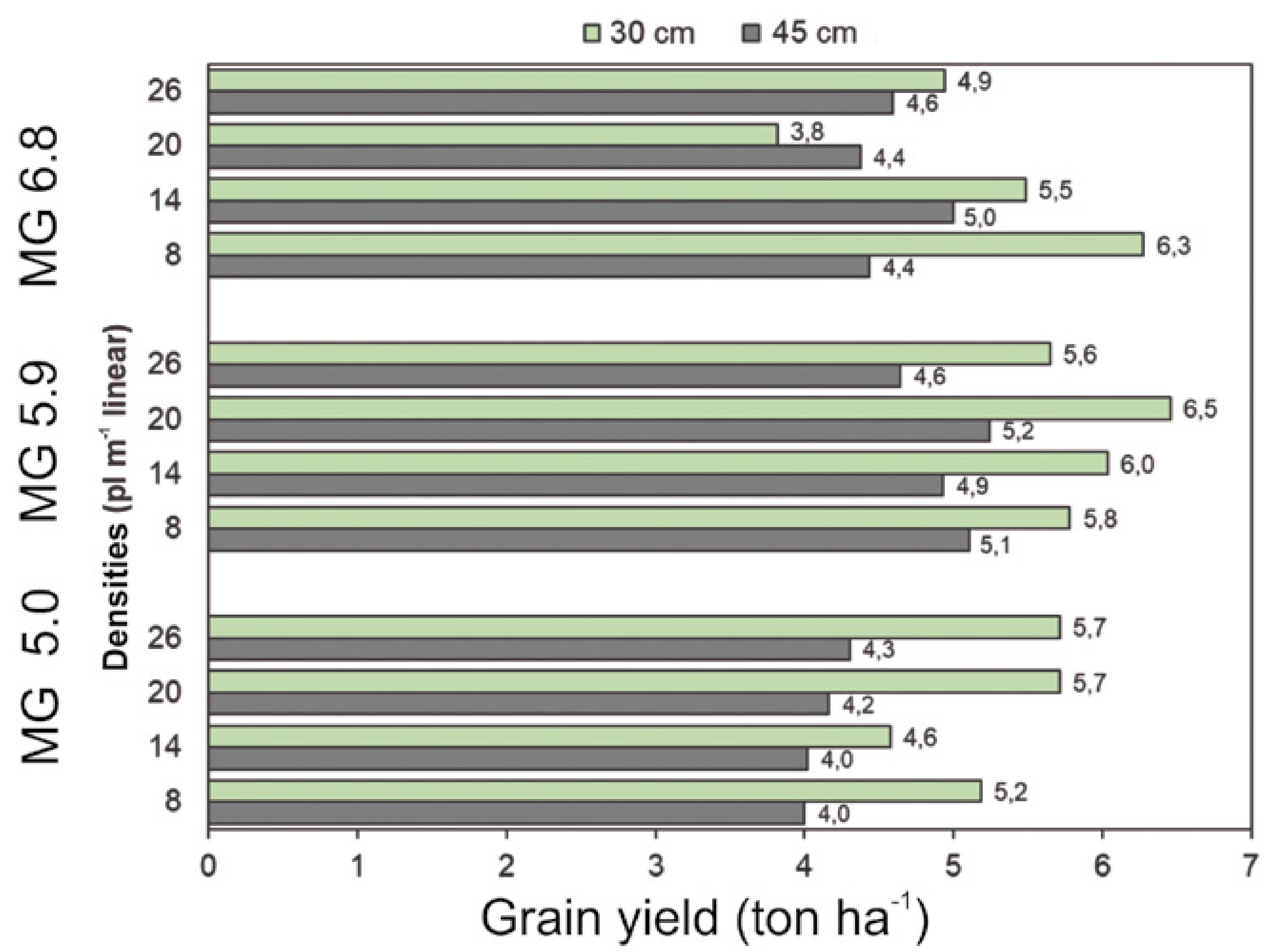


Figure 1.9.2.2. Soybean yield (ton ha^{-1}) in two spacings between rows (30 and 45 cm), three maturation groups (5.0, 5.9 and 6.8) and four seed densities per linear meter (8, 14, 20 and 26) in Santa Maria, Rio Grande do Sul, Brazil, sowing in the month of August (08/17/2018).

Changing row spacing can be a strategy to minimize intraspecific competition among plants. In this sense, the FieldCrops Team aims to understand the interaction between cultivar x sowing time x plant population x row spacing. Understanding how to harness solar radiation will help define management practices to increase crop yield.

Courtesy: Darlan Scapini Balest

2. Soybean Climate Requirements

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The main factor responsible for variability in soybean production is climatic elements, especially in non-irrigated production systems. An example is the influence of the amount and distribution of rainfall on soybean yield variability in southern Brazil, particularly in Rio Grande do Sul, compared to the states of the Midwest region of Brazil, where historically, rains are distributed during the soybean growing period. In the 2004/05 and 2011/12 harvests, the average soybean yield in the state of Rio Grande do Sul was 0.7 ton ha^{-1} and 1.5 ton ha^{-1}, respectively, while the average yield of crops (2016/17 to 2020/21) was 3.1 ton ha^{-1}. The cause of crop failure in these two years (2004/05 and 2011/12) in RS was the low and irregular distribution of rainfall during the cultivation season (CONAB, 2022).

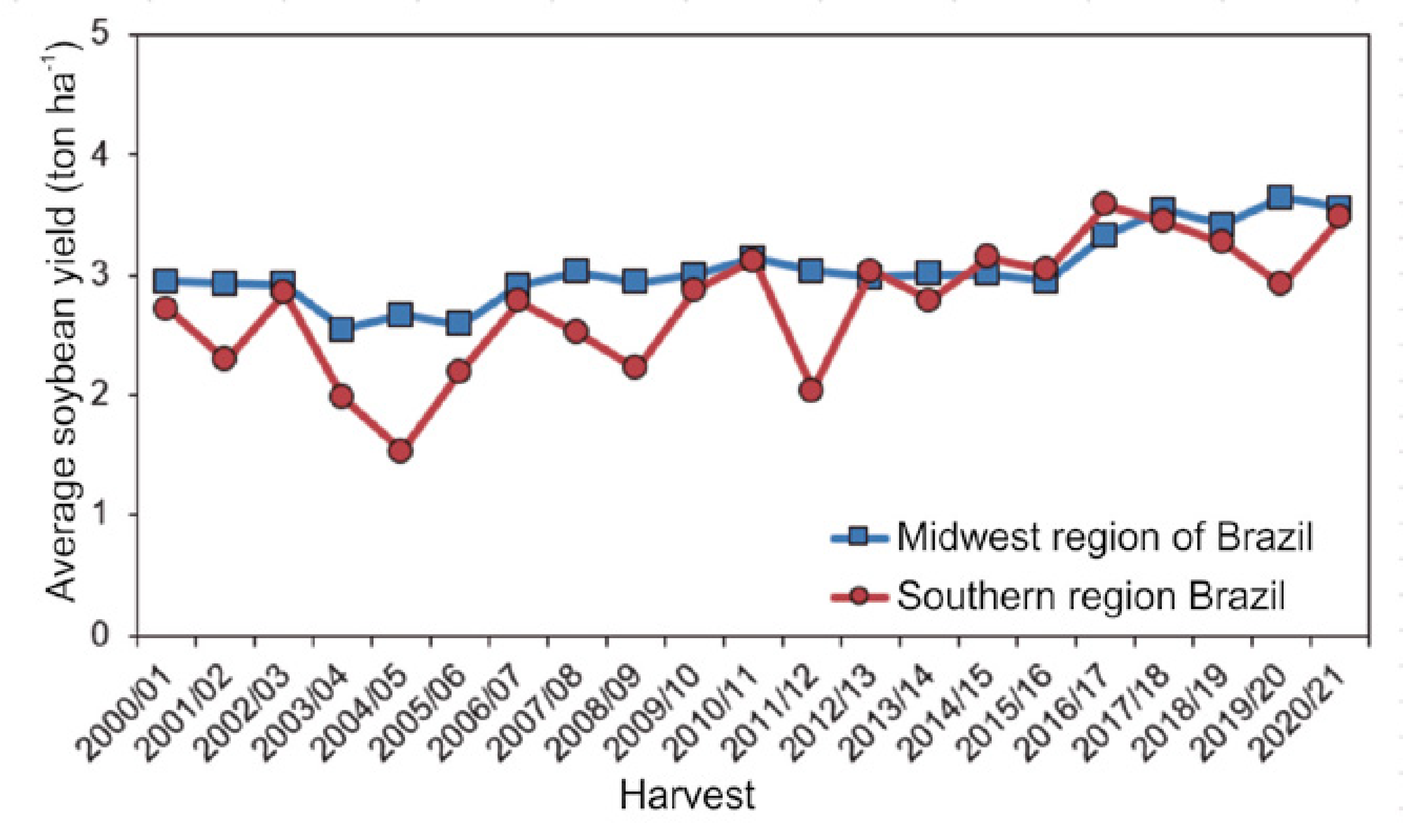


Figure 2.1. History (2000/01 to 2020/21) of the average yield of soybeans from the South and Midwest regions of Brazil. In addition to rain, other meteorological elements such as solar radiation, air temperature, and photoperiod directly influence the growth, development, and potential yield of soybeans. Due to the influence of climate and meteorological variables on the productive system, this chapter will highlight the climatic demands of soybean culture and the main elements that determine the growth, development, and, above all, the yield of soybean crops.

2.1. Rain

A soybean plant comprises approximately 90% of its mass as water, playing a crucial role in essential physiological processes and biochemical factors (Taiz & Zeiger, 2013). The establishment of the crop, spanning from sowing to the V2 stage, is highly sensitive to water deficit or excess in the soil. This stage is critical as it contributes to the development of one of the main yield components—the number of plants per area. The peak water demand by soybean plants occurs during the flowering and grain-filling phase, reaching 9 mm per day under potential conditions. This is contingent upon water availability in the soil and a root system capable of meeting the high demands of the plant and the atmosphere (Figure 2.1.1). The increased water demand during flowering and grain filling is attributed to the larger leaf surface (leaf area index) transpiring (Figure 2.1.1).

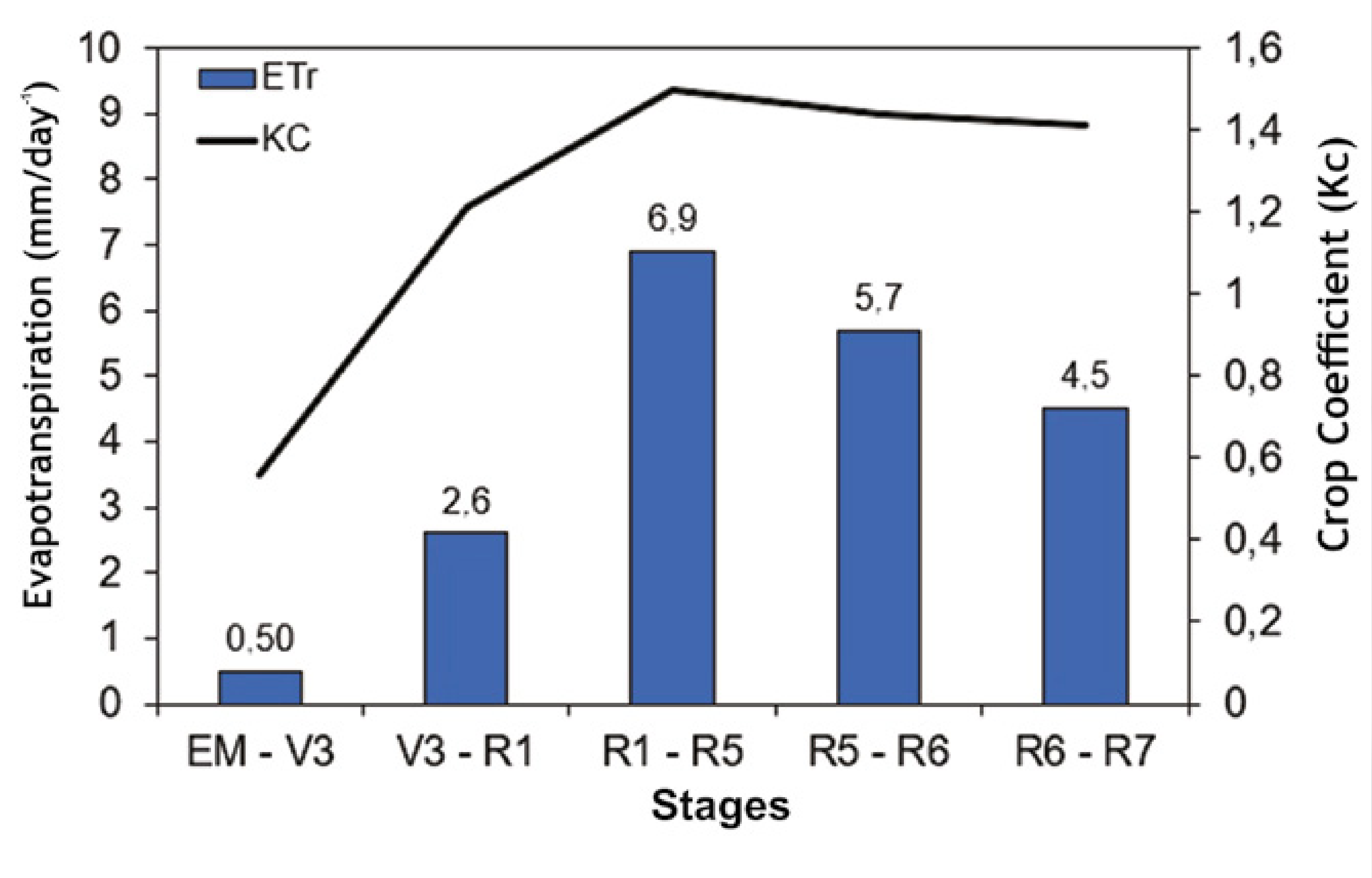


Figure 2.1.1. Real evapotranspiration (ETr) of the crop (simulation with DSSAT - CROPGRO model) represented in the columns and the coefficient of culture (Kc) of the FAO in the black line, relative to the stages of soybean development.

Throughout the crop development cycle, a crop with a yield potential of 6 ton ha^{-1} needs approximately 800 mm of water (Figure 2.1.2). The regular distribution of rains and/or irrigations is crucial throughout the cycle, especially during the grain-filling phase (Zanon et al., 2016a). Generally, with a millimeter of water during the crop development cycle, a crop with maximum efficiency can produce 9.1 kg of soybeans (Zanon et al., 2016a). However, the total water demand increases with higher maturity groups (MG), as larger MGs have a longer development cycle compared to smaller MGs sown simultaneously (Alliprandini et al., 2009). According to Tagliapietra et al. (2021), the water demand for cultivars with MG ≤ 5.5 is 765 mm (Figure 2.1.2 A), for MGs 5.6 to 6.4 it is 830 mm (Figure 2.1.2 B) and for MG ≥ 6.5 it is 875 mm (Figure 2.1.2 C).

The point of maximum efficiency in water use relative to yield represents the attainable water productivity (PAA, expressed in kg ha^{-1} mm^{-1}). The estimated YW for MGs ≤ 5.5 is 9.2 kg ha^{-1} mm-1 (Figure 2.1.2 A), for MGs between 5.6 to 6.4 it is 8.6 kg ha^{-1} mm^{-1} (Figure 2.1.2 B), and for MGs ≥ 6.5 it is 8.5 kg ha^{-1} mm^{-1} (Figure 2.1.2 C). Cultivars with MGs ≤ 5.5 exhibit greater water use efficiency. Therefore, in irrigated systems and/or with restrictions on water volume for irrigation, the use of low MGs and short-cycle cultivars with high yield potential is recommended to enhance water and energy efficiency, as well as the profitability of the producer (Tagliapietra et al., 2021).

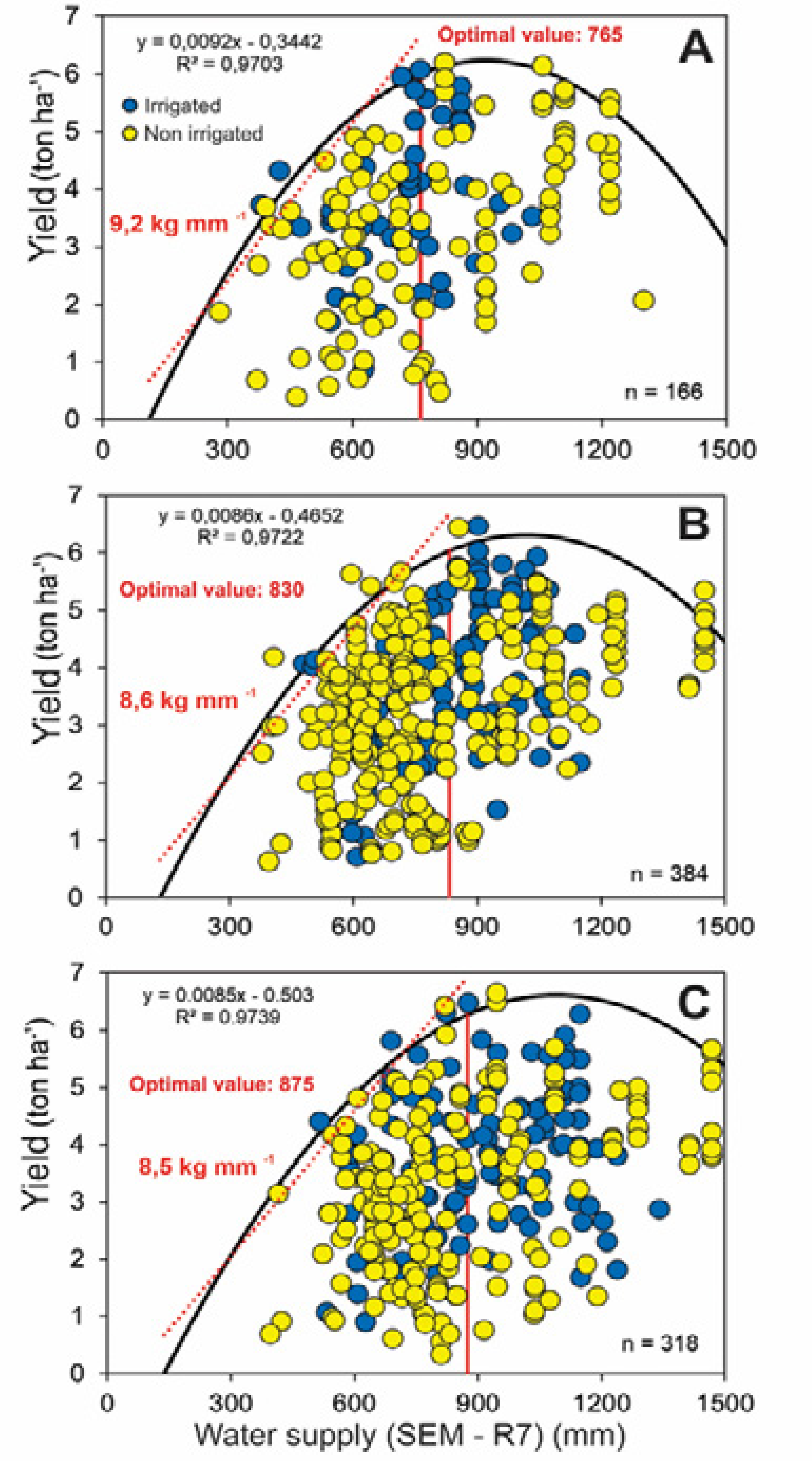


Figure 2.1.2. Soybean yield (ton ha^{-1}) in relation to water supply (mm) during the growing season (SEM – R7) for different cultivars with MGs ≤ 5.5 (A), MG 5.6 to 6.4 (B), and MG ≥ 6.4 (C). The water supply includes the sum of available water in the soil at sowing, precipitation, and total irrigation. Blue circles represent irrigated experiments, yellow circles represent experiments without irrigation. The black solid line represents the limit function, the solid red line indicates the optimal value of water supply during the total cycle, and the red dashed line represents the slope of the limit function.

2.1.1. Availability and accessibility of soil water

The maximum amount of water a plant can absorb from the soil between two rainfall or irrigation events depends on two capacities: (i) the capacity of the soil to supply water to the plants and (ii) the capacity of the plants to access the water provided by the soil. This view can be expressed by the equation of available water capacity (AWS, mm):

$$CAD = \sum_{i=1}^{n} (CC \ - PMP)(CC - PMP)_i * L_i$$

where CC (cm^3 cm^{-3}) and PWP (cm^3 cm^{-3}) are, respectively, the field capacity and the permanent wilting point in each soil layer Li (cm) occupied by roots, and the factor 10 converts the result from cm to mm. The difference (CC - PWP) is classically defined as the maximum available water (MAW) and represents the capacity of each Li soil layer to provide water for plants. The number of Li layers considered in the equation represents the profile of soil that the plant can exploit throughout the cycle.

2.1.1.1. Ability of soil to supply water to plants (AWS)

AWS is associated with soil properties such as texture, density, organic matter content, and mineralogy. On a spatial scale with significant variation in soil classes, texture is the factor that most affects AWS (Figure 2.1.1.1.1). AWS variability in each class occurs due to differences in sand, silt, and clay, which naturally exist within the same textural class, as well as differences in organic matter, mineralogy, and density of soil. For most textural classes identified by HYBRAS, the average AWS is just above 0.1 cm^3 cm^{-3} of soil, being much smaller in sand class soils and very clayey and much larger in the silty clay loam class (Ottoni et al., 2017).

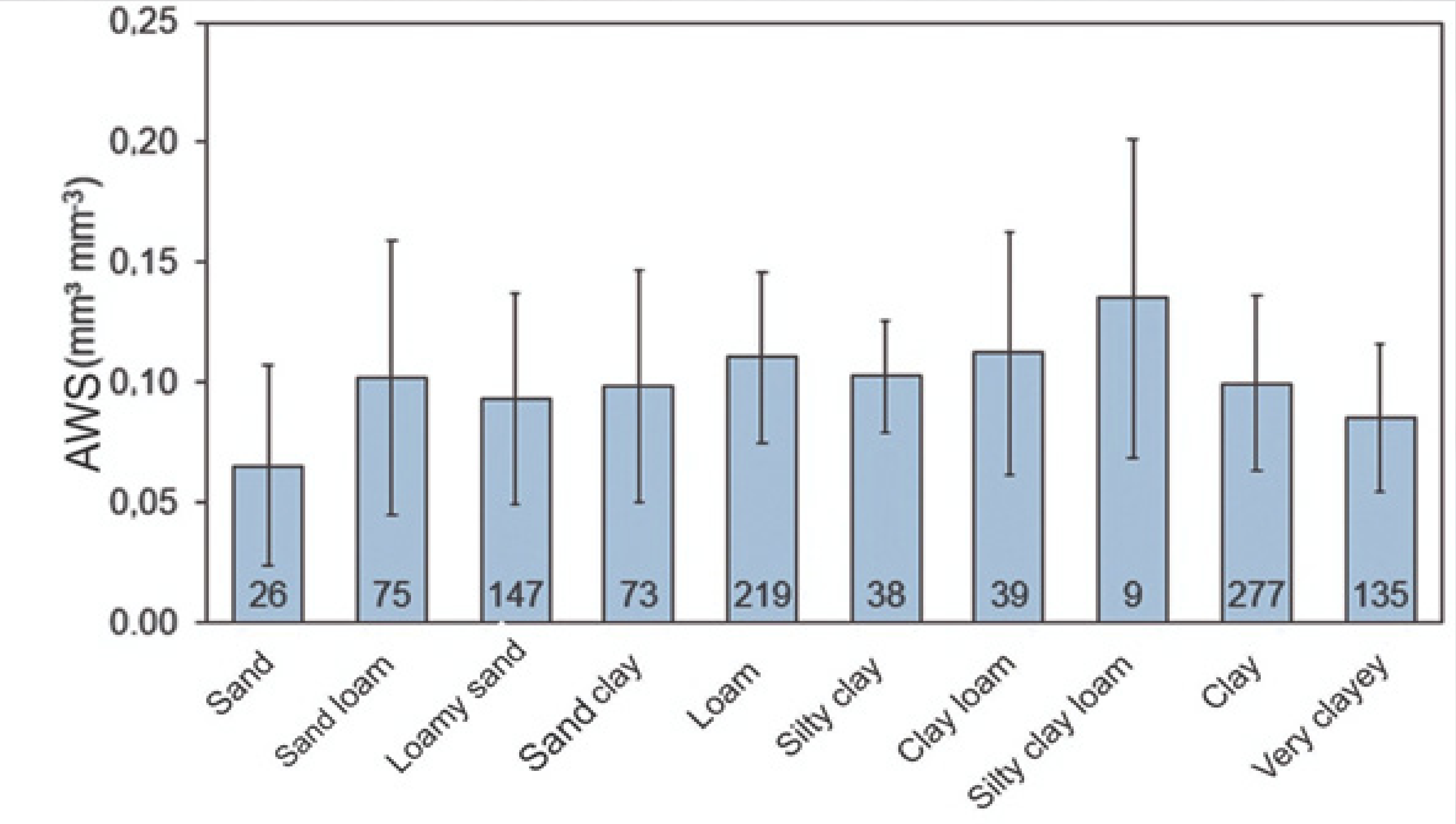


Figure 2.1.1.1.1. Available water content (AWS) according to soil texture classes. Numbers in the columns represent the number of data. Information extracted from the HYBRAS database (Ottoni et al., 2017).

The increase in organic matter (OM) in the soil enhances AWS, but the magnitude of the increase depends on soil texture and mineralogy. Minasny and McBraney (2017) analyzed over 50,000 measurements globally and found a weak relationship between AWS and the percentage of OM. Each 1% increase in OM results in only a 0.2% increase in AWS in clay soils with little sand, reaching a 1.2% increase in AWS in sandy soils. In this scenario, increasing OM from 1% to 5% up to 50 cm depth in the soil generates a gain of 30 mm AWS. However, Hudson (1994) indicates that in silty loam soil, clay loam, and sandy soils in the United States, there was an increase of 10 to 15% in AWS with a change from 1 to 5% of OM, resulting in an AWS increment from 50 to 75 mm. Nevertheless, reaching 5% OM content in the soil, especially at great depths in tropical and subtropical environments in Brazil, is challenging and time-consuming, perhaps not even possible. Hence, while it is theoretically possible to increase AWS by raising OM, practical implementation presents difficulties. AWS can also be affected by soil compression. Database estimates with more than 2,000 soil samples from North America and Europe (Schaap et al., 2001) indicate that an increase of

0.4 g cm^{-3} in soil density (a relatively large change) causes a 1 to 9% decrease in AWS. However, the impact of compression on AWS is confined to certain portions of the soil profile, as substantial density changes occur in compacted layers, generally not exceeding a thickness of 20 cm (Reichert et al., 2007). In these layers, AWS would be reduced to 15 to 18 mm due to severe compaction.

AWS is not highly sensitive to soil management because it is stored in a pore class of intermediate size, which is minimally affected by compression or decompression, changes in aggregation due to an increase or decrease in OM, and biological activity. These factors have a more significant impact on the larger pore class, macropores, which favor infiltration and drainage.

2.1.1.2. Ability of plants to access water

The ability of plants to access water in the soil depends on the number of soil layers occupied by roots throughout the cycle and their activity in these layers. The depth of the root system and the number of roots allocated in each layer determine a plant's ability to access ground water. These variables change over the cycle based on the morphological characteristics of each plant species, influenced by soil water content, chemistry, and physics. To illustrate the importance of rooting depth, the Available Water Storage (AWS) in sandy soil (65% sand, 25% silt, and 12% clay) increases from 95 to 153 mm with a rooting depth increase from 50 to 80 cm. In clay soil (24% sand, 25% silt, and 51% clay), the AWS increases from 122 to 195 mm over the same depth change (50 to 80 cm), given the higher AWS of clayey soil. Apart from underscoring the significance of rooting depth in increasing AWS, it is evident that, even with a lower AWS, well-rooted sandy soil (up to 80 cm) can offer more water to plants than a clayey soil with restricted root growth (50 cm). This emphasizes the need for management practices that promote deepening of roots whenever possible to enhance water supply. In shallow soils like Litholic Neosols, there is a heightened risk of water deficiency due to inherent limitations in AWS. Water accessibility significantly impacts yield, with plants having shallow roots or concentrated near the surface being more susceptible to water deficit. Battisti & Sentelhas (2017) demonstrate that soybean plants with more than 50% of roots allocated below 30 cm can achieve yields exceeding 7,000 kg ha^{-1}, while those with 70% of roots within the first 30 cm do not surpass 4,000 kg ha^{-1} (Figure 2.1.1.2.1).

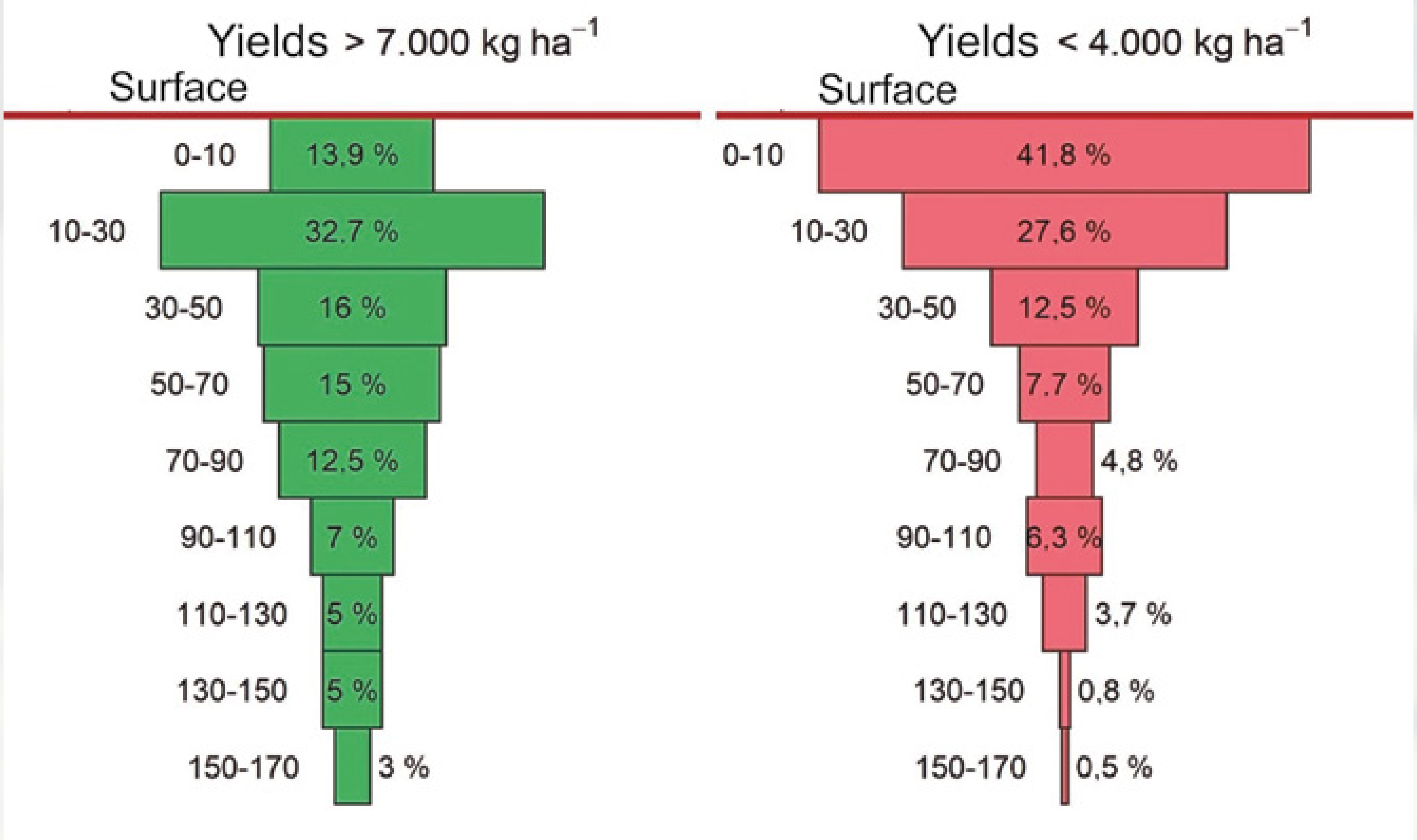


Figure 2.1.1.2.1. Distribution of soybean roots in crops with yields greater than 7,000 kg ha^{-1} (left) and less than 4,000 kg ha^{-1} (right), indicating the depth of layers in centimeters. Adapted from Battisti and Sentelhas (2017).

The concentration of roots near the surface may be associated with chemical and physical limitations imposed by the soil, such as low base saturation, high acidity, high aluminum saturation, and restrictions in layers with high mechanical strength. From a physical standpoint, soil can impede the deepening and proliferation of roots in layers with high mechanical strength. In plantations managed directly, it is common to find a compressed layer beginning 5 to 10 cm below the surface, with a thickness ranging from 7 to 15 cm (Reichert et al., 2007). During periods of water deficit, the reduction of water content in the compacted layer can increase mechanical strength beyond the pressure of penetration that roots can exert, thereby restricting root growth and deepening.

Currently, there is no comprehensive and systematic diagnosis of the extent to which roots are inhibited from growing due to soil limitations in Brazilian soybean crops.

Furthermore, the precipitation regime masks the relationship between rooting depth and yield. In years with sufficient and well-distributed rainfall throughout the growth cycle, grain productivity generally remains unaffected, even if access to water is restricted to the shallowest soil layers due to limitations in root deepening.

Mulazzani et al. (2022) (unpublished data), in a study conducted in Rio Grande do Sul, examined 12 compaction scenarios over 30 years and found the following: compression resulted in less than a 5% reduction in soybean productivity in years with accumulated rainfall > 750 mm and intervals between rains of less than 2 weeks. Conversely, in years with accumulated rainfall < 590 mm and intervals between rains exceeding 2 weeks during the reproductive and/or 3 weeks during the vegetative phase, yield reduction exceeded 70%. In the same study, the impact of reduced rooting depth on soybean productivity was assessed using the same 30-year meteorological dataset. Decreasing rooting depth from 90 to 50 cm led to an accumulated yield reduction of 24,000 kg ha^{-1} over 30 years. This reduction corresponds to 15% of the estimated potential yield for the same period and is equivalent to 25% of the average crop yield in Rio Grande do Sul over the last 5 years (2016 – 2021).

A survey of soybean crops in Argentina from 2009 to 2020, conducted by Universidad Nacional de Entre Ríos - Argentina, illustrates the relationship between rooting depth, soil water storage capacity, and yield (Figure 2.1.1.2.2). Deeper roots enable plants to access a larger volume of water in the soil profile, resulting in less water deficit throughout the growth cycle and, consequently, higher yields.

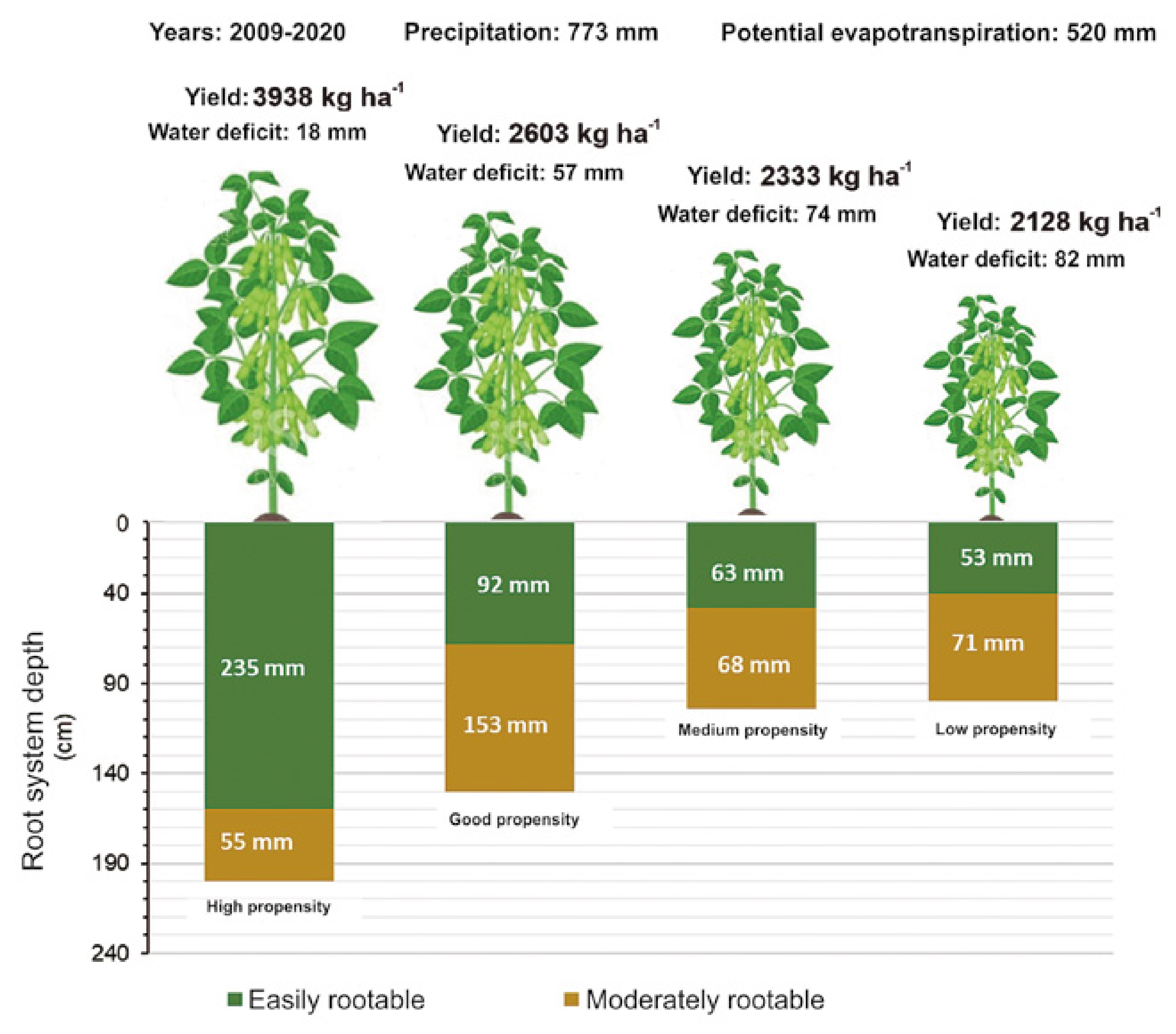


Figure 2.1.1.2.2. The relationship between rooting depth, soil water storage capacity, and grain yield in soybean crops in Argentina between 2009 and 2020. Source: César Eugenio Quintero, National University of Entre Rios, Argentina.

2.1.2. Water deficiency

The water deficit is the main limiting factor for soybean production worldwide (Rosa et al., 2018). In Brazil, the yield gap due to water deficit is estimated at 1197 kg ha^{-1}, reaching 3000 kg ha^{-1} (50% of the potential yield) in southern Brazil (GYGA, 2021; Tagliapietra et al., 2021). Water deficiency affects physiological processes and plant growth, triggering mechanisms to delay and/or tolerate dehydration. Some of these mechanisms include stomatal closure, leaf coiling, trichome development, reduction of leaf area through early leaf senescence (decreasing exposure to sunlight), and osmotic regulation (Figure 2.1.2.1) (Streck, 2004; Taiz et al., 2016). These changes in physiological mechanisms and the occurrence of oxidative stress impact the plant's efficiency in carrying out photosynthesis and, consequently, grain yield (Guo et al., 2018; Riar et al., 2018; Wu et al., 2018; Pagliarini et al., 2017; Martignago et al., 2020).

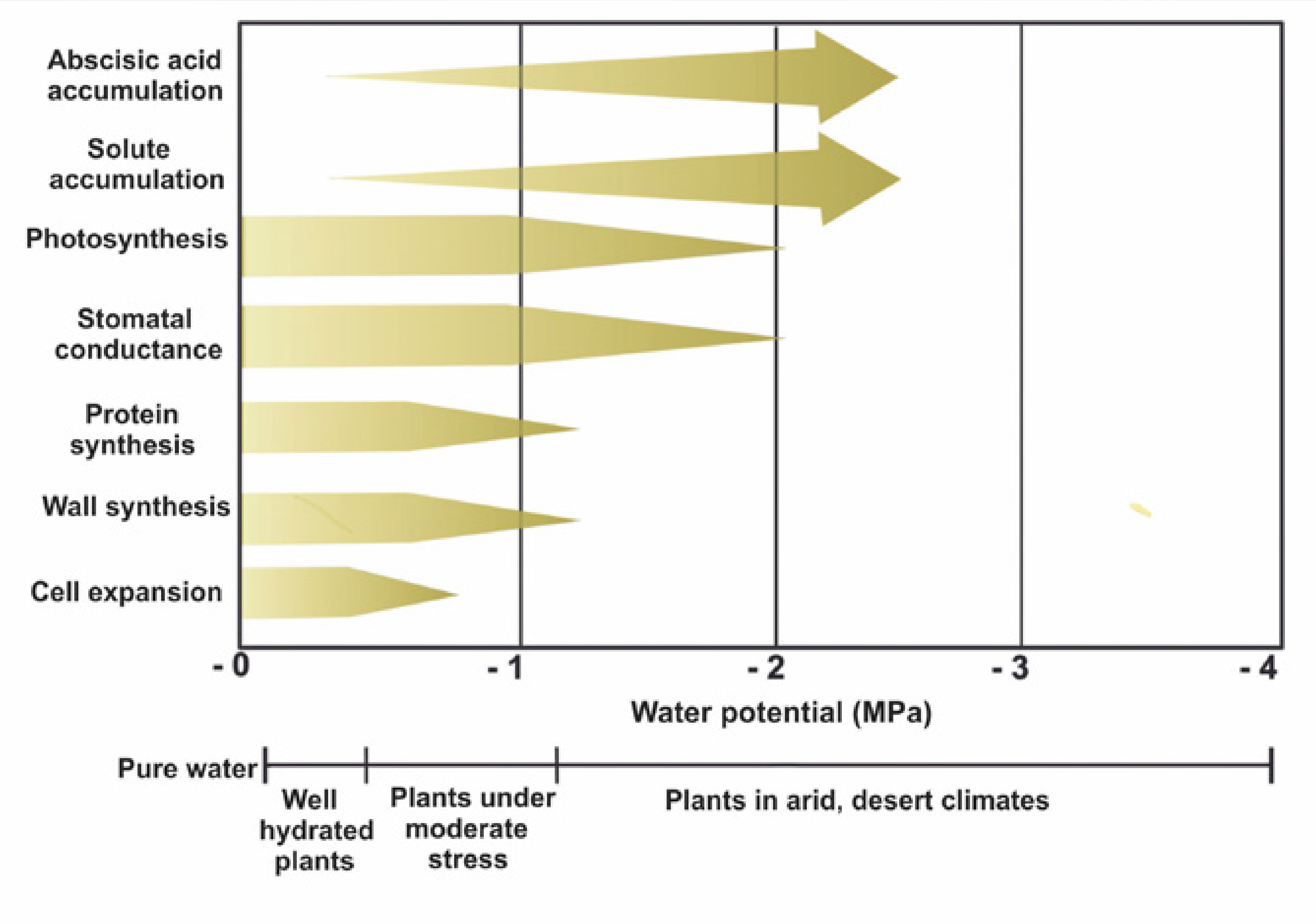


Figure 2.1.2.1. Relationship between alteration in physiological processes and leaf water potential. The thickness of the arrows corresponds to the process intensity. Source: Adapted from Taiz et al. (2017).

The occurrence of water deficit can occur in soils that provide access to water when the flow of absorption of water by the roots does not fully supply the perspiration flow. The flow of water from the soil to the roots, in the xylem to the stomata, passage from the liquid phase to the gaseous in the stomata and the flow of vapor from the leaves to the atmosphere involves numerous mechanisms in the soil, in the plant, in the atmosphere and the interaction between them. The mechanistic description of all the processes involved is quite complex. For this, generic and simpler strategies have been used to roughly describe how hydric stress occurs due to the imbalance between absorption of water through the roots and transpiration. In conditions of good water availability in the soil, what determines the consumption of water by the plant is the deficit of vapor pressure (atmospheric demand, function of temperature and relative humidity) and the Leaf Area Index (LAI). The vapor pressure deficit determines the rate of perspiration, while LAI is the multiplicative factor that determines the volume of needed water by the plant in a certain time. Daily water consumption can be expressed by the following formula: Water consumption = transpiration rate x leaf area index at what rate of sweating is expressed in ml of water cm^{-2} sheet day^{-1}. The reduction of water availability in the soil and the constant atmospheric demand for water, activates the perception from the lack of water by the roots of the plants, increasing the tension of the water column in the xylem, production, accumulation, and translocation of abscisic acid to the aerial part of the plant. The second symptom of water deficit is reduced leaf growth (Figure 2.1.2.2 A) and anticipation of leaf senescence (Figure 2.1.2.2 B) to maintain the perspiration rate and prevent disruption of the xylem water column (permanent wilting point). This reduction in leaf growth causes changes in the source-sink relationships, in which the plant passes prioritize the translocation of photo assimilates to the roots stimulating root growth. With the evolution of drying of the soil, the plant starts stomatal closure induced by abscisic acid, which reduces the rate of perspiration and water consumption. With reduced water absorption nutritional stress occurs concomitantly (since the plant absorbs nutrients from the soil solution) and thermal (perspiration cooling function). At the cellular level, the ability of leaves to assimilate carbon dioxide (CO_2) and roots absorb nutrients is reduced. With that, the process of photosynthesis (determining factor of yield) is affected, and there is also a reduction in photophosphorylation (ATP formation) and the inhibition of the enzymatic activity of ribulose^{-1},5-bisphosphate carboxylase oxygenase (RuBisCO).

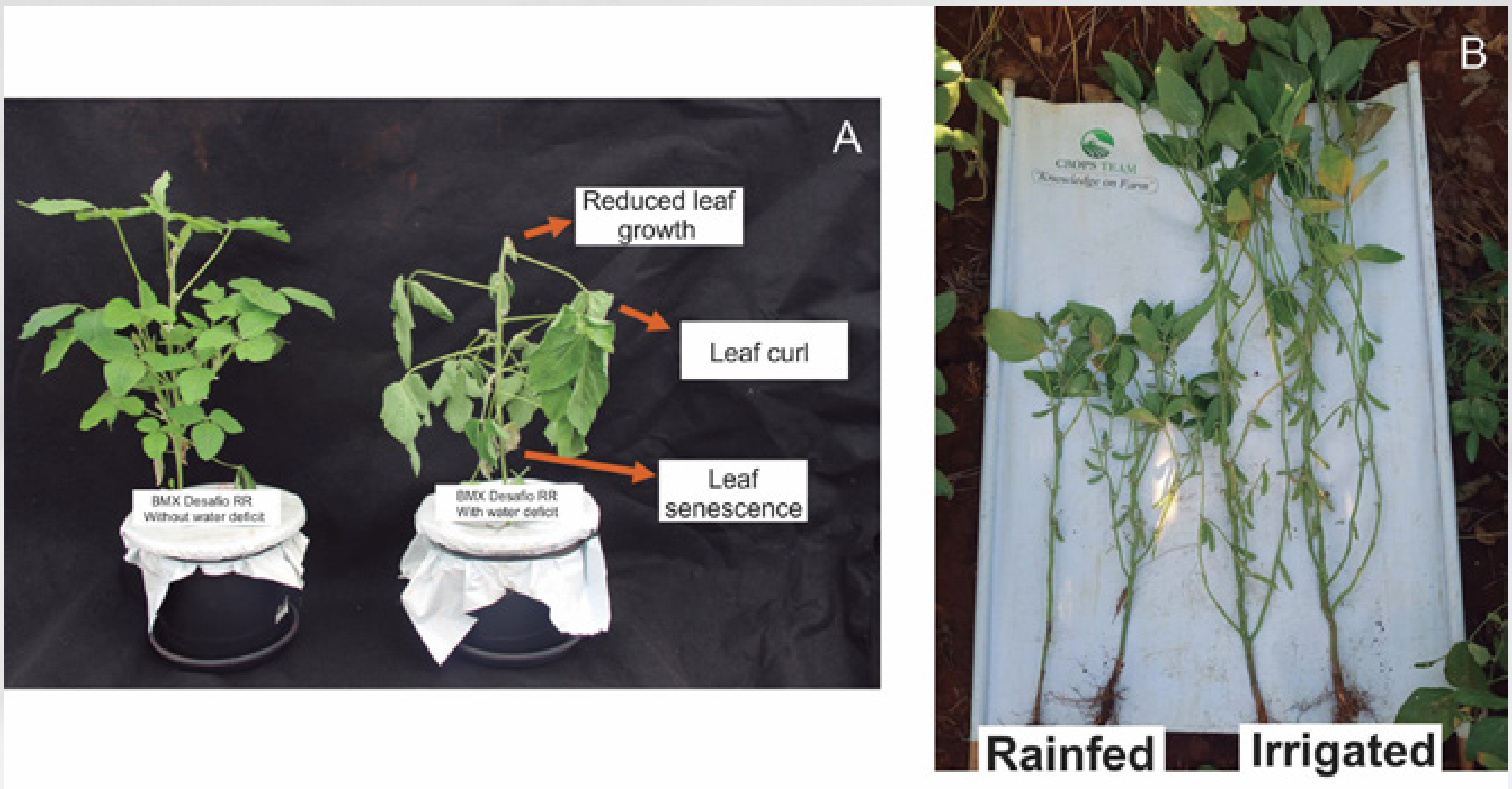


Figure 2.1.2.2. Visual symptoms of water deficiency in soybeans at 12 days of water suppression (A) and morphological differences in soybeans cultivated in the municipality of Alegrete (2021/22 harvest) in rainfed and irrigated environments by center pivot (B).

These biochemical mechanisms of maintaining the water potential of the plant for a longer time are controlled by hormonal signaling pathways and transcription factors stress responses, which are the basic mediators to tolerate or avoid the negative effects of water deficit (Jumrani & Bhatia, 2019; Martignago et al., 2020) in conditions of water deficit, there is induction of the synthesis of hormones such as abscisic acid and ethylene, which act as chemical messengers activating various physiological processes, including stomatal closure, stimulation of root growth, leaf senescence, and osmolyte accumulation to prevent water stress (Morgan & Drew, 1997; Ullah et al., 2018; Becker et al., 2021; Winck et al., 2022).

Recently, studies have been carried out on the selection of transgenic events in soybean to tolerate drought (Marinho et al., 2015; Pagliarini et al., 2017; Marinho et al., 2019; Ribichichi et al., 2020; Winck et al., 2022). The transgenic events for improving drought tolerance in plants can promote gain or loss of function for specific genes at different levels, which encode enzymes or regulatory proteins, such as transcription factors or protein kinases activated by mitogens (Taiz et al., 2016). In this context, EMBRAPA Soja has conducted studies of new transgenic events in soy that overexpress genes related to water deficit tolerance, such as AREB (Figure 2.1.2.3A), DREB, GOLS, and NCED (Oliveira et al., 2022; Fuhrmann-Aoyagi et al., 2021; Molinari et al., 2020; Marinho et al., 2019; Pagliarini et al., 2021; Honna et al., 2016). Another biotechnology being developed by Verdeca is HB4® soy, which is also a transgenic event that reduces the sensitivity of plants to ethylene and helps plants tolerate water deficit (Manavella et al., 2006; Manavella et al., 2008). In Argentina, under field conditions, soybean HaHB4® showed a slight delay in the onset of physiological maturation and an increase in grain yield due to the increase in the number of seeds per plant (Fig. 2.1.2.3B), (González et al., 2020). The yield gain averaged 4% in the transgenic cultivar; however, in hot and dry environments, this gain was up to 10.5% (Ribichich et al., 2020).

The introduction of these genes into the soybean plant will aid producers in managing water restriction, especially in regions with frequent occurrences and/or long periods of water deficit.

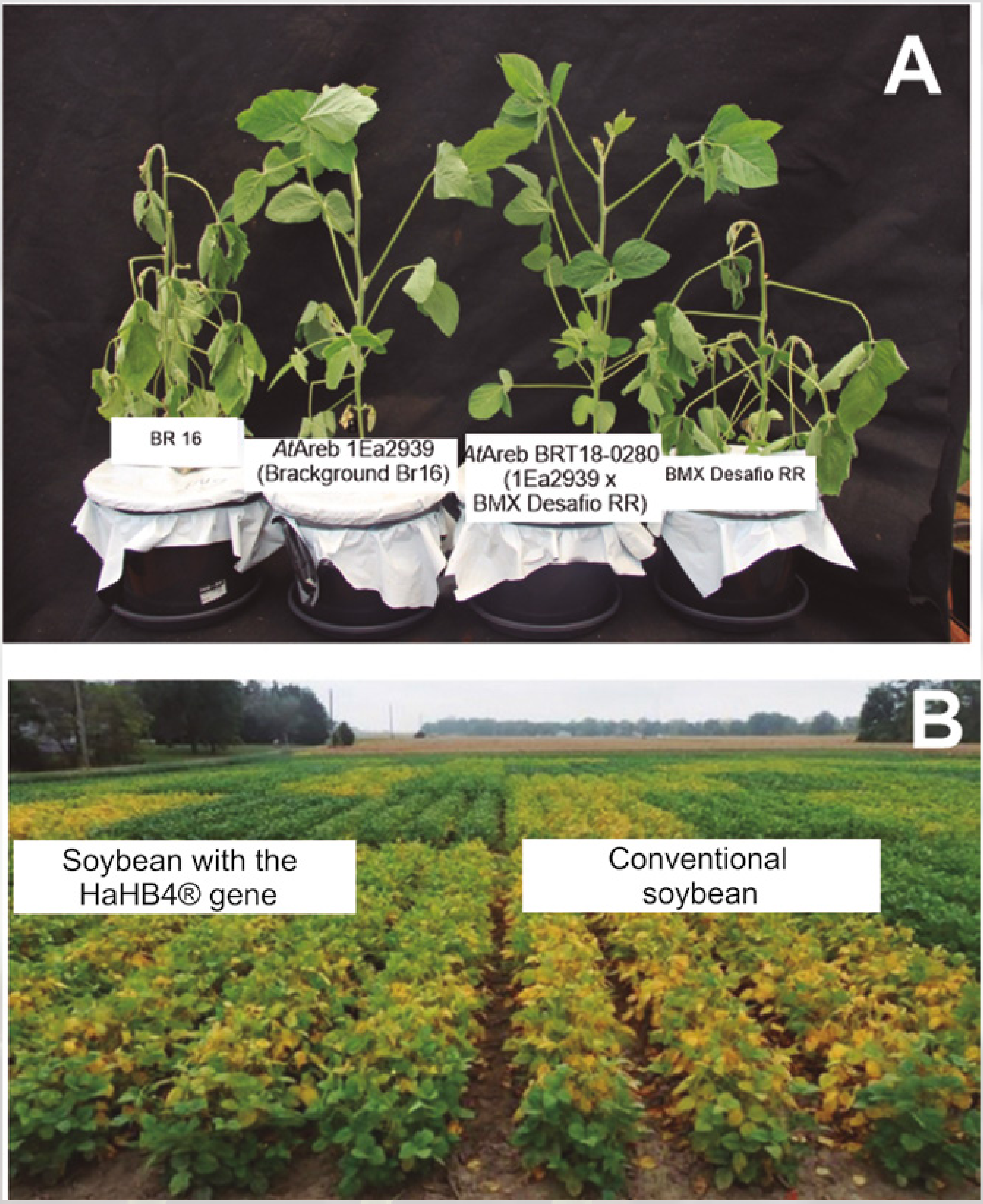


Figure 2.1.2.3. Soybean plants at 15 days after water suppression, from left to right: BR16, AtAREB 1Ea2939 (BR16 with the gene AtAREB), AtAREB BRT18-0280 (cross line between 1Ea2939 x BMX Desafio RR) and BMX Desafio RR (A), and soybean lineage with the HaHB4® gene (left) and the same strain without the HaHB4® gene (right) (adapted from Gonzalez et al., 2020) (B).

In Latin America, the occurrence of water deficits can vary greatly, ranging from intense to practically non-existent, owing to the variability in rainfall distribution and volume. In the soy-producing regions of southern Latin America, encompassing the pampas of Argentina, Uruguay, southern Brazil, and Paraguay, average monthly rainfall fluctuates between 100 and 150 mm during soybean production months (October to April) (Figure 2.1.2.4 and 2.1.2.5). Despite this considerable volume, precipitation in this region is irregular, leading to recurrent episodes of water deficit stress, particularly intensified by the occurrence of the La Niña phenomenon.

In the tropics of Latin America, including the Brazilian Midwest, MATOPIBA, and parts of Bolivia, rainfall typically commences in September, with monthly averages ranging from 75 to 150 mm. From October to November, precipitation gradually increases, peaking between 250 and 400 mm per month during December, January, and February (Figure 2.1.2.4 and 2.1.2.6). However, in March and April, average monthly precipitation decreases again, nearly reaching zero during the winter months. In this tropical region, soy is predominantly sown in September/October, benefitting from the well-distributed rainfall during the development phases, thus avoiding water deficit occurrences. However, water deficit events become recurrent during the second cultivation, significantly impacting corn yields as winter arrives in the Southern Hemisphere.

During these months, the highest rain accumulations typically occur at the extremities of the continent, resulting in a shortage of rainfall in central Brazil, while other regions such as the South and North of Brazil, Colombia, and Venezuela experience high accumulated rainfall.

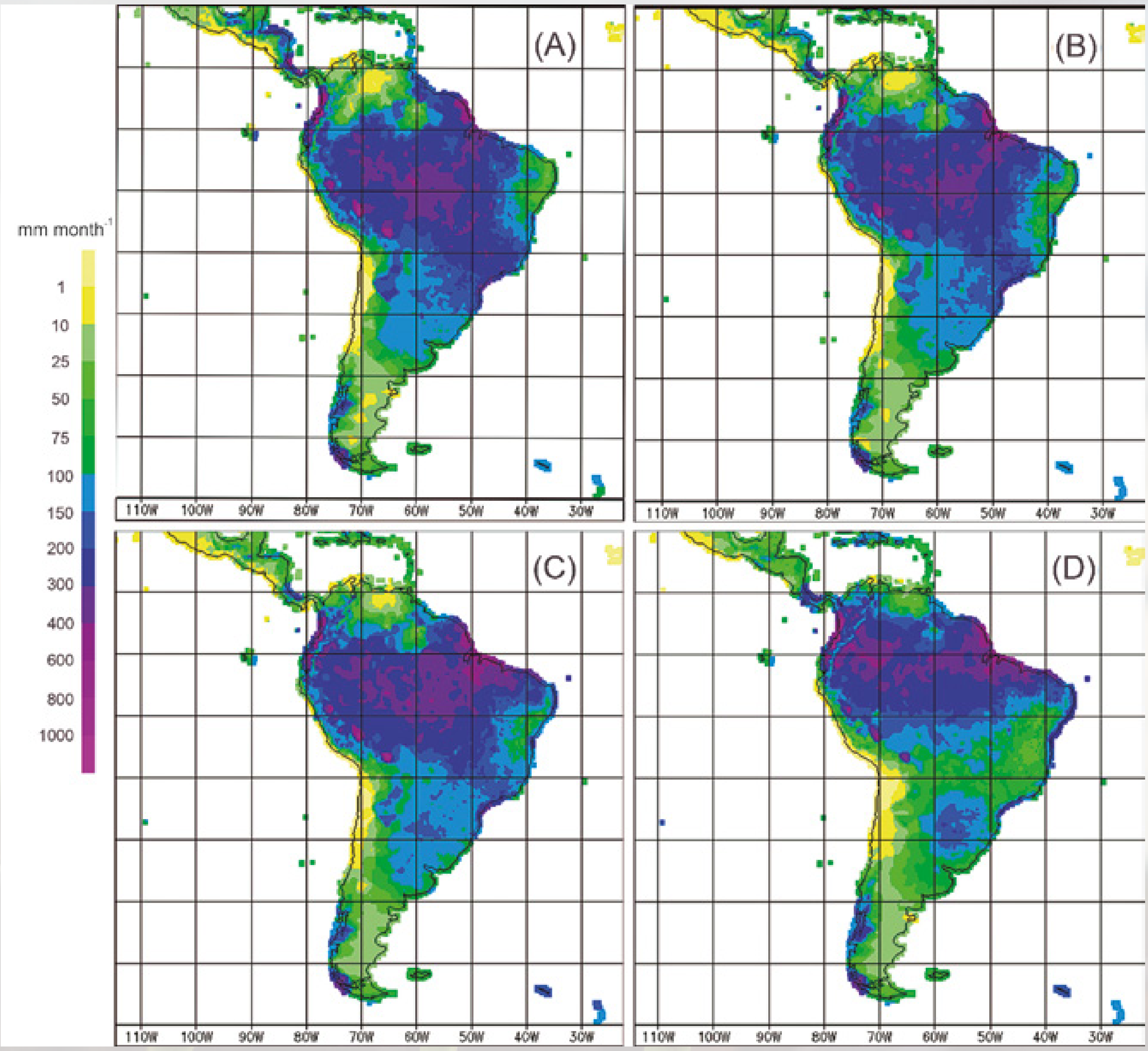


Figure 2.1.2.4. The climatology of rainfall in South America for the months of January (A), February (B), March (C) and April (D), based on the period 1982-2019. Source: GPCC.

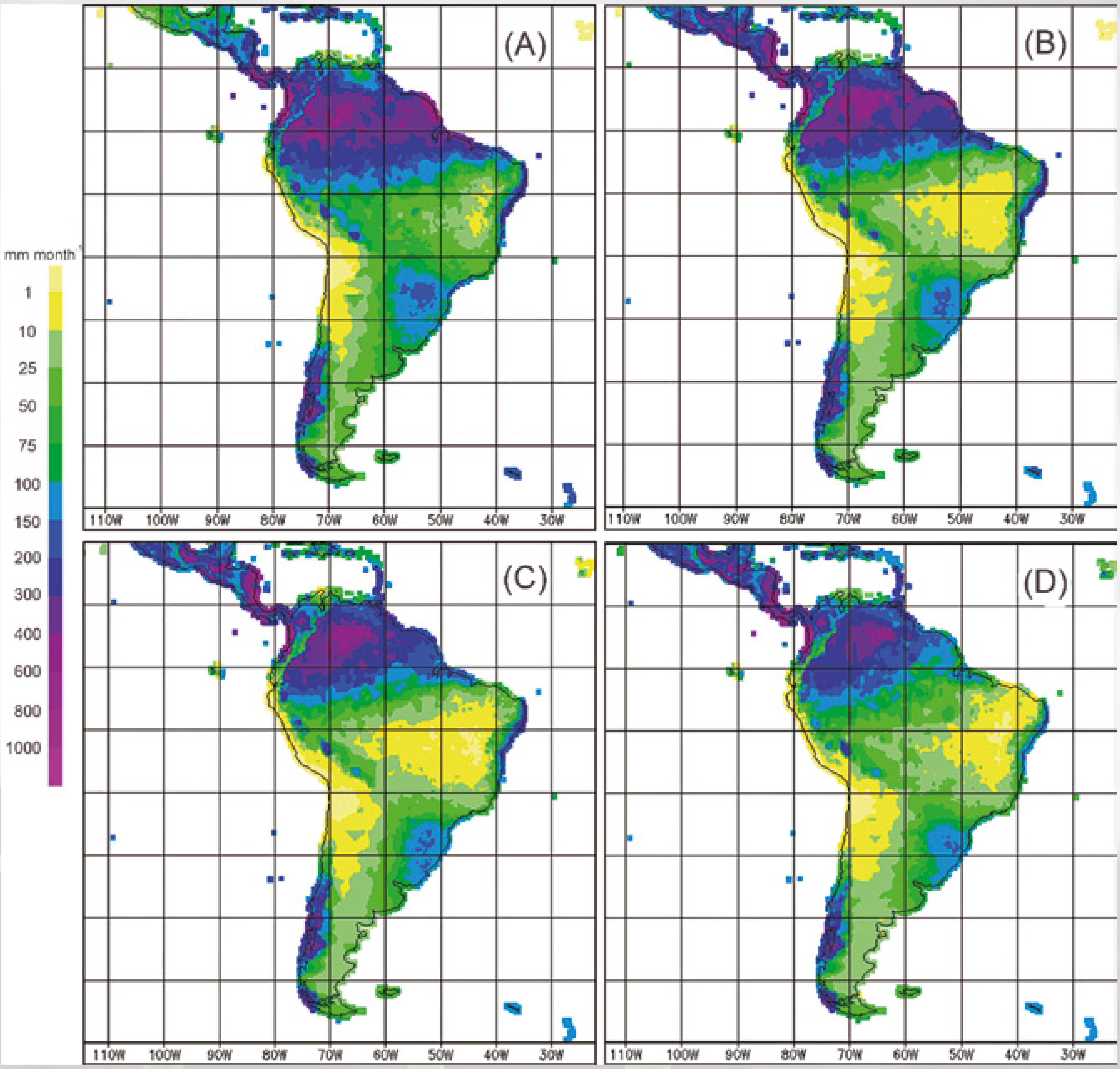


Figure 2.1.2.5. The climatology of rainfall in South America for May (A), June (B), July (C) and August (D), based on 1982-2019. Source: GPCC.

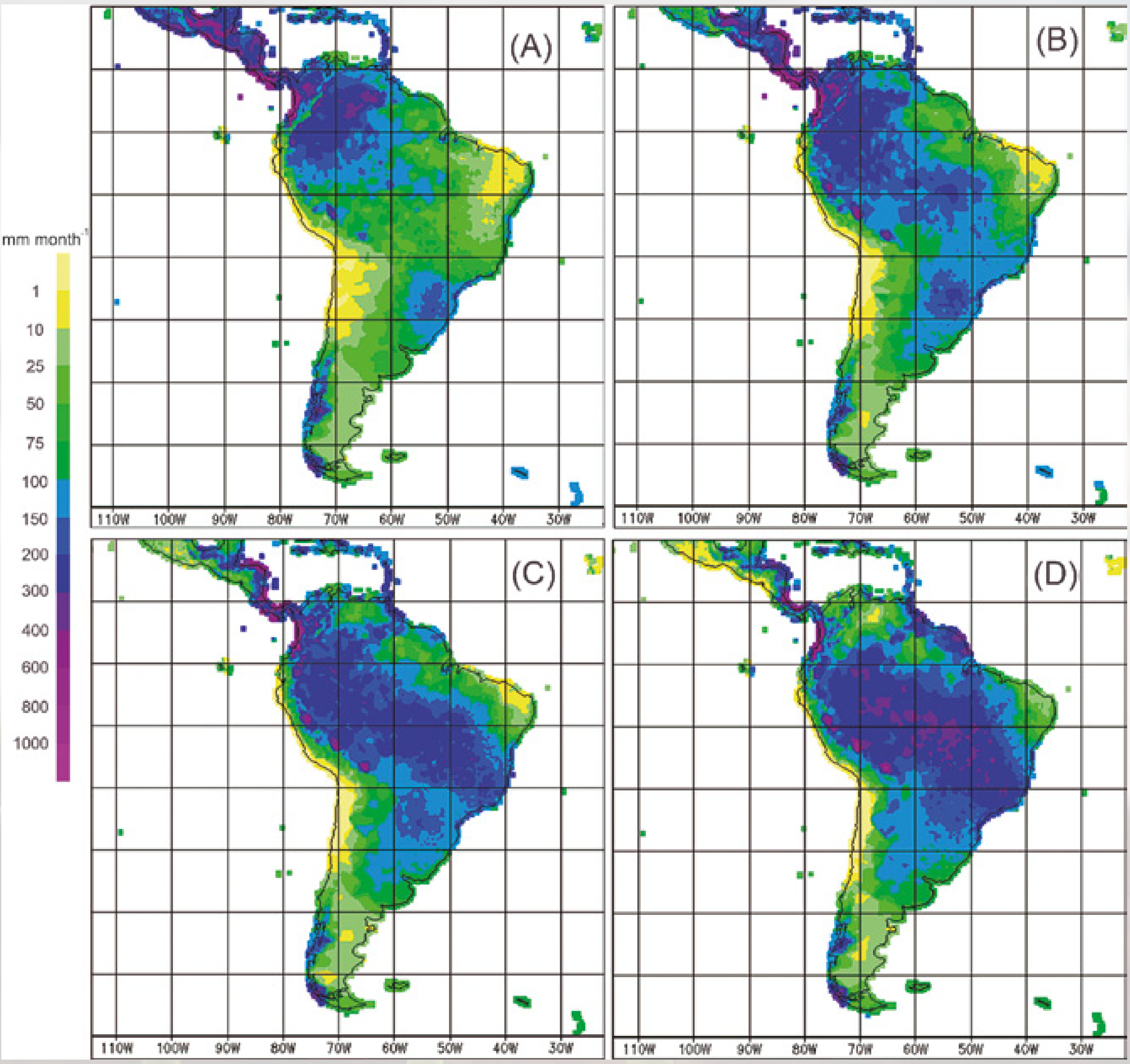


Figure 2.1.2.6. The climatology of rainfall in South America for September (A), October (B), November (C) and December (D), based on 1982-2019. Source: GPCC.

In addition to accumulated precipitation, evapotranspiration (the combined process of soil evaporation and plant transpiration) plays a crucial role in determining the probability of water deficit occurrence. In Brazil, our analysis focused on the disparity between precipitation and potential evapotranspiration. We found that the southern half of Rio Grande do Sul experiences a soil water deficit ranging between 20 and 60 mm (Figures 2.1.2.7 and 2.1.2.8). In certain years, variations in annual precipitation and evapotranspiration can exacerbate this water deficit, leading to significant losses in soybean crops, particularly during La Niña events.

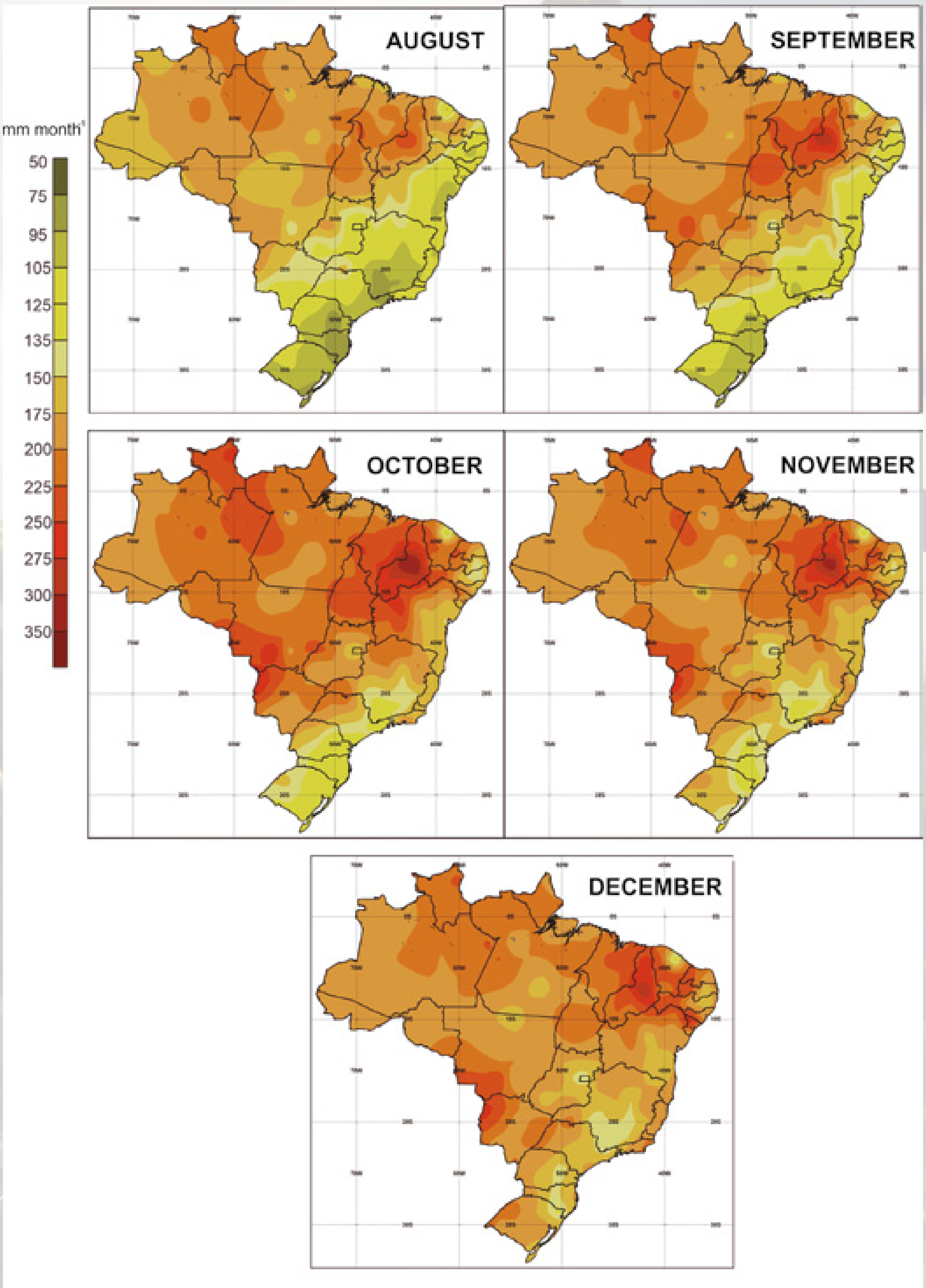


Figure 2.1.2.7. The climatology of evapotranspiration in Brazil for August, September, October, November and December, based on the period from 1981-2010. Source: INMET.

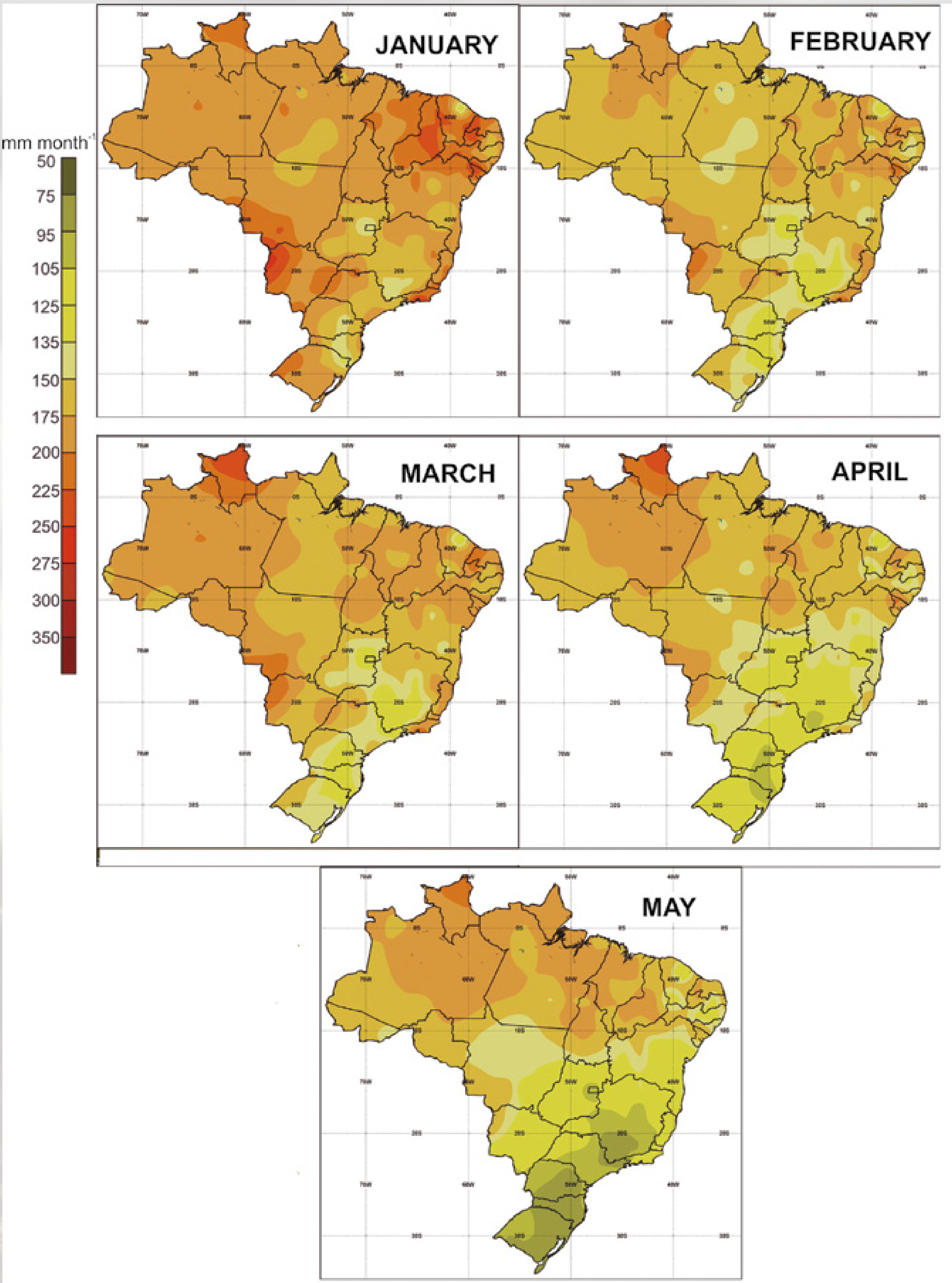


Figure 2.1.2.8. The climatology of evapotranspiration in Brazil for January, February, March, April and May, based on the period 1981-2010. Source: INMET.

The annual variations in precipitation in the southern region of Brazil are closely linked to the ENSO phenomenon (El Niño Southern Oscillation) (see item 2.6). ENSO refers to temperature fluctuations (warming = El Niño and cooling = La Niña) in the Equatorial Pacific Ocean relative to historical norms, which in turn affect the trade winds in the equatorial zone. Trade winds are consistent winds blowing from the tropics towards the equator, creating an east-to-west wind flow. During El Niño years, these trade winds weaken, hindering cloud formation in northern Brazil and redirecting Amazon humidity westward, where it encounters barriers in the Andes Mountains, ultimately resulting in increased moisture over southern Brazil. Conversely, during La Niña years, the trade winds strengthen, promoting cloud formation in northern Brazil and reducing rainfall in the southern region, thereby elevating the risk of water deficiency in soybean crops. Computational agriculture models allow for the observation of yield interactions with water deficiency.

In the Midwest, a monsoon regime prevails, characterized by summer precipitation coinciding with the onset of soybean cultivation. Conversely, in the southern region, an isoigro regime prevails, with precipitation distributed throughout the year. However, despite this distribution, the southern region of Brazil is more susceptible to droughts due to large-scale phenomena such as ENSO (Arsego et al., 2018). The significance of well-distributed rainfall throughout the cycle is evident in São Luiz Gonzaga, Rio Grande do Sul, Brazil, where accumulated rainfall exceeds 800 mm (Figure 2.1.2.9). The CSM-CROPGRO model demonstrates that soybean yields vary accordingly, with São Luiz Gonzaga, Rio Grande do Sul, Brazil, exhibiting the lowest yield due to water conditions, while Campo Verde, Mato Grosso, Brazil, attains the highest yield (Figure 2.1.2.9).

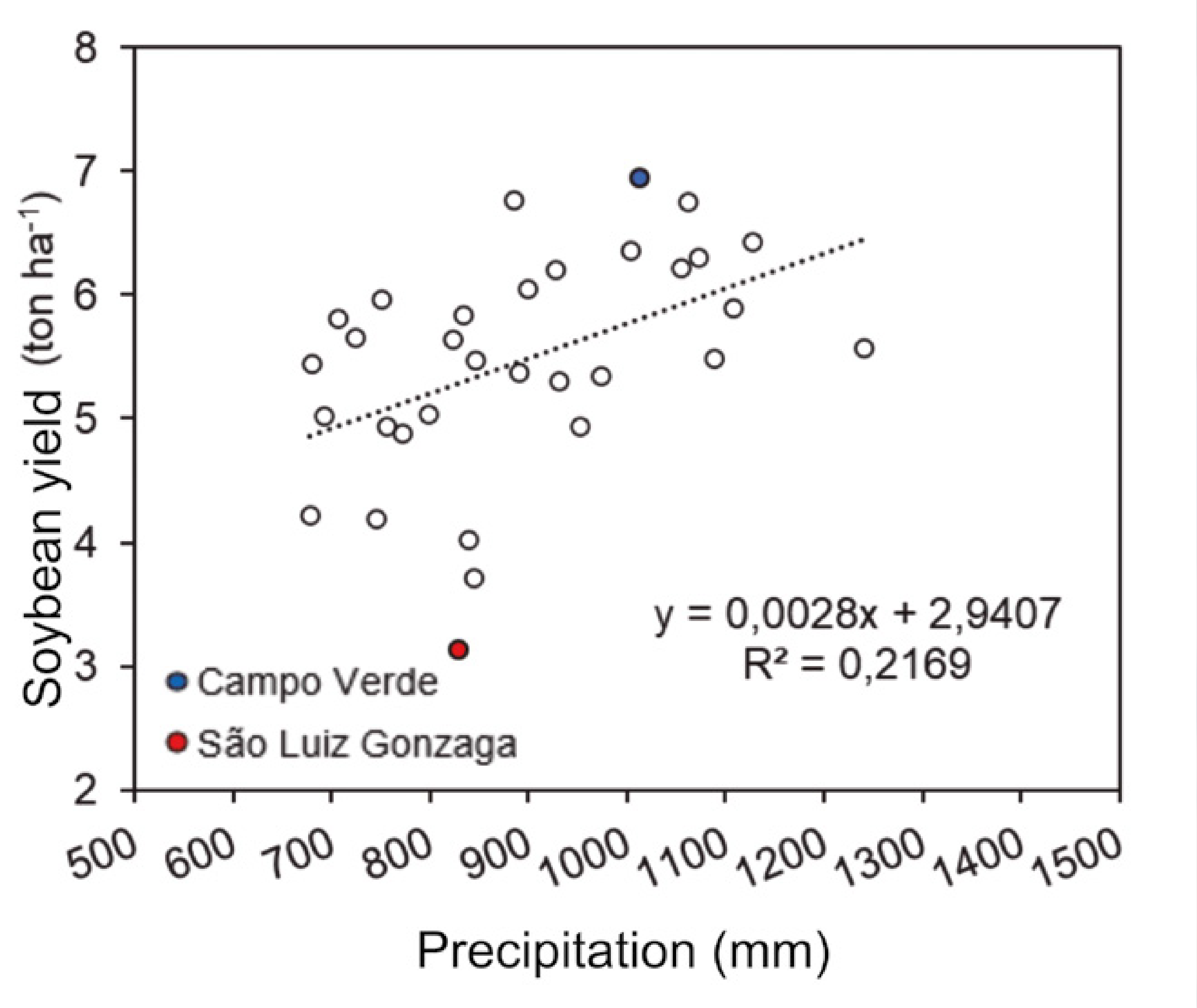


Figure 2.1.2.9. Relationship between soybean yield and precipitation for various locations in Brazil. Yield data were generated using the CSM-CROPGRO soybean model (represented by circles). The red circle denotes São Luiz Gonzaga, Rio Grande do Sul, Brazil, while the blue circle represents Campo Verde, Mato Grosso, Brazil, which recorded the lowest and highest yields, respectively.

The effects of the intensity and duration of water deficit on soybean yield will depend on the developmental stage during which they occur. The most critical stages for soybean crops with respect to water deficit are seeding emergence (SEM-EM) and grain filling (R5-R6). Water deficit during the SEM-EM period can lead to seed unviability, uneven plant emergence, and seedling mortality. In the vegetative phase, low-intensity water deficit encourages root growth at the expense of aerial plant parts, while higher intensity deficit leads to senescence of older leaves (down). Consequently, the meristem of the node where the leaf was attached fails to differentiate into reproductive organs (flowers) due to the lack of photo-assimilates for nourishment. This results in what producers commonly refer to as "canela" which is the lower part of the plant without grain production. When water deficiency occurs between the flowering (R1) and pod formation (R4) stages, there can be simultaneous abortion of reproductive structures and leaf senescence. During the grain-filling phase, vegetative growth ceases, and the plant's water demand and Leaf Area Index (LAI) reach their maximum levels. These factors exacerbate the impact of water deficiency, directly affecting two productivity components: the number of grains per pod and grain weight.

To mitigate the effects of water deficiency in soybean crops, producers can adopt various management strategies and practices, including:

a) Increasing water storage in the soil: This can be achieved by breaking compacted soil layers and implementing crop rotation.

b) Deepening root systems: This is facilitated in soils without physical compression (as depicted in Figure 2.1.2.10) by allowing roots to penetrate deeper into the soil profile (up to the maximum limit of 2MPa) or by addressing chemical impediments in the subsurface, such as aluminum toxicity.

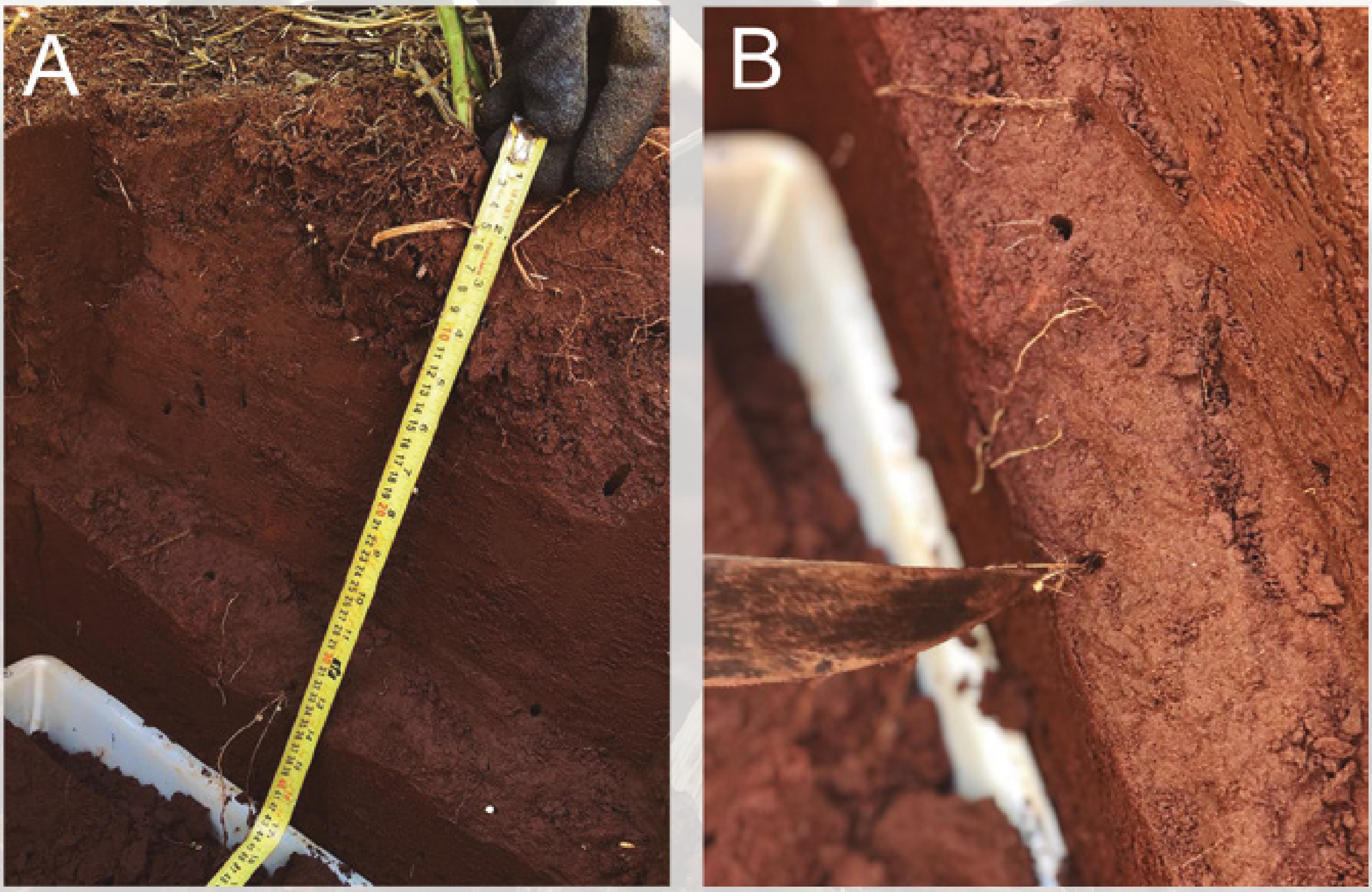


Figure 2.1.2.10. Biopores formed by the diverse crops favoring drainage and deeeper root growth (A and B). Soybean Money Maker Championship crop in Cruz Alta, Rio Grande do Sul, Brazil.

The significance of exploring the root system in the soil profile can be illustrated through two scenarios: In the first scenario, consider a plant with root growth extending to a depth of 0.15 meters (Figure 2.1.2.11), situated in soil with a field capacity of 30% and a permanent wilting point of 14% (water storage capacity – AWS of 16%). In this case, within 1 square meter of area, the soil volume explored by the roots amounts to 0.15 cubic meters (1 m^2 x 0.15 m deep). Given that the soil can retain 16% of its volume in water, there exists 0.024 cubic meters of water available to the plants, equivalent to 24 mm of rainfall (Figure 2.1.2.11).

In the second scenario, suppose the same soil has an AWS of 16%, but now the root depth extends to 0.40 meters. The volume of soil explored by the roots increases to 0.4 cubic meters (1 m^2 x 0.40 m). With the soil still retaining 16% of its volume, the available water for the plants amounts to 0.064 cubic meters, which translates to 64 mm of rainfall (Figure 2.1.2.11).

Thus, following a rainfall event of the same volume in both situations, in the second situation (plants with 40 cm of root), there is an additional 40 mm (64 - 24 mm) of water available to the plants compared to the first situation. Assuming a water use efficiency of 8 kg of grain per mm, this translates to an estimated yield difference of 320 kg ha^{-1} (8 kg x 40 mm), or equivalently, 5.3 more soybean bags per hectare. This calculation considers the additional water provided to the plants by only one rainfall event during the growing season.

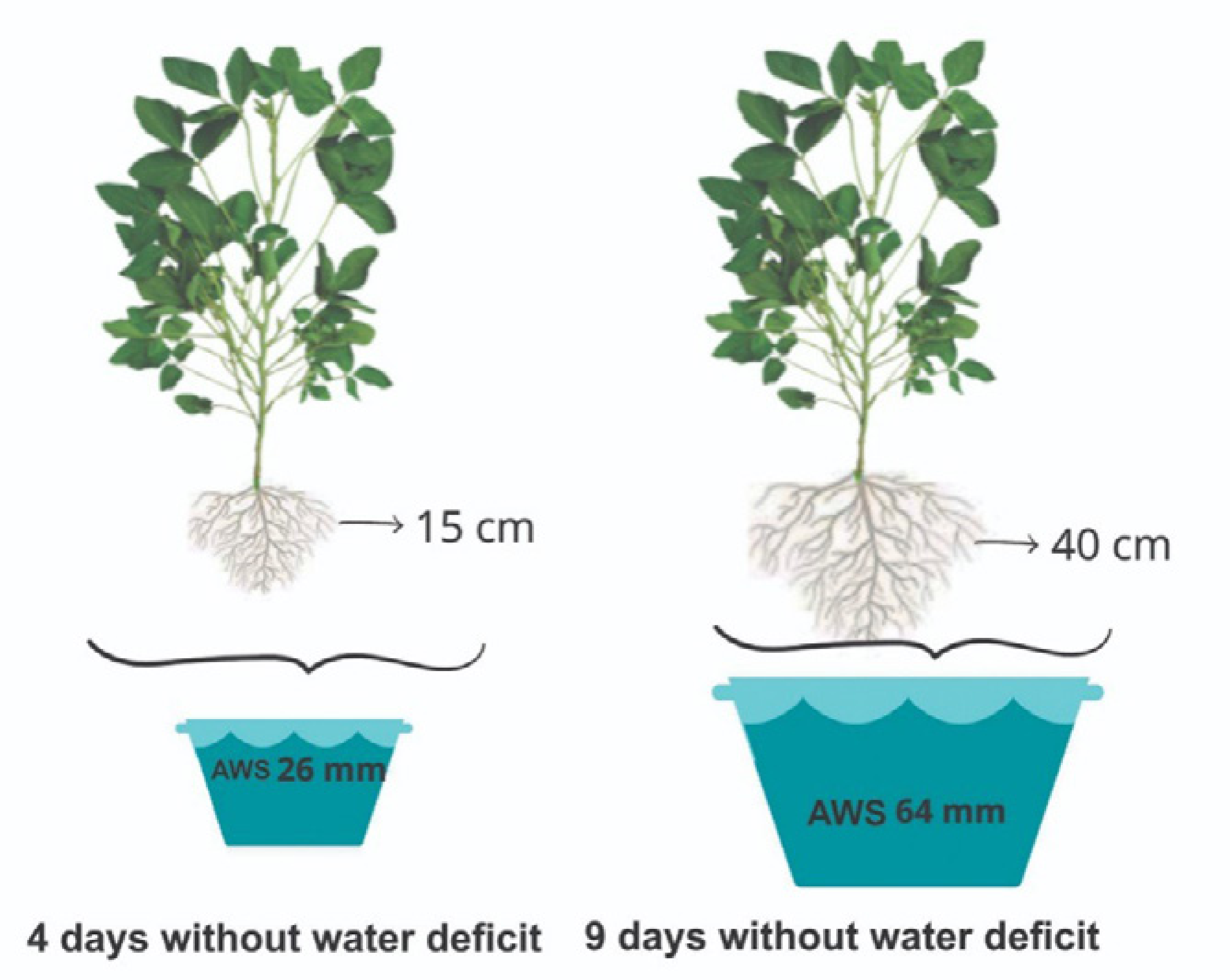


Figure 2.1.2.11. Illustrative scheme of the soil water storage capacity of (AWS) and the number of days without water deficit symptoms at different depths of the soybean root system.

c) Water supplementation through irrigation: Presently, various methodologies exist for irrigating soybean crops, with center pivot irrigation being the most prevalent. In the southern half of Rio Grande do Sul, irrigation is commonly achieved through furrows or plastic tubes in lowland areas (floodplains).

d) Direct planting into straw: This practice reduces water loss from the soil through evaporation and helps enhance the infiltration rate of water into the soil.

e) Choice of cultivars: Soybean cultivars vary in their tolerance to water deficiency (see item 1.6), as well as in their growth cycles (MGs). This variability allows producers to mitigate the effects of drought. Soybean cultivars can be classified into two physiological strategies for coping with drought based on the timing and intensity of stress: (i) Reduction of physiological processes through stomatal closure to conserve water and survive prolonged dry spells (also known as “drought avoidance”). (ii) Maintenance of physiological processes even under conditions of low soil moisture content. The first strategy is suitable for regions experiencing extended periods of drought or areas with limited soil water storage capacity. Cultivars employing this strategy are highly sensitive to soil water reduction, which can lead to reduced carbon accumulation, particularly in environments with regular rainfall. While they exhibit lower water consumption, their water use efficiency remains unchanged under water deficit conditions. The second strategy is characterized by greater water use efficiency in drought conditions, as plants maintain growth rates despite low soil moisture levels. However, this strategy may require higher water consumption over time to tolerate short-term water deficiencies without compromising productivity potential.

f) Staggered sowing: This practice involves scheduling soybean planting to avoid critical developmental stages coinciding with the same period each year.

2.1.3. Water excess

The expansion of soybean cultivation in Latin America and the Caribbean has been occurring in many areas traditionally untouched by this crop, including lowland regions that have been dedicated to irrigated rice monoculture for decades (Figure 2.1.3.1). This emerging trend is particularly noteworthy in Rio Grande do Sul, Brazil (Figure 2.1.3.1), where there has been a substantial increase in soybean cultivation in lowlands since the 2009/2010 agricultural year. The cultivated area has surged from 10 thousand hectares to 350 thousand hectares by the 2020/21 agricultural year. This expansion accounts for nearly 36% of the annual sown area, traditionally dedicated to irrigated rice, now incorporating soy cultivation in Rio Grande do Sul (IRGA, 2021).

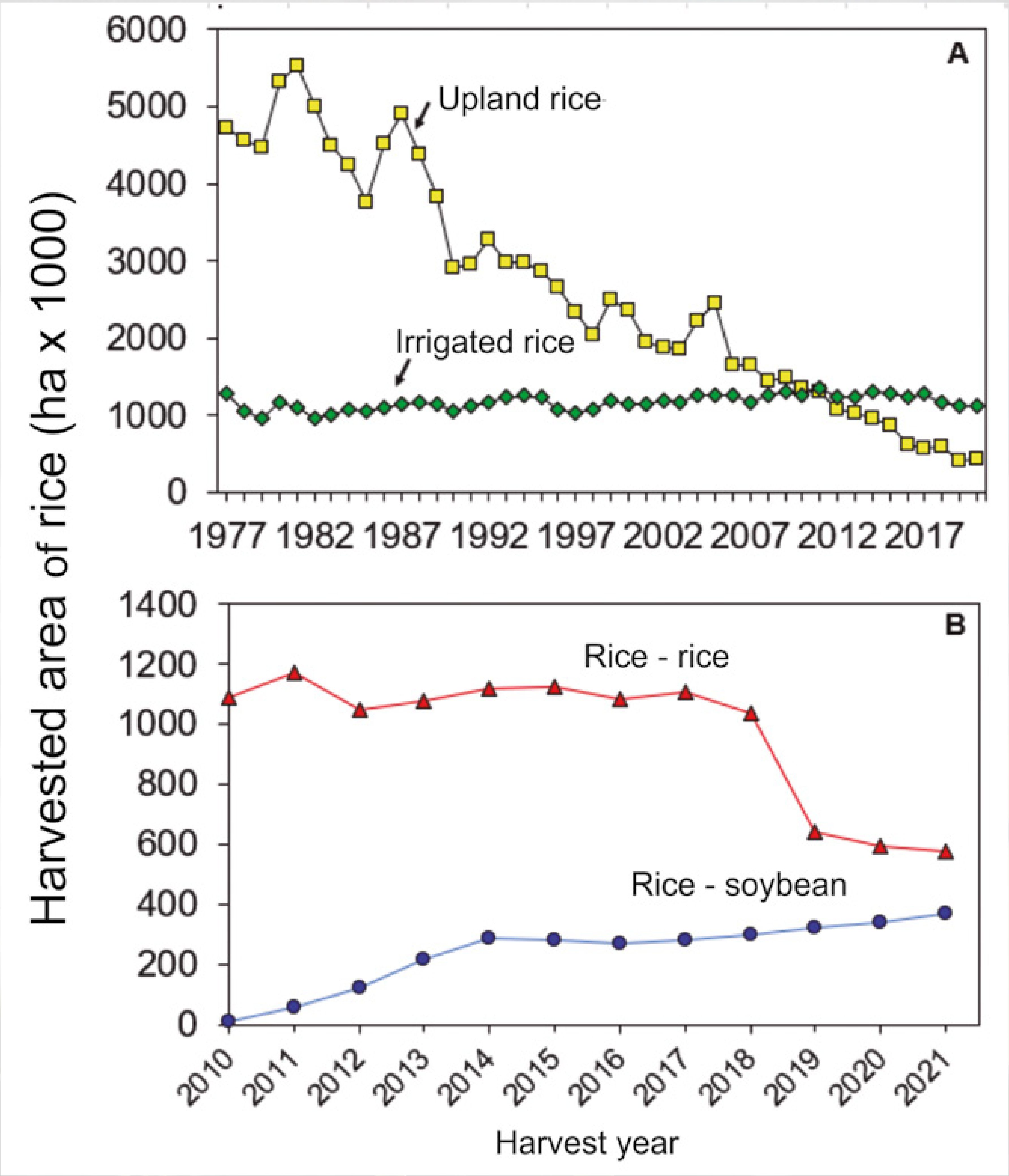


Figure 2.1.3.1. Harvested area for upland and irrigated rice in Brazil (A), and harvested area in rice-rice and rice-soybean areas in Rio Grande do Sul, Brazil (B). Source: IRGA 2022; IBGE 2022.

Lowland soils are typically found in flat regions and have a history of traditional cultivation with irrigated rice, possessing specific characteristics such as low hydraulic conductivity and hydromorphism (Sartori et al., 2016). The soil profile in these areas, cultivated with rice for decades, typically consists of a shallow superficial layer, and the subsurface is nearly impervious to penetration.

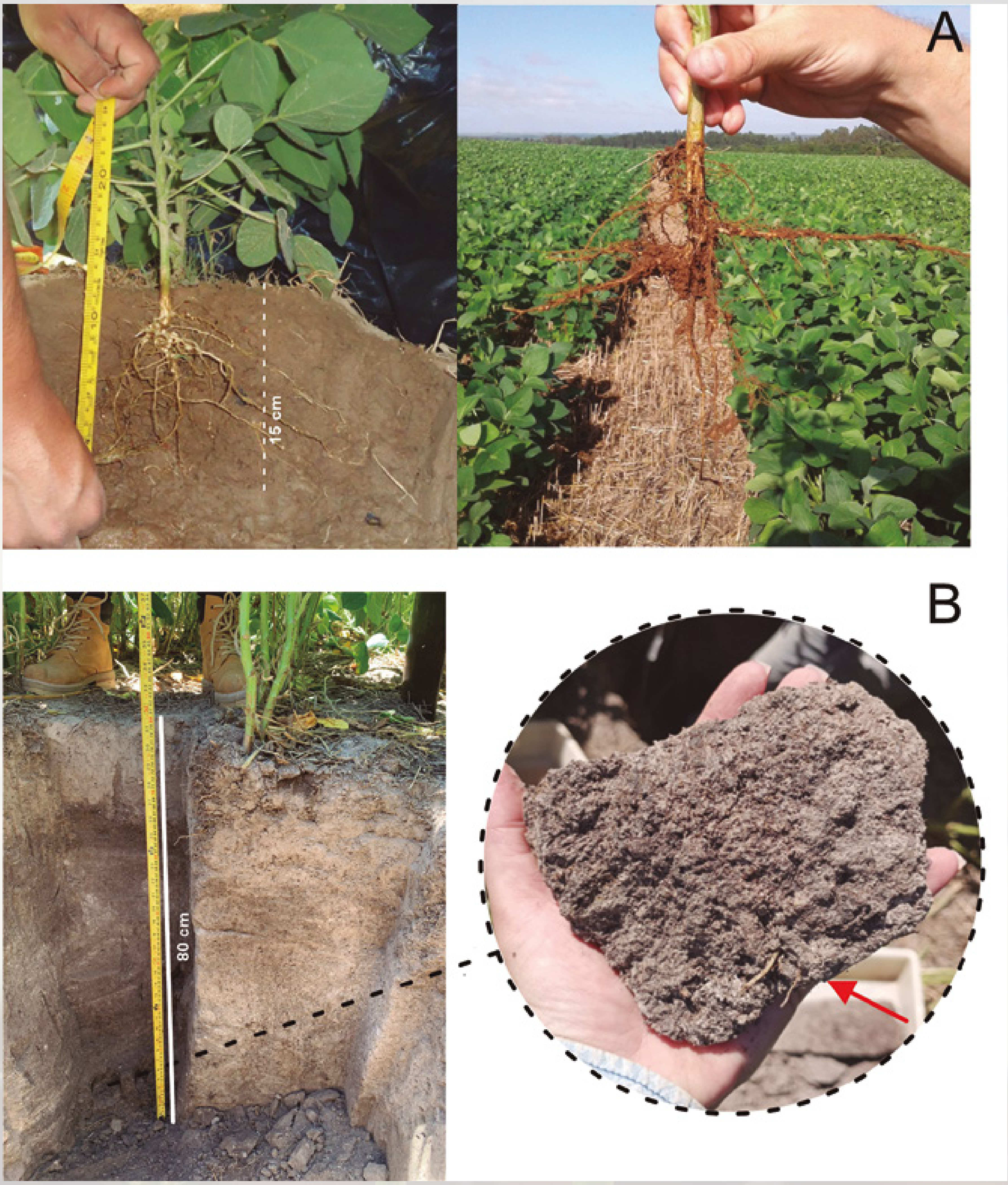


Figure 2.1.3.2. Soil profile in Cachoeirinha, Rio Grande do Sul, Brazil (A) with a depth of 15 cm, showing superficial roots. Soil profile in Barra do Ribeiro, Rio Grande do Sul, Brazil (B) with a depth of 80 cm and roots extending deep (60-80 cm), showcasing water and soybean roots (refer to Figure 2.1.3.2 A). Well-managed practices facilitate root deepening to depths close to one meter (Ribeiro et al., 2021) (see Figure 2.1.3.2 B).

Although soy is a species originating in wetland areas of northern China and exhibits genetic variability regarding tolerance to excess moisture, the periods and intensity of soil flooding during the crop development cycle (see Figure 2.1.3.3) can induce anatomical, morphological, and physiological changes. In most cases, these alterations lead to the death of plants and a subsequent reduction in yield (Mundstock et al., 2017).

Figure 2.1.3.3. Soybean cultivation in lowlands facing water excess in Paraíso do Sul, Rio Grande do Sul, Brazil, during the 2020/21 agricultural year. Courtesy: Ijesica Luana Streck.

The main effect of soil saturation with water is the hindrance of gaseous exchanges between the root system and soil pore space. This is because the diffusion resistance of gases, particularly oxygen, is much higher in water than in air (Cornelius et al., 2005). The initial response of plants under flooding conditions is metabolic. Flooding interferes with the availability of oxygen in the soil, leading to the occurrence of hypoxia (low oxygen levels, chemically represented as O_2) or anoxia (absence of O_2) (Sairam et al., 2008; Dias Filho, 2012). Oxygen (O_2) serves as the final electron acceptor in the respiratory chain. The absence of O_2 paralyzes and gradually inhibits aerobic respiration in cells, reducing the production of heat and energy from 36 ATPs to 2 ATPs. This energy decrease, coupled with toxic products (ethanol and lactate) generated by fermentative respiration, ultimately blocks the biochemical process. The transport of H^+ through ATPase becomes sluggish, the pH gradient between the cytosol and the vacuole is not maintained, and protons migrate from the vacuole to the cytoplasm. The fermentation process produces cellular acidity due to lactic acid production in the cytosol, leading to irreversible disruption of metabolism in the cytoplasm and resulting in cell death (Taiz et al., 2017). Excess water can compromise the development of the root system of plants, particularly affecting nodulation resulting from the symbiosis between soybean plants and Bradyrhizobium bacteria. These bacteria have a high oxygen demand, and due to water excess, soybean experiences a significant reduction in biological nitrogen fixation, consequently impacting its vegetative growth. In prolonged flooding periods, such as for 7 days, the lack of N_2 becomes evident through leaf yellowing (Figure 2.1.3.4) (Bacanamwo & Purcell, 1999).

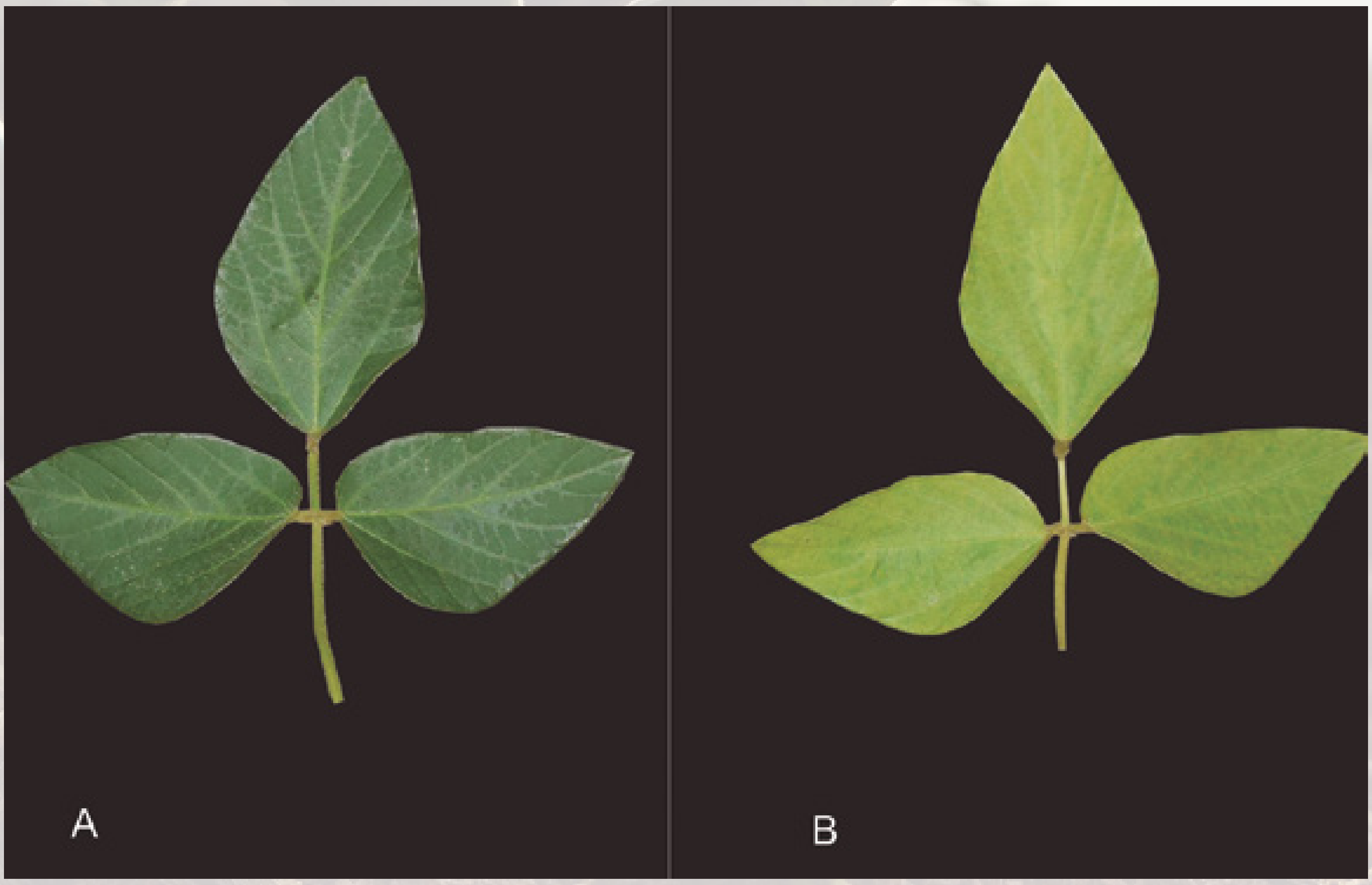


Figure 2.1.3.4. On the left, a trefoil of a plant under ideal cultivation conditions (A), and on the right, a trefoil of a plant experiencing water excess conditions, exhibiting chlorosis (B).

Plants employ survival strategies when subjected to stress conditions. In the case of soybeans responding to prolonged water excess in the soil, these adaptations are associated with anatomical and morphological changes, such as the development of aerenchyma and the formation of adventitious roots (Figure 2.1.3.5). Anatomical cross-sections of adventitious roots from soybean plants grown under flooding conditions reveal a significant rupture of cortex cells, indicating the formation of aerenchyma. This creates void spaces that act as conduits for the transfer of oxygen (O_2) to the roots (Thomas & Lange, 2014). However, a notable challenge arises with the breaking of the epidermis of the stem of soybean plants close to the soil surface due to aerenchyma formation. This creates a “gateway” for opportunistic fungi, ultimately leading to plant death (Figure 2.1.3.6). This phenomenon is one of the primary factors explaining the low soybean yields in lowland areas. The phase between seed germination and the emergence of plants is particularly sensitive during the growth cycle, with virtually no differences in tolerance observed among commercial cultivars (Thomas & Lange, 2014).

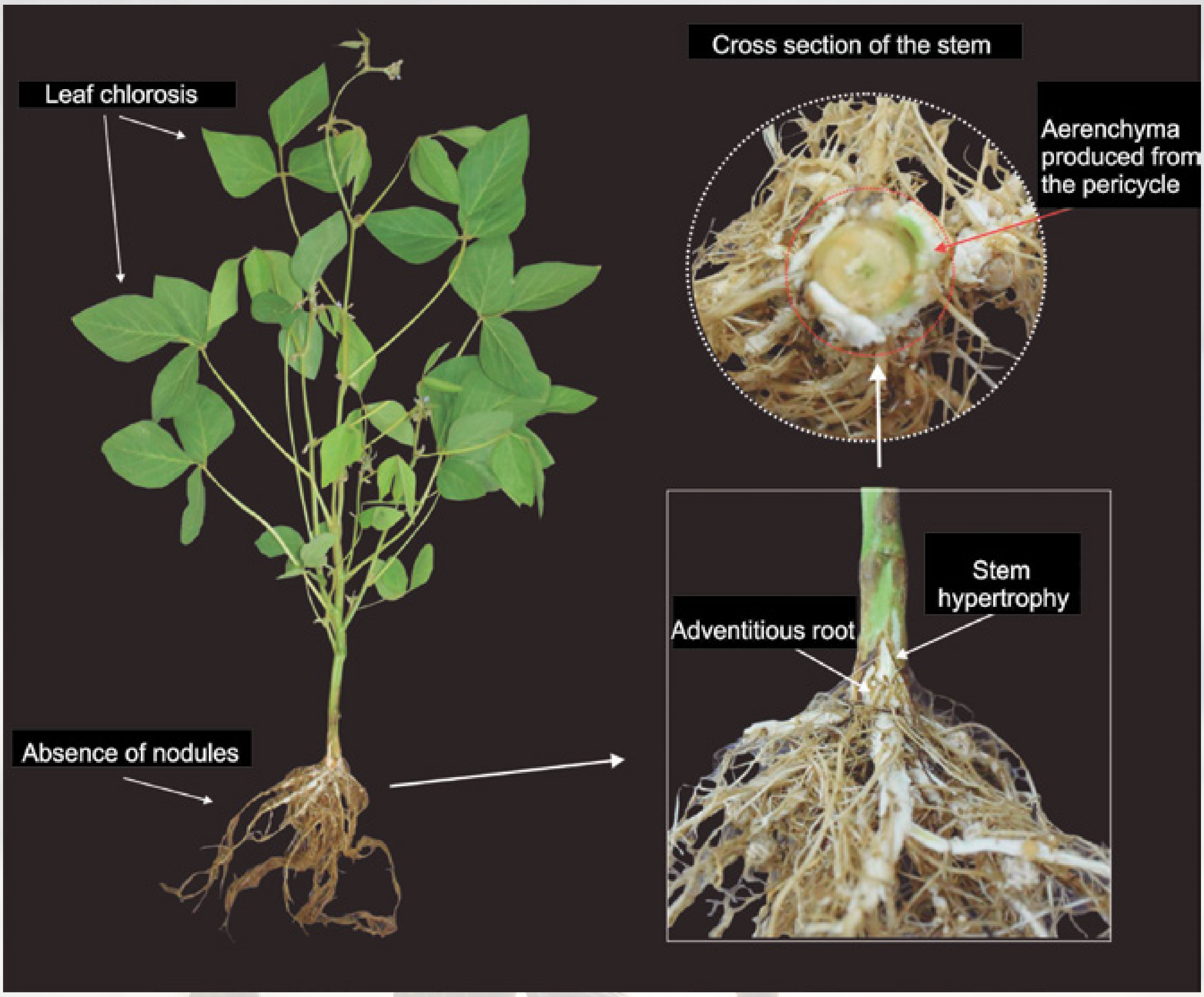
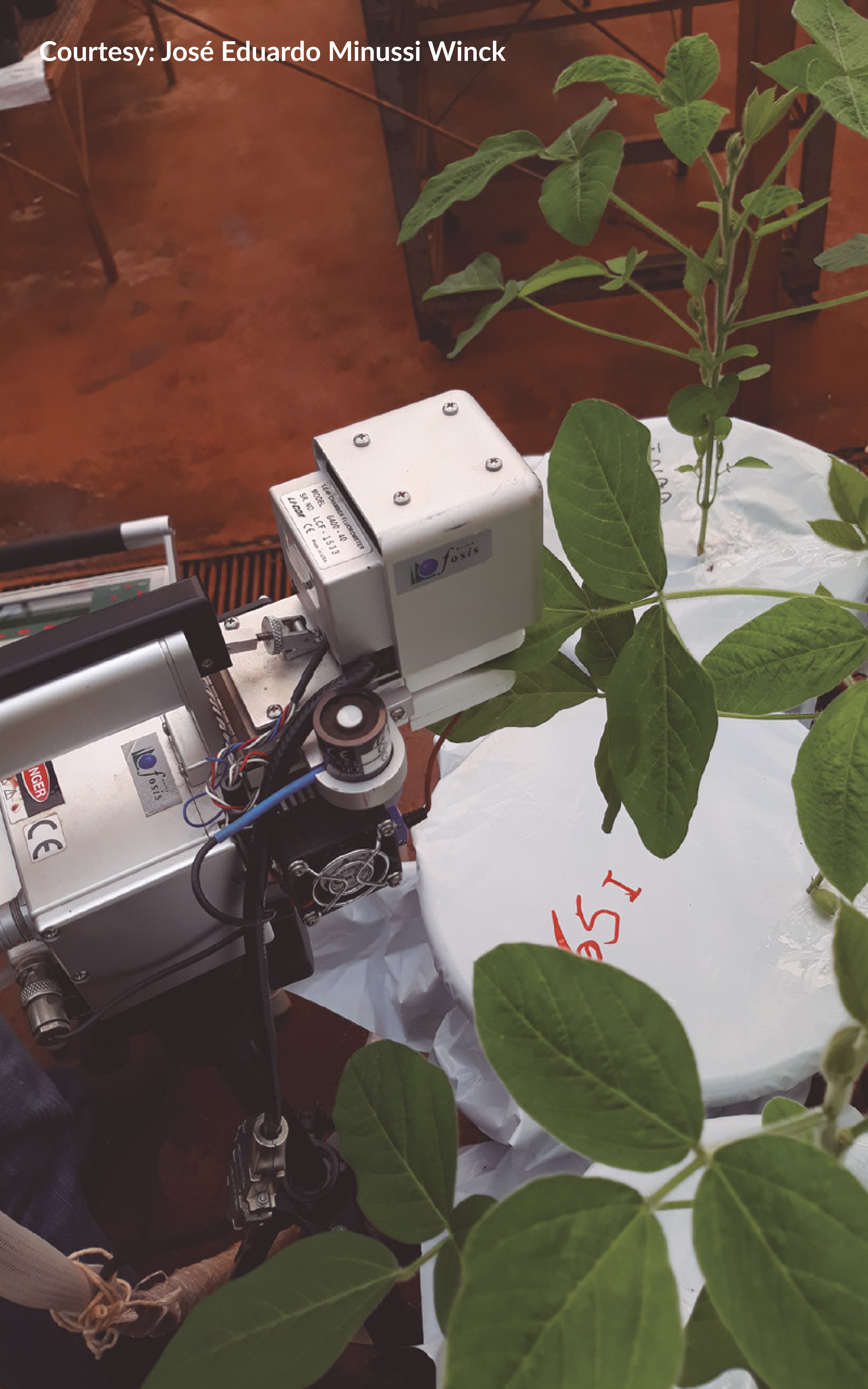


Figure 2.1.3.5. A soybean plant subjected to flooding for 15 days, with a water depth of 3 cm above the soil surface after the R1 stage.

Figure 2.1.3.6. Aerial view of “holes” in a soybean crop caused by water excess during the 2020/21 harvest in Itaqui, Rio Grande do Sul, Brazil. Courtesy: Lorenzo Dalcin Meus.

Courtesy: José Eduardo Minussi Winck



2.2. Temperature

Temperature plays a crucial role in influencing physiological processes and plant biochemical reactions, acting as a catalyst or decelerator for metabolic activities like photosynthesis, transpiration, respiration, germination, and flowering. Consequently, air temperature significantly impacts both the growth and development of plants. In terms of physiological processes, plant respiration shows a direct proportionality to temperature increases, whereas gross photosynthesis tends to decrease beyond a certain temperature threshold. This reduction in gross photosynthesis affects net photosynthesis and, consequently, the yield potential of a crop (refer to Figure 2.2.1).

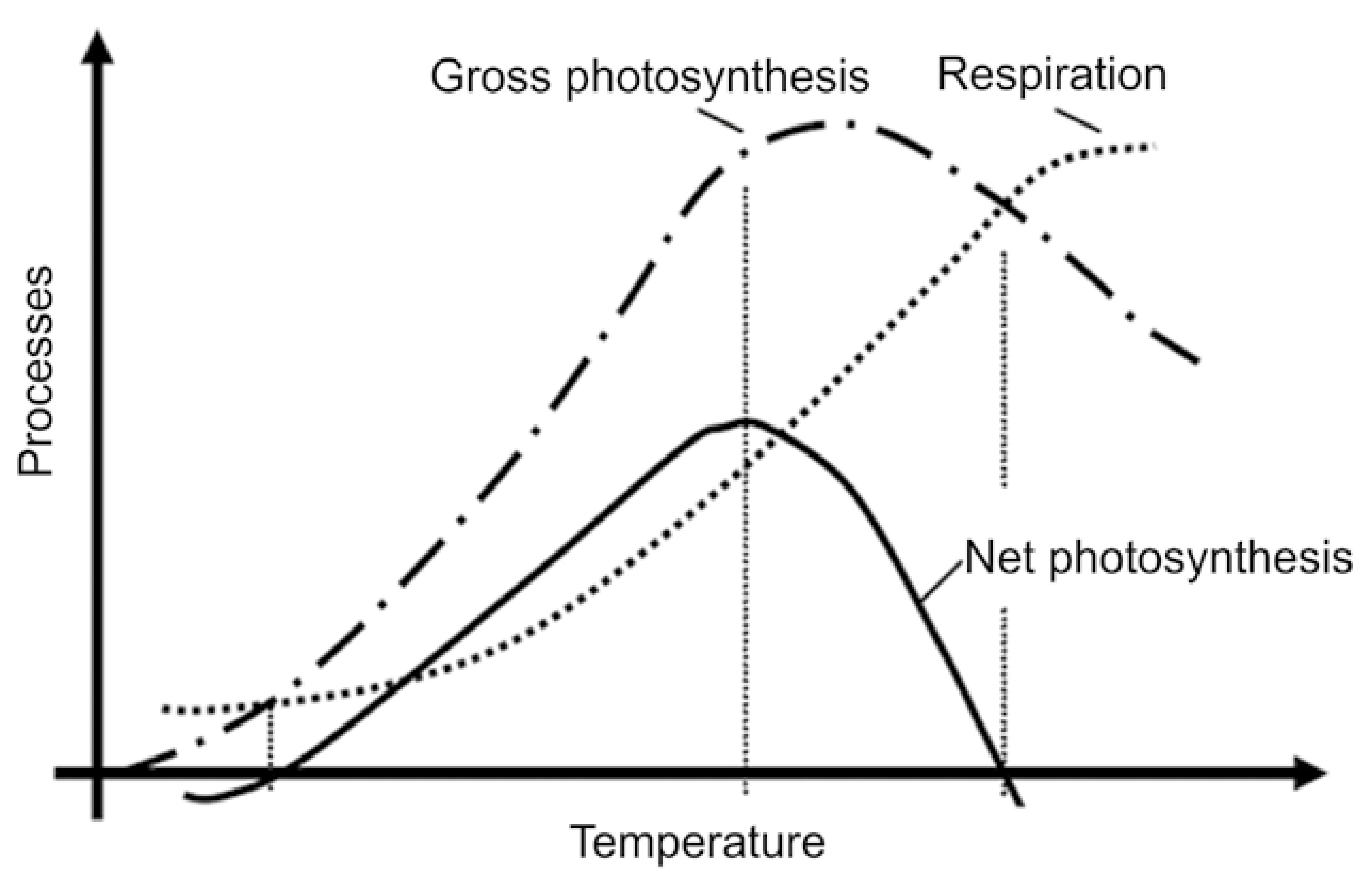


Figure 2.2.1. The response of gross photosynthesis, respiration, and liquid photosynthesis to air temperature.

The first studies that identified the influence of temperature on plant development were conducted in France during the eighteenth century by Réaumur (1735). These studies revealed that the cycle of a plant varied depending on the cultivation location. However, upon analyzing the sum of air temperatures during different cycles, it was observed that the thermal sum remained constant regardless of the location. For each plant species, there exist minimum, optimum, and maximum temperatures for development, known as cardinal temperatures (Pascale & Damario, 2004). Consequently, temperature influences the duration of developmental stages, either prolonging or shortening the crop cycle.

In the case of the soybean crop, the temperature range that facilitates establishment, growth, development, and grain production is broad, varying throughout the growing cycle in alignment with different stages of crop development (refer to Figure 2.2.2). During the early development period, from seeding to emergence, soybean plants grow and develop within temperatures ranging from 5 to 45°C, with the optimal temperature for development being 31.5°C.

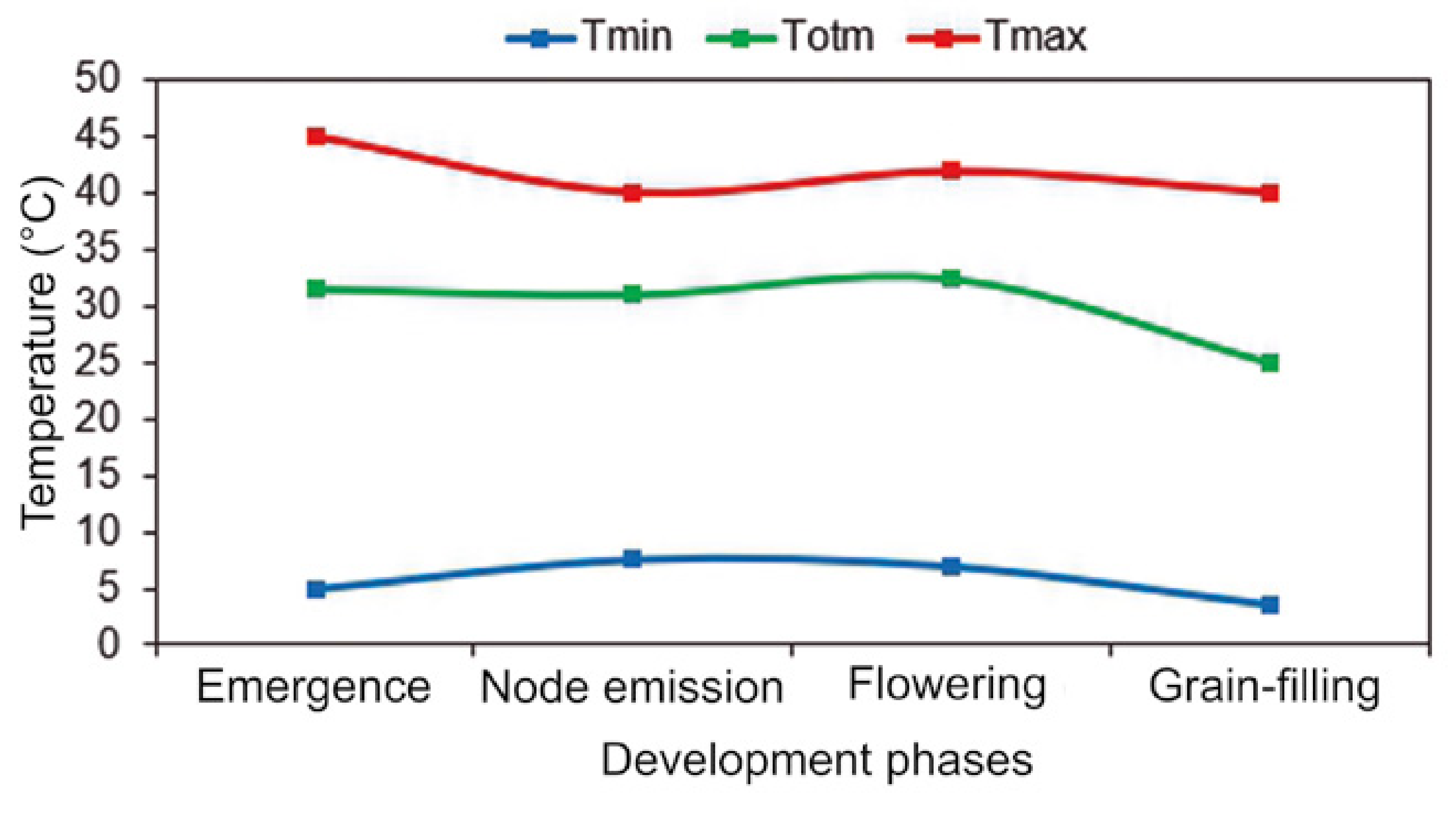


Figure 2.2.2. Cardinal temperatures for the soybean crop: Tmin, Topt, and Tmax represent minimum, optimum, and maximum temperatures, respectively. Source: Adapted from Setiyono et al. (2007).

Temperatures below 5°C and above 45°C cease the development of soybean plants. When the air temperature deviates from the optimum range during the sowing-emergence phase, the initial establishment success of a soybean crop becomes increasingly reliant on seed vigor. Air temperatures above 35°C can raise the temperature of bare soil to 50-60°C, causing plant death due to heat stress (See item 1.9). The sowing-emergence phase is critical, as it determines the number of plants per hectare. Following germination, the vegetative growth stages (V1 to Vn) have cardinal temperatures of 7.6°C (lower basal temperature), 31°C (optimal temperature), and 40°C (upper basal temperature). Temperatures exceeding the upper basal temperature (40°C) during the vegetative phase can lead to peroxidation of membrane lipids and the formation of reactive oxygen species, resulting in symptoms like leaf necrosis (Figure 2.2.3).

As flowering begins, soybean plants become more sensitive to extreme temperatures. Temperatures above 40°C can cause flower abortion and impact seed development. The optimal temperature during the reproductive phase is 25°C, explaining the higher yield potential in higher altitude regions of Rio Grande do Sul (e.g., Vacaria and Passo Fundo) compared to crops at lower altitudes (Missions Region), where warmer nights prevail. High-temperature stress poses a significant concern for soybeans in the context of global warming scenarios. During the 2021/22 summer, intense heat waves occurred in southern Brazil, with temperatures exceeding 35°C for several days, leading to damage to soybean leaves (see Figure 2.2.3) and resulting in reduced yield potential. Loss of yield potential occurs irreversibly due to reduced interception of solar radiation.

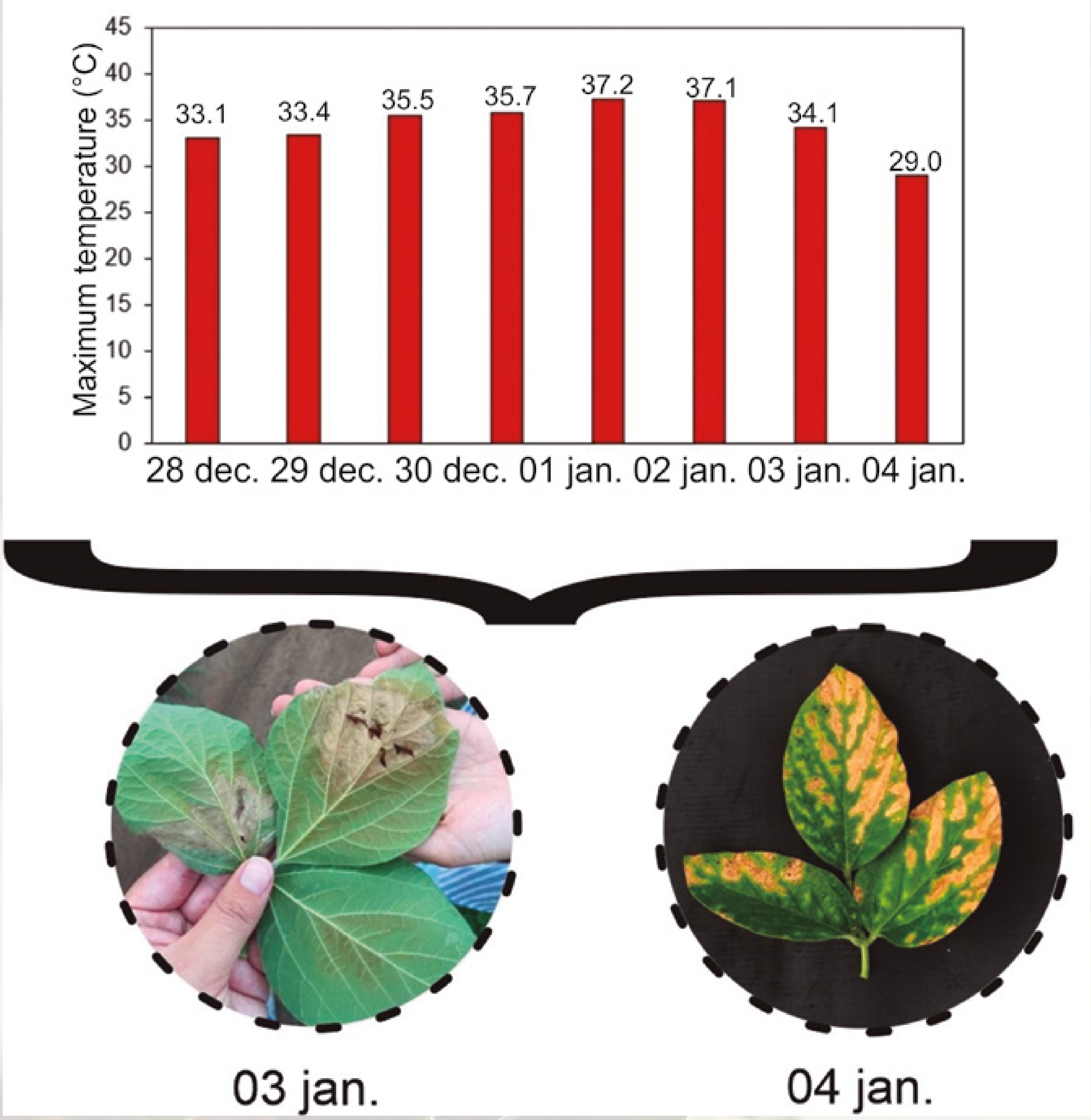


Figure 2.2.3. Damage caused on soybean leaves due to thermal stress during the month of December 2021 and January 2022 in Santa Maria, Rio Grande do Sul, Brazil. Leaf damage was recorded on January 3rd and 4th 2022.

2.3. Solar radiation

Solar radiation is the meteorological element that provides energy for soybean plants to carry out photosynthesis, a process that converts light energy into organic carbon structures such as glucose. Solar radiation is a set of electromagnetic wavelengths (λ) and photons that reach the Earth's surface. These photons carry a form of energy known as quanta, essential for photosynthesis—the process by which plants oxidize water, release oxygen, and convert carbon dioxide into metabolic compounds, particularly sugars. Sunlight radiation is thus a critical meteorological factor influencing soybean yield potential. In Brazil, the southern regions and much of the Midwest benefit from this variable, evidenced by climatology data showing extensive periods of cloudless solar radiation (measured in hours) in these areas (see Figure 2.3.1). These regions are among the world's largest producers of soybeans.

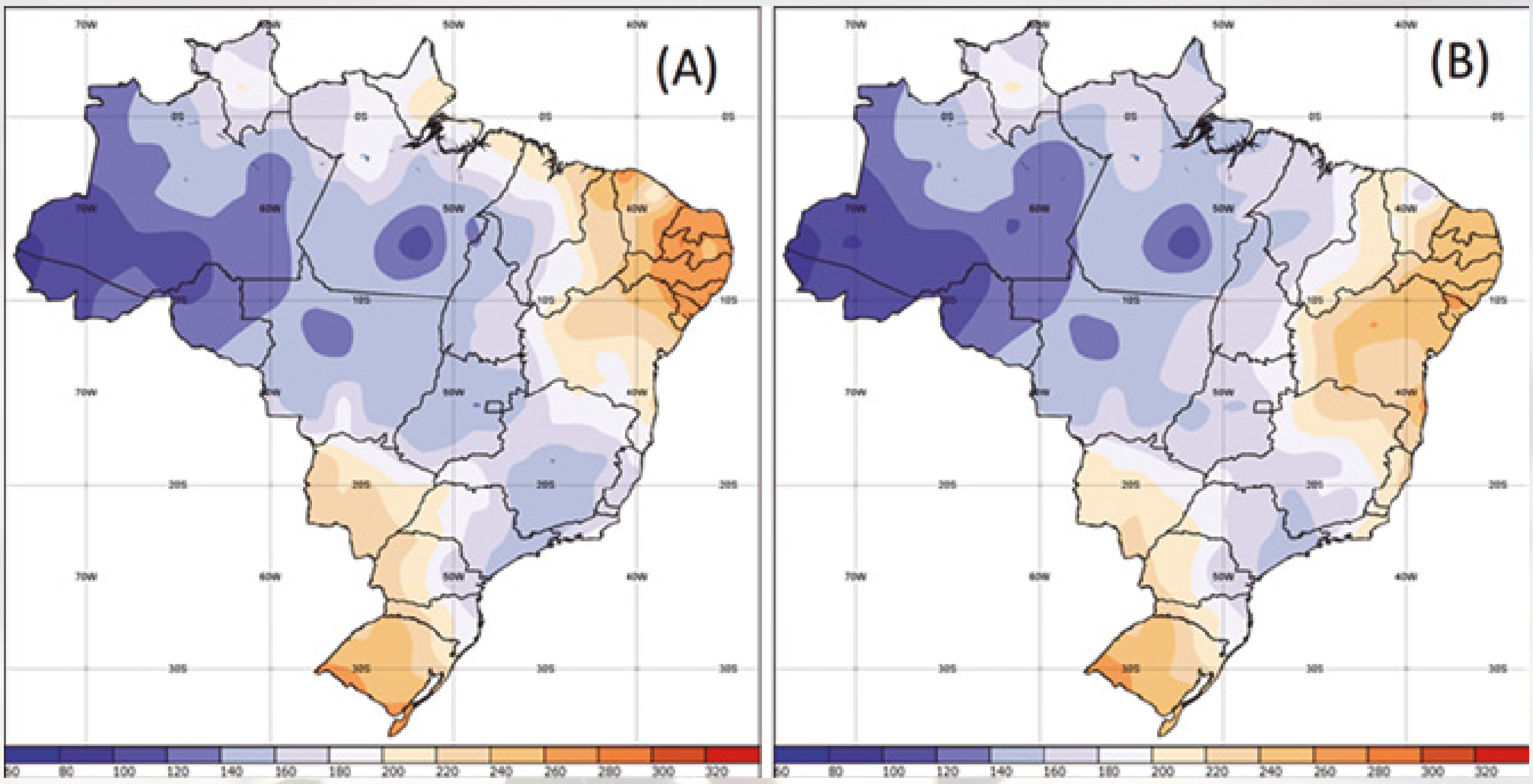


Figure 2.3.1. Climatology of solar brightness (number of hours with cloudless solar radiation) for the months of December (A) and January (B) in Brazil, based on the period 1981-2010. Sunshine hours count only the number of hours of sunlight without clouds, while solar radiation includes both direct solar glare and diffuse radiation. Source: INMET.

The solar radiation used by plants for the photosynthetic process is contained within the range of visible light (400 nm to 700 nm), known as photosynthetically active radiation (PAR), corresponding to approximately 45% to 50% of the total incident global solar radiation (Pereira et al., 2002). The soybean crop absorbs about 2/3 of the incident photosynthetically active radiation during its development cycle from emergence to physiological maturity (Cafaro La Menza et al., 2017). Through radiation-use efficiency (RUE), it is possible to assess how efficiently a crop converts radiant energy from the sun into biochemical energy (ATP) and subsequently into carbon dioxide compounds (vegetable biomass) and grain productivity. RUE values range from 1.09 to 2.95 g MJ^{-1} m^{-2} (Cafaro La Menza et al., 2017), varying throughout the crop cycle and production environment. By implementing management practices such as adjusting the sowing time, it is feasible to synchronize the critical crop period (pod formation and grain filling) with the peak solar radiation availability, thereby increasing the yield potential (Zanon et al., 2016). The absorption of light energy by plants occurs through specialized active pigments called chlorophyll, present in chloroplasts, along with accessory pigments called carotenoids. Chlorophylls a and b are predominant in green plants, absorbing in the near-blue (430 nm) and red (660 nm) regions of the visible spectrum (Taiz et al., 2017). Due to lower efficiency in absorbing green light (around 550 nm) within the middle range of the visible spectrum, a portion of it is reflected, imparting the characteristic green color to plants. To optimize energy utilization, a structure composed of chlorophylls, pigments, and proteins, known as the antenna complex, associates with and directs absorbed radiation to the reaction center photochemical complexes, known as photosystems I and II (PSI and PSII), have maximum absorption at wavelengths of 700 nm and 680 nm, respectively (Taiz et al., 2017). These two photosystems are connected in series by a redox potential-driven electron transport chain, which facilitates the energy storage reactions of photosynthesis. Consequently, solar radiation is converted and conserved as ATP and NADPH, which are organic coenzymes. These substances are subsequently utilized in the Calvin-Benson cycle to synthesize sugars and carbon chains to produce more complex compounds. In the Calvin-Benson cycle, certain enzymes are light-dependent for activity and activation. Moreover, the opening of stomata for gas exchange and CO_2 assimilation—essential substrates for the Calvin-Benson cycle—is induced by blue light. This light is perceived by non-photosynthetic phototropin photoreceptors, which mediate the stomatal opening response.

2.3.1. Light restriction and supplementation

Cloudy days reduce the availability of solar radiation for soybean crops. The FieldCrops team has been conducting experiments since 2019 in Entre Ríos, Argentina; Alta Floresta, Mato Grosso, Brazil; and Santa Maria, Rio Grande do Sul, Brazil, aiming to assess the impact of solar radiation restriction on growth, development, and yield (Figure 2.3.1.1).

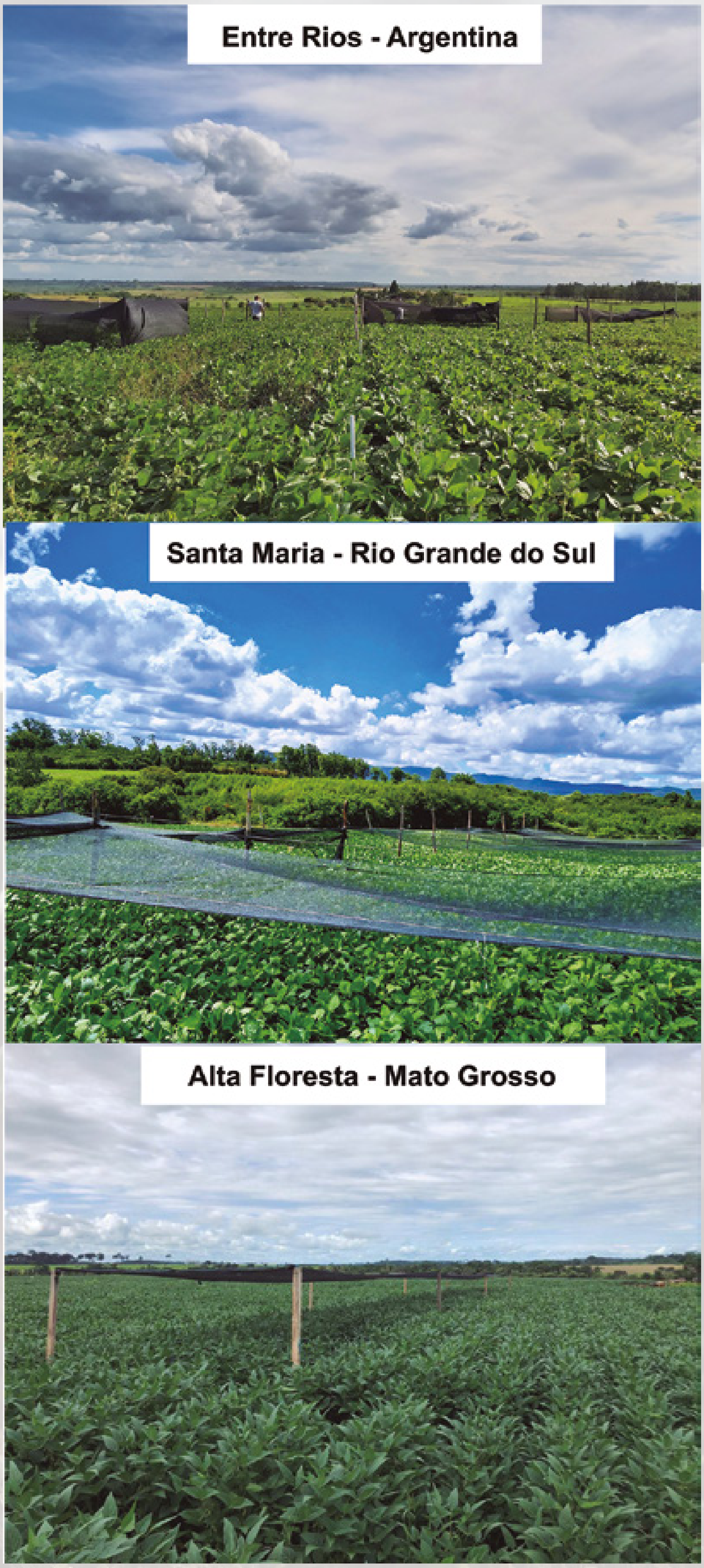


Figure 2.3.1.1. Experiments investigating solar radiation restriction in soybean conducted in Entre Ríos, Argentina; Rio Grande do Sul, Brazil; and Mato Grosso, Brazil.

Preliminary results indicate a trend of increased yield losses due to solar restriction during the developmental stages of early flowering and grain filling (Figure 2.3.1.2).

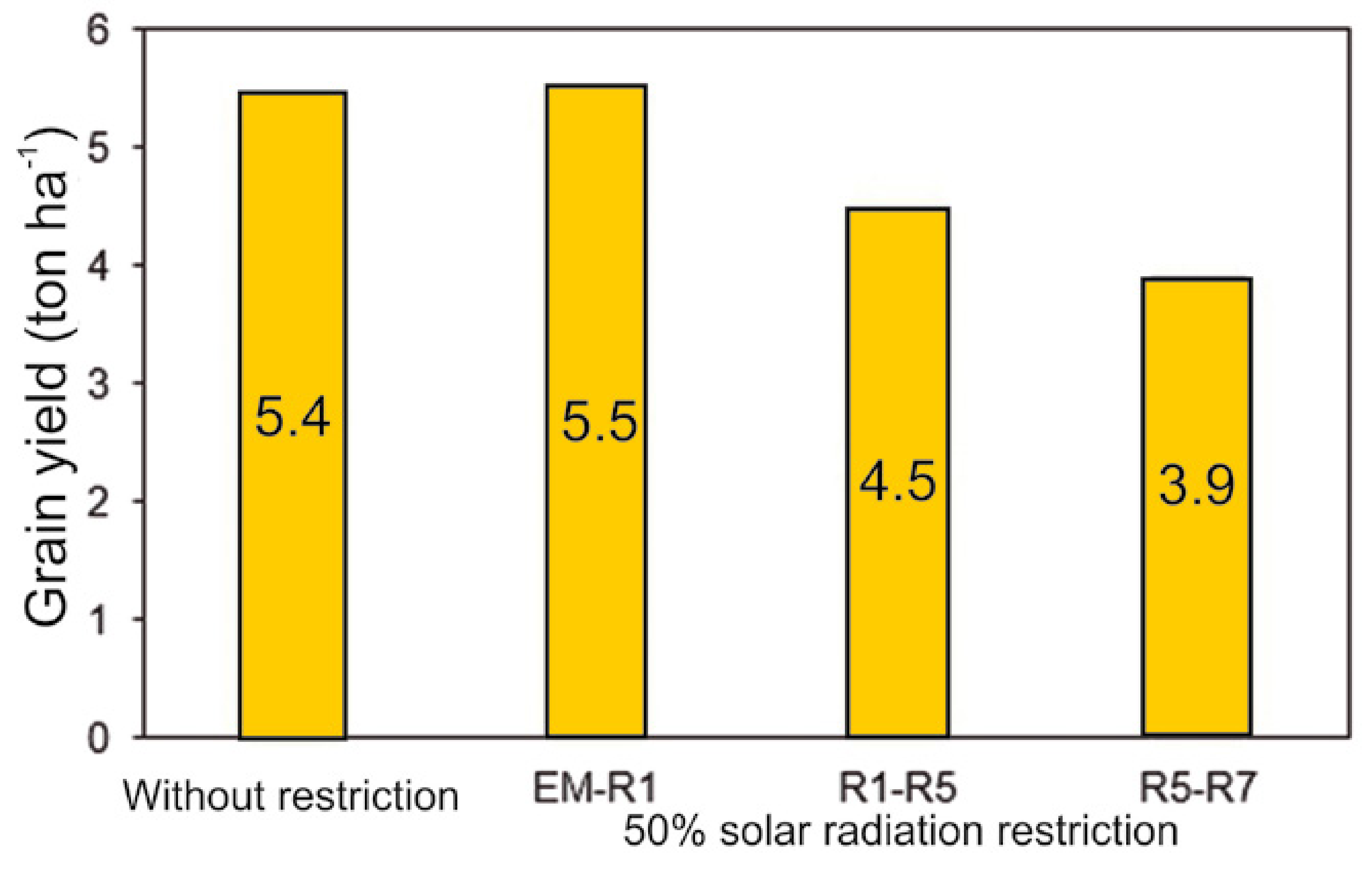


Figure 2.3.1.2. Relationship between grain yield (ton ha^{-1}) and incident sunlight radiation at different developmental stages. Total incident solar radiation (without restriction), 50% solar radiation restriction from emergence to flowering (EM-R1), from flowering to grain filling (R1-R5), and from grain filling to physiological maturity of soybeans (R5-R7) in Alta Floresta, Mato Grosso. Brazil.

Supplemental light irrigation is an emerging tool in soybean management aimed at maximizing yield. The development of new technologies in long-lasting LED lamps and efficient spectral composition provides economically viable large-scale lighting solutions for grain crops (Cocetta et al., 2017; Gupta, 2017). The most efficient spectral composition involves a specific ratio of red and blue wavelengths, which results in a beneficial blue-red hue for plant growth (Figure 2.3.1.3).

The adoption of daily light supplementation in large crop applications, particularly within pivot irrigation systems, is gaining traction. Until the completion of this book edition, the FieldCrops team has been rigorously testing a scientific hypothesis over the past three agricultural seasons. They aim to demonstrate that light supplementation is a viable and cost-effective method to maximize soybean yields in farming.

Figure 2.3.1.3. Artificial lighting experiments using LED lamps in soybean cultivation at the experimental area of the Advanced Farm 360 project, in collaboration with the Polytechnic College of UFSM, during the 2021/2022 harvest in Santa Maria, Rio Grande do Sul, Brazil.

2.4. Photoperiod

Photoperiod is the duration, in hours, of the day length plus the duration of twilight, that is, the period that from early morning to late sunset. Photoperiodism is the response of plant development to photoperiod (Chang, 1974). The photoperiod at a location depends on the latitude and the time of year. The variation in photoperiod throughout the year occurs due to the changing angle of incidence of solar radiation, which is influenced by solar declination. As our planet changes position relative to the sun, we observe differences in photoperiod during the year, such as on the two equinoxes (03/21 and 09/21) when the photoperiod is close to 12 hours at all latitudes. There are also two solstices

(06/21 and 12/21) when the photoperiod reaches its extreme values, being maximal in summer and minimal in winter for the Southern Hemisphere.

The photoperiod is an important regulator of the life cycle of the soybean crop, which is classified as a short-day plant. This means that the soybean plant is induced to flower when the number of daylight hours is shorter than its critical photoperiod (Garner & Allard, 1920). Photoperiodic stimuli are perceived in the soybean leaf (thus photoperiodic induction begins after the VC stage), with alterations in the levels of phytochromes (P660 and P730). During the night, the amount of phytochrome P660 increases, while during the day, phytochrome P730 predominates. Therefore, during long nights, soybean plants are induced to flower due to higher concentrations of phytochrome P660. This flowering induction occurs during the nocturnal period (nyctoperiod) in plants sensitive to photoperiod variations. The response to photoperiod also varies at different stages of the development cycle and depends on the maturity group (MG). To better understand soybean plants' response to photoperiod, it is necessary to clarify the concepts of critical photoperiod and optimal photoperiod.

2.4.1. Critical Photoperiod and Optimal Photoperiod

The critical photoperiod in soybeans is defined as the photoperiod above which the soybean plant theoretically cannot flourish, and the duration of the development cycle is at its maximum (Setiyono et al., 2007). Conversely, photoperiods below the critical photoperiod induce the soybean plant to flower (Figure 2.4.1.1). The optimal photoperiod is the photoperiod below which the induction to flowering is at its maximum and the duration of the development cycle is minimal (Setiyono et al., 2007) (Figure 2.4.1.1).

The induction of flowering can be represented as occurring at a maximum or below the optimum photoperiod. Additionally, flowering can occur without induction within the critical photoperiod or above it (Figure 2.4.1.1). The critical and optimal photoperiod values vary from 17 to 24 hours and from 6 to 13 hours, respectively, depending on the MG.

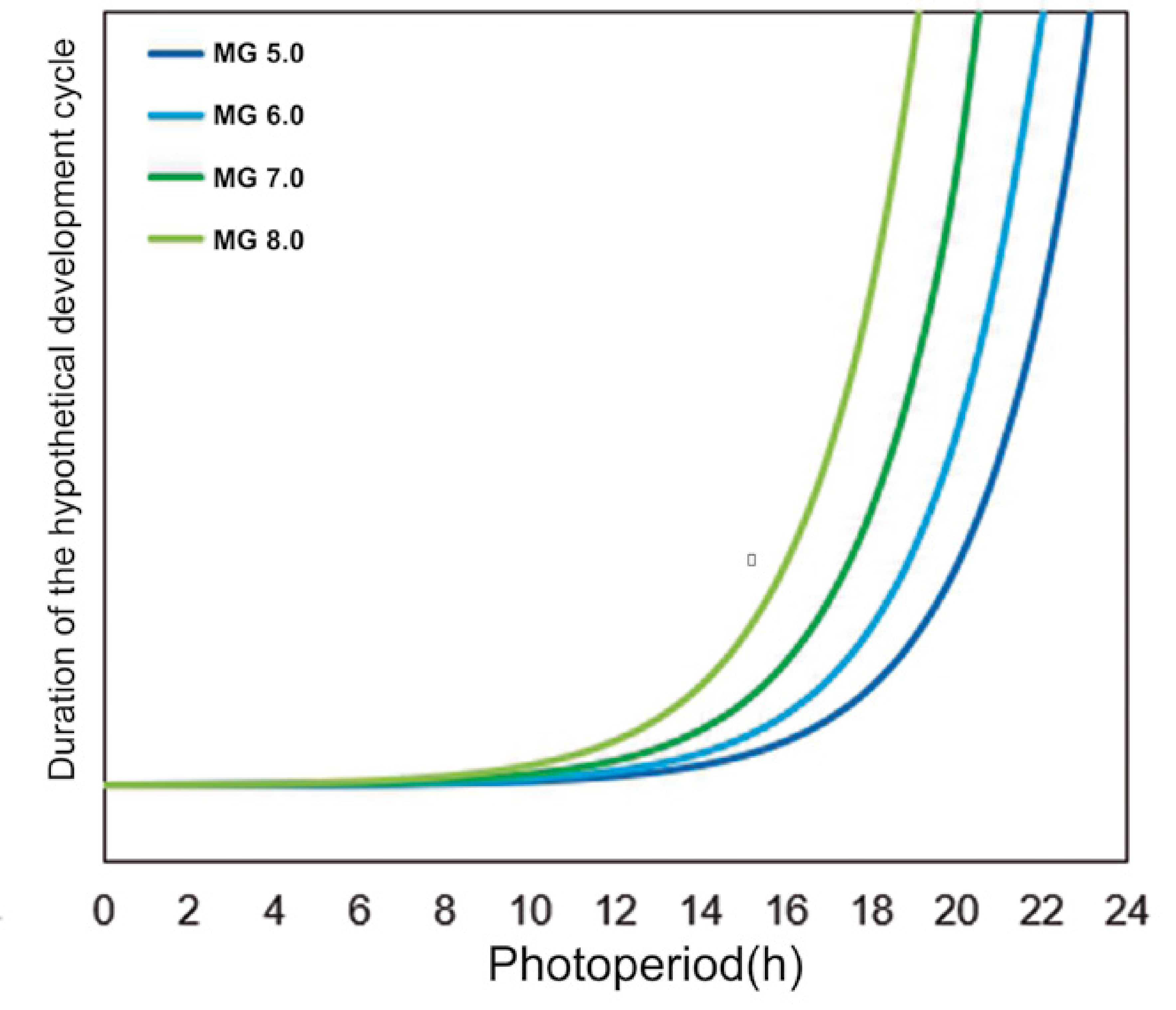


Figure 2.4.1.1. Soybean cycle length in response to photoperiod for different maturity groups. Adapted from Sinclair et al., (2005).

Considering the variation of photoperiod in four locations in the Southern Hemisphere, and assuming an optimal photoperiod of 13 hours and a critical photoperiod of 17 hours (Figure 2.4.1.2), soybean plants sown before September 1st are exposed to shorter photoperiods than the optimal length, maximizing induction to flowering. Therefore, in Southern Brazil, soybean sowings with low maturity group (MG) ratings (between 4.8 and 5.5), done too early (in August), may result in soybean plants with reduced stature and lower yield potential. Similarly, sowings carried out too late in Southern Brazil (in February) also result in soybean plants with reduced height and productivity potential, because by March, the photoperiod approaches and falls below the optimal range (refer to Figure 2.4.1.2).

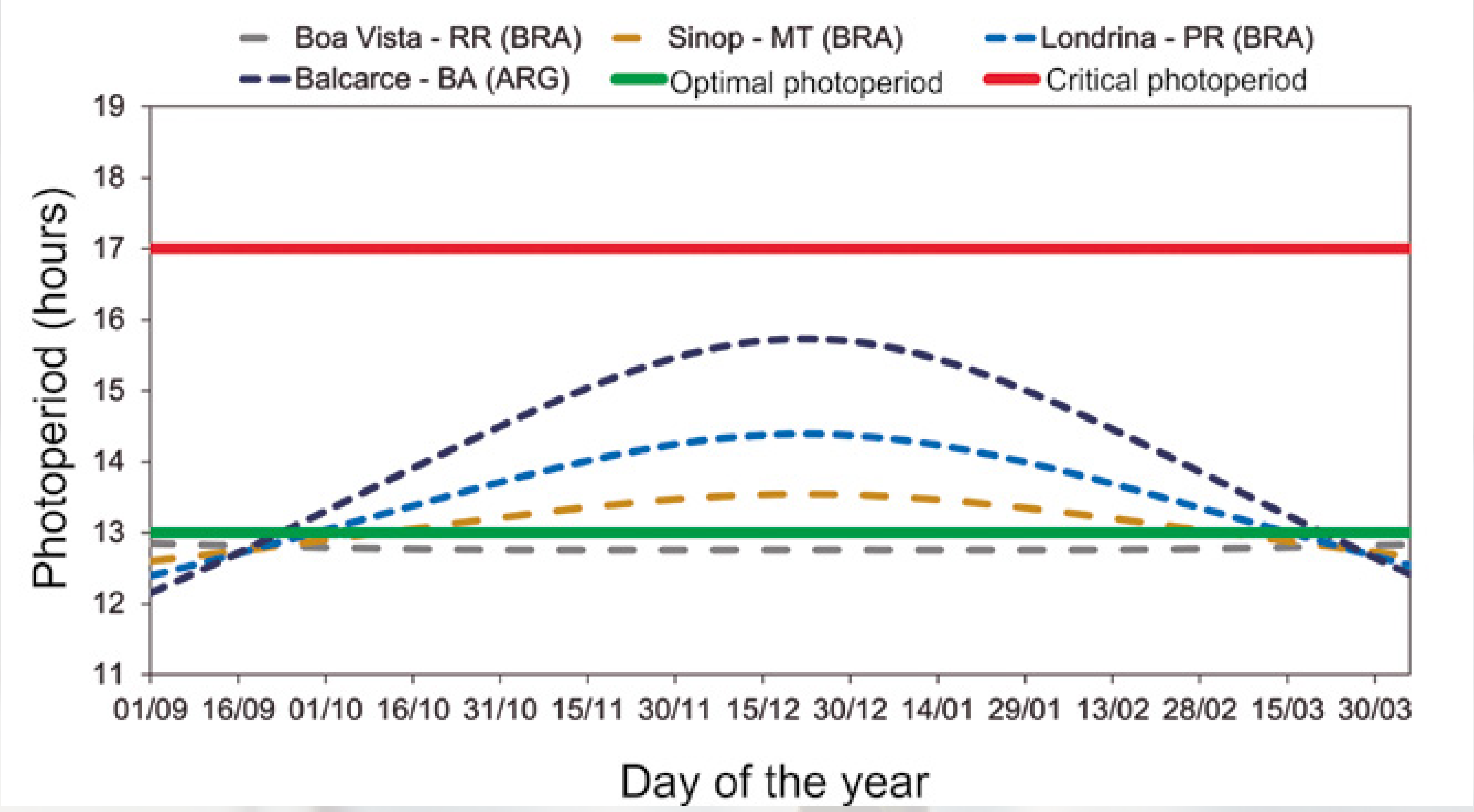


Figure 2.4.1.2. Variation of photoperiod from September to April in different locations in the Southern Hemisphere. The green horizontal line represents the optimal photoperiod of 13 hours, while the red horizontal line indicates the critical photoperiod of 17 hours.

In the vegetative phase, as mentioned earlier, temperature influences the rate of leaf emergence. However, the cessation of new leaf production is linked to reproductive development, which is influenced by photoperiodic induction and growth type. The photoperiod that maximally induces flowering, or when the photoperiod is shorter than a cultivar's optimal photoperiod, determines a minimum leaf number.

Consequently, each cultivar has a minimum leaf count during its vegetative period under optimal photoperiod conditions. Photoperiod sensitivity remains a significant constraint for broader soybean adaptation. This characteristic results in varying adaptability ranges for each cultivar as one moves north or south.

2.4.2. Juvenility

The juvenile stage of a plant is the period between emergence and the beginning of photoperiodic induction. During this stage, the plant does not respond to changes in photoperiod. Therefore, a long juvenile period (LJP) serves as a feature that delays the onset of flowering (Hartwig & Kiihl, 1979; Kiihl & Garcia, 1989).

In non-breeding soybean plants, the juvenile stage is short and lasts from emergence to VC (when the leaves extend to unifoliolates), which makes soybeans highly sensitive to photoperiod. Consequently, soybean sowings are restricted to certain latitudes and specific seasons (Setiyono et al., 2007). The high sensitivity of soybeans to latitude or sowing date has historically limited the crop's cultivation in tropical regions. In these areas, the average photoperiod during soybean growing seasons is lower compared to temperate and subtropical regions where soybeans have been cultivated for centuries. The shortest photoperiod in tropical or sowing regions, such as September or January in subtropical areas, induces early flowering. This premature flowering can lead to reduced plant height and productivity, and in some cases, make cultivation unfeasible.

The solution to extend the vegetative phase of the crop emerged in the 1970s with the introduction of cultivars carrying long juvenile genes (Hartwig & Kiihl, 1979). In these cultivars, the rate of development from sowing to flowering is slower (late flowering) compared to cultivars lacking long juvenile genes when the plant is exposed to a photoperiod close to or below optimal conditions (Sinclair et al., 2005). This extended vegetative phase allows for increased vegetative growth under shorter photoperiods (11 to 13 hours) in low-latitude regions (tropics). Controlling flowering, and thereby plant size, became a fundamental consideration in genetic improvement for developing cultivars less sensitive to variations in sowing dates and locations (latitude). Modifications and incorporations of these genetic traits facilitated the expansion of soybean cultivation into low-latitude regions, making soybeans one of the most adaptable crops on the planet.

Despite the significance of LJP (long juvenile genes) for soybean cultivation in the Brazilian Midwest, little is known about their influence on the soybean development cycle in the South region of Brazil, or their impact on grain productivity. From a scientific standpoint, understanding these characteristics is crucial for enhancing soybean genetics and strategically placing cultivars with LJP in both low and high latitude regions (such as southern Brazil and Argentina).

From a practical perspective, cultivars with LJP offer more flexibility, enabling soybean planting within a broader window while maintaining yield potential. This flexibility is vital for cultivating off-season soybeans in southern Brazil, particularly in Rio Grande do Sul (RS).

To investigate the effect of LJP, a study was conducted in Santa Maria, Rio Grande do Sul, Brazil, during 2017/18 season. The latitude of Santa Maria County (29.7°S) s representative of the average latitudes in Rio Grande do Sul, which vary from 27°S to 33°S, and it experiences the longest photoperiodic range in Brazil. Eight different sowing dates were implemented: 08/05/2017, 09/02/2017, 10/17/2017, 11/21/2017, 12/19/2017, 01/16/2018, 02/16/2018, and 03/22/2018 (withdrawing due to cold damage – see Figure 2.4.2.1). Various soybean cultivars were chosen to represent the primary maturity groups (MG): MG 4.8 (NS 4823 RR - without LJP), MG 5.5 (BMX Elite IPRO - without LJP), MG 6.2 (TMG 7062 IPRO - with LJP), MG 6.8 (BMX Icon IPRO - with LJP), and MG 7.8 (TEC 7849 IPRO - without LJP). Fertilization and phytosanitary management were implemented with the goal of achieving yields above 6.0 ton ha^{-1}, thus expressing the highest potential productivity of genetic interactions with the environment, along with supplemental irrigation to prevent water deficiency interference.

Figure 2.4.2.1. Damage resulting from frost formation on June 17th, 2018, affecting crops planted on March 28th, 2018, in Santa Maria, Rio Grande do Sul, Brazil.

As explained in Chapter 1.6, the longer the MG (maturity group), the longer the cycle will last. In Figure 2.4.2.2, panel A (October sowing), the cycle duration decreases as the MG decreases. However, in panel B (sowing in August), this trend did not occur; instead, two smaller MGs exhibited longer cycles. This change in cycle length is related to LJP (late juvenile phase) in cultivars with MG 6.2 and 6.8, which experienced a delay in flowering due to the initial period lacking induction.

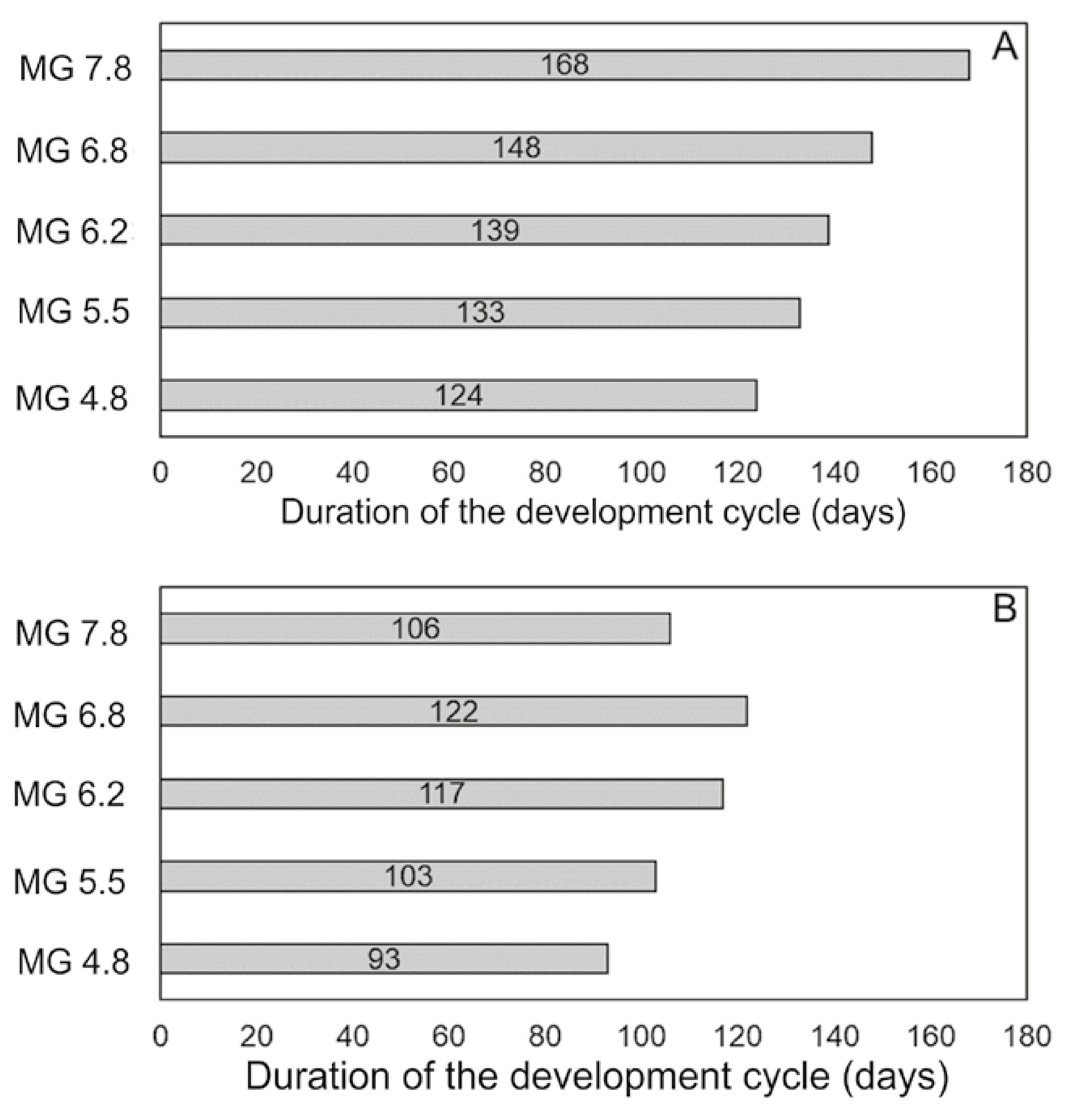


Figure 2.4.2.2. Duration of the development cycle (in days) for five soybean cultivars sown in October (Panel A) and August (Panel B) in Santa Maria, Rio Grande do Sul, Brazil.

The month of October in southern Brazil is identified as the optimal sowing period to achieve high yields (Zanon et al., 2018). According to Zanon et al. (2016), LJP (long juvenile period) delays flowering initiation, even under maximum photoperiod induction. In Figure 2.4.2.3, it is evident that advancing sowing to September and August reduces the vegetative phase more significantly in cultivars without LJP compared to those with LJP. Practically, for early sowing in regions aiming for two soybean crops in summer, it is advisable to use a cultivar with LJP. This ensures plants reach more fertile nodes and greater height, facilitating efficient mechanized harvesting and good yield. During October, November, and December, no significant difference was observed in the duration of the vegetative phase between cultivars with and without LJP (Figure 2.4.2.3). However, from January onwards, cultivars lacking LJP exhibited a greater reduction in the vegetative phase duration. This case study demonstrates that LJP enhances soybean crop adaptability when sown outside the recommended timeframe.

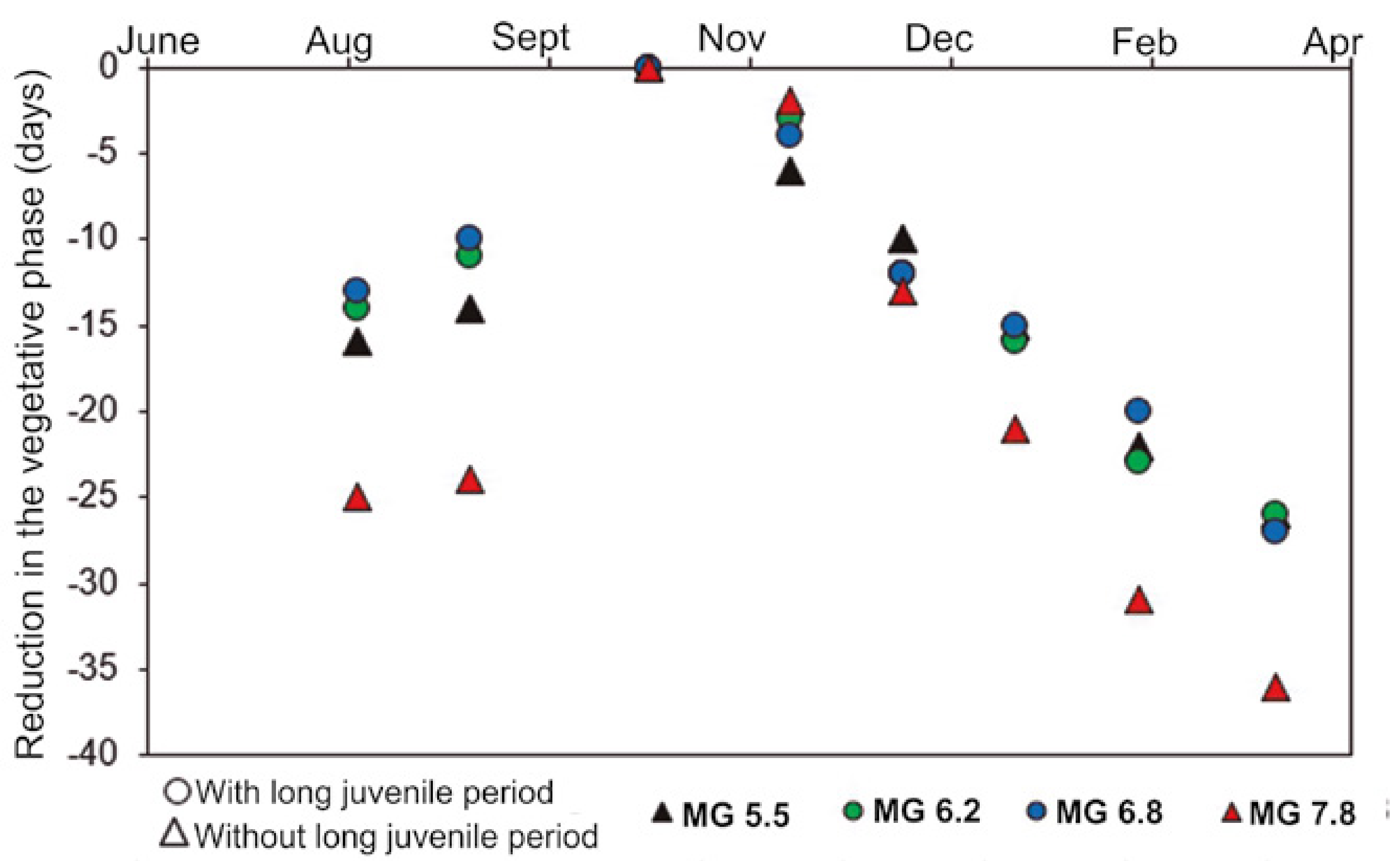


Figure 2.4.2.3. Reduction in the duration of the vegetative phase observed in four soybean cultivars sown from August to March in Santa Maria, Rio Grande do Sul, Brazil.

It has been concluded that cultivars with low juvenile potential (LJP) exhibit less reduction in productive potential compared to cultivars without LJP during both early and late sowing times. Additionally, LJP enhances the plasticity and stability of soybean cultivars. These characteristics are particularly desirable for crops sown under less favorable cultivation conditions, such as the cultivation of soybeans during the second season (safrinha) in Rio Grande do Sul or when sowing is advanced to October (Figure 2.4.2.4).

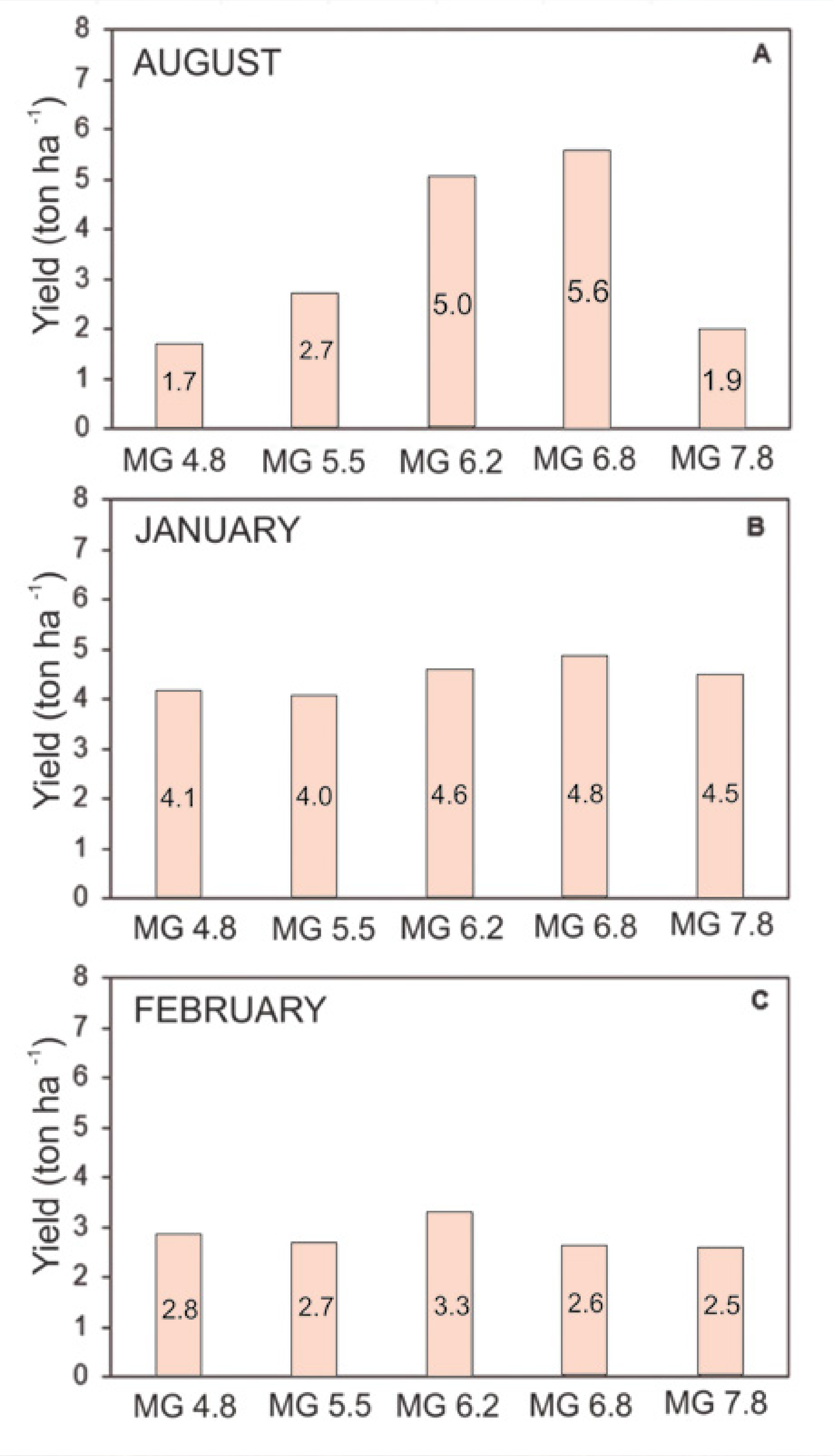


Figure 2.4.2.4. Yield comparison of five soybean cultivars sown in August (Panel A), January (Panel B), and February (Panel C) in Santa Maria, Rio Grande do Sul, Brazil.

2.5. Photothermal Coefficient

The photothermal coefficient (Q, MJ m^{-2} d^{-1} °C^{-1}) is calculated by dividing the incident solar radiation by the mean air temperature (adjusted for the base temperature, Tb). In practice, the photothermal coefficient (Q) integrates the effects of solar radiation and temperature on plant growth and development during critical stages of component formation and productivity (Fischer, 1985). For soybeans, a Tb of 7.6 °C and 0 °C is assumed for the vegetative and reproductive phases, respectively (Setiyono et al., 2007). Relationships between grain yield and Q during key stages for determining yield components have been reported for wheat crops, rice, and *Cicer arietinum* (Fischer, 1985; Islam & Morison, 1992; Sadras et al., 2015). Recently, a study conducted in a subtropical environment reported for the first time the relationship between Q and yield potential in soybean crops (Figure 2.5.1) (Zanon et al., 2016). The experiments were conducted with supplemental irrigation, without biotic stresses, and without nutritional restrictions. In this case, it was found that yield loss due to delayed sowing dates is associated with differences in Q values during critical stages of soybean yield determination (R3-R7). The values of Q decrease linearly with delayed sowing and are higher in maturity groups less than 6.9 for seedings that ended in September and October.

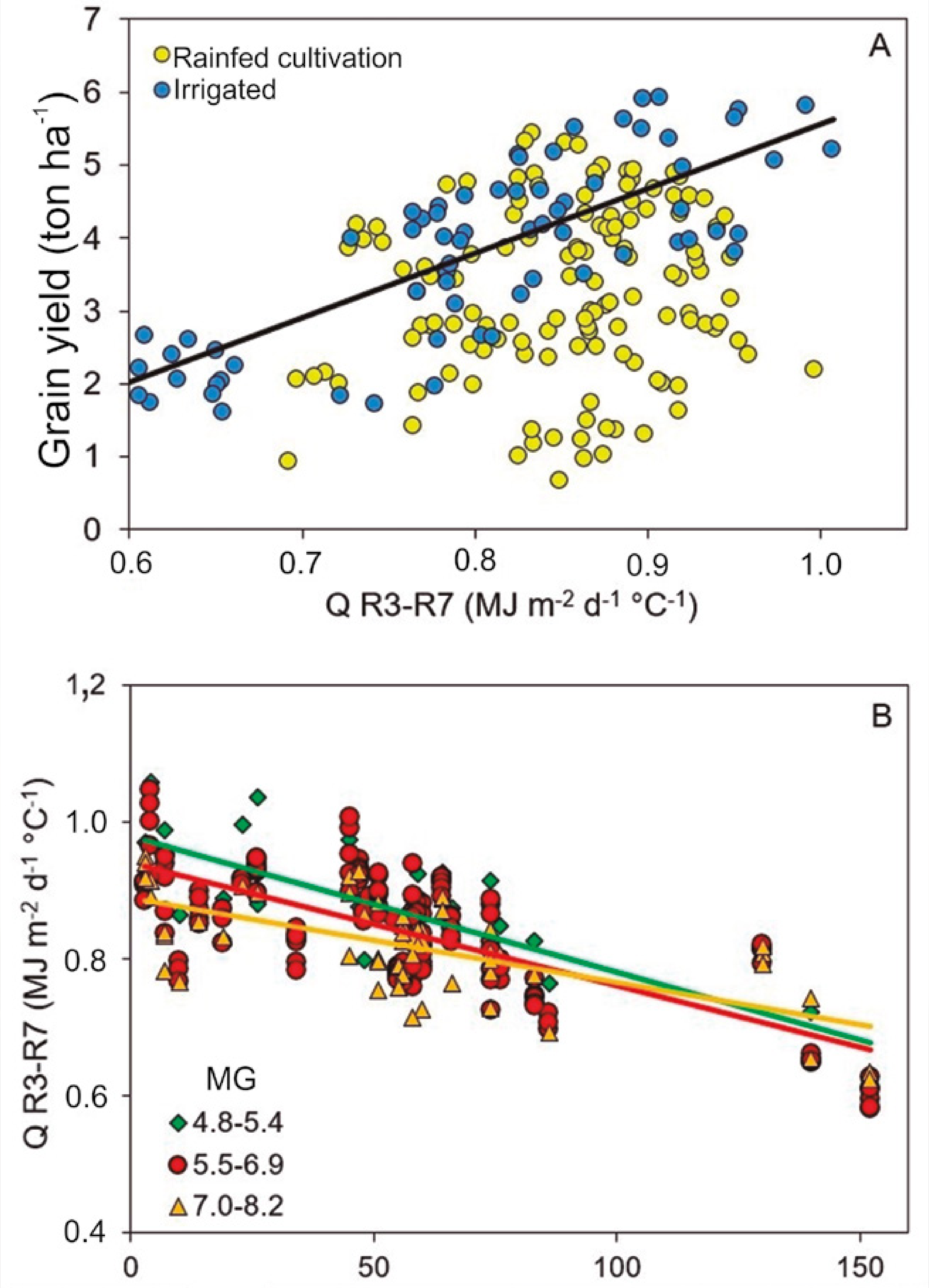


Figure 2.5.1. Relationship between soybean grain yield and the photothermal coefficient (Q) between stages R3 and R7 in rainfed cultivation (yellow circle) and irrigated (blue circle) (Panel A), and the photothermal coefficient (Q) between stages R3 and R7 as a function of sowing date in cultivars classified as early (MG 4.8 – 5.4, green diamonds), intermediate (MG 5.5 – 6.9, red circles), and late (MG 7.0 – 8.2, yellow triangles) (Panel B). Data were collected over four agricultural seasons (from 2011/12 to 2014/15). Regression lines are displayed only when they were significant at a 5% probability level. Source: Zanon et al. (2016).

There is a strong relationship between yield potential (YP) and the photothermal coefficient, as estimated for 32 locations in Brazil (Figure 2.5.2). The increase in yield is associated with a higher incidence of radiation in the southern region of the country. The highest YP values are observed at latitudes further south, where this relationship can be explained by the photothermal coefficient due to increased solar radiation. Alongside this, adjusting the maturation group and sowing date can assist in maximizing yield potential for the region. This adjustment aligns the peak leaf area with the period of highest solar radiation availability, typically occurring towards the end of December.

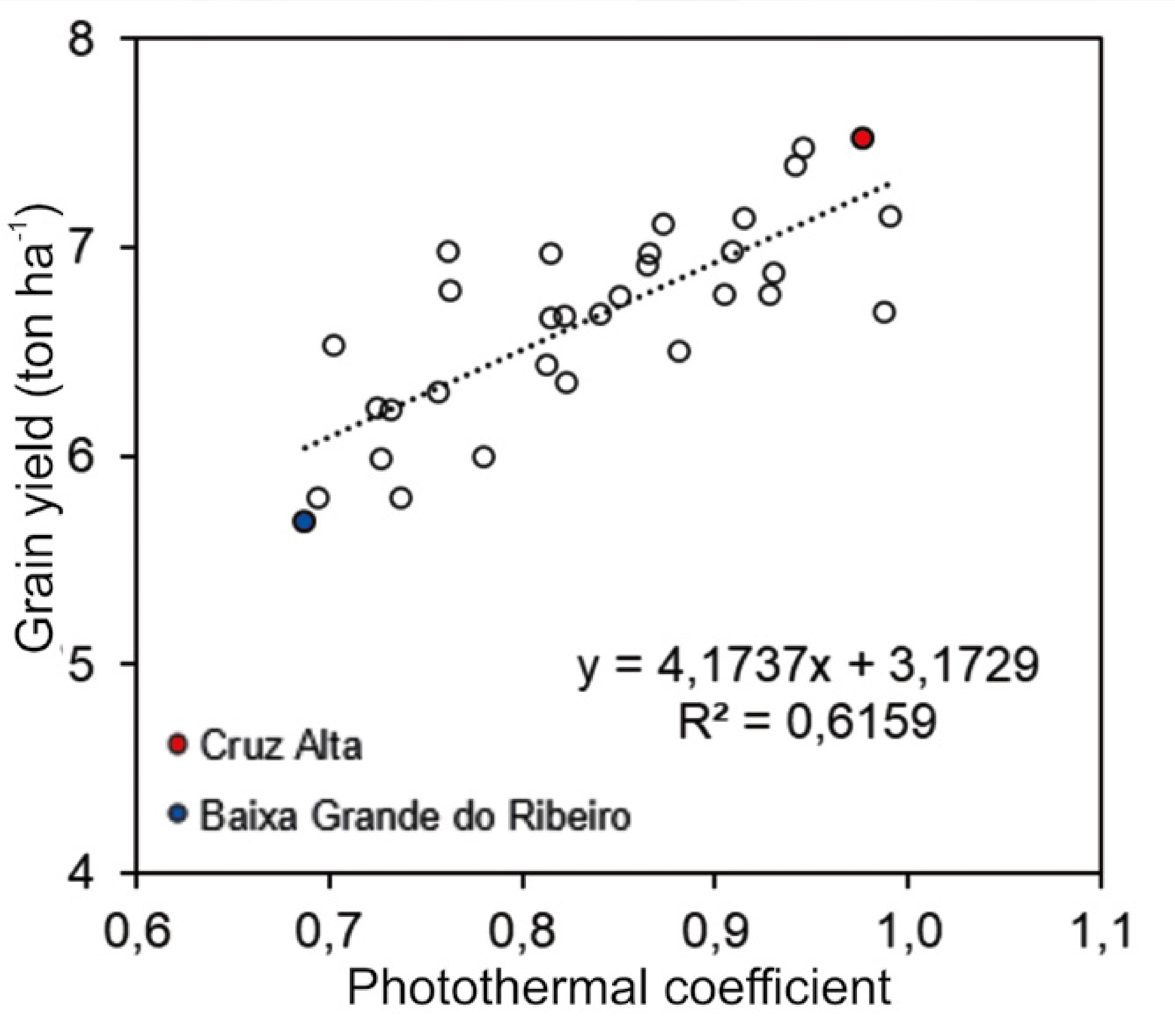


Figure 2.5.2. Relationship between grain yield and the photothermal coefficient for different locations in Brazil. High Cross red circle - Rio Grande do Sul, Brazil (latitude 28°S) and blue circle Baixa Grande do Ribeiro, Piauí, Brazil (latitude 7°S).

2.6. Climatic phenomena

El Niño-Southern Oscillation (ENSO) is a phenomenon of global scale that impacts the climate in various regions of the world (Araújo et al., 2013). It is characterized by abnormal heating or cooling of ocean surface waters in the Equatorial Pacific. ENSO drives interannual atmospheric variability in South America, leading to changes in meteorological variables such as temperature, rainfall distribution and frequency, and solar radiation availability in certain areas of the planet (Grimm, 2003, 2004; Kayano et al., 2011, 2013). The ENSO phenomenon results from a coupling of two components—oceanic and atmospheric—exhibiting different phases. These phases are defined by anomalies in Sea Surface Temperature (SST) and trade winds in the Equatorial Pacific. An El Niño phase is characterized by positive SST anomalies exceeding 0.5°C for at least 5 consecutive months, accompanied by weakened trade winds in the Equatorial Pacific near South America. Conversely, a La Niña phenomenon occurs with cooling of surface waters in the 3.4 Equatorial Pacific, showing SST anomalies below -0.5°C for at least 5 consecutive months, along with strengthened trade winds (Figure 2.6.1). The intensification of trade winds promotes upwelling of colder waters along the western coast of South America, resulting in below-normal SSTs. When SST anomalies range between -0.5°C and 0.5°C for 5 consecutive months, it characterizes a neutral climate phase associated with the ENSO phenomenon.

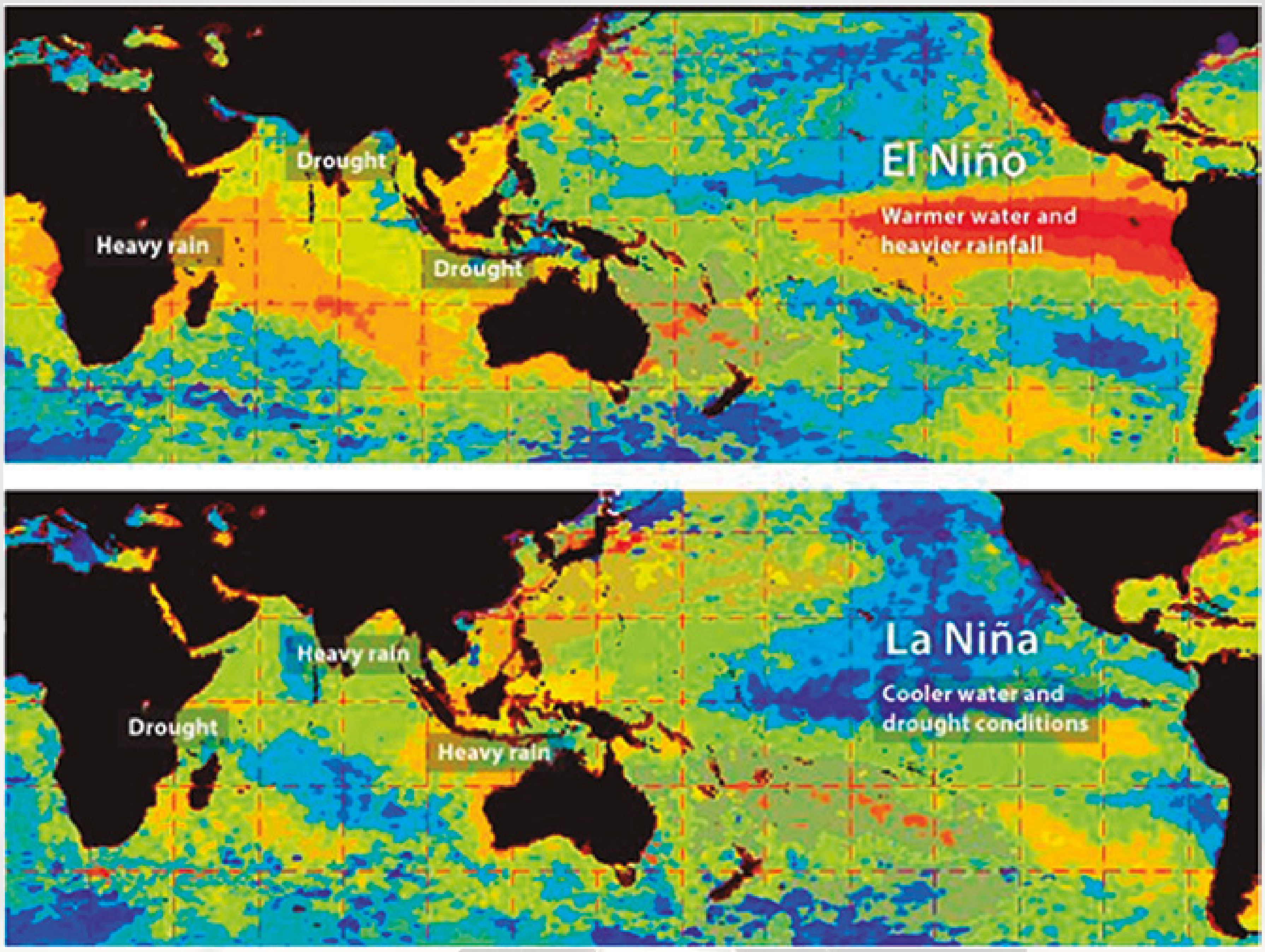


Figure 2.6.1. Spatial configuration of sea surface temperatures (SST) in the Pacific Ocean during the warm phase (El Niño) and cold phase (La Niña) of the ENSO phenomenon. Source: Adapted from http://www.cyclonextreme.com/meteorologieelnino.htm.

The ENSO phenomenon is considered one of the main factors responsible for the significant interannual variability of climate in South America, particularly concerning precipitation. The positive phase of this phenomenon (El Niño) promotes increased moisture availability in the Center-South region of Brazil, leading to greater cloud cover and reduced solar radiation, potentially impacting crop yields. However, water shortage (or water deficit) is the primary factor causing soybean yield losses in Southern Brazil. Therefore, years characterized by El Niño often experience the highest soybean yields in the states of the southern region of Brazil, owing to above-normal rainfall (Alberto et al., 2006; Arsego et al., 2018; Nóia Júnior et al., 2020). Regarding the Central-North region of Brazil, the positive phase of the El Niño-Southern Oscillation (ENSO) primarily impacts a reduction in rainfall. Conversely, the negative phase (La Niña) leads to less organized and more sporadic rainfall in the center-southern region of Brazil, resulting in frequent droughts that cause significant yield losses in soybean cultivation. Conversely, for the Central-North region of Brazil, the negative phase increases moisture availability, benefiting rainfall in areas with typically low annual precipitation. Numerous studies have quantified the impact of the ENSO phenomenon on soybean yields in southern Brazil. In well-defined La Niña years, yields are lower for sowings in September and October, with losses exceeding 1000 kg/ha at higher latitudes (> 28° S) (refer to Figure 2.6.2). Conversely, in years characterized by El Niño, the further north the latitude and the earlier the soybean planting, the greater the tendency for yield improvement (Nóia Júnior et al., 2020).

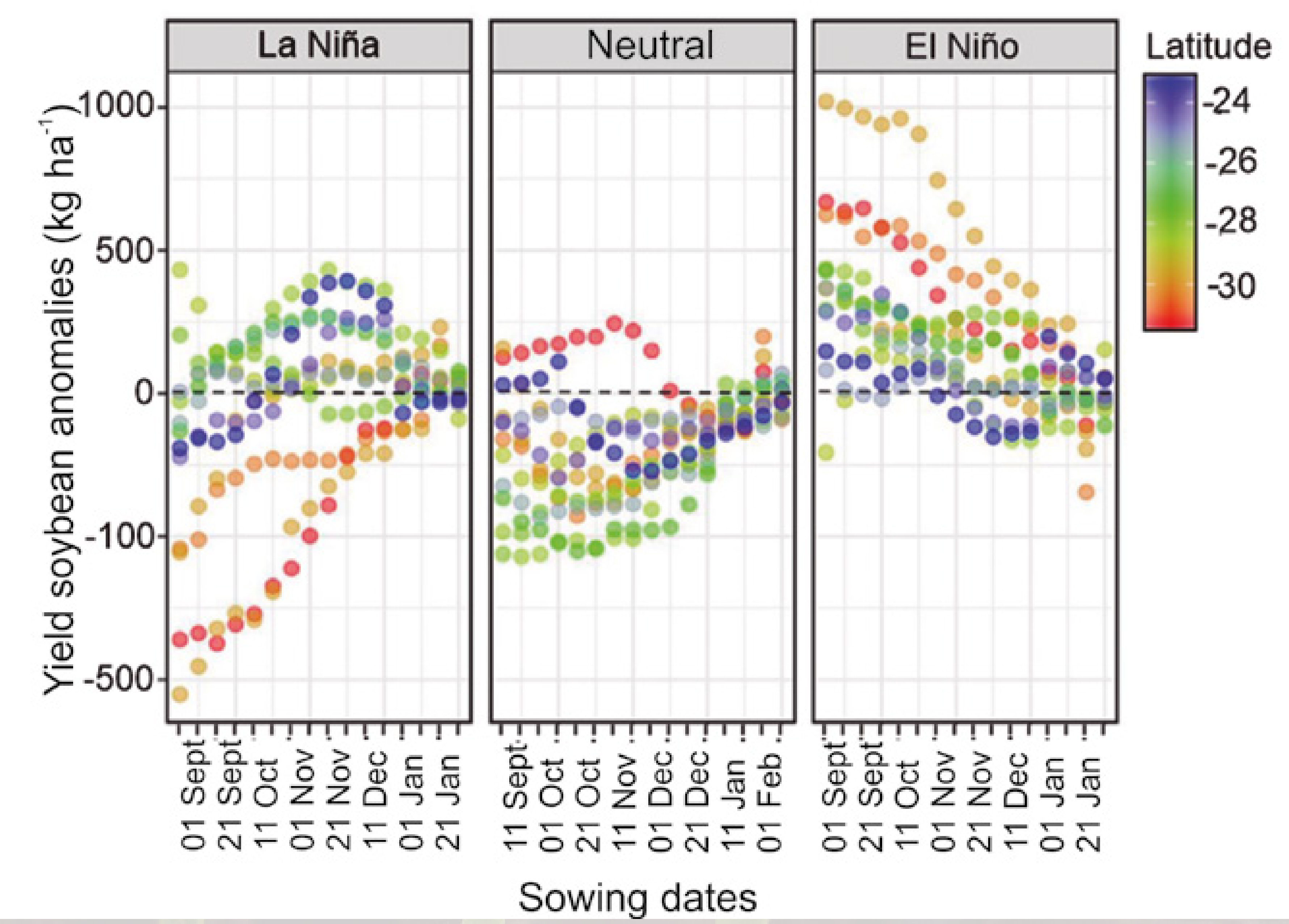


Figure 2.6.2. Anomalies in soybean production during La Niña, Neutral, and El Niño years relative to the overall average productivity for each sowing date and location (represented by latitude) in southern Brazil. Soybean productivity anomalies were calculated by subtracting the average productivity of each simulated sowing date and location for a specific ENSO phase from the overall average productivity for that date and place of sowing. Source: Adapted from Nóia Júnior et al. (2020).

Another study examining the impacts of the ENSO phenomenon on soybean yields in Rio Grande do Sul indicates that SST anomalies in the Niño 3.4 region in January strongly correlate with soybean yields across three different production regions in RS (Arsego et al., 2018). This study included a spatial analysis depicting homogeneous productivity behavior groups of soybeans in the state of Rio Grande do Sul. Group G1 represents the northeast region of RS and exhibits the highest average productivity over the study period, the group G2 represents areas close to the central region of the RS, situated between the G1 and G3 groups with intermediate productivities. The G3 group represents areas concentrated more towards the northwest and west of RS, exhibiting smaller average yields over the study period. The main correlations found are related to the occurrence of the El Niño phenomenon, showing increased productivity in all three regions of the study. In one year, a drop in productivity was observed during the warm phase of the phenomenon, attributed to an event of El Niño Modoki rather than the more common El Niño Canonical (Figure 2.6.3).

The primary distinction between these two types of El Niño lies in their warming patterns. During El Niño Canonical, warming extends neatly from the west coast of South America to the central region of the Equatorial Pacific Ocean. Conversely, El Niño Modoki lacks this broad warming in the Equatorial Pacific Ocean, instead exhibiting cooling along the west coast of South America, specifically along the coasts of Peru and Ecuador.

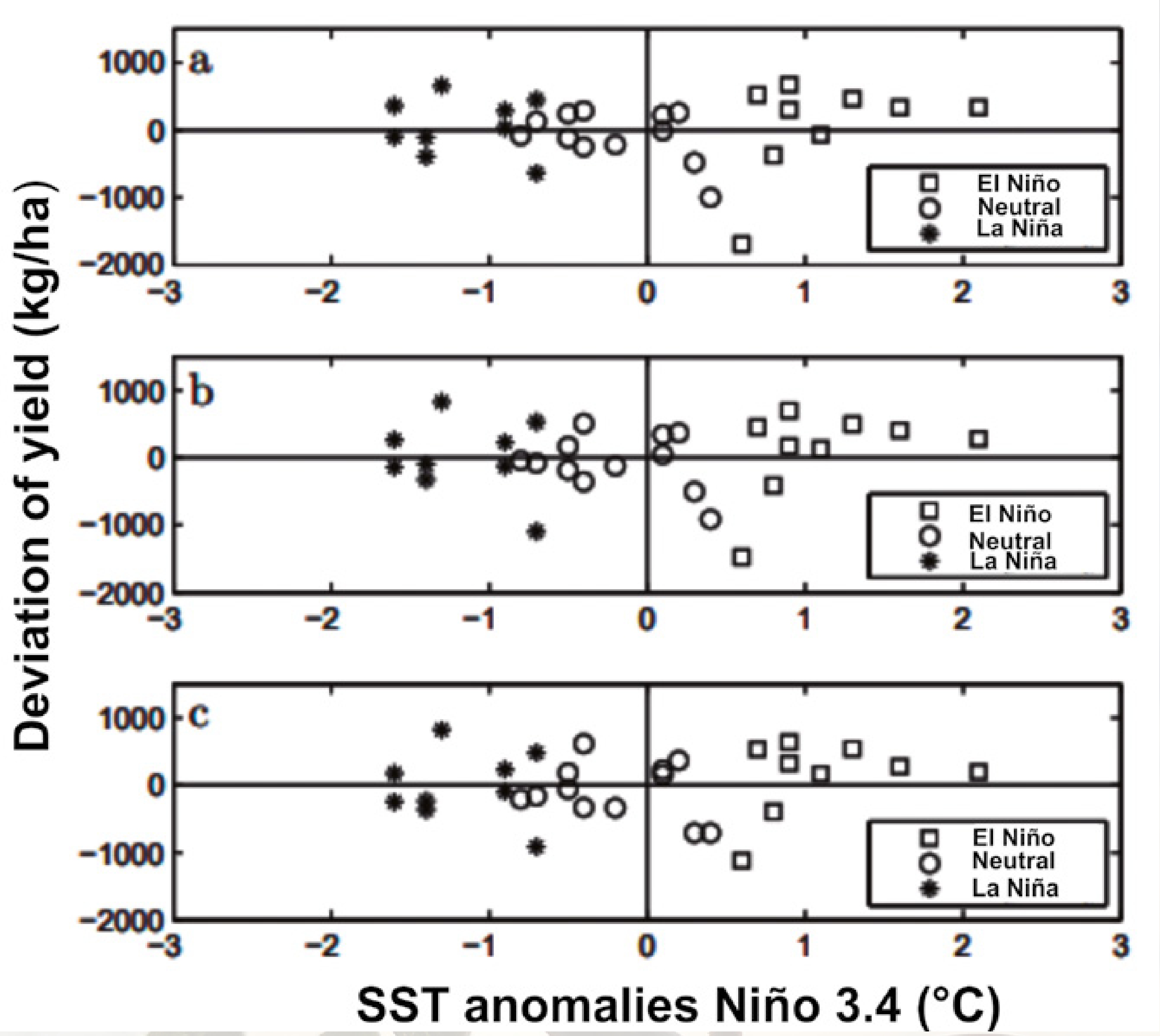


Figure 2.6.3. Relationship between SST anomalies in the Niño 3.4 region in January and yield anomalies for three groups (G1, G2, G3). El Niño events are represented by squares, neutral conditions by circles, and La Niña events by asterisks. Source: Adapted from Arsego et al. (2018).

The establishment of the ENSO phenomenon directly affects active meteorological systems in South America, especially during spring and summer, notably the South Atlantic Convergence Zone (SACZ). This system is responsible for organizing and maintaining air humidity across North, Midwest, and Southeast Brazil, leading to increased rainfall frequency in these regions. This rainfall pattern supports agricultural production, allowing for two harvests during this period. The SACZ does not maintain a fixed position over the years, i.e. their acting position varies. In years when the South Atlantic Convergence Zone (SACZ) shifts further north, it results in more regular rainfall for areas in MATOPIBA (Maranhão, Tocantins, Piauí, and Bahia), Mato Grosso, and Goiás, benefiting from good harvests of soybeans and cotton. Conversely, in other years when the SACZ moves southwards, areas like Mato Grosso do Sul, the southern parts of Mato Grosso, Goiás, Minas Gerais, São Paulo, and central northern Paraná benefit from increased rainfall.

Monitoring weather forecasts is indispensable for better harvest planning. In the southern region, the influence of the El Niño-Southern Oscillation (ENSO) phenomenon significantly impacts climate conditions, causing extended periods of drought as well as heavier rainfall. With the support of accurate weather predictions, producers can strategically manage their resources, reducing risks and achieving higher productivity. For the central-northern region of Brazil, it has been observed that the ENSO phenomenon affects the onset and end of the rainy season, directly impacting the start of harvest and often causing issues with the timing of the second harvest. There are several public websites that provide valuable weather forecasts, with main ones including: https://portal.inmet.gov.br/ and http://tempo.cptec.inpe.br/ for short-term forecasts, and for longer-term forecasts: https://www.cpc.ncep.noaa.gov/ and https://iri.columbia.edu/.

Analyzing vintage data from 1980 to 2022 in Rio Grande do Sul (RS), it was found that El Niño occurred in 14 years, La Niña in 16 years, and Neutral conditions in 13 years (Figure 2.6.4). Productivity in southern Brazil was notably above historical averages in 85% of El Niño years, compared to 50% in La Niña years and 54% in Neutral years. However, there were exceptions in El Niño years, such as the 2004/2005 season, that may occur in the presence of the El Niño Modoki phenomenon, caused by the warming of the Pacific Ocean.

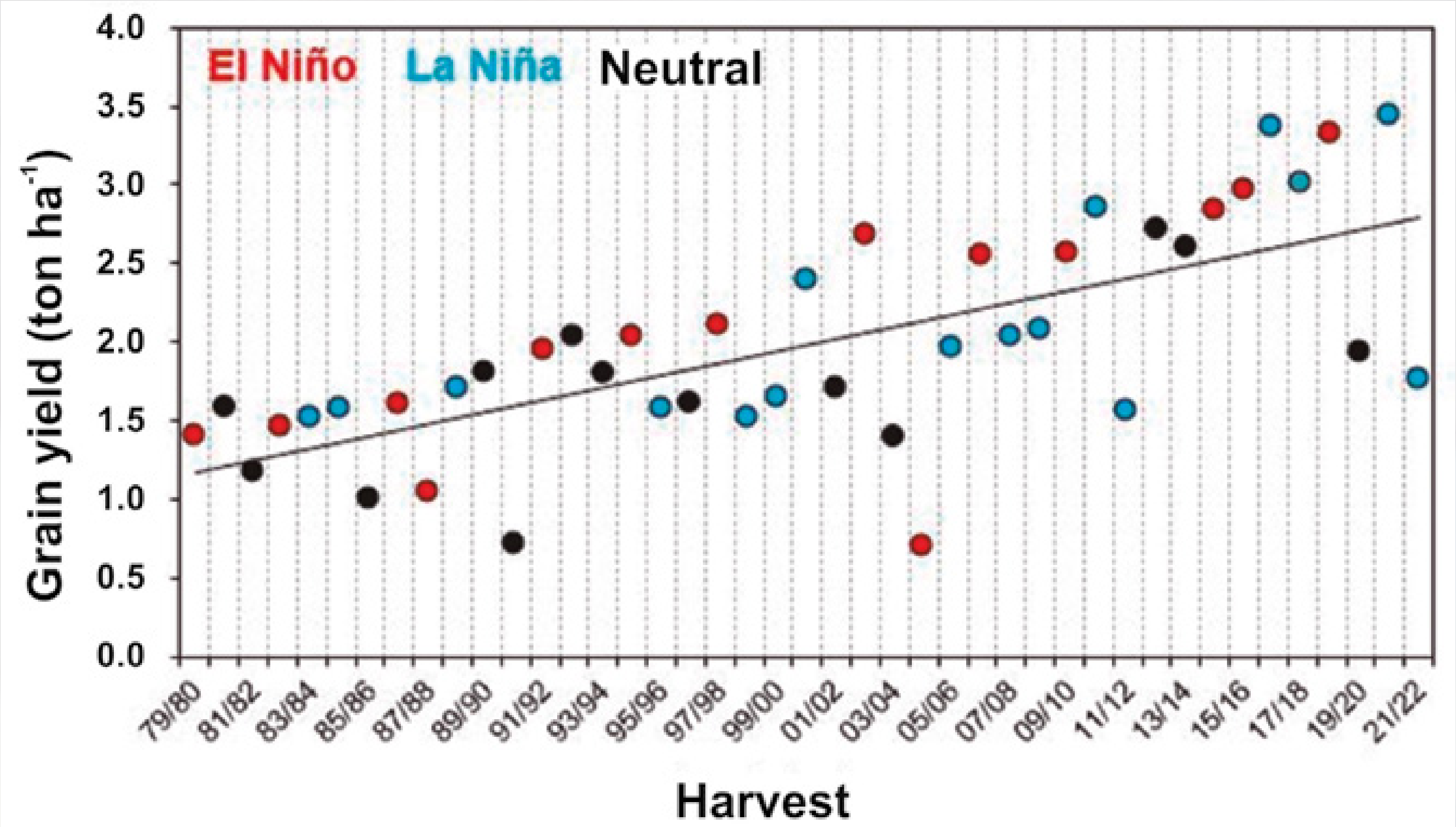


Figure 2.6.4. Association between average soybean productivity in Rio Grande do Sul, Brazil, and the occurrence of the ENSO phenomenon from 1979/1980 to 2021/2022. The line represents the rate of yield increase.

2.7. Climate changes

Over the last few decades, there has been a considerable increase in episodes of weather extremes around the world, mainly characterized by more intense heat waves, severe droughts, and frequent floods. It is believed that this increase in the frequency of extreme events is primarily related to the rise in greenhouse gas emissions from the industrial revolution (18th century) to the present day (IPCC, 2021).

As the population has grown and people's purchasing power has increased, concentrations of atmospheric emissions of the main greenhouse gases—primarily carbon dioxide, nitrous oxide, and methane—have risen. The great scientific question that arises is how these changes in gas concentrations will impact the climate in the coming years, decades, and centuries. In this sense, the United Nations (UN) created the Intergovernmental Panel on Climate Change (IPCC), a group of scientists from around the world who study and report observed changes in climate and their possible causes, as well as future climate change risks and impacts.

The IPCC releases reports every 5-6 years, which present different projections of future climate scenarios generated from climate models that consider various global emissions scenarios of greenhouse gases. The fifth report (AR5) of the IPCC, published in 2013, presents four future climate scenarios differing by the concentrations of greenhouse gases by the end of the current century, represented by the acronym RCP (Representative Concentration Pathways). In the sixth report (AR6) of the IPCC, published in 2021, there are five future scenarios represented by the acronym SSP (Shared Socio-Economic Pathways), which extend the RCPs and include scenarios of carbon sequestration.

Climate change is poised to bring even more changes and challenges for world agriculture due to shifts in weather patterns already occurring over recent years in Brazil. In some regions, severe events are increasingly frequent, causing various harms to society. Studies have been conducted and are ongoing to monitor the evolution of new temporal trends that will be faced in the near future in South America. A study by Marengo and Camargo (2008) regarding maximum and minimum temperatures in the Southern Region of Brazil indicated a positive trend in annual maximum and minimum temperatures, with emphasis on the increase in minimum temperatures between the years 1960 and 2002.

Other studies on the impacts of climate change over southern Brazil point to an increase in extreme precipitation events and the annual accumulated precipitation in these areas (Haylock et al., 2006; Alexander et al., 2006; Malhi et al., 2009).

There are certain factors whereby human activity directly influences weather conditions. Among these, in the Brazilian scenario, are deforestation and improper land use, which affect the thermodynamic characteristics of the lower atmosphere. For example, there were more extreme drought events in the Amazon in the years 2010, 2015, and 2016 (Marengo et al., 2008). Over the years, there has been significant technological evolution, along with management practices aimed at minimizing the effects of rainfall shortages or excesses on crops (Radin et al., 2017). However, further progress is still needed in management and technology to address future challenges. The relationship between climate elements and agriculture is highly complex; any oscillation or change in climate will impact the growth and development of crops, along with physical and biological processes (Silva Junior, 2007).

2.7.1. How could climate changes affect the soybean crop?

From the perspective of soybean ecophysiology, CO_2 is the primary substrate for conducting photosynthesis. This means that along with water and solar radiation, CO_2 serves as the fuel for soybean plants to function and produce grains. As a C3 metabolism plant, increased concentrations of CO_2 benefit the ecophysiological performance of soybeans. However, if global warming occurs, an increase in air temperature can negate the benefits of increased CO_2 on soybean yield for two reasons: reduction of the developmental cycle and increased respiration of the canopy. Furthermore, with increasing temperature, the evaporation of water from the soil, and consequently the evapotranspiration of a soybean crop, tend to increase. Therefore, the result is a complex relationship between the soybean plant and the air and soil environment.

The FieldCrops Team has been working to understand how future climate scenarios projected by the IPCC can affect soybean productivity considering genetics and the management currently carried out by Brazilian producers. In a study conducted in Rio Grande do Sul, Brazil, Cera et al. (2017) estimated the yield potential and productivity with limited water in soybeans under two future climate scenarios, SRES A1B and RCP4.5, using the Cropgro-Soybean agricultural simulation model. In the SRES A1B scenario, the CO2 concentration would reach 717 ppm, and there would be an increase between 1.7°C to 4.4°C by 2100. In the RCP4.5 scenario, the CO_2 concentration would reach 538 ppm by 2100, and the average global temperature would be between 1.1°C and 2.6°C warmer at the end of the century compared to today’s climate.

Three maturity groups were considered (4.8, 5.5, and 6.0), along with six sowing dates (09/01, 10/01, 11/01, 12/01, 01/01, and 01/02). The results of the Cropgro-Soybean model without water restriction show that productivity during the baseline period (average productivity observed from 1980 to 2009) is higher under potential conditions for sowings conducted on 09/01, 10/01, and 11/01 (Figure 2.7.1.1) compared to productivity under limited water conditions (Figure 2.7.1.2). Productivity under potential conditions, based on the RCP4.5-CMIP5 Scenario baseline, varies between 6 and 7 ton ha^{-1} across most of the state of RS, for sowings on 09/01, 10/01, and 11/01 (Figure 2.7.1.3).

The RCP4.5-CMIP5 scenario is projected to be drier compared to the SRES Scenario A1B-CMIP3. This is well supported by comparing simulations from the Cropgro-Soybean model under potential conditions with those performed under water deficit conditions (Figures 2.7.1.3 and 2.7.1.4).

Under potential conditions across three future periods, yields would be high (up to 7 ton ha^{-1}). However, under limited water conditions, baseline yields are below 1 ton ha^{-1}, particularly in the state of RS and across all sowing dates (Figure 2.7.1.2 A, E, I, M, Q, and U). For the future period, only the sowing on 01/09 showed anomalies above 0.5 ton ha^{-1} in the central region of the state. Other regions experienced negative productivity anomalies, particularly for sowing from October to December (Figure 2.7.1.4).

The figures below illustrate the yield potential and simulated productivity anomalies using the Cropgro-Soybean model under two climate scenarios and six different sowing dates. The areas shown in the figures are labeled as 1, 2, and 3, representing the regions of Campanha, Tupanciretã, and Cachoeira do Sul, respectively, which are the largest areas cultivated with soybeans. Area 4 (dotted line) represents the area with the highest soybean productivity in Rio Grande do Sul, calculated as the average of five harvests (2008/2009 to 2013/2014), according to IBGE (2016). The colored scale on the left side indicates current climate productivities, while the right side shows productivity anomalies under future climates.

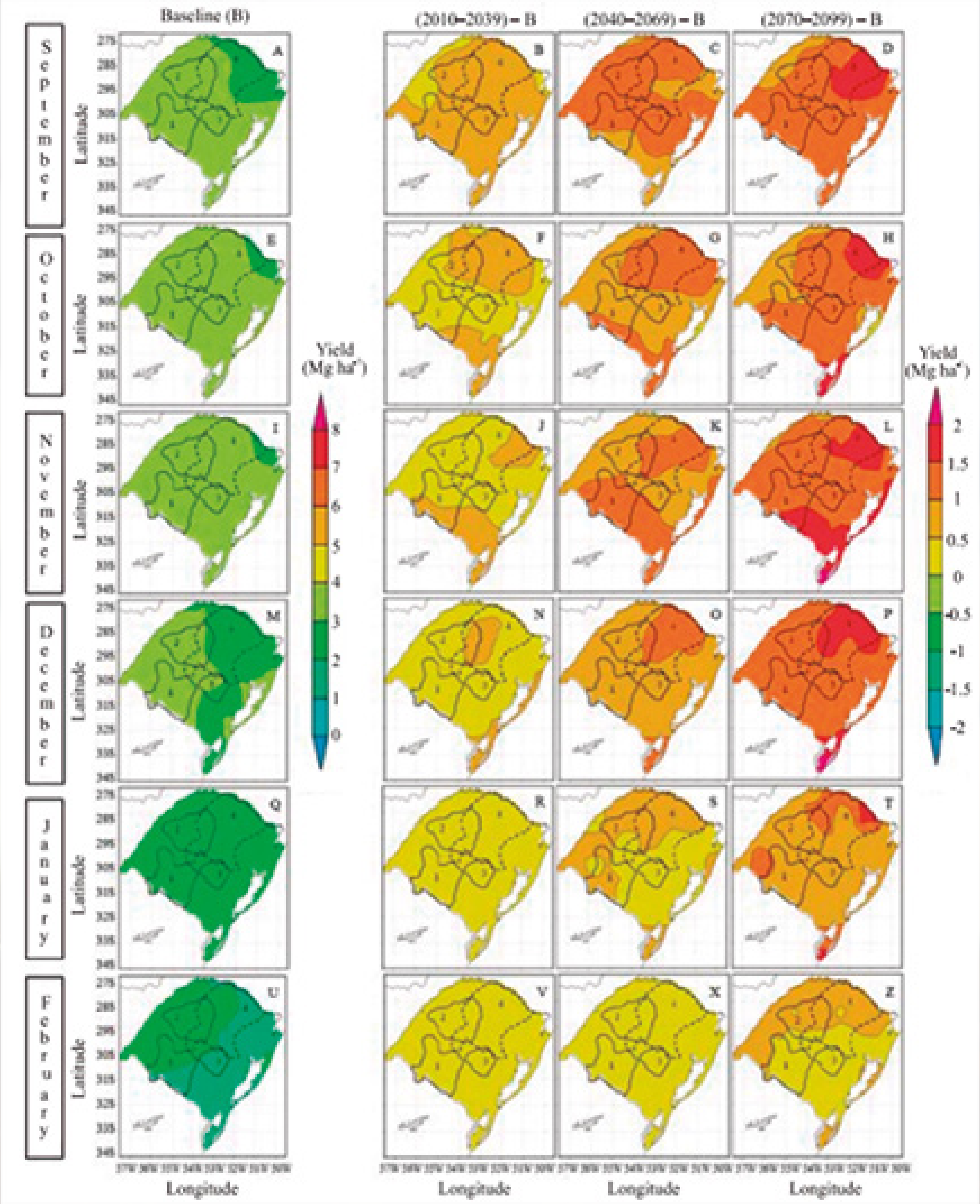


Figure 2.7.1.1. Soybean yield potential at 13% moisture (ton ha^{-1}) under current climate – baseline (A, E, I, M, Q and U) and potential anomalies productivity (ton ha^{-1}) in the state of Rio Grande do Sul, Brazil, simulated with the Cropgro-Soybean model for three climate scenarios future (2010-2039, 2040-2069 and 2070-2099) of SRES A1B-CMIP3, in six sowing dates 09/01 (B, C, D), 10/01 (F, G, H), 11/01 (J, K, L), 12/01 (N, O, P), 1/1 (R, S, T) and 1/2 (V, X, and Z). Source: Cera et al. (2017).

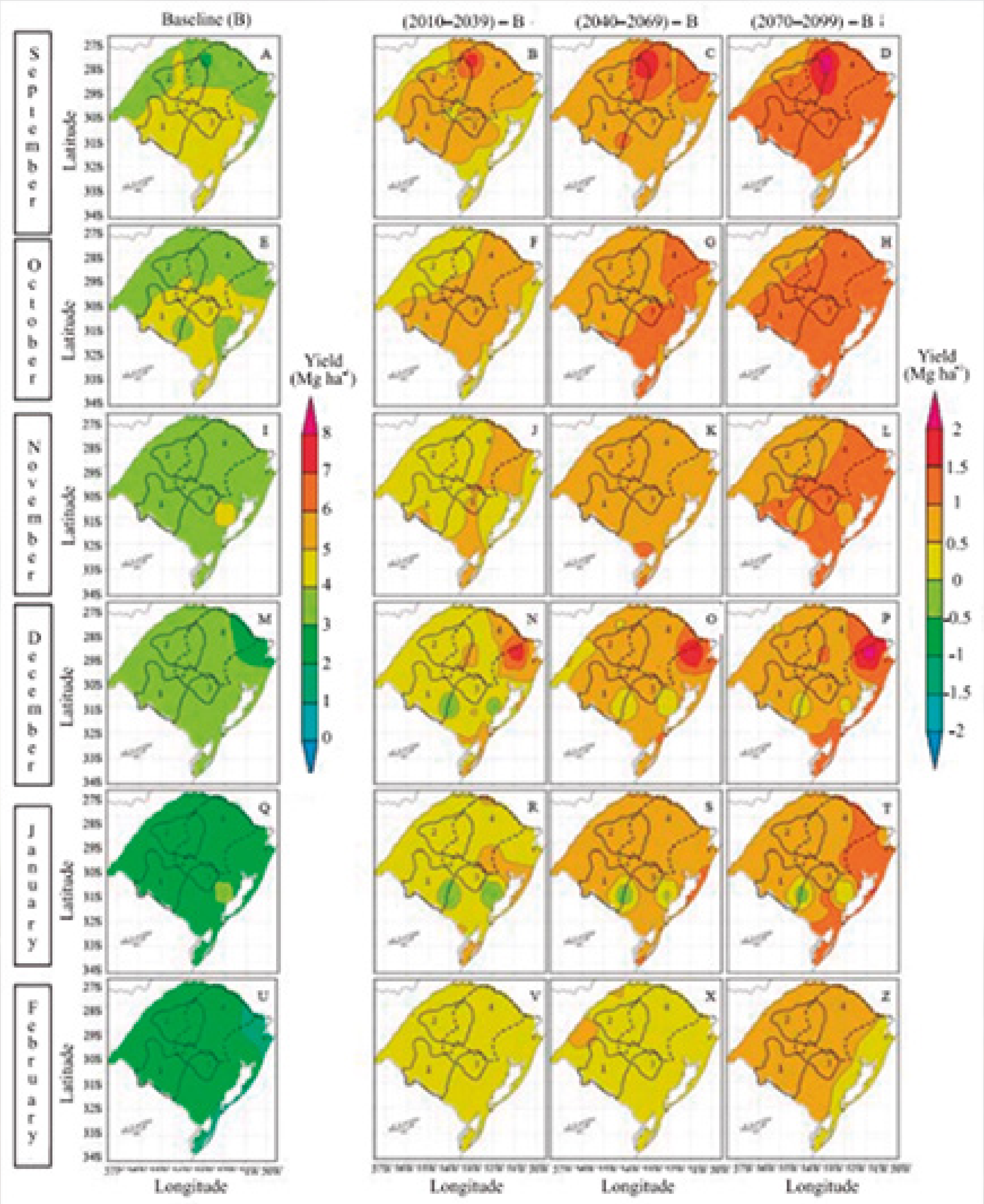


Figure 2.7.1.2. Yield limited by soybean water at 13% moisture (ton ha^{-1}) under the current climate – baseline (A, E, I, M, Q, and U) and anomalies of Soybean productivity with water limitation (ton ha^{-1}) in the state of Rio Grande do Sul, Brazil, simulated with the Cropgro-Soybean model for three future climate scenarios (2010-2039, 2040-2069 and 2070-2099) of the SRESA1B-CMIP3, in six sowing dates 01/09 (B, C, D), 01/10 (F, G, H), 1/11 (J, K, L), 1/12 (N, O, P), 1/1 (R, S, T), and 1/2 (V, X, and Z). Source: Cera et al. (2017).

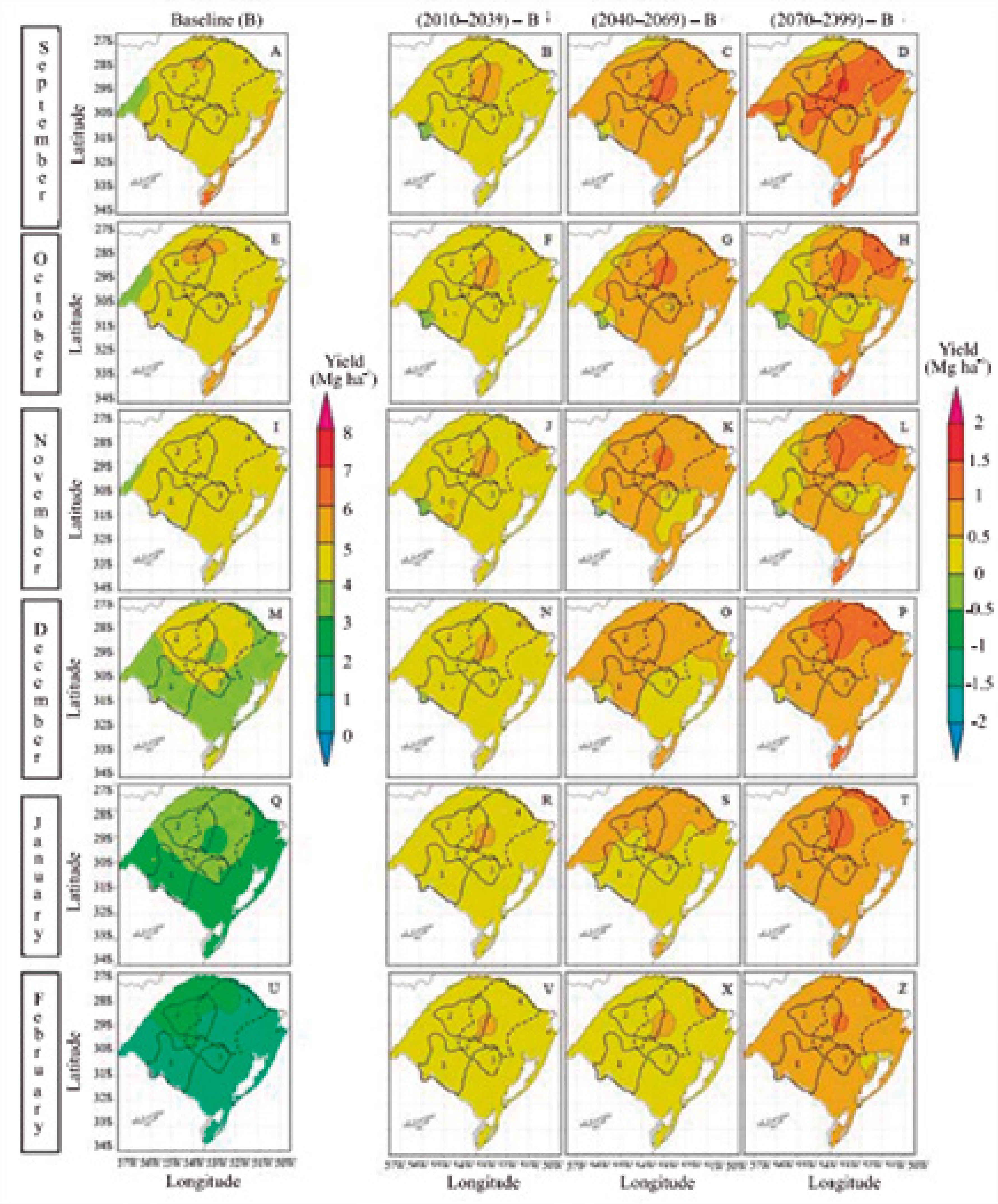


Figure 2.7.1.3. Soybean yield potential at 13% moisture (ton ha^{-1}) under current climate – baseline (A, E, I, M, Q, U) and potential yield anomalies (ton ha^{-1}) in the state of Rio Grande do Sul, Brazil, simulated with the Cropgro-Soybean model for three future climate scenarios (2010-2039, 2040-2069 and 2070-2099) of RCP4.5-CMIP5, on six sowing dates 09/01 (B, C, D), 10/01 (F, G, H), 11/01 (J, K, L), 12/01 (N, O, P), 1/1 (R, S, T) and 1/2 (V, X, Z). Source: Cera et al. (2017).

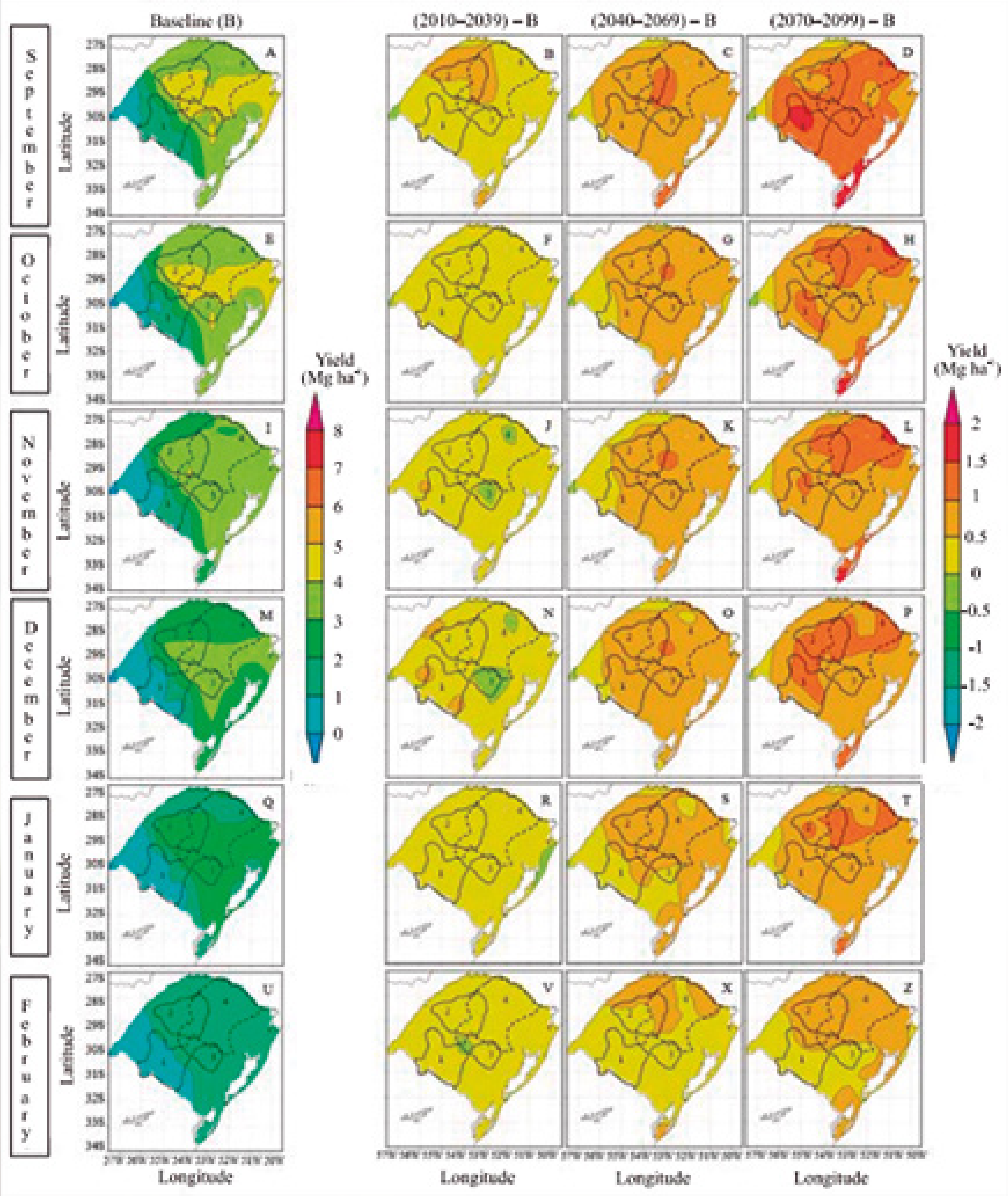


Figure 2.7.1.4. Yield limited by soybean water at 13% moisture (ton ha^{-1}) under current climate – baseline (A, E, I, M, Q and U) and yield anomalies limited by soybean water (ton ha^{-1}) in the state of Rio Grande do Sul, Brazil, simulated with the Cropgro-Soybean Model for three future climate scenarios (2010–2039, 2040–2069 and 2070–2099) of the RCP4.5-CMIP5, in six sowing dates 01/09 (B, C, D), 01/10 (F, G, H), 1/1 (J, K, L), 12/1 (N, O, P), 1/1 (R, S, T), and 1/2 (V, X, and Z). Source: Cera et al. (2017).

The perspective on increasing soybean yield in the main soybean-producing regions of Brazil until the end of the 21st century was updated by Silva et al. (2021). This study focuses on 16 agroclimatic zones strategically chosen to represent key areas of soybean production. The trend of increasing average yield was associated with the positive effect of increased CO_2 on crop water productivity, which outweighs the negative effects of increased temperature and water stress in rainfed soybeans (see Figure 2.7.1.5).

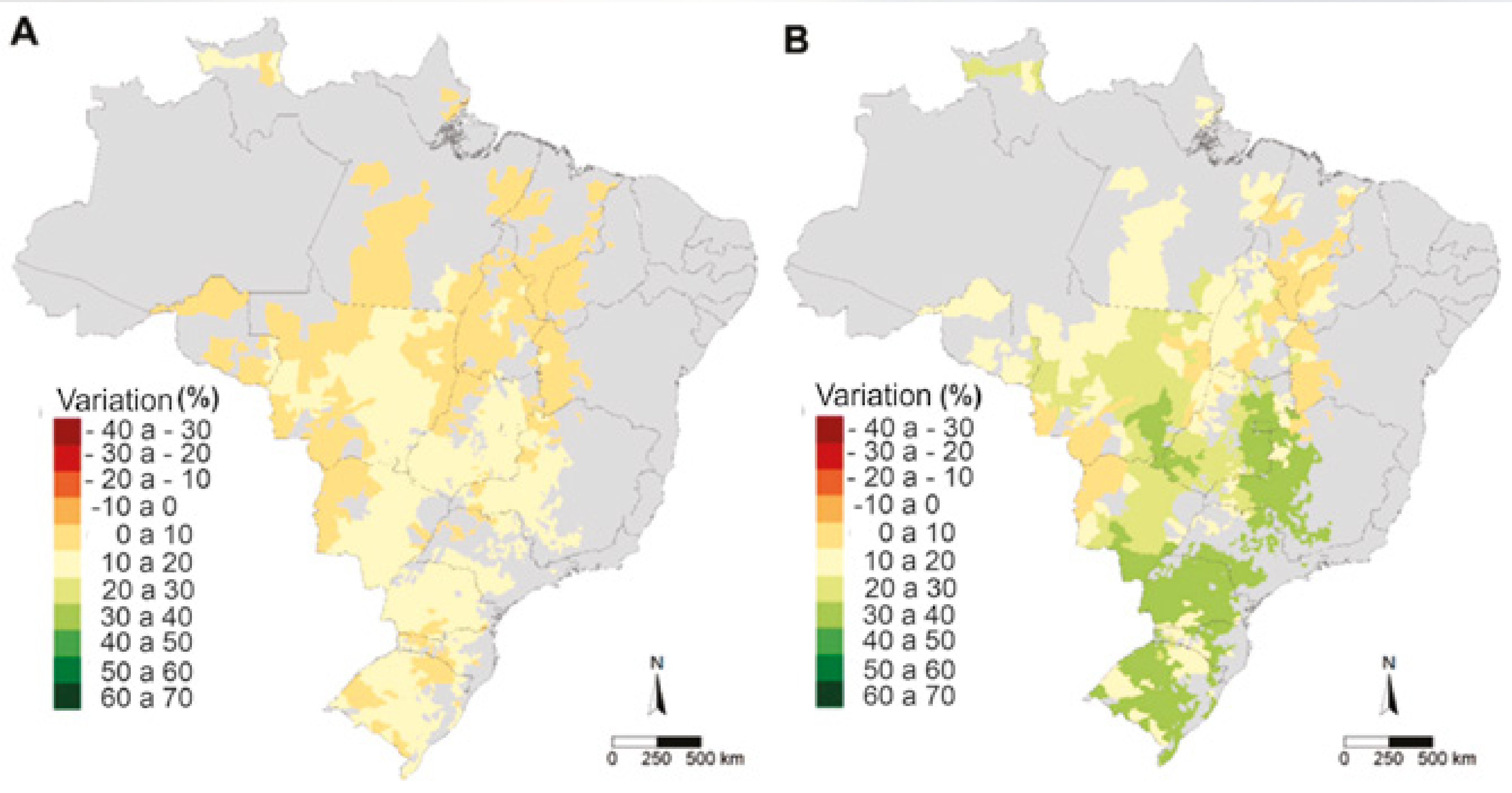


Figure 2.7.1.5. Average variation of soybean yield in 20 Models Global Climate Zones (GCMs) and in 16 agroclimatic zones (CZs) to both RCP 4.5 (A) and RCP 8.5 (B) scenarios. Source: Silva et al., (2021).

FOLHITO 27 anos

Nutrindo a *planta* Melhorando o *sistema*

VOCÊ GANHA

FÍSICA

- RETENÇÃO DE ÁGUA;
- PROTEÇÃO CONTRA EROSÃO;
- QUALIDADE DE ESTRUTURA DE SOLO;

QUIMÍCA

- AUMENTO CTC;
- FORNECIMENTO DE NUTRIENTES;

BIOLÓGICA

- POTENCIALIZAÇÃO DO AMBIENTE FAVORÁVEL AOS MICRORGANISMOS;

- A GRANEL
- ENSACADO

SEDE DA FOLHITO ESTRELA/ RS

FÁCIL APLICAÇÃO

FROTA PRÓPRIA

CONSULTORES TÉCNICOS

3. Nutrition

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Darlan Scapini Balest; Victoria Brittes Inklman; Renan Augusto Schneider;
Kelin Pribs Bexaira; Cristian Savegnago; Leonardo Silva Paula; Marcos Dalla Nora;
Edgardo Santiago Arevalo; Maria Soledad Armoa Baez; Luciano Zucuni Pes;
Nereu Augusto Streck; Filipe Selau Carlos; Evandro Henrique Figueiredo Moura da Silva;
Fabio Ricardo Marin; Gustavo Brunetto; María de los Ángeles Zamero;
Nicolas Cafaro La Menza; Alvaro Carnelosso; Israel Dalmazzo Saldanha;
Maurício Fornalski Soares; Bianca Bock Almeida; Heitor Santos Bitencourt;
Vladison Fogliato Pereira; Kaleb Emanoel Ferreira do Amaral; Alencar Junior Zanon

Suboptimal crop management is one of the main factors contributing to the soybean yield gap, with plant nutrition gaining prominence as a critical support for achieving high yields (Edreira et al., 2017). Balanced soybean plant nutrition aims to minimize metabolic disruptions in the plant, thereby maximizing yield potential. Nutrition is closely linked to the plant's physiological state, nutritional status, and changing nutrient requirements throughout its development stages (Karrou & Maranvill, 1994; Marschner, 1995).

Nutrient needs vary over time and the development cycle, influenced by environmental, genetic, and management factors. In soybean crops, the order of macronutrient demand is N > K > Ca > S = Mg > P, and for micronutrients, it is Fe > Mn > Zn = B > Cu > Mo. Regarding nutrient export (maintenance needs), the order is N > K > P > Ca = S > Mg for macronutrients and Fe = B > Zn > Mn > Cu > Mo for micronutrients.

Understanding the interplay between ecophysiology and plant nutrition is crucial for implementing demand-driven fertilization practices throughout crop development. Nitrogen, due to its high demand, has been extensively studied for limitations in Brazil. Additionally, the importance of other macro and micronutrients, including their absorption, soil mobility, impact of deficiencies, and symptoms, as well as nutrient absorption, partitioning, and reallocation in experiments yielding over 6 ton ha^{-1}, will be detailed.

3.1. Soil correction and conditioning

Correction, also known as liming, is an essential practice for growing crops in acidic soils. It is recommended to use limestone ($CaCO_3$/$MgCO_3$) to raise the soil pH, reducing acidity and modifying soil chemistry, i.e., when applied at the right dose, it increases the availability of nutrients in the soil solution. Limestone neutralizes the phytotoxic effects of aluminum (Al), hydrogen protons (H+), and manganese (Mn) and provides calcium (Ca) and magnesium (Mg). Liming improves the productive environment by reducing the formation of insoluble precipitated complexes between Al and iron (Fe) with anions, e.g., phosphorus (P), which is very susceptible to fixation, or sulfur, which when mineralized is easily complexed with Al. On the other hand, N2 fixation requires balanced nutrition and a non-acidic environment for microbial activity to be more efficient (see item 3.2).

Soils become acidic when basic elements like Ca, Mg, Na, and K contained in soil colloids are replaced by hydrogen ions. Soil acidity is associated with nutrient availability to plants as well as a range of toxicities. In acidic soils, there is a low availability of Ca, P, Mg, and Mo and a high availability of Fe, Cu, Mn, Zn, Co, Ni, and Al.

In acidic soils, some nutrients may be chemically less available to plants or physically less available due to low root growth caused by the presence of toxic elements such as Al. When root growth is restricted, plants are unable to explore enough soil volume to compensate for the reduced availability of a particular nutrient. In this case, a higher amount of nutrients would be necessary for optimal plant growth; however, the reduced root growth in the subsoil would still limit access to deeper water in the profile, causing the plant to have lower efficiency in using the applied nutrients.

Acidification is a natural process in grain production systems, as nutrient leaching, nutrient export, nitrogen fertilization, and N_2 fixation are processes that acidify the soil. Producers have adopted the practice of sequential liming with doses varying from 1.5 to 2.0 ton ha^{-1} of limestone. This new concept aims to provide resilience to the soil due to the various acidifying factors that continuously act. This practice is raising yields where there are good fertility conditions, being more related to the addition of Ca and Mg than to the correction of acidity itself. However, high doses (>3 ton ha^{-1} of limestone) affect the availability of micronutrients and increase the occurrence of cyst nematode or take-all disease in wheat, caused by the pathogen [*Gaeumannomyces graminis var. tritici*].

A correlation between soil pH and productivity was analyzed through the limit function with data from 512 soybean fields monitored by the FieldCrops Team between the 2015/2016 and 2020/2021 seasons. A limit function with the highest yields showed a productivity plateau found in areas with pH between 5.5 and 6.5. For every 0.1 pH below 5.5, grain yield decreases by 151 kg ha^{-1}, which is approximately 2.5 sc ha^{-1} (Figure 3.1.1).

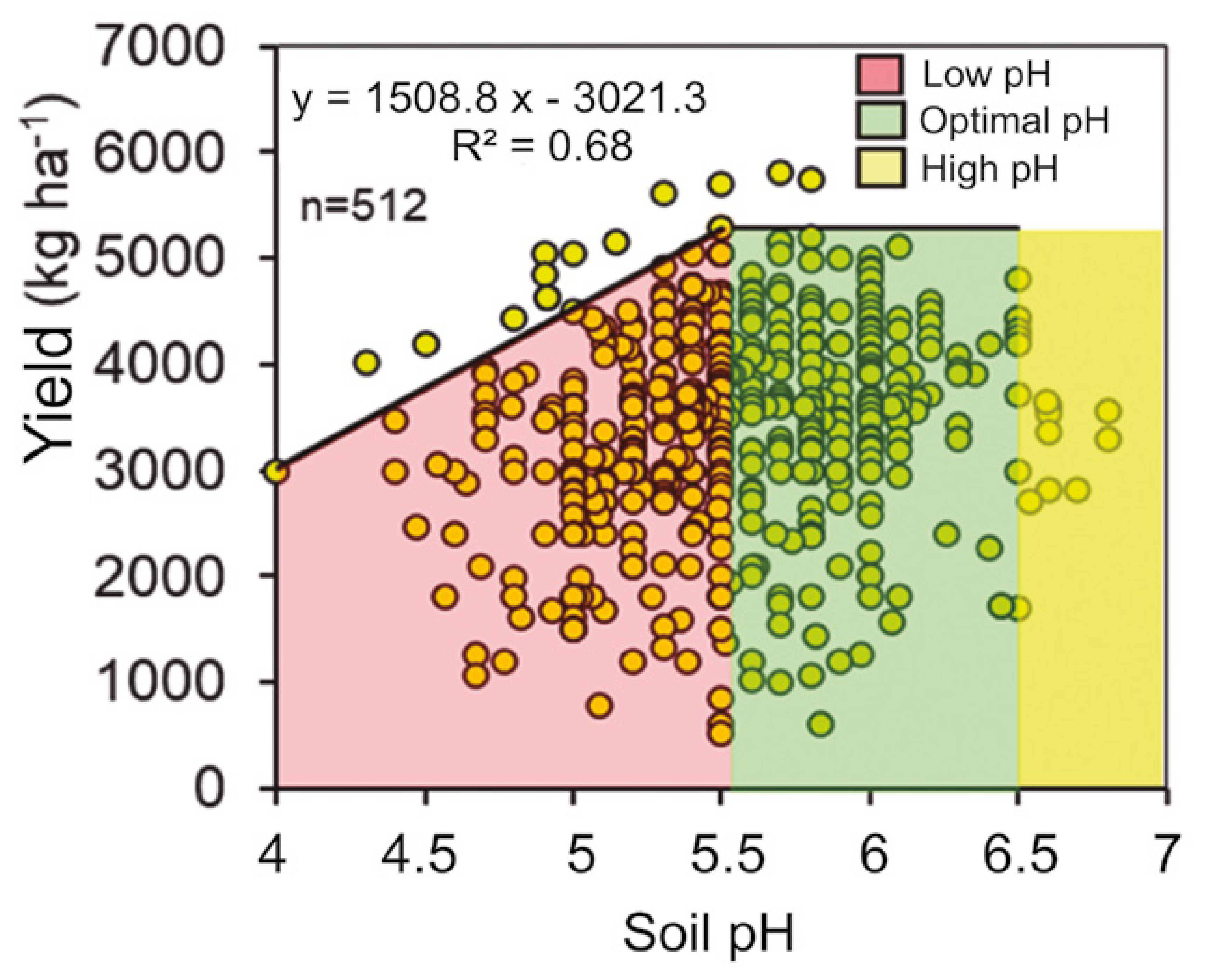

Figure 3.1.1. Relationship between soybean yield and soil pH.

Agricultural gypsum ($CaSO_4$) is a natural rock extracted from mines and is also a by-product of the phosphate fertilizer industry. Currently, its use is increasing in soybean areas from North to South Brazil. Gypsum can be considered a soil conditioner because it is a source of Ca and S, neutralizes toxic Al, and redistributes nutrients along the soil layers, thus increasing the area explored by the roots. Regarding its effects on the soil physics, the application of agricultural gypsum results in greater clay flocculation and increased soil permeability (Pavan et al., 1986), which increases soybean yield in years with water deficit (Zandoná et al., 2015).

Soybeans respond positively to agricultural gypsum in the simultaneous presence of high subsurface soil acidity (with Al saturation >10%) and water deficiency (Tiecher et al., 2018). High doses of agricultural gypsum can cause nutritional deficiencies in the crop's root zone due to the migration of cations to the subsurface, mainly: potassium (K), calcium (Ca), and magnesium (Mg). The most commonly used doses range from 1 to 2 ton ha^{-1} of agricultural plaster, with application intervals of 18 to 30 months. However, there are parameters for recommending the appropriate dose. Sometimes, the dose is determined based on the clay content of the soil, while in other cases, it is related to the availability of calcium (Ca) and sulfur (S), whether for corrective fertilization or maintenance purposes.

3.2. Fertilizing

Soybean crop fertilization revolves around the symbiotic relationship between two key species: the leguminous plant (*Glycine max*) and bacteria (*Bradyrhizobium japonicum*). It is crucial to grasp this dynamic from the outset, as effective symbiosis enables the provision of high amounts of nitrogen, fulfilling approximately 60% of the plant's demand (Ciampiti & Salvagiotti, 2018). Inoculation with *Bradyrhizobium* and co-inoculation with competitive and high-capacity BNF strains, such as *Azospirillum* spp., are essential practices. The soil pH should ideally range from 5.5 to 6.5 or be adjusted to promote active bacterial growth. Nutrients play distinct roles at different stages of Biological Nitrogen Fixation

(FBN): during infection or nodule onset (Cobalt), nodule growth (Boron and Calcium), nodule functioning (Phosphorus, Molybdenum, Iron, Zinc, Cobalt, Calcium, Sulfur, and Copper), and overall host plant growth (Phosphorus, Potassium, and Sulfur). Notably, the application of nitrogen significantly inhibits Biological Nitrogen Fixation, especially during vegetative stages (Santachiara et al., 2019). Properly nourishing the soybean-bacteria symbiosis will lead to higher crop growth rates, as the highest yields are associated with increased contributions from Biological Nitrogen Fixation (Santachiara et al., 2017).

Figure 3.2.1 shows the relationship between the level of a nutrient in the soil and the probability of response to fertilization. With “medium”, “low” to “very low” availability levels, it is recommended to carry out a correction fertilization, to raise the nutrient level to “high”, since the through put is compromised and the expected response is high. The correction can be quick, performed in a single cultivation, considerable investment may be required, or gradual, usually carried out in two cultivations. The important is to reach the “high” level of the nutrient in the soil, to aspire to high productivity.

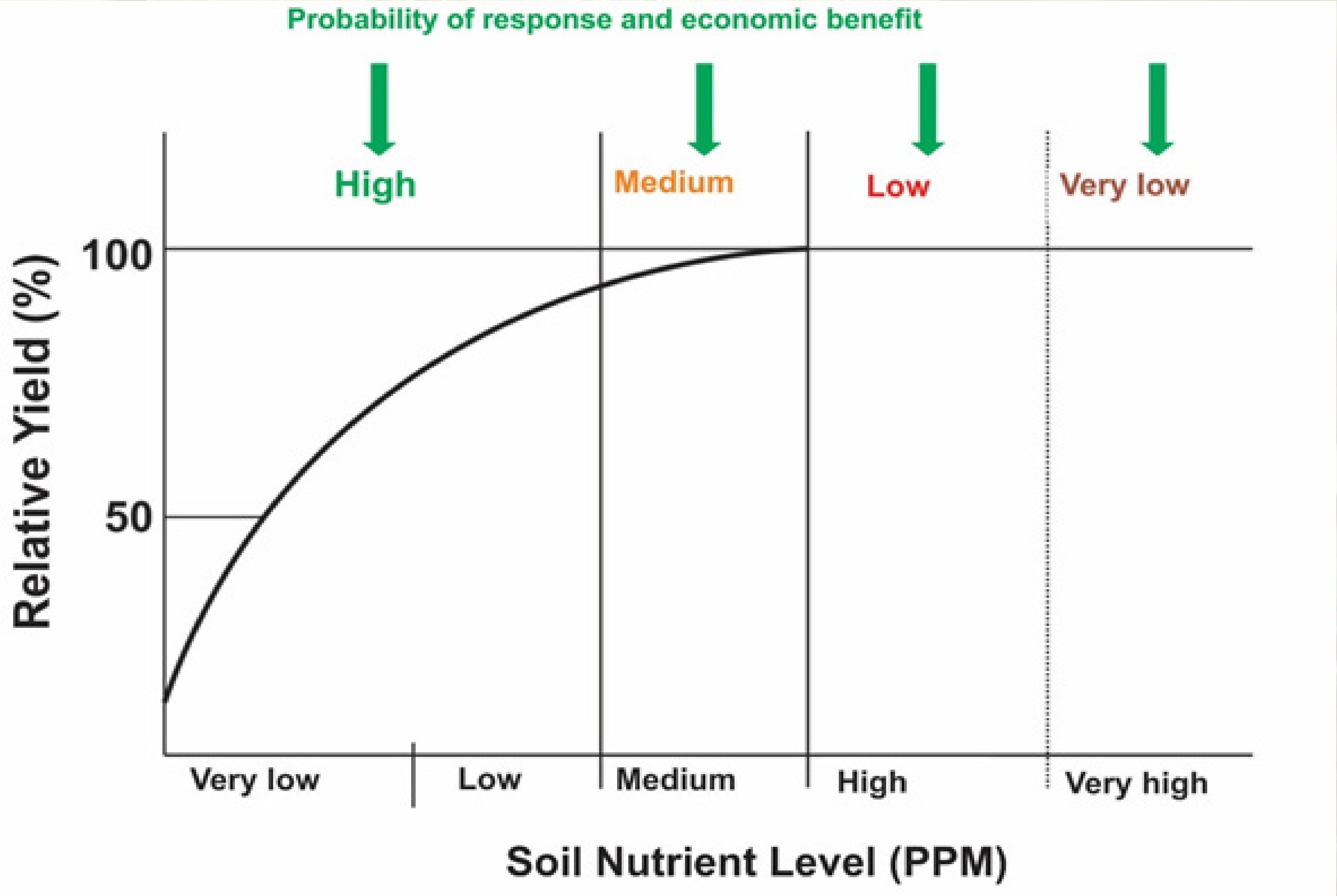

Figure 3.2.1. Relationship between relative yield and nutrient level in the ground.

At average soil fertility levels, the expected response to fertilization is lower and may depend on other factors such as moisture, other nutrients, and their interactions. The recommended fertilization is for 'maintenance' to preserve the average level and prevent soil fertility reduction. At high to very high fertility levels, the expected response to fertilization is very low or zero. Fertilization is only recommended to 'replace' the nutrients extracted by the crops.

Despite requiring a large amount of nutrients, soy is adapted to soils with low natural fertility, and its productivity does not decrease drastically, unlike cereals such as wheat or corn on poor soils (see Figure 3.2.2). With a "very low" fertility level in soil, soybeans can achieve 50 to 70% of their potential yield, whereas wheat yields drop to less than 55% and corn to less than 40%. However, at high fertility levels, the nutrient requirements for soy, wheat, and corn are comparable (refer to Figure 3.2.2).

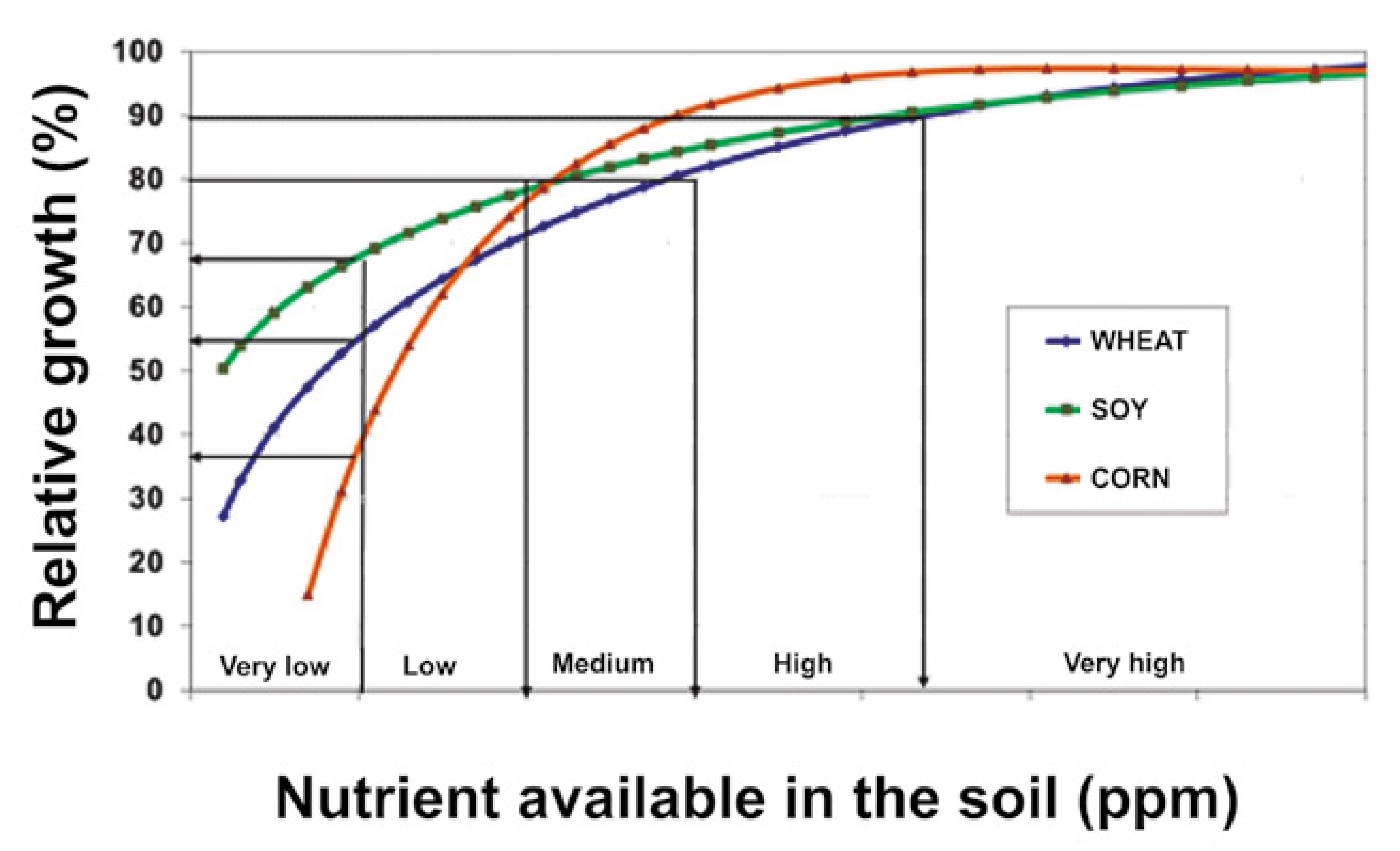

Figure 3.2.2. Relationship between relative growth and availability of nutrients in the soil.

3.2.1. Nutrients: from soil to plant

Understanding the mobility of nutrients in soil is crucial for assessing their availability and determining the appropriate methods, timing, frequency, and sources of nutrients to use. Nutrients are classified into three categories based on their mobility in soil: mobile, partially mobile, and immobile (Table 3.2.1.1). The mobile nutrients are highly soluble, with a significant fraction present in the soil solution. Due to their high mobility, they can move over long distances in the mass flow, becoming readily available to plants and susceptible to leaching. Less mobile nutrients, while also soluble, are found in smaller amounts in the soil solution as they are absorbed onto clay complexes and are easily released back into the soil solution, providing moderate availability. Immobile nutrients are strongly retained by clay particles in the soil and are not easily released into the soil solution. The movement of these nutrients towards the roots occurs via concentration or diffusion gradients.

The combination of nutrient availability near the rhizosphere and the nutritional need of the crop initiates the root-ion contact process, which can occur through mass flow, diffusion, or root interception (Table 3.2.1.1). The mechanism of nutrient supply depends on the specific ionic species involved, root density, and water flow within the plant. However, absorption is influenced not only by nutrient availability and demand but also by the number of transporters, pumps, and transmembrane channels, transpiration rate, aeration, water flow, physiological state, and nutrient demand (nutritional status). Absorption occurs when an element enters in ionic or molecular form (Table 3.2.1.1), within intercellular spaces or any region or organelle of the living cell tissue epidermis, cortex, or endodermis. Upon entering the plant, nutrients are assimilated into root cells or transported to the xylem, eventually reaching the aerial parts (leaves), where they are also assimilated.

Table 3.2.1.1. Classification of nutrients based on their ionic form absorption, mobility in the soil and within the plant, mechanisms used for absorption and associated visual impairment symptoms.

Nutrient	Ion absorbed(1)	Soil mobility	Absorption	Mobility in the plant	Symptoms of deficiency
Nitrogen	NO_3^- e NH_4^+	Mobile	Mass flow	High	Old leaves
Potassium	K^+	Partially mobile	Diffusion	High	Old leaves
Phosphorus	$H_2PO_4^-$	Immobile	Diffusion	High	Old leaves
Sulfur	SO_4^{2-} e SO_2	Mobile	Mass flow	Low	New leaves
Calcium	Ca^{2+}	Partially mobile	Mass flow	Low	Young leaves/ meristems
Magnesium	Mg^{2+}	Partially mobile	Mass flow	High	Old leaves
Iron	Fe^{3+}	Immobile	Mass flow	Intermediary	New leaves
Manganese	Mn^{2+}	Immobile	Mass flow	Low	New leaves
Zinc	Zn^{2+}	Immobile	Mass flow	Intermediary	New leaves
Boron	H_3BO_3	Mobile	Mass flow	Intermediary	Young leaves/ meristems
Copper	Cu^{2+}	Immobile	Mass flow	Intermediary	New leaves
Molybdenum	MoO_4^{2-}	Partially mobile	Mass flow	Intermediary	Old leaves

Absorbed predominant (1)
Predominant mechanism of root-nutrient contact (Malavolta, 1980) (2)
Mobility in the plant Adapted from Marschner (2012) (3)

Redistribution occurs after nutrient assimilation in a plant organ, involving the transfer of nutrients from one organ or accumulation region to another. Ions stored in leaves during vegetative growth are redistributed to other organs (such as new leaves, reserve organs, fruits, and growth regions) before senescence and abscission.

The mobility of nutrients (redistribution via phloem organs) in plants depends on the specific function of each element within the plant; this mobility can also be influenced by the specific crop under evaluation (Marschner et al., 1995). Mobile nutrients redistribute rapidly to the younger parts of the plant. With mobile nutrients deficient in the soil, there is remobilization of nutrients from older leaves to the growing organs (young and reproductive structures) (Table 3.2.1.1). Conversely, symptoms of deficiencies in poorly mobile or immobile nutrients tend to appear more severely on younger leaves and apical meristems, reflecting insufficient redistribution (Table 3.2.1.1).

The accumulation of nutrients in soybean crops is largely influenced by the phenological stage and dry mass production of the plant (Figure 3.2.1.1), which occurs in three distinct phases: (i) low acquisition rate for approximately 30 days after emergence, (ii) maximum nutrient absorption between flowering (R2) and the beginning of grain filling (R5), and (iii) reduced rates of nutrient accumulation during seed maturation (Bender et al., 2015) (Table 3.2.1.3).

Comparing the total absorption of nitrogen (N), phosphorus (P), and potassium (K) per ton of grain produced in major crops, we find that soybean absorbs 65, 5.3, and 26.8 units respectively, corn absorbs 23.4, 4, and 15 units respectively, and rice absorbs 15.4 and 14.8 units respectively (Table 3.2.1.2).

The nutritional requirements to produce a ton of grain soybean are higher compared to other crops., motivated by the energy expenditure required to produce oil and protein (for more information, see item 3.6), the nitrogen (N) demand identified by Bart et al. (2018) is at the lower end of the dataset analyzed by Salvagiotti et al. (2008), with an average demand of 80 kg of N per ton of grain.

Table 3.2.1.2. Accumulation of nutrients in high-yielding crops: Soybean with an average yield of 6.6 ton ha^{-1} (Field-Crops Team., 2022), corn with average yield of grains of 12.2 ton ha^{-1} (Bender, et al., 2013) and rice with average yield of 11.8 ton ha^{-1} (Quintero et al., 2020, unpublished data).

	Soybean		Corn		Rice	
	Total absorption (kg ha^{-1})	Maximum rate (kg ha^{-1} day^{1})	Total absorption (kg ha^{-1})	Maximum rate (kg ha^{-1} day^{1})	Total absorption (kg ha^{-1})	Maximum rate (kg ha^{-1} day^{1})
Biomass	15.554	158.47	23.000	432	22.517	557
N	429	5.45	286	8.8	178	2.3
P	34	0.36	50	1.05	48	0.7
K	177	3.52	182	5.49	172	4.2
Ca	100	1.07	-	-	18.4	0.5
Mg	43	0.58	59	2.2	8.6	0.1
S	19	0.63	26	0.6	29.9	0.287
	(g ha^{-1})	(g ha^{-1})	(g ha^{-1})	(g ha^{-1})	(g ha^{-1})	(g ha^{-1})
B	250	4.3	83	3.5	481	7.8
Cu	100	1.1	141	1.5	195	3.6
Fe	1.695	29.0	1.376	99.6	5.821	122.3
Mn	796	20.2	558	18.2	12.146	203.2
Zn	344	6.1	498	14.7	654	11.6

Table 3.2.1.3. Nutrient accumulation in a soybean cultivar of maturity group (MG) 5.5 with a cycle length of 123 days (EM - R8) and yield of 6.6 ton ha^{-1}.

	Maximum accumulated		Demand	Export		Maximum accumulation rate		
	Kg ha^{-1}	Stage	Kg ton^{-1}	IC (%)	Kg ton^{-1}	Kg ha^{-1} day^{-1}	DAE	Stage
Biomass	11484.1	R7	-	48	-	158.47	95	R5.3
N	364.3	R7	66.2	82	54.1	5.45	95	R5.3
K	227.8	R7	41.4	43	17.8	3.52	37	V7
P	27.2	R7	4.9	84	4.2	0.36	95	R5.3
S	42.9	R7	7.8	65	5.1	0.63	95	R5.3
Ca	80.8	R7	14.7	17	2.5	1.07	37	V7
Mg	38.4	R7	7.0	32	2.3	0.58	95	R5.3
		g ha^{-1}			**g ha^{-1}**		**g ha^{-1}**	
Fe	1804.6	R7	327.9	35	113.5	29.0	95	R5.3
Mn	856.7	R7	155.7	18	28.1	20.2	65	R3
Zn	459.2	R7	83.4	59	49.4	6.1	65	R3
B	310.3	R7	56.4	41	23.1	4.3	37	V7
Cu	79.7	R7	14.5	70	10.1	1.1	37	V7

IC = harvest index
DAE = days after emergence
kg ton^{-1} = Amount absorbed to produce one ton of grain
Data presented in the table are in dry mass

Soybean dry matter production exhibits high growth rates between 30 and 100 days of the cycle (100-160 kg ha^{-1} day^{-1}). The maximum accumulation of dry matter is observed between growth stages R5 and R7 (see Figure 3.2.1.1). It's noteworthy that there is not significant translocation of photosynthates from stems and leaves to the grains during this period, as indicated by the stable biomass of stems and leaves between R5 and R7. This suggests that grain biomass primarily originates from intercepted radiation and synthesis during the grain filling period.

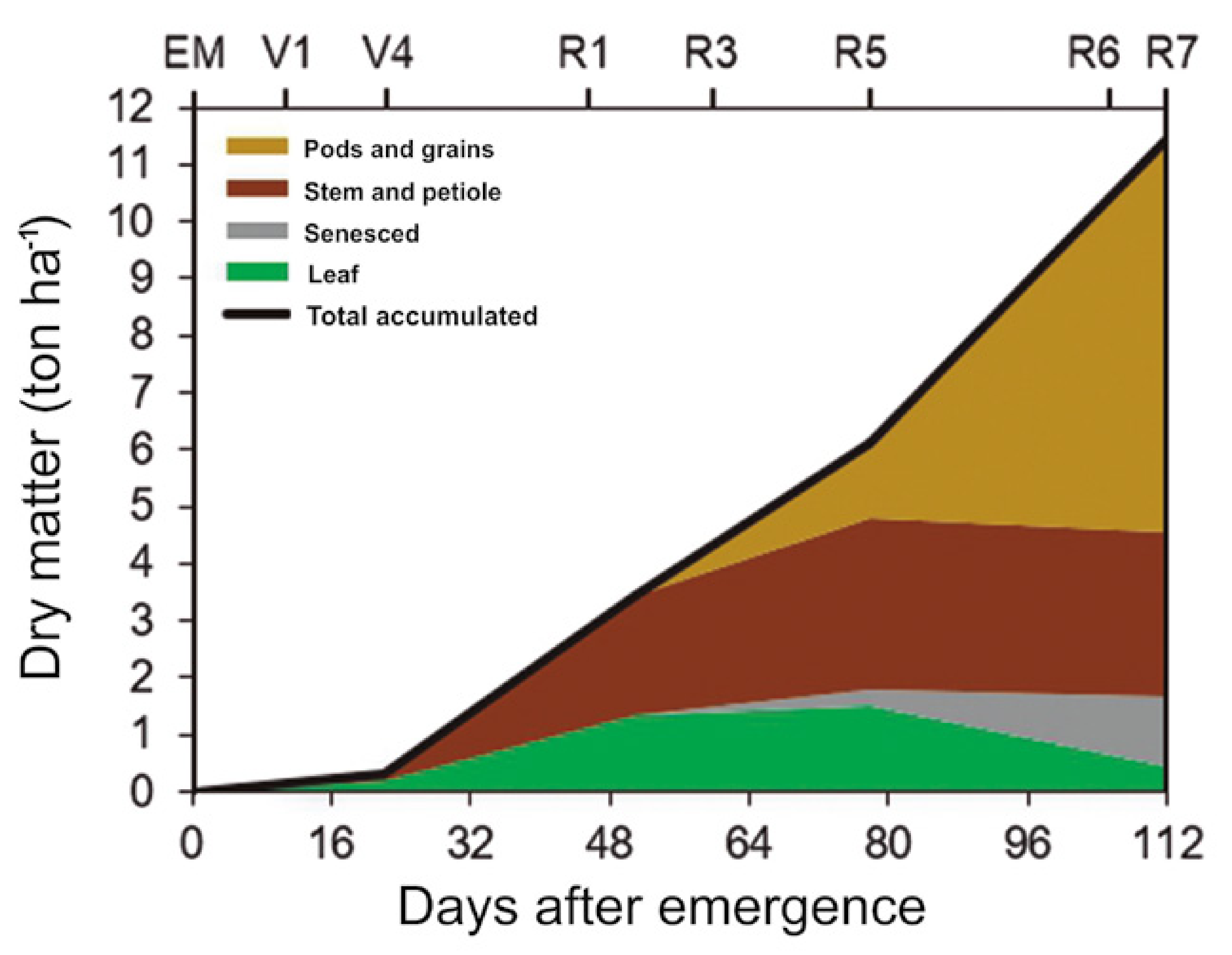

Figure 3.2.1.1. Accumulation of dry matter in soybeans during the crop's growth and development cycle with a yield of 6.6 ton ha^{-1}.

Therefore, studies on the rate of nutrient absorption become important for detecting at which stage of development a crop is most demanding in a specific element. This information allows for the prediction of when nutrient applications should be made to meet the nutritional requirements during different cultural development stages (refer to Table 3.2.1.3). However, it is unclear whether current fertilizer recommendations adequately support the nutritional needs of soybeans for achieving high levels of biomass and grain production (Bender et al., 2015). In Brazil, nutrition programs commonly focus on low productivity (<3 ton ha^{-1}). Nutrients play essential roles in metabolic functions or structural components of plants (refer to Table 3.2.1.4). When a nutrient fails to perform its function, various physiological processes such as photosynthesis and respiration are affected, influencing crop development and production.

Table 3.2.1.4. Function of nutrients in the soybean plant.

Nutrient	Function
Nitrogen	Essential constituent of amino acids/proteins, nucleic acids, nucleotides and chlorophyll.
Potassium	Participation in transport across the membrane, neutralization of anions and maintenance of osmotic potential.
Phosphorus	Sources of energy for biosynthetic reactions and plant metabolism, in addition to acting as a structural element of nucleic acids (RNA, DNA).
Sulfur	Structure and regulation of proteins, participates in photosynthetic and respiratory electron transport, through iron-sulfur grouping
Calcium	Structural element conferring rigidity to the cell wall system and stability, and also a signaling agent for environmental stimuli for physiological responses.
Magnesium	Participates in photon capture and in the transfer of excitation energy from light-harvesting complexes to the reaction center of photosystem 2.
Iron	Involved in electron transfer mechanisms, nucleic acid metabolism and has catalytic and structural functions.
Manganese	It acts in photosynthesis, being involved in the structure, functioning and multiplication of chloroplasts.
Zinc	Acts in photosynthesis, being involved in the structure, functioning, and multiplication of chloroplasts.
Boron	Cell wall structure and its growth such as cell division, cell elongation, sugar translocation, and plant hormone function.
Copper	Electron transport and energy capture by proteins and oxidative enzymes.
Molybdenum	Processes of N2 fixation, nitrate reduction, and transport of nitrogenous compounds in plants.

The nutritional requirement (NE) of a crop refers to the total amount of nutrients accumulated in the entire plant throughout its production cycle. To accurately determine the nutritional requirement, it is essential to consider the nutrients absorbed by the whole plant, not just the harvested part. This requirement can vary significantly depending on the productive potential and the specific crop being grown. By understanding the nutritional demands of the entire plant, farmers can effectively manage nutrient applications to optimize crop growth and yield.


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Controlled Release Nitrogen
25-0-0+0,5% B
FERTILIZANTE MINERAL MISTO

3.3. Nitrogen

Soybeans have a high demand for nitrogen (N), accumulating approximately 80 kg of N per hectare in aboveground dry matter (MSS) at stage R7 for each ton of grain produced (Salvagiotti et al., 2008; Tamagno et al., 2017). To meet this nitrogen requirement, soybeans rely on biological nitrogen fixation (BNF) and other sources of nitrogen, including mineralization of organic matter, atmospheric deposition (dry and wet), nitrogen from irrigation water, and a small amount of nitrogen fertilizer applied at sowing by some growers. Biological nitrogen fixation (BNF) alone contributes about 60% of the plant's nitrogen needs (Ciampitti & Salvagiotti, 2018). For every kilogram of nitrogen absorbed, approximately 12.7 kilograms of soybeans can be produced (Santachiara et al., 2017).

Even a small nitrogen deficiency can lead to the elongation of lateral roots, while severe or prolonged nitrogen deficiency can inhibit taproot growth and total root length. Low nitrogen content can also result in developmental alterations, including reduced growth, early flowering, decreased branching, and smaller leaves due to reduced cell division and expansion.

The reduction in branching, stunted growth, and inhibited leaf expansion are key physiological responses to nitrogen deficiency, closely associated with the presence of cytokinins produced in roots in response to nitrate (NO^{3-}). Activation of axillary buds by NO_3^- stimulates cytokinin production, while low NO^{3-} levels maintain bud dormancy, thereby reducing branching.

Reduced chlorophyll synthesis or breakdown of chlorophyll proteins binding to existing chlorophyll in photosystems. Nitrogen deficiency leads to the breakdown of chlorophyll through proteolysis, resulting in the release of amino acids, amides, and NH_4^+ ions. These released nitrogen compounds are highly mobile in the phloem. Consequently, during low-N conditions, older leaves act as source tissues, providing nitrogen for young and developing tissues such as leaves, flowers, and seeds. Therefore, symptoms of nitrogen deficiency first appear on older leaves.

In soybeans, nitrogen is absorbed at very high rates, reaching over 350 kg of nitrogen per hectare. This absorption rate is equivalent to that of a corn crop yielding 15 ton ha^{-1}. According to studies by the FieldCrops Team, the maximum nitrogen accumulation rate in soybeans was 7.5 kg ha^{-1} day^{-1} at growth stage R5, which is consistent with findings by Cafaro La Menza et al. (2020). For a yield of 6136 kg ha^{-1}, nitrogen export is estimated at 298 kg ha^{-1} with a nitrogen harvest rate of 82% (see Figure 3.3.1). About 50% of the nitrogen contained in the leaves and petioles is translocated to the grains, with smaller contributions from the stem. Soybeans absorb approximately 60% of the nitrogen by the beginning of grain filling (stage R5) (Thies et al., 1995; Bender et al., 2015; Cafaro La Menza et al., 2020).

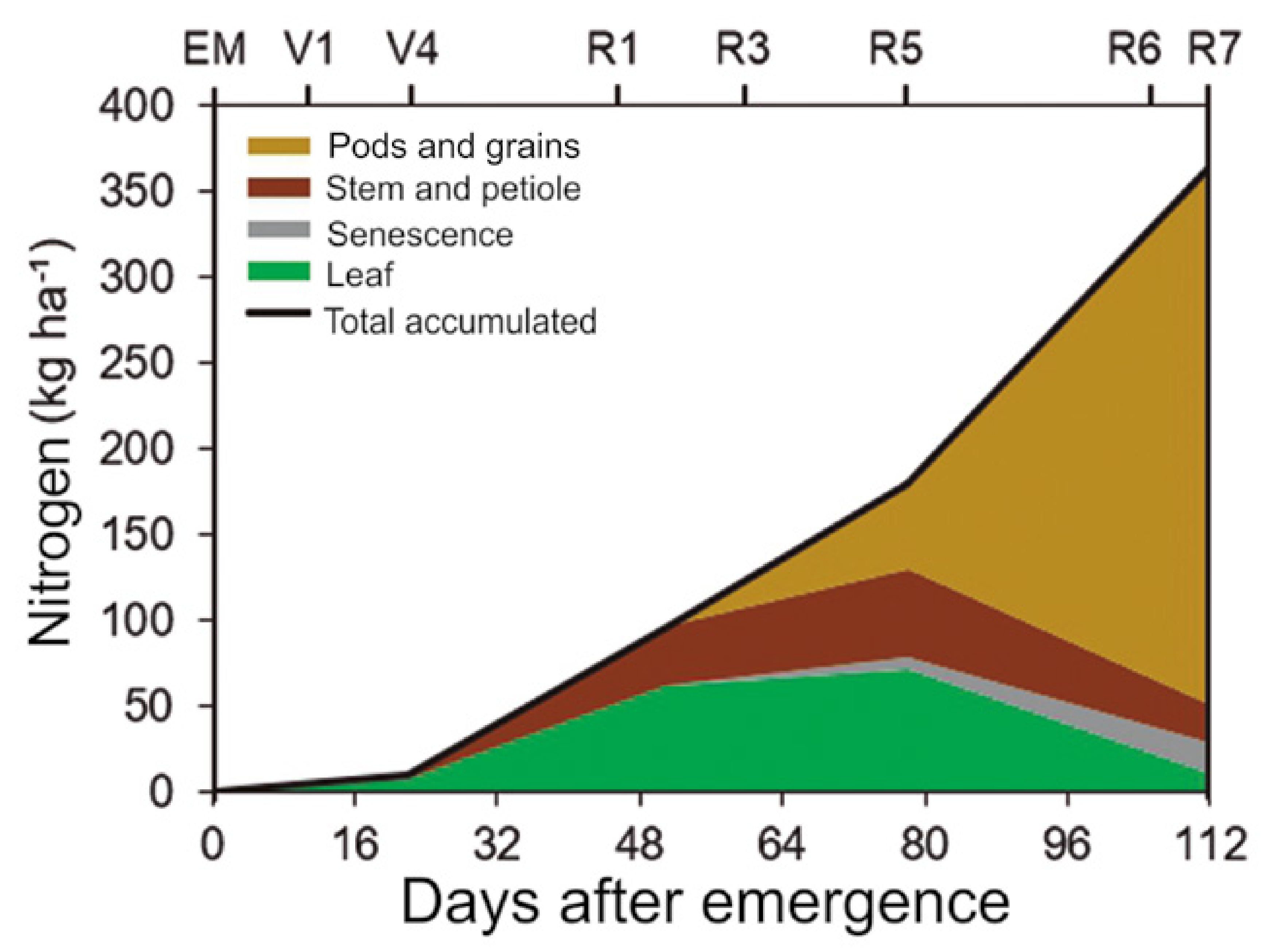


Figure 3.3.1. March of accumulation and redistribution of nitrogen in the crop of soybeans with yield of 6.6 ton ha^{-1}.

3.3.1. Nitrogen limitation in soybean crops of high yield

To achieve high yield potential, soybeans need to sustain a high rate of photosynthesis and accumulate large amounts of nitrogen (N) in grains (Salvagiotti et al., 2008). Recently, questions have arisen regarding the capacity of biological nitrogen fixation (FBN) and soil (mainly through the mineralization of organic matter) to meet the nitrogen requirements for ensuring high yields (>4.5 ton ha^{-1}) in soybean crops (Salvagiotti et al., 2008; Ciampitti & Salvagiotti, 2018; Cafaro La Menza et al., 2020). A study by Cafaro La Menza et al. (2017) conducted in Argentina and the United States indicates a limitation in nitrogen supply due to producers' management practices, affecting up to 11% of yield. This limitation was found to be influenced by yield potential, with higher yield potential associated with greater nitrogen limitation. Research conducted by Ortez et al. (2018) further supports these findings. Limited nitrogen supply has been observed in both the United States (12%) and Argentina (4%) (Ambrosini et al., 2019). In Paraná, Ambrosini et al. (2019) found a 4.6% limitation due to nitrogen deficiency.

Since the 2018 crop season, the FieldCrops Team has been evaluating nitrogen limitations in soybean crops with a history of high productivity in municipalities including Cruz Alta/RS, Tupanciretã/RS, Júlio de Castilhos/RS, Santa Maria/RS, and São Francisco de Assis/RS (Figure 3.3.1.1), Brazil. In this study, two treatments were compared: 'N-complete' and 'standard producer management'. The 'N-complete' treatment involves providing nitrogen according to the plant's absorption rate and demand, based on its productivity potential. In contrast, the 'standard' treatment relies mainly on biological nitrogen fixation (FBN), soil organic matter (OM) mineralization, and a small amount (<20 kg N ha^{-1}) applied at sowing. More information on this methodology can be found in Cafaro La Menza et al. (2017).

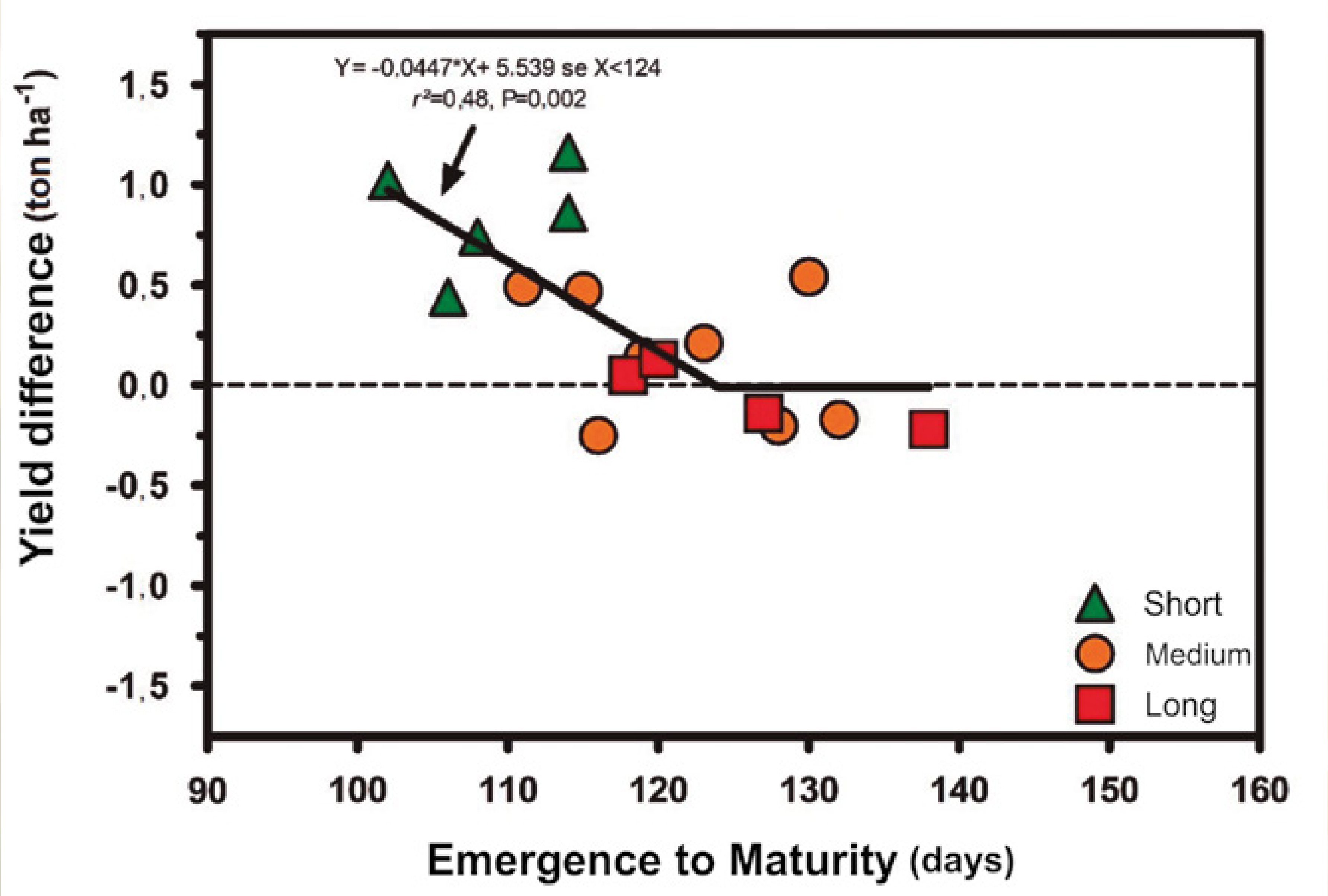


Figure 3.3.1.1. Relates the difference in between the N-complete treatment and the standard treatment under different environmental conditions. Each environment is a combination (location x sowing time x group of maturation x year). Bilinear regression $p<0.05$ (solid line) fitted.

The number of days until harvest significantly influences the productivity difference between treatments (N-complete and standard). For each day of the cycle, the response to fertilization decreases by 45 kg ha^{-1} up to 124 days into the cycle (Figure 3.3.1.1), indicating a greater limitation in short-cycle cultivars sown until mid-November. Cultivars with a cycle longer than 124 days show no response. It is important to note that in Brazil, most cultivars mature between 100-130 days from emergence.

Therefore, there is a limitation of nitrogen (N) in early-cycle cultivars under conditions of high productive potential, as shown in studies conducted in the United States and Argentina by Cafaro La Menza et al. (2017, 2019, 2020), Ortez et al. (2019), and in Brazil by Ambrosini et al. (2019) and Lamb and Echer (2019), which corroborate the nitrogen (N) gap in soybean crops. Applying mineral nitrogen (N) on a large scale to intensify the soybean production system would increase production costs and have detrimental effects on the biogeochemical cycling of nitrogen (N), potentially causing serious environmental impacts and harming biological nitrogen fixation (Bhattacharyya et al., 2021). Therefore, alternative solutions must be sought to reduce this nitrogen (N) gap, such as using cover crops in the system and strategically applying mineral nitrogen (N) and/or foliar applications during peak plant demand moments. Cover crops significantly enhance soil nitrogen (N) and other nutrient availability while increasing organic matter content. Ihakeem et al. (2021) report that nitrogen (N) productivity is higher in species mixtures (intercropping) compared to single species cultivation. The increase in nitrogen (N) was attributed to legume consortia with grasses and cruciferous species, which are more productive in biomass than individual legumes. Although legumes contribute nitrogen (N) to the soil through biological nitrogen fixation (FBN) and accumulate more nitrogen (N) in their composition, relying solely on legumes for their lower biomass production results in lower nitrogen (N) productivity. A study conducted by the FieldCrops team in 838 crops in Rio Grande do Sul revealed that the highest soybean yields were achieved using a vetch + oats cover crop consortium (Figure 3.3.1.2).

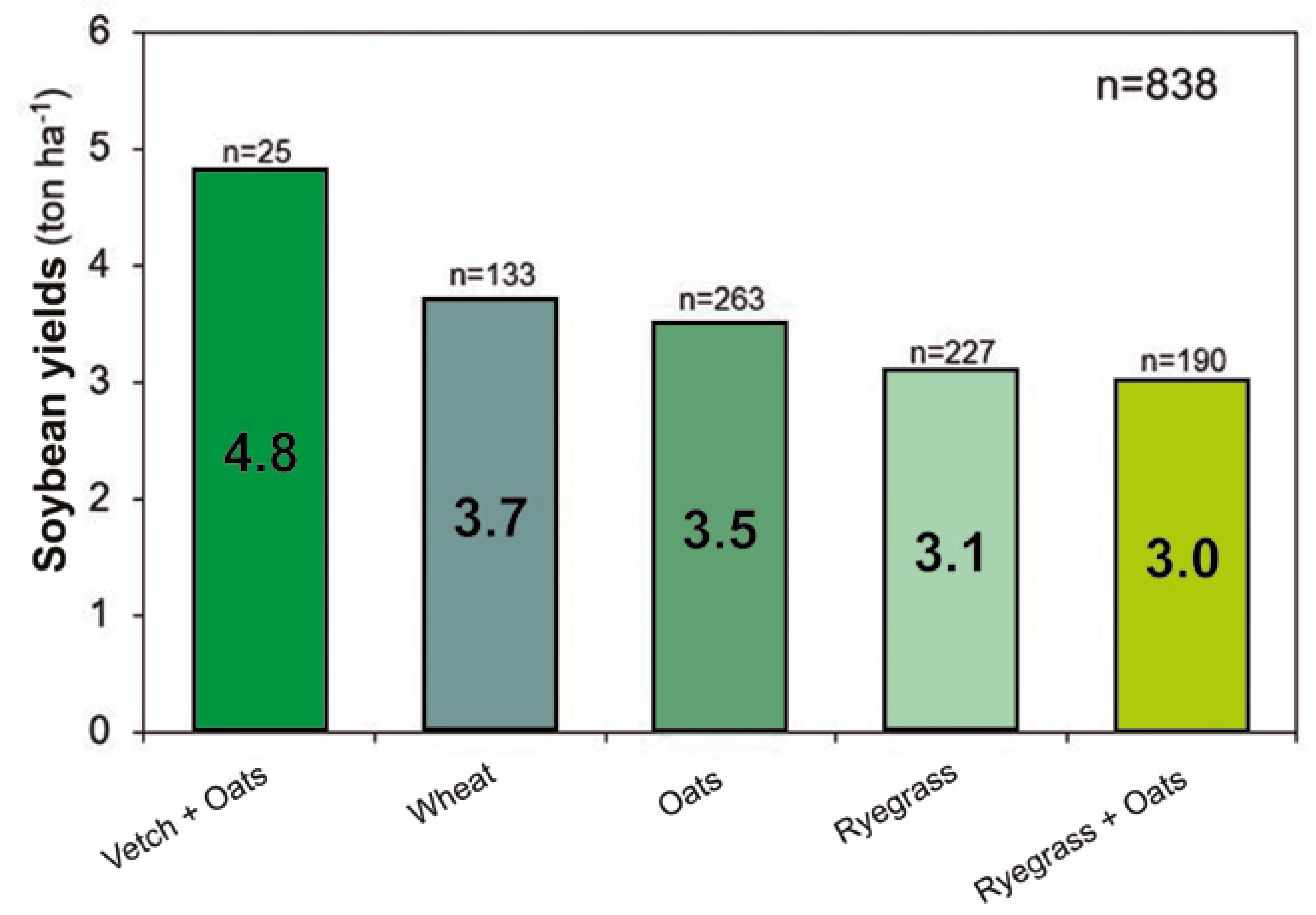


Figure 3.3.1.2. Survey of soybean yields from 838 crops in Rio Grande do Sul in succession to different types of cover crops. Source: FieldCrops Team, 2021.

3.4. Among the basic cations (potassium, calcium, and magnesium)

Potassium

Potassium (K) is the most abundant mineral cation in plant composition. However, it is not a structural component of plants; rather, it acts as an enzymatic activator, regulates turgor pressure and osmotic balance, and is vital for loading photoassimilates. Additionally, potassium is necessary for the photosynthetic fixation of CO_2. The degree of soil cation exchange capacity (CEC) saturation with potassium (K) and its interaction with other cations significantly impacts their availability.

Soil potassium deficiency is common in Brazilian soils but less so in Argentine soils. This nutrient exhibits high mobility in the soil and is prone to losses through leaching. Inadequate potassium supply negatively affects plant resistance to stresses such as drought, salinity, and disease. During potassium deficiency, photosynthesis is greatly impaired due to reduced stomatal conductance. This deficiency also results in wrinkling and deformation of grains, vegetative opening, uneven maturation, and incomplete grain filling. Potassium is absorbed at high rates early in the growth cycle, exceeding 3.5 kg ha^{-1} day^{-1} towards the end of the vegetative growth phase, with 48% of the demand absorbed by the R1 stage, reducing its uptake mainly after the R5 stage (Figure 3.4.1).

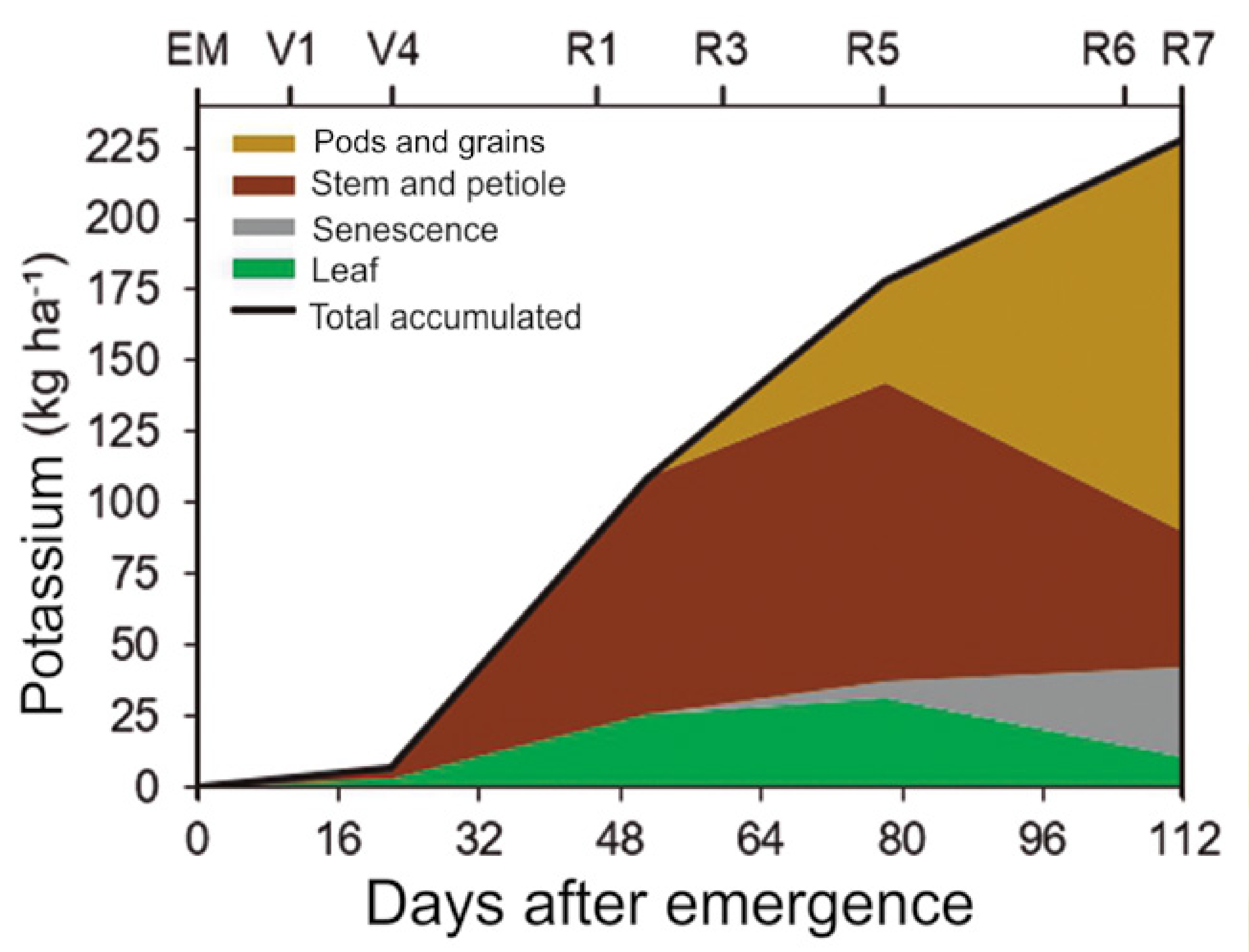


Figure 3.4.1. Uptake and redistribution of potassium in soybean. Data from a 6.6 ton ha^{-1} crop.

Calcium

Calcium (Ca) is essential as a structural element and plays a crucial role in cellular signaling. Its deficiency results in reduced growth of meristematic tissues in stems, leaves, and root tips. Typical foliar symptoms of calcium deficiency include necrotic lesions on leaf margins and tips, brownish veins, and leaf deformities. Prolonged calcium deficiency can lead to the death of apical meristems.

Calcium and magnesium (Mg) exhibit similar behavior in plants. They are primarily retained or fixed in their initial destinations such as stems, leaves, and petioles and do not translocate efficiently to the grain. This results in a low harvest index ranging from 17% to 32% (Figures 3.4.2 and 3.4.3). Up to stage R5, approximately 60% of the calcium is absorbed (Figure 3.4.2).

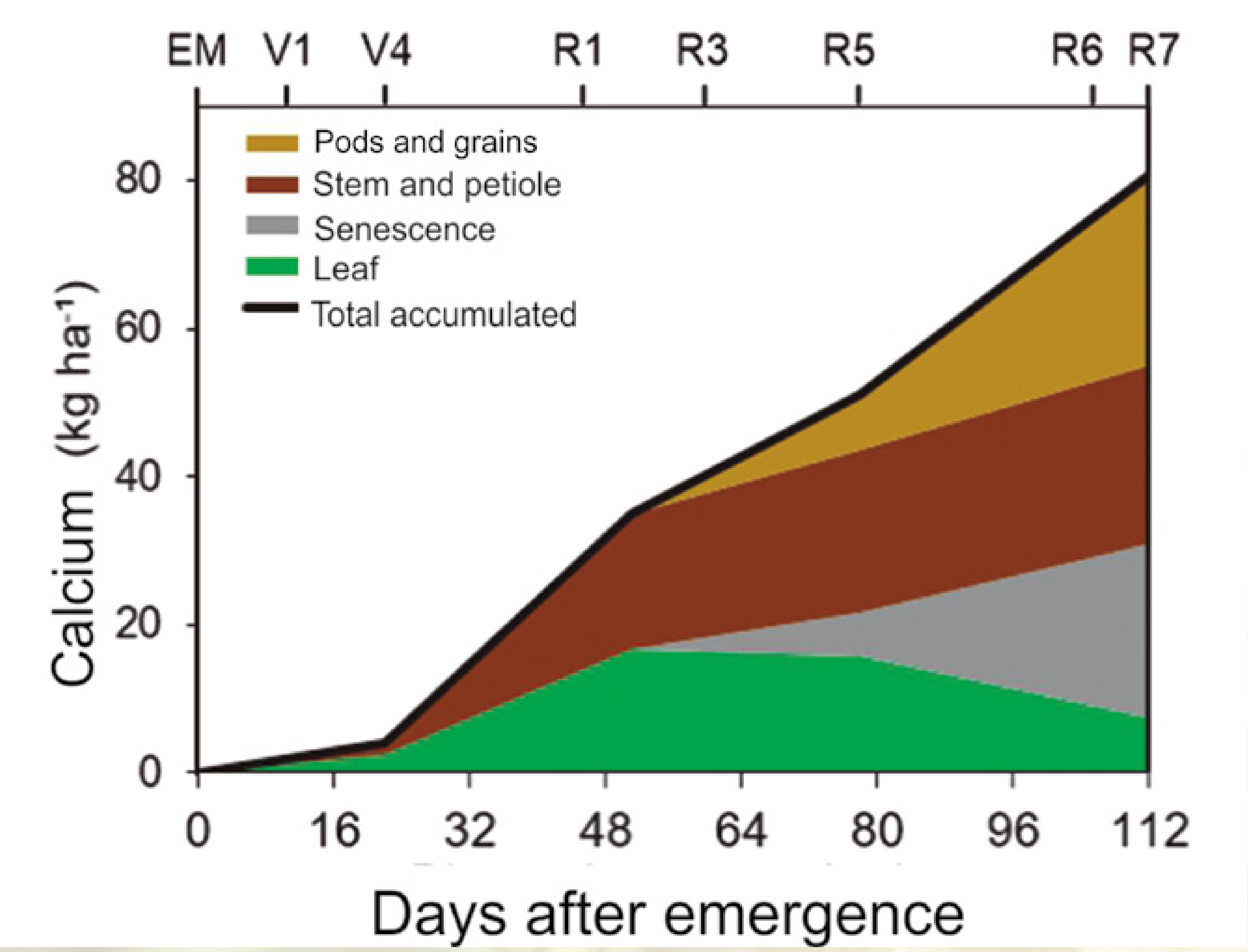


Figure 3.4.2. Calcium absorption and redistribution in soybean. Data from a 6.6 ton ha^{-1} crop.

Magnesium

Magnesium (Mg) is a critical component of the tetrapyrrole ring of chlorophyll and serves as the primary enzyme activator among mineral nutrients. In plants deficient in Mg, photoassimilates accumulate in mature leaves before photosynthesis is affected, leading to an excess of carbohydrates and increased production of reactive oxygen species (ROS) in chloroplasts. This misallocation of photoassimilates to roots results in significant reductions in root growth, leaf abscission, and reduced stem diameter.

The first visible symptom of Mg deficiency is chlorosis, which gradually develops from the tips of fully expanded older leaves and is eventually accompanied by a purple hue and brown wilting (necrosis) between the leaf veins. Magnesium absorption is relatively slow compared to other cations, with the plant absorbing approximately 49% of its demand up to stage R5 (Figure 3.4.3).

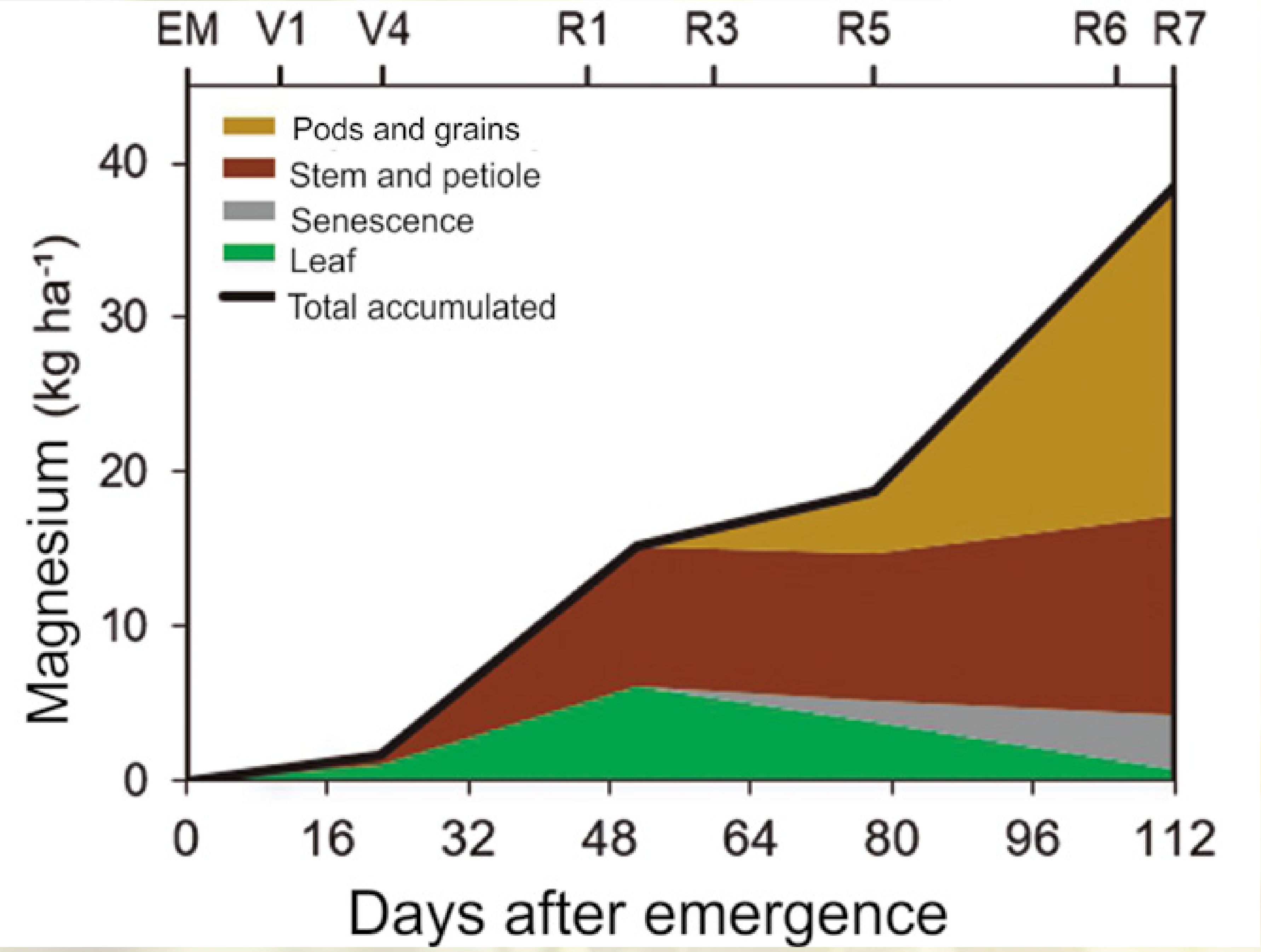


Figure 3.4.3. March of absorption and redistribution of magnesium in soybean. Data from a 6.6 ton ha^{-1} crop.

3.5. Anionic macronutrients (phosphorus and sulfur)

Phosphorus

Phosphorus (P) is the most deficient nutrient in soybean cultivation soils due to its strong interaction with the solid phase of the soil, leading to adsorption by iron and aluminum oxides and low mobility in the soil. Therefore, phosphorus is a key element in initiating a fertilization plan. Phosphorus is essential for plant metabolism, and a prominent feature of P deficiency is a marked decrease in CO_2 assimilation, leaf expansion, biomass production, number and efficiency of rhizobia nodules, and overall slow growth resulting in stunted plants. Plants respond to phosphorus limitation by increasing the density of root hairs and/or the frequency and length of lateral roots.

The deficiency symptoms are evident on leaves, which develop a reddish-purple color due to anthocyanin accumulation.

Normally, anthocyanins accumulate against a dark green background caused by reduced cell division and expansion in P-deficient plants. Phosphorus is absorbed at a rate of up to 400 g ha^{-1} day^{-1} between stages R5 and R7 (approximately 80 to 115 days of development). Around 25% of the phosphorus absorbed by the plant is translocated from the shoot (stems, petioles, and leaves) to the grains, with only 54% absorbed by stage R5 (Figure 3.5.1).

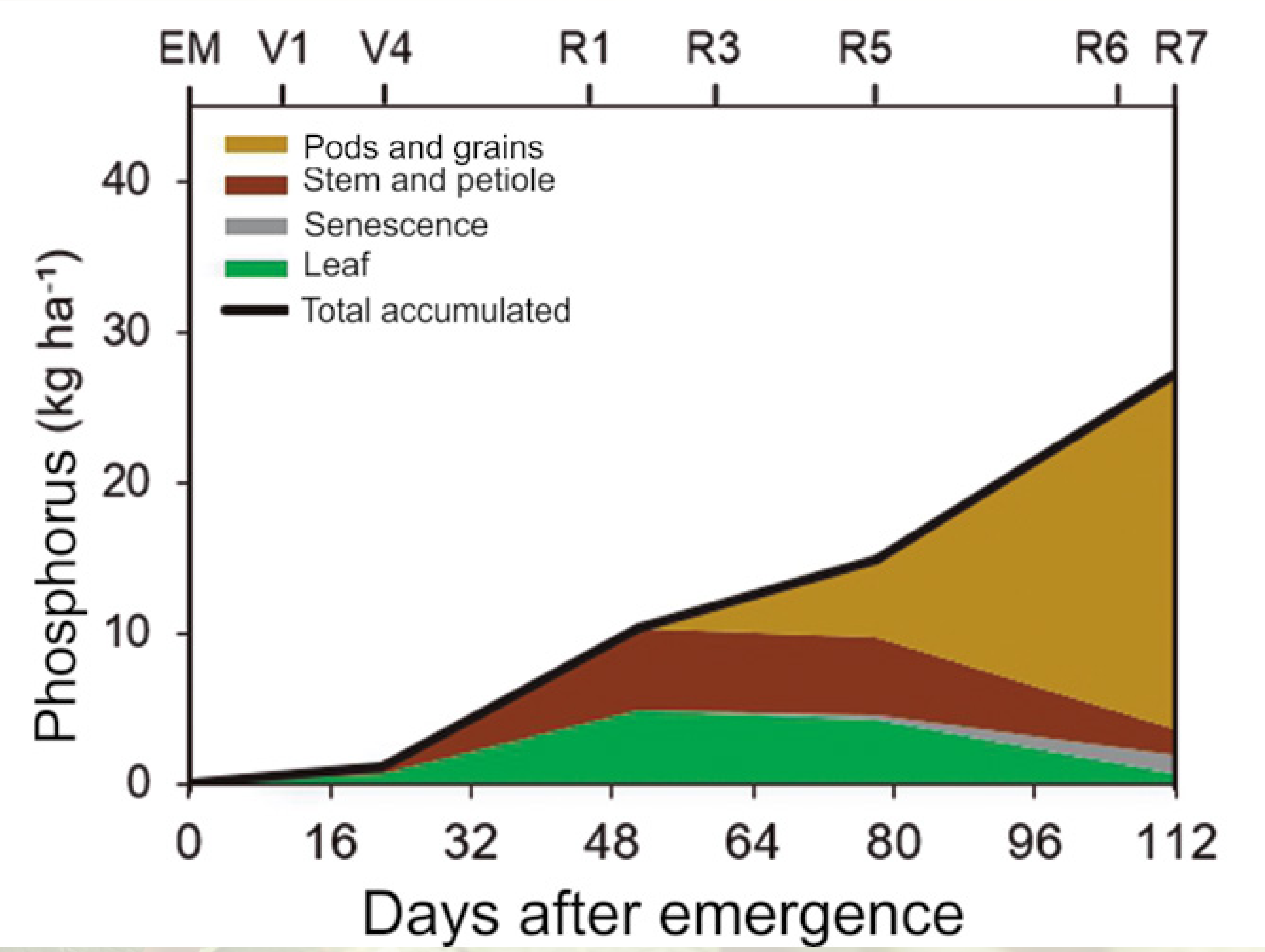


Figure 3.5.1. Phosphorus absorption and redistribution March in soybean. Data from a 6.6 ton ha^{-1} crop.

Sulfur

Sulfur (S) should not be neglected in areas of high soybean yield, as the critical nutrient availability level in the soil is 7.6 mg dm^{-3} (measured from 0-20 cm depth) (Pias et al., 2019). Similar to phosphorus (P), sulfur requires fertilization to maintain its concentration. The assimilation of sulfur and nitrogen (N) is coordinated, such that deficiency in one nutrient can repress the assimilative pathway of the other (Koprivova et al., 2000). Soil organic matter serves as an important source of sulfur.

A key symptom of sulfur deficiency is a significant reduction in photosynthetic efficiency and rapid development of chlorotic (yellowing) leaves. Plants growing under suboptimal sulfur supply exhibit delayed growth, chlorosis, premature flowering, reduced nodulation and symbiotic nitrogen fixation, and decreased seed formation (Viecelli et al., 2017). Chlorosis induced by sulfur (S) deficiency rarely progresses to necrosis, but the manifestation of symptoms depends on the nitrogen (N) status.

Mature (older) leaves become chlorotic under N deficiency due to protein degradation and starch export to younger leaves (sink tissues). In contrast, sulfur deficit primarily affects younger leaves first. Sulfur is actively absorbed by soybeans between stages R5 and R7, exceeding 600 g ha^{-1} day^{-1} (approximately 80 to 115 days of development). Soybeans have a high harvest index rate of 65% and exhibit limited remobilization of sulfur to grains (Figure 3.5.2). About 30% of the sulfur demand is absorbed between stages R1 to R5, and after stage R5, absorption increases to 50%.

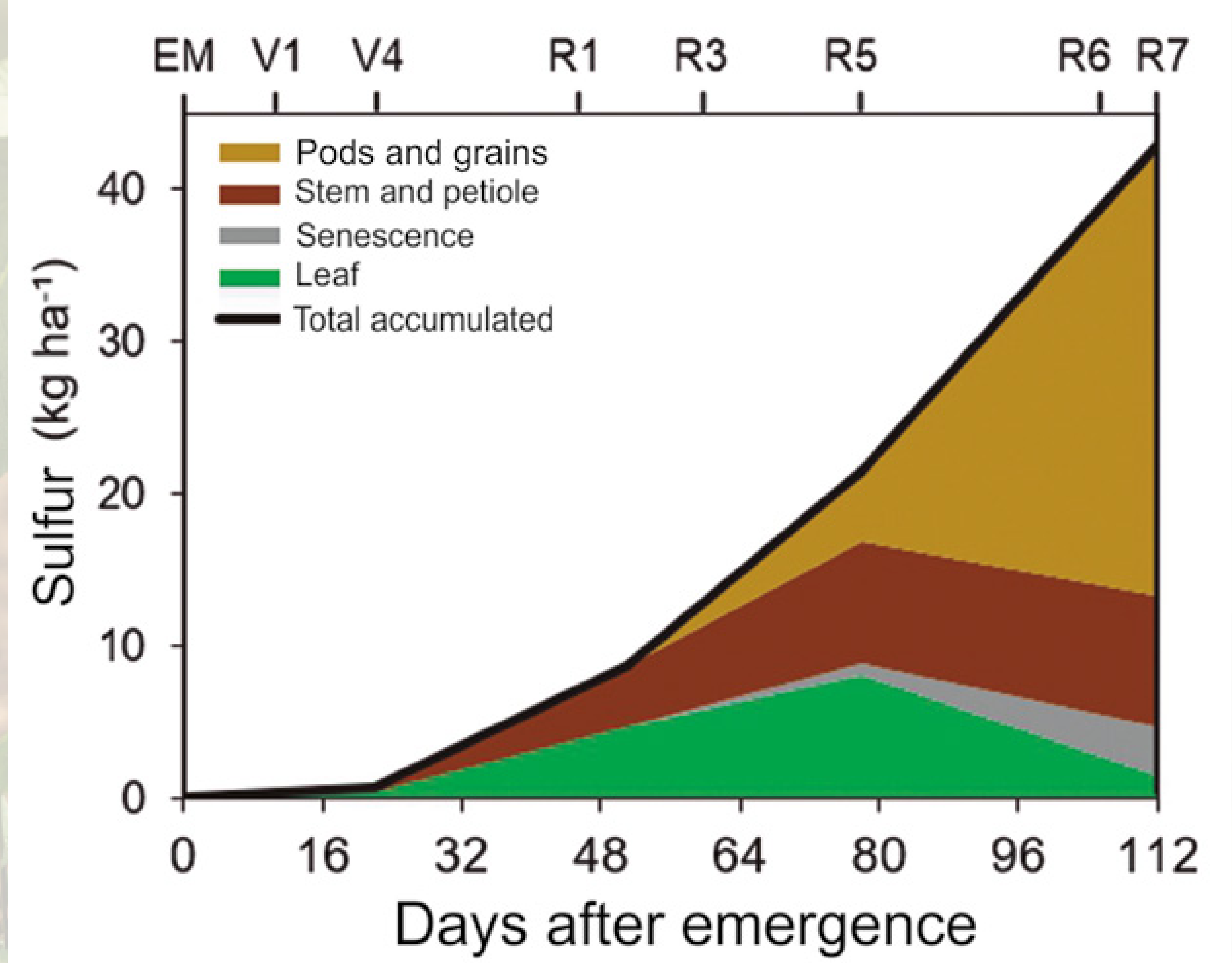


Figure 3.5.2. March of absorption and redistribution of sulfur in soybean. Data from a 6.6 ton ha^{-1} crop.

3.6. Micronutrients

Boron

Boron (B) is the only micronutrient available over a wide pH range as a neutral molecule, although it is found in the anionic form only in alkaline soils. Organic matter and certain minerals are important sources of boron. Due to its mobility in soil, boron is susceptible to leaching losses. High concentrations of calcium can exacerbate boron deficiency, as can soil acidity. Boron deficiency affects pollination by inhibiting pollen tube growth, reducing root growth, and causing abnormalities in legume formation. When deficiency symptoms occur, they are most severe on younger leaves, which exhibit pale coloration, restricted growth, and subsequent wrinkling. Approximately 41% of boron is harvested by the plant, with 42% absorbed by stage R1 (Figure 3.6.1).

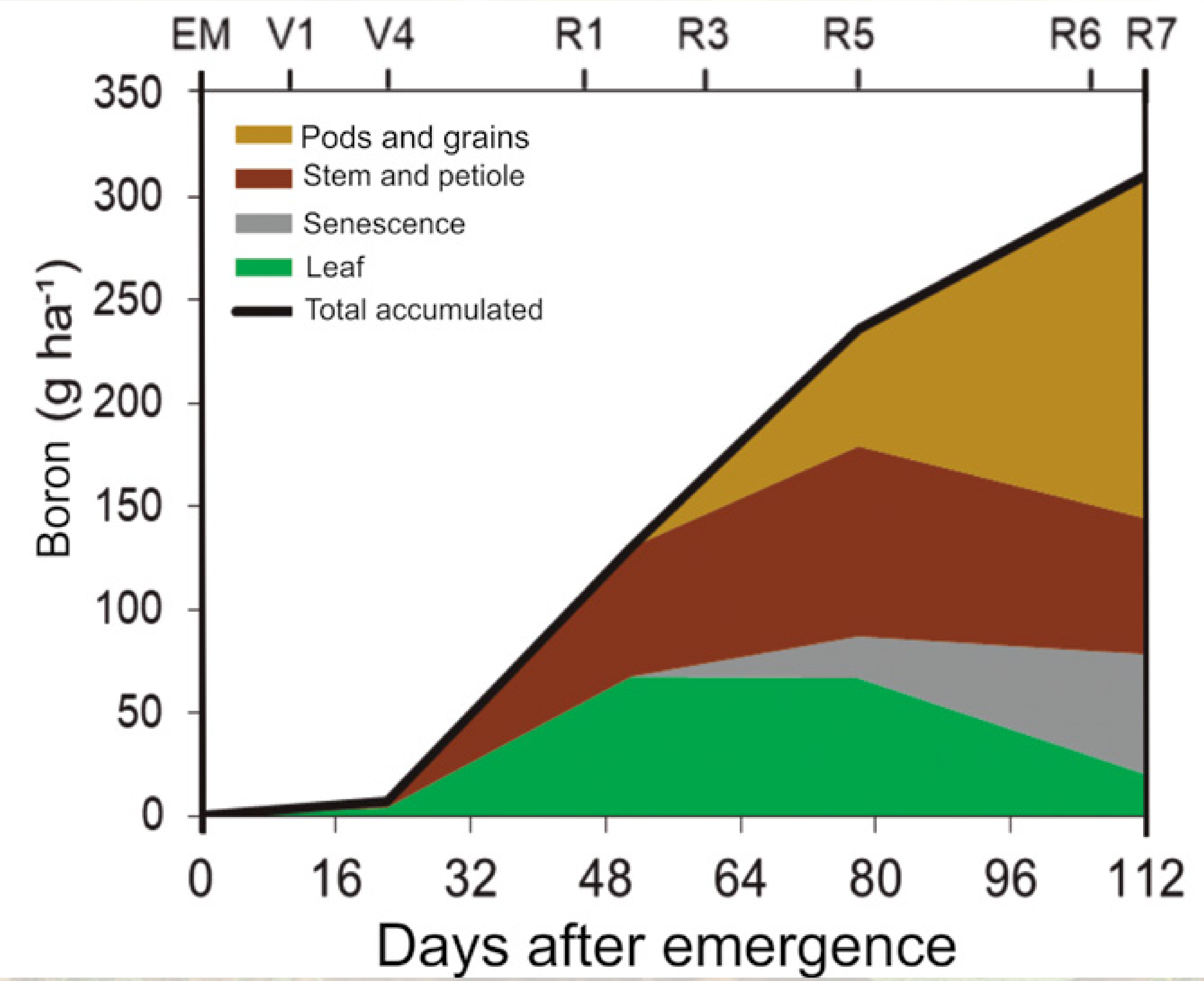


Figure 3.6.1. Uptake and redistribution of boron in soybean. Data from a 6.6 ton ha^{-1} crop.

Copper

Copper (Cu) has limited availability in areas with excessive liming and low organic matter content. Regions of the Brazilian cerrado commonly exhibit significant copper deficiency. Copper absorption by plants can be inhibited by high concentrations of phosphorus (P), zinc (Zn), iron (Fe), and manganese (Mn). Deficiency of copper in plants leads to reduced nodulation, lower protein synthesis, and decreased photosynthetic activity, ultimately impacting overall plant growth. Symptoms of copper deficiency typically appear first on young leaves, which may exhibit a grayish-green or bluish-green coloration along the margins toward the base. Approximately 50% of the copper is absorbed after stage R5, with the highest rates of absorption occurring towards the end of the growth cycle. The root system is the primary contributor to copper remobilization within the plant (Figure 3.6.2).

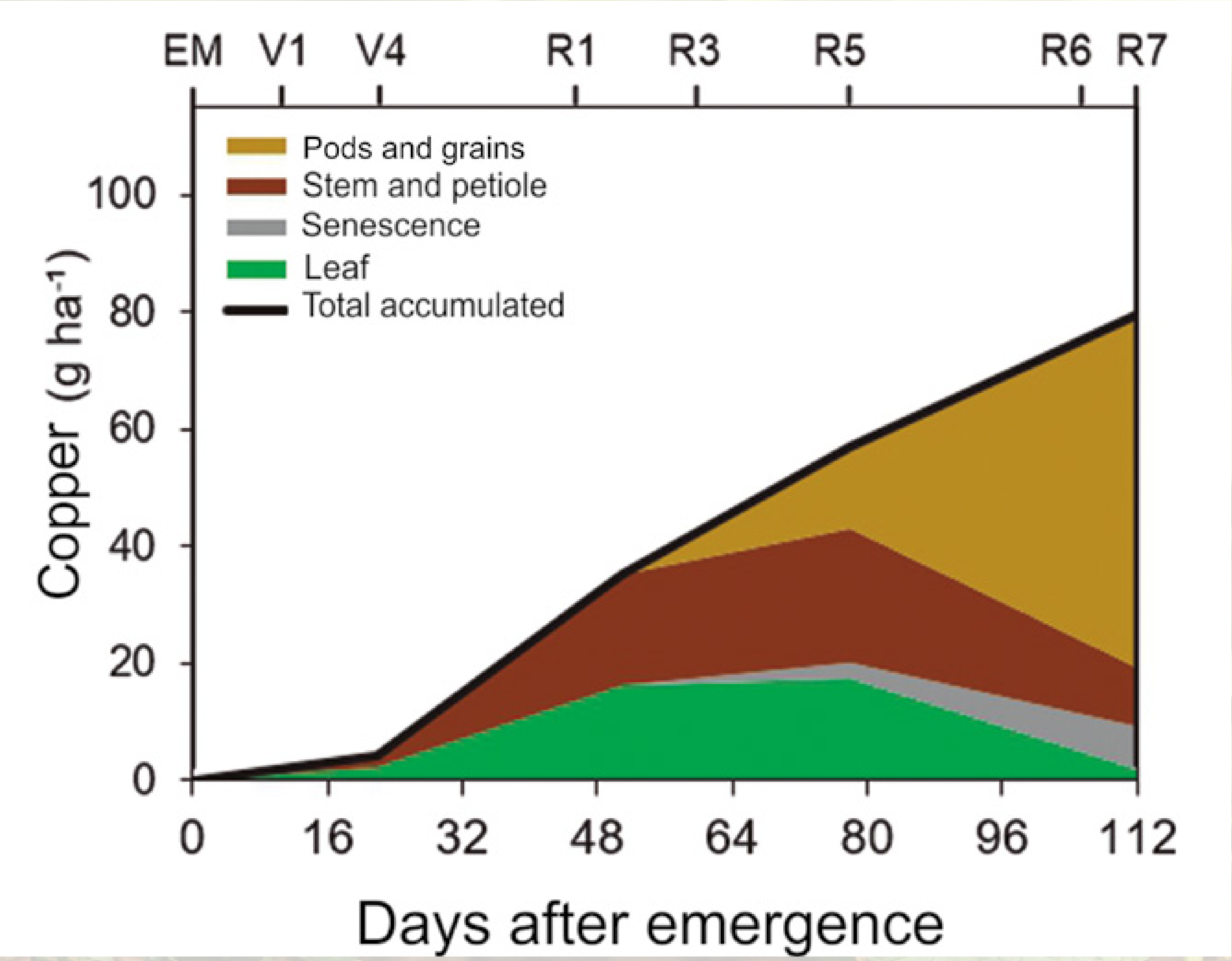


Figure 3.6.2. Pace of absorption and redistribution of copper in soybean. Data from a 6.6 ton ha^{-1} crop.

Iron

Iron (Fe) functions as an enzyme activator. Generally, its concentration in the soil solution is low, particularly in soils with a pH greater than 5 in Brazil. Iron availability is influenced by the presence of manganese (Mn). Plants employ mechanisms to mobilize and make iron available for absorption. Iron is predominantly found as ferric ion (Fe^{3+}) in the soil and needs to be reduced to ferrous ion (Fe^{2+}) for uptake by plants.

Plants deficient in iron exhibit reduced growth, thin stems, fewer pods or vegetables, and less grain filling. Symptoms typically start as pale yellow interveinal chlorosis on younger leaves. With prolonged deficiency, these chlorotic leaves can turn dark yellow. Iron has a harvest index of 35% and shows two absorption peaks: one between growth stages V4 and R1 and another between stages R5 and R7 (Figure 3.6.3). By stage R1, more than 43% of the cumulative iron demand is absorbed.

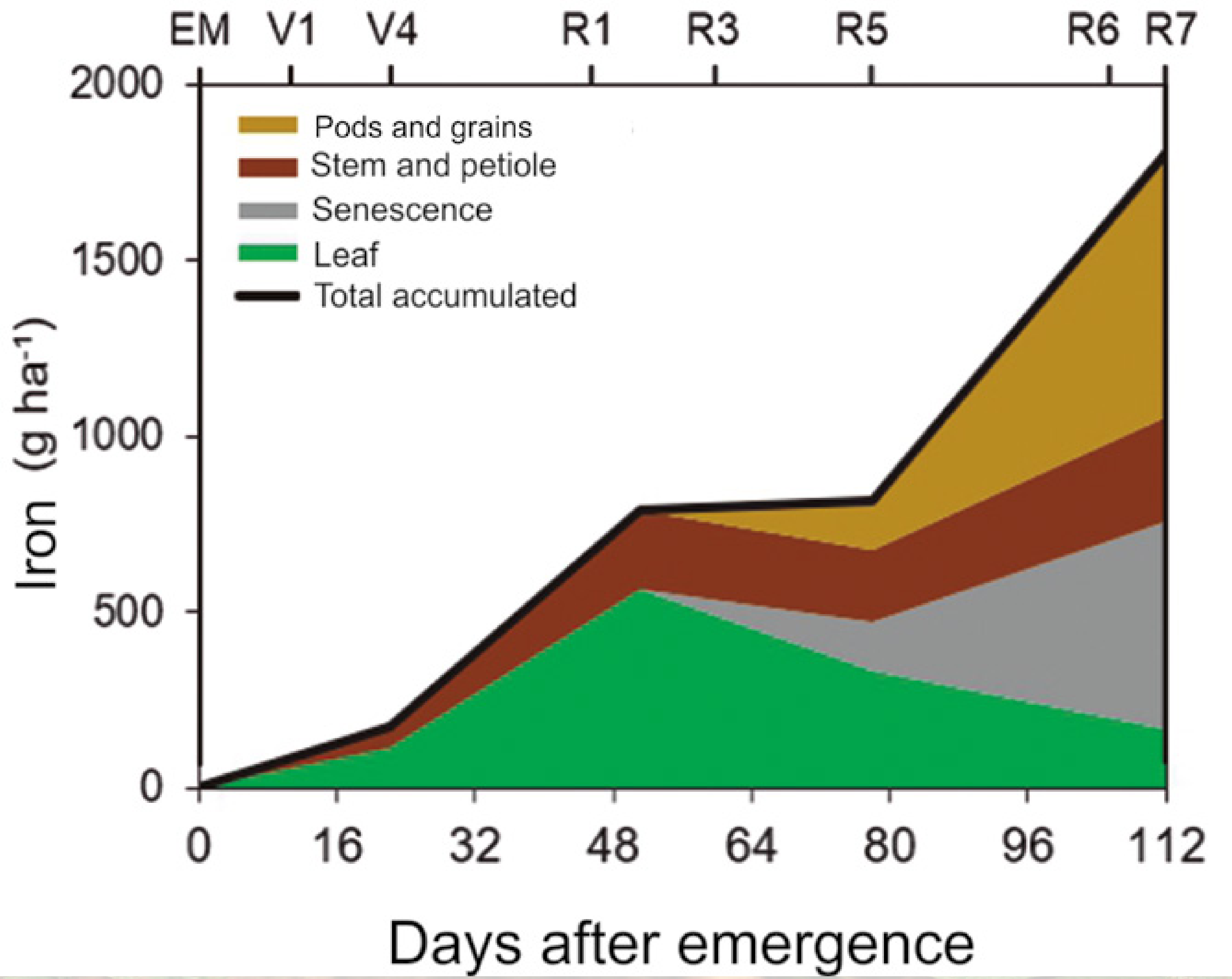


Figure 3.6.3. Absorption and redistribution of iron in soybean. Data from a 6.6 ton ha^{-1} crop.

Molybdenum

Molybdenum (Mo) is required in small amounts by plants. Its absorption can be reduced by the presence of sulfate ions. Mo deficiency in the soil may result in reduced synthesis of the nitrogenase enzyme, leading to decreased biological nitrogen fixation (BNF) and, consequently, reduced yield. Additionally, when molybdenum availability in the soil is low, it is redistributed from the leaves to the nodes, exacerbating deficiency symptoms in the plant (Salisbury & Ross, 1991). Symptoms of nutritional disorders in plants grown in Mo-deficient soils (acidic and low in organic matter) are characterized by yellowing of plants and twisted young leaves, with necrotic spots on the leaf margins (Sfredo et al., 2010). During flowering, fruiting, and the beginning of grain filling, molybdenum is absorbed at high rates, with approximately 50% of the demand absorbed by stage R5 (Figure 3.6.4).

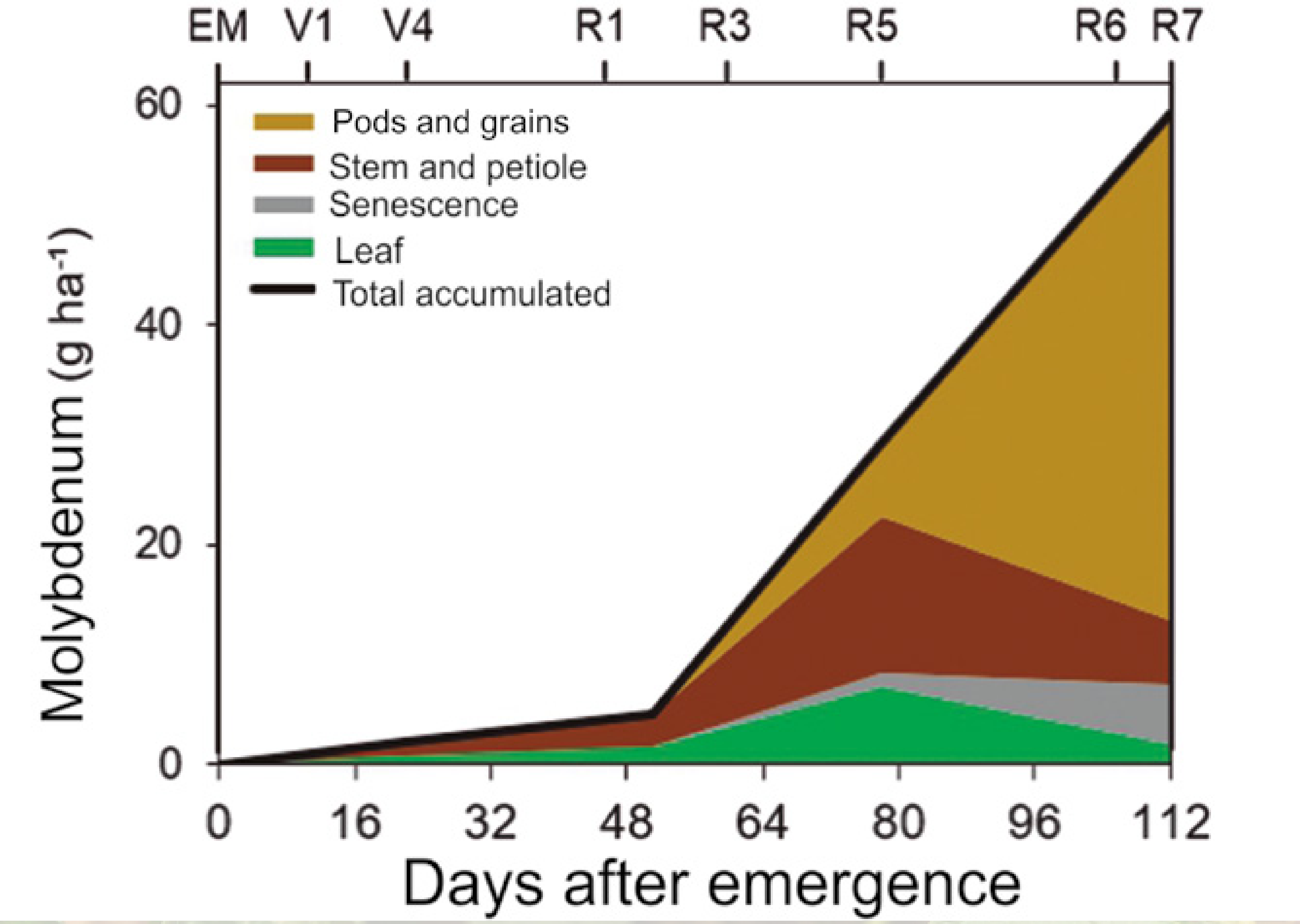


Figure 3.6.4. Uptake and redistribution of molybdenum in soybean. Data from a 6.6 ton ha^{-1} crop.

Manganese (Mn) is a deficient element in areas of the Brazilian cerrado. The presence of Mn and other cations in the soil solution affects its availability, along with elevated soil pH. In photosynthesis, Mn deficiency significantly disrupts the electron transport chain involved in light-activated reactions. Soybeans are particularly sensitive to Mn deficiency, and symptoms readily manifest in deficient crops. Plants affected by Mn deficiency appear stunted, with short and thin stems. Mn deficiency primarily impacts branching, pod number, and seeds per pod. The leaf blade and veins turn pale to white when deficiency occurs in younger leaves, while the veins remain prominently green. Manganese is absorbed in approximately 90% of its demand by stage R5, with a low harvest rate of 18%. Leaves contribute significantly to the remobilization of Mn within the plant (Figure 3.6.5).

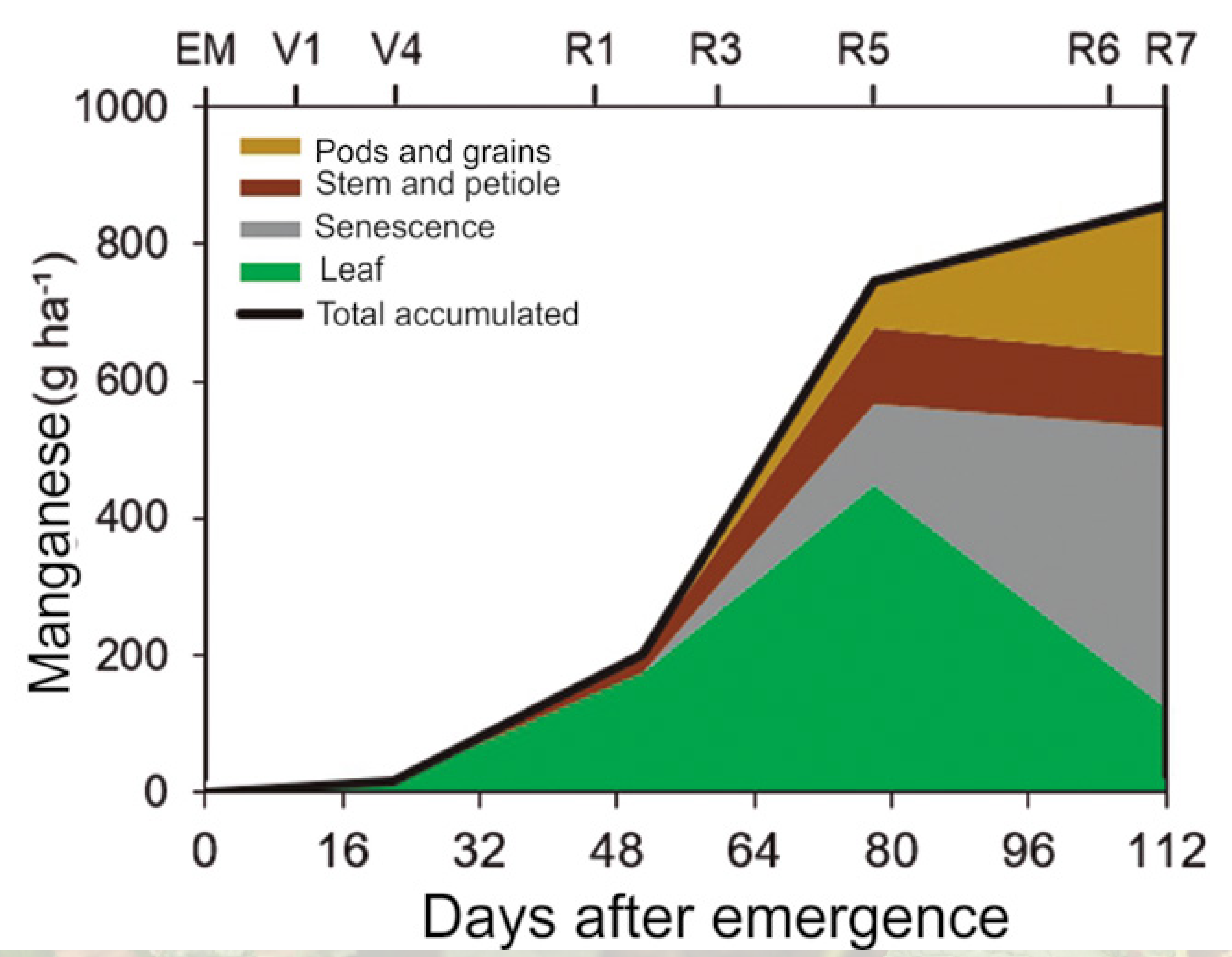


Figure 3.6.5. Uptake and redistribution of manganese in soybean. Data from a 6.6 ton ha^{-1} crop.

Zinc

Zinc (Zn) availability is compromised by high concentrations of phosphorus (P), excessive liming, high organic matter content, and sandy soils. Zinc deficiency affects leaf development and internode elongation. Plants experiencing mild zinc deficiency may exhibit white to yellowish bands or streaks of discolored tissue along each side of the midrib, starting from the leaf base. The margins of the veins and leaf edges typically remain green. Zinc is absorbed at high rates starting from flowering (R1), with approximately 50% absorbed by grain filling (R5), meeting 71% of the plant's demand. Zinc has a high harvest rate of 59% and approximately 30% of zinc is remobilized to the grains (Figure 3.6.6).

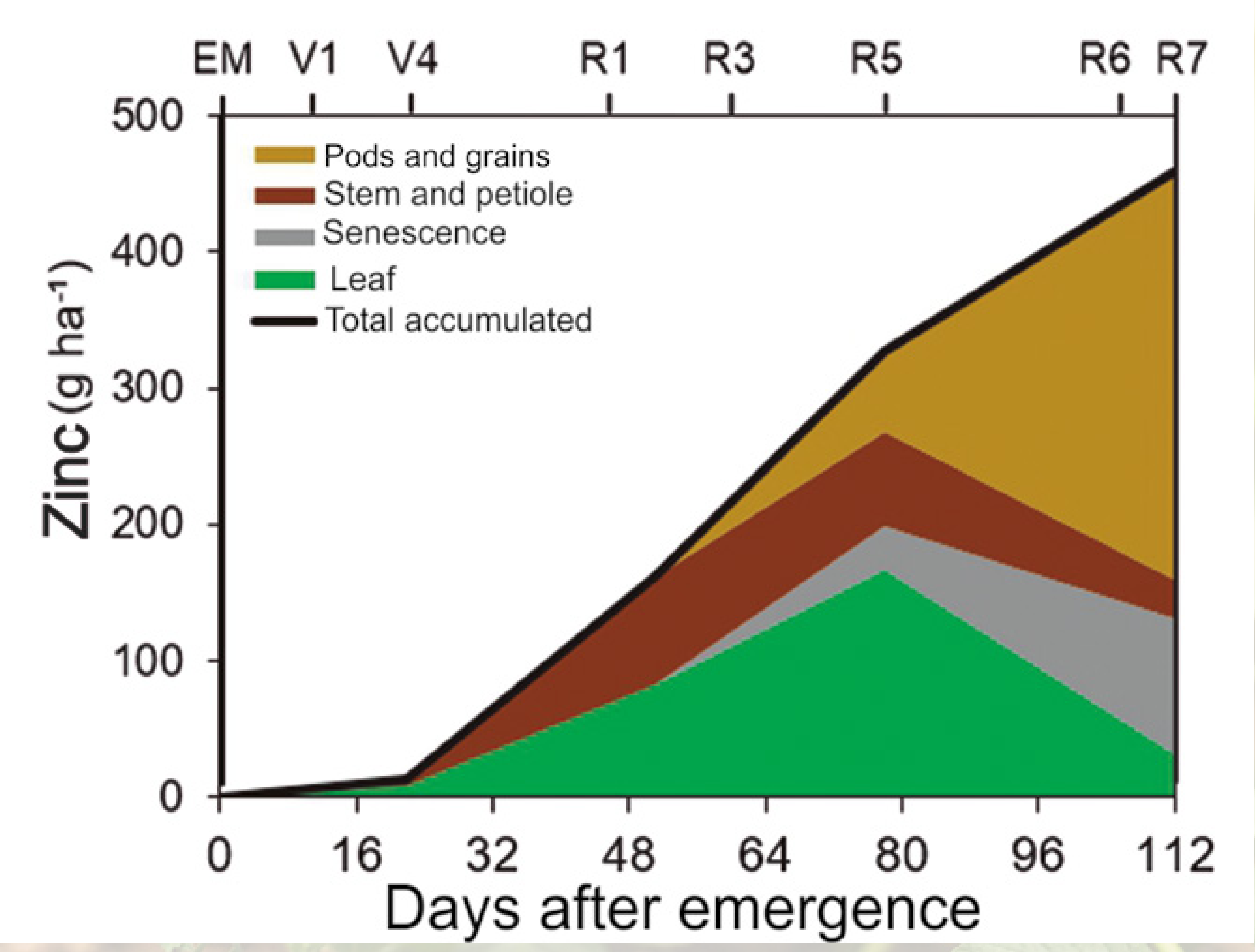
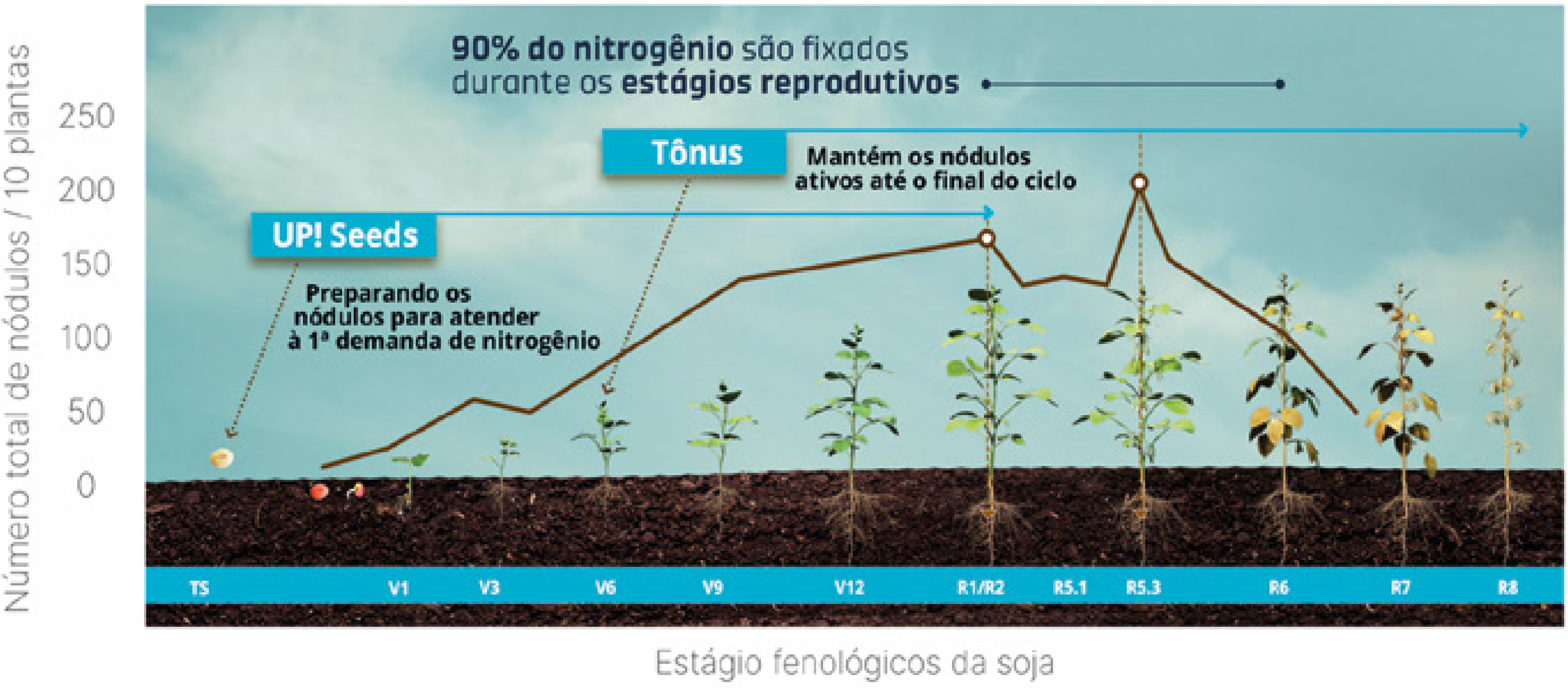


Figure 3.6.6. Zinc accumulation and redistribution March in soybean. Data from a 6.6 ton ha^{-1} crop.


Número total de nódulos / 10 plantas
250
200
150
100
50
0
90% do nitrogênio são fixados durante os estágios reprodutivos
Tônus
Mantém os nódulos ativos até o final do ciclo
UP! Seeds
Preparando os nódulos para atender à 1ª demanda de nitrogênio
TS
V1
V3
V6
V9
V12
R1/R2
R5.1
R5.3
R6
R7
R8
Estágio fenológicos da soja


UP! SEEDS
1L
ICL


TÔNUS
Nódulos ativos durante todo o ciclo
3kg
ICL

3.7. Foliar Fertilization

3.7.1. Physiological bases for foliar fertilization

Foliar fertilization, or the application of nutrients directly to plant leaves, has been a recognized method for over a hundred years. It serves as an important management strategy to maximize crop yields, complementing traditional soil fertilization practices. Plants have evolved intricate anatomical, physiological, and morphological structures to absorb water and minerals through their roots from the soil, while also adapting to avoid dehydration in their above-ground parts exposed to the air, such as leaves. Therefore, the natural route for mineral nutrient absorption occurs primarily through the roots. However, it's crucial to acknowledge that the earliest plants existed in aquatic environments and absorbed nutrients and water through all tissues. Physiologically, this ability has not been entirely lost.

Nutrients applied to the soil via fertilizers undergo a series of processes to reach the interior of the plant and exert their metabolic functions. Typically, fertilizers in the soil must dissolve, move, or be intercepted by roots, then absorbed and translocated to the plant's growing points. During this journey through the soil and plant, nutrients can be lost through volatilization, leaching, or percolation, or they may form insoluble compounds such as precipitation or adsorption, rendering them inaccessible for plant uptake. Consequently, not all applied nutrients are effectively assimilated by plants. This inefficiency is particularly pronounced with traditional fertilizers, where less than 50% of nitrogen (N) and even less of phosphorus (P) is utilized. In some regions, this inefficiency has led to the application of high doses of fertilizers, resulting in soil and water contamination (Fernández et al., 2013). In this context, foliar fertilization emerges as a more environmentally friendly alternative, as it delivers nutrients directly to plant tissues uring critical periods of demand, maximizing absorption efficiency (Marschner, 2012). However, the effectiveness of foliar application depends on several factors. First, the nutrient must reach the leaf surface and remain in a soluble form until absorbed and translocated to the action site within the plant. This requires using a high-quality product, including considerations of droplet size and number, to achieve satisfactory coverage on the leaf surface and ensure resistance to degradation, drying, and washing in case of rain (ideal formulation).

Plants are covered with a waxy hydrophobic cuticle that regulates the exchange of water, solutes, and gases with the environment. This cuticle also restricts the entry of compounds into the plant interior. Despite these barriers, we now understand that plant surfaces are permeable to nutrient solutions. The ability of a nutrient solution to penetrate into the plant depends on surface characteristics, which can vary with organ, species, variety, and cultivation conditions. Epidermal structures like stomata and lenticels, present on leaves and fruits, are permeable to solutions applied to the surface and play a significant role in nutrient absorption.

Plant surfaces tend to be hydrophobic to varying degrees, limiting the absorption of nutrient solutions in pure water (unformulated). Therefore, it is crucial to use foliar formulations that strike a balance between nutrients and adjuvants to optimize overall effectiveness. Environmental factors such as relative humidity and temperature can influence the physical properties and efficacy of foliar fertilizer formulations and should be considered before application.

The mobility of a nutritional element within the phloem significantly impacts the effectiveness of foliar fertilization by influencing its absorption, translocation, and utilization by plants. When applying foliar fertilizers, the distinction between phloem-mobile and phloem-immobile nutrients is crucial. Phloem-immobile nutrients (such as calcium, boron, manganese, and silicon) benefit only the tissues directly exposed to the foliar spray. In contrast, phloem-mobile nutrients (including nitrogen, phosphorus, potassium, sulfur, and magnesium) have the potential to provide systemic and long-range benefits throughout the plant. However, there are limitations to the amount of nutrients that can be effectively applied via foliar spraying, and the rapid dilution of applied nutrients within the plant reduces the potential systemic benefits of phloem-mobile nutrients. Some nutrients have intermediate or restricted mobility within the plant (e.g., iron, zinc, copper, molybdenum). Regardless of mobility, the primary role of foliar fertilization is to prevent immediate and transient deficiencies that cannot be quickly addressed through soil applications. The effectiveness of foliar fertilization depends on interactions between crop phenology (growth stages) and environmental conditions. Understanding these principles is essential for optimizing the use of foliar fertilization to address specific nutrient needs of crops and to maximize overall plant health and productivity. By considering nutrient mobility and plant physiology, practitioners can make informed decisions about foliar fertilizer applications to achieve desired outcomes efficiently and sustainably.

3.7.2. When are the most opportune conditions for foliar fertilization?

Fernández et al. (2013) outline the advantageous conditions that contribute to the success of foliar fertilization:

1 - When the supply of certain nutrients from the soil is deficient due to inadequate traditional fertilization practices. This deficiency may occur when nutrient deficiencies were not previously detected or when fertilization was performed in an unbalanced manner. Additionally, foliar fertilization is beneficial when soil conditions limit nutrient availability, such as in high pH soils with significant fixation and/or adsorption of elements like phosphorus (P), or in very sandy soils.

2 - In certain circumstances, peak periods of crop growth can lead to a demand for nutrients that exceeds the supply available even in fertile soils. The rapid growth phase or grain filling stage may require nutrients at levels that surpass the plant's absorption capacity or the soil's ability to supply nutrients. During these high-demand periods, competition between roots and shoots can occur, potentially reducing the allocation of carbohydrates and restricting root growth metabolism, thereby diminishing nutrient absorption.

3 - The plant's architecture and organ development can create a local demand for nutrients that exceeds the plant's delivery or transport capacity. Limitations in the transport of immobile elements in the phloem to organs with inadequate vascular connectivity or low transpiration rates can result in deficiencies of elements such as boron (B) or calcium (Ca). This transportation limitation is also responsible for nutritional deficiencies of boron (B), copper (Cu), iron (Fe), and zinc (Zn) in reproductive structures (e.g., floral fertilization).

4 - Biofortification of crops, especially to enhance the content and bioavailability of iron (Fe) and zinc (Zn) in grains, is aimed at improving the nutritional quality of food.

3.7.3. Plant tissue analysis

The analysis of plant tissues is essential for understanding the nutritional status of crops, confirming symptoms, and making recommendations. Often, there is an analogy drawn with soil analysis, where sampling and tissue analysis lead to a diagnosis and recommendations for fertilization—which is not entirely incorrect. However, in annual crops like soybeans, it is recommended to take leaf samples at the beginning of the reproductive phase (flowering). The time between sample collection, arrival at the laboratory, and receipt of results can range from 15 to 30 days. This delay often means that the window for corrective action through foliar fertilization has already passed in these cases. However, systematic monitoring and assessment of crop nutritional status through eaf analysis enable the detection of deficiencies or imbalances that are common in certain conditions, situations, or regions, allowing for corrective measures within the fertilization plan.

Conducting plant tissue analysis does not necessarily imply immediate foliar fertilization, but it assists in developing fertilization strategies for upcoming years. The possibility of applying nutrients via foliar spray is subject to physiological and economic limitations. Physiological constraints relate to potential phytotoxicity at higher application rates, while economic considerations involve product costs, which restrict the frequency of applications. The expected response to foliar fertilization is proportional to the amounts applied relative to the plant's demand. For macronutrients, the application rates are typically limited to a few kg ha^{-1} (e.g., less than 10 kg ha^{-1} for N or 1 to 2 kg ha^{-1} for P, depending on solution concentration), whereas for micronutrients, rates can range from 0.1 to 1 kg ha^{-1}. Meeting the total macronutrient demand through foliar application is challenging; however, for micronutrients, it can be a viable option.

For instance, applying 5 to 10 kg ha^{-1} of N via foliar spray on soybeans at stage R3, compared to a potential consumption of 429 kg ha^{-1}, might seem insignificant. Nevertheless, Moreira et al. (2017) demonstrated a statistically significant yield increase over three years in Brazil: an average grain yield of 4257 kg ha^{-1} without added N, 4468 kg ha^{-1} with 5 kg ha^{-1} of foliar N, and 4516 kg ha^{-1} with 10 kg ha^{-1} of foliar N—a response ranging from 5 to 6% (200-250 kg ha^{-1}). The relevance of foliar application rates becomes apparent when considering the soybean's daily nitrogen absorption rate (Table 3.2.1.2). During peak absorption periods, the soil-soybean-rhizobium system may not fully satisfy the plant's nitrogen demand. Foliar fertilizers can boost soybean yields when deficiencies are present, and applications coincide with the onset of peak nutrient demand (Figures 3.3.1; Figures 3.4.1 to 3.6.6).

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4. Biostimulants

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There are numerous terms associated with the science still in development regarding plant growth regulators: stimulants, metabolic enhancers, plant strengtheners, vegetable elicitors, plant conditioners, phytostimulators, biofertilizers, and biostimulants. These substances are gaining importance, especially as many soybean crops are achieving high yields. Therefore, there is a pressing need for further studies into the fundamental interactions of plant ecophysiology, such as how soybean cultivars respond to hormones and biostimulants under agricultural conditions. This represents a recent management strategy that, when used effectively, can enhance tolerance to climatic variations and management challenges, optimize resource efficiency, and promote high-yielding and profitable crops.

What is the most correct terminology?

Before delving deeper into the discussion, the terminology surrounding biostimulants and biofertilizers should be clarified. These terminologies are key classifications used to describe growth regulators. Generally, products with growth-stimulating effects fall under the category of “biofertilizers,” defined as “products containing active principles or organic agents, free of agrotoxic substances, capable of directly or indirectly affecting all or part of cultivated plants, increasing their yield, regardless of their hormonal or stimulating value” (Normative Instruction 61, 2020). In this definition, biofertilizers encompass substances such as amino acids obtained through fermentation or hydrolysis of natural organic materials, as well as humic acids, fulvic acids, humines, seaweed extracts or processed algae, and plant extracts (Abisolo, 2020; Brazil, 2020). Therefore, depending on the context, we will use the terms biofertilizer and biostimulants in our discussion based on their respective applicability.

Why consider the application of biostimulants?

Plant growth and development are influenced by both exogenous factors (such as temperature, photoperiod, and solar radiation) and endogenous factors (including plant hormones or phytohormones). Biostimulants, which are naturally produced by plants, serve as transducer substances, acting as "chemical messengers" that facilitate communication between cells, tissues, and organs in higher plants. Based on the plant's perception of environmental stimuli, different parts of the plant (roots, stems, and leaves) are informed about the status of other parts through the synthesis or alteration in concentration of one or more biostimulants (Costa, 2010). The function of biostimulants is not solely determined by their chemical composition; rather, it also depends on how the target tissues perceive them. The same plant hormone can induce different effects depending on the site of action, concentration, developmental phase of the plant, external stimuli, and timing of the stimulus (Petri et al., 2016). One approach to using biostimulants involves influencing the primary and secondary physiological metabolism of plants to mitigate negative impacts during stressful situations.

Plants can face stress from various factors, including unfavorable environmental conditions such as water deficit/excess, extreme temperatures (below or above the cardinal range- Figure 2.2.2), attacks by pests and pathogens, or management failures leading to nutritional deficiencies and/or phytotoxicity. In response to stress conditions, plants produce excessive amounts of reactive oxygen species, such as superoxide (O_{2-}) and hydrogen peroxide (H_2O_2), which initiate a cascade of reactions leading to the oxidation of proteins in plant cell membranes. This oxidative stress affects the selective permeability of the membrane, significantly reducing the efficiency of photosynthetic activity and the accumulation of carbon, proteins, and DNA (Dolchinkova et al., 2013). In agricultural settings, this process manifests as reduced growth (e.g., leaf area index, biomass) and lower grain yields (Goel & Madan, 2014).

Moving forward, we will explore the main categories of biostimulants that act directly or indirectly on hormonal balance, crop growth, and plant tolerance to both biotic and abiotic stresses.

4.1. Main plant hormones related to biofertilizers

4.1.1. Abscisic Acid (ABA)

ABA (abscisic acid) is a key hormone that regulates various physiological processes in plants, primarily playing a crucial role in plant adaptation to environmental stresses. ABA plays a critical role in regulating the growth and development of plants, impacting processes such as root and stem elongation, seed germination, and bud sprouting. Its actions are diverse and include physiological processes such as stomatal closure, bud dormancy, induction of reserve protein synthesis in seeds, embryo development, transport of photoassimilates from leaves to developing seeds, leaf and fruit abscission, and plant response to water stress (Taiz & Zeiger, 2013).

In conditions of water scarcity, plants synthesize a significant amount of ABA in the roots, which is then transported to the leaves via the transpiration stream (xylem). ABA signaling in leaves triggers stomatal closure, reducing transpiration rates (Liu et al., 2005). Severe water deficit leads to inhibited photosynthesis and growth due to increased ABA and solute concentrations in the leaves. Additionally, ABA regulates seed maturation in response to water stress and enhances plant tolerance to saline environments (Taiz et al., 2017; Wilkinson et al., 2012).

Recent genetic studies in soybeans have focused on utilizing transcription factors (TF), such as FT (Flowering Locus T), to confer drought tolerance (Winck et al., 2021). These TFs can mediate drought tolerance through ABA-dependent and ABA-independent pathways. In the ABA-dependent pathway, gene families like AREB (ABA Responsive Element Binding) are known to promote increased tolerance to water deficit (Marinho et al., 2015). Under conditions of water deficit, there is an increase in ABA levels which bind to specific receptors, forming complexes with enzymes that then bind to transcription factors like AREB, triggering the expression of genes involved in defense mechanisms (Marinho et al., 2015). Overexpression of AREB transcription factors enhances plant sensitivity to ABA, resulting in stomatal closure and synthesis of osmoprotective enzymes. This biotechnological approach promotes slower growth of the aerial parts, reduced daily transpiration, greater water economy, and consequently, an increased tolerance to water deficit conditions.

4.1.2. Auxins (IAA)

Auxins, such as Indole-3-acetic acid (IAA), are hormones produced at points of plant growth that accelerate cell elongation. The highest concentrations of auxins are found in apical meristems, with some also present in roots, though the majority are produced in the aerial parts of the plant. Auxins also play a crucial role in pollen tube elongation and coordinate plant tropisms, guiding growth in response to light (phototropism) and gravity (geotropism). IAA controls many metabolic processes, but different plant tissues require varying concentrations of auxins to stimulate growth effectively (Figure 4.1.2.1). Relatively high concentrations of auxins, particularly exogenous auxins, can lead to growth inhibition, as seen with auxinic herbicides like 2,4-D.

In agriculture, auxins such as Indole-3-acetic acid (IAA) are widely used to prevent fruit and leaf abscission, promote flowering, initiate lateral root growth, form flower buds, and aid in fruit development. Auxins also play a role in controlling apical dominance by inhibiting cell division in lateral buds (Taiz & Zeiger, 2009). IAA is produced in the aerial parts of the plant and translocated to the root system. Alongside cytokinins, auxins help balance carbon partitioning between shoots and roots in response to environmental conditions, thereby regulating plant development under stress (Kazan, 2013).

The concentration of auxins in plants is highest in actively growing tissues, particularly in young leaves, and decreases as leaves mature. Roots are highly sensitive to auxins, responding positively to low concentrations but showing inhibition at higher concentrations (Faria et al., 2017). IAA is structurally related to the amino acid tryptophan and its precursor, indole-3-glycerol phosphate, both of which are involved in auxin biosynthesis. Abiotic stresses that disrupt nitrogen supply (a constituent element of tryptophan) such as water deficit or excess can reduce auxin concentrations, leading to leaf abscission, loss of apical dominance, and stimulation of secondary meristem growth (ramifications). Commercially, auxins are used to maintain apical dominance in plants and delay leaf abscission. However, excessive auxin levels can be toxic to plants, particularly to eudicot weeds, which are more susceptible.

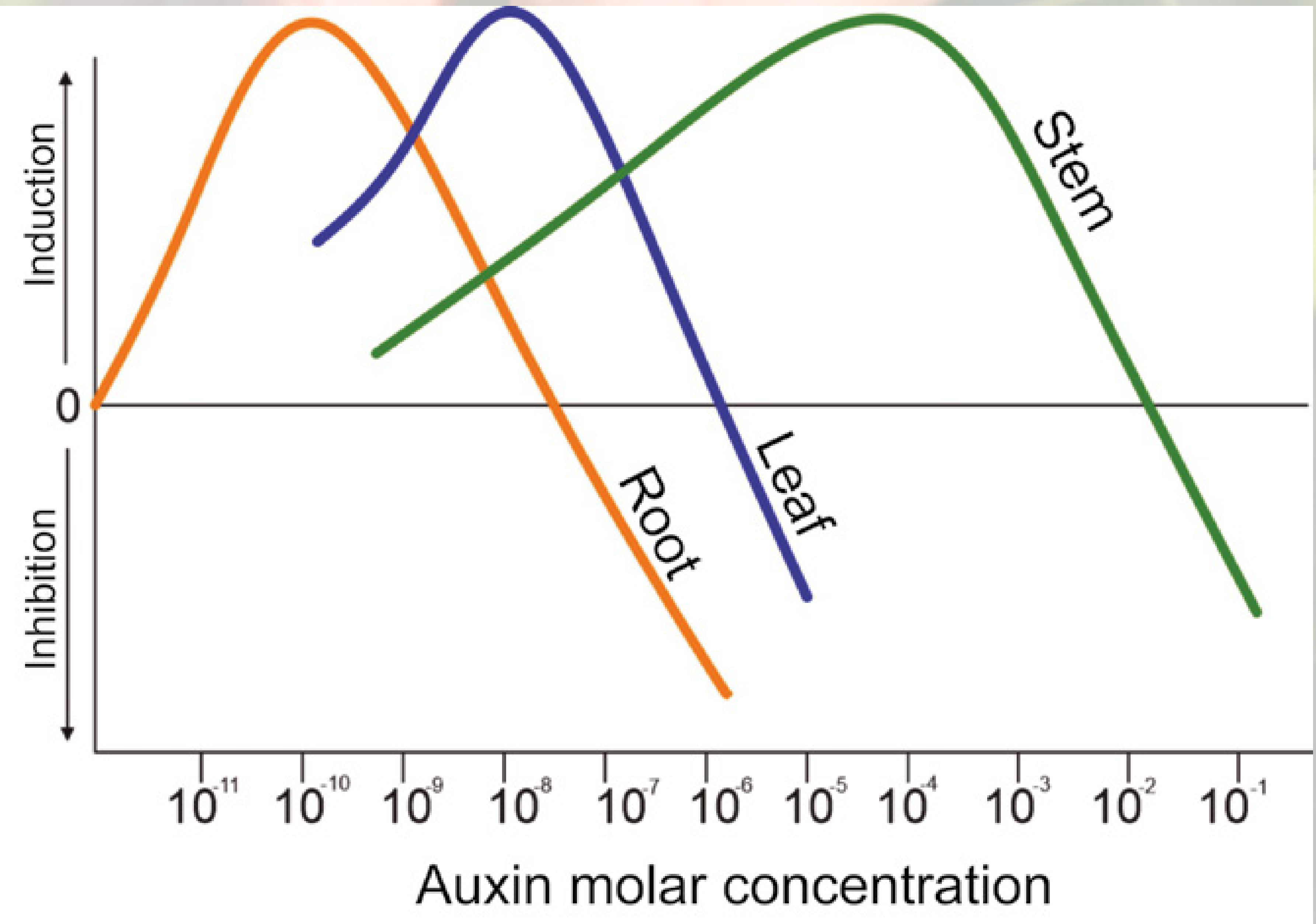

Figure 4.1.2.1. Relationship between auxin concentration and root, bud and stem enlargement. Adapted from Thimann, 1937.

4.1.3. Cytokinin (CIT)

Cytokinins (CIT) are phytohormones considered key regulators of plant development, physiological processes, and cell division. They exert a crucial effect on the shoot/root ratio alongside auxin (AIA) (Werner et al., 2003). Cytokinins have these main effects: 1) Stimulation of cell division (cytokinesis) in the aerial parts, promoting branch growth. 2) Delay of senescence. Application decreases nutrient remobilization and stimulates cell division (Faria et al., 2017). Cytokinins are biosynthesized mainly in roots, developing embryos, young leaves, and fruits. They are also synthesized by bacteria, fungi, insects, and nematodes associated with plants (Taiz & Zeiger, 2013).

Plant apical dominance depends on the balance between cytokinin and auxin. An increase in the cytokinin/auxin ratio modifies apical dominance and promotes lateral bud growth. Direct applications of cytokinin to axillary buds stimulate bud cell division and growth. Cytokinin also promotes chloroplast development and leaf expansion. It influences the organization of chloroplast components, maintains the photosynthetic apparatus, and may also play a role in chlorophyll synthesis (De Campos et al., 2015). Additionally, cytokinin influences nutrient mobilization, and a plant's nutritional condition regulates its cytokinin levels. Applying commercial cytokinin-based products before flowering can stimulate vegetative growth and branch emission. This can be an alternative to increase the leaf area index (LAI) when problems arise establishing a soybean crop or when sowing occurs late in the growing season, resulting in low LAI due to a shortened development cycle (Figure 4.1.3.1).

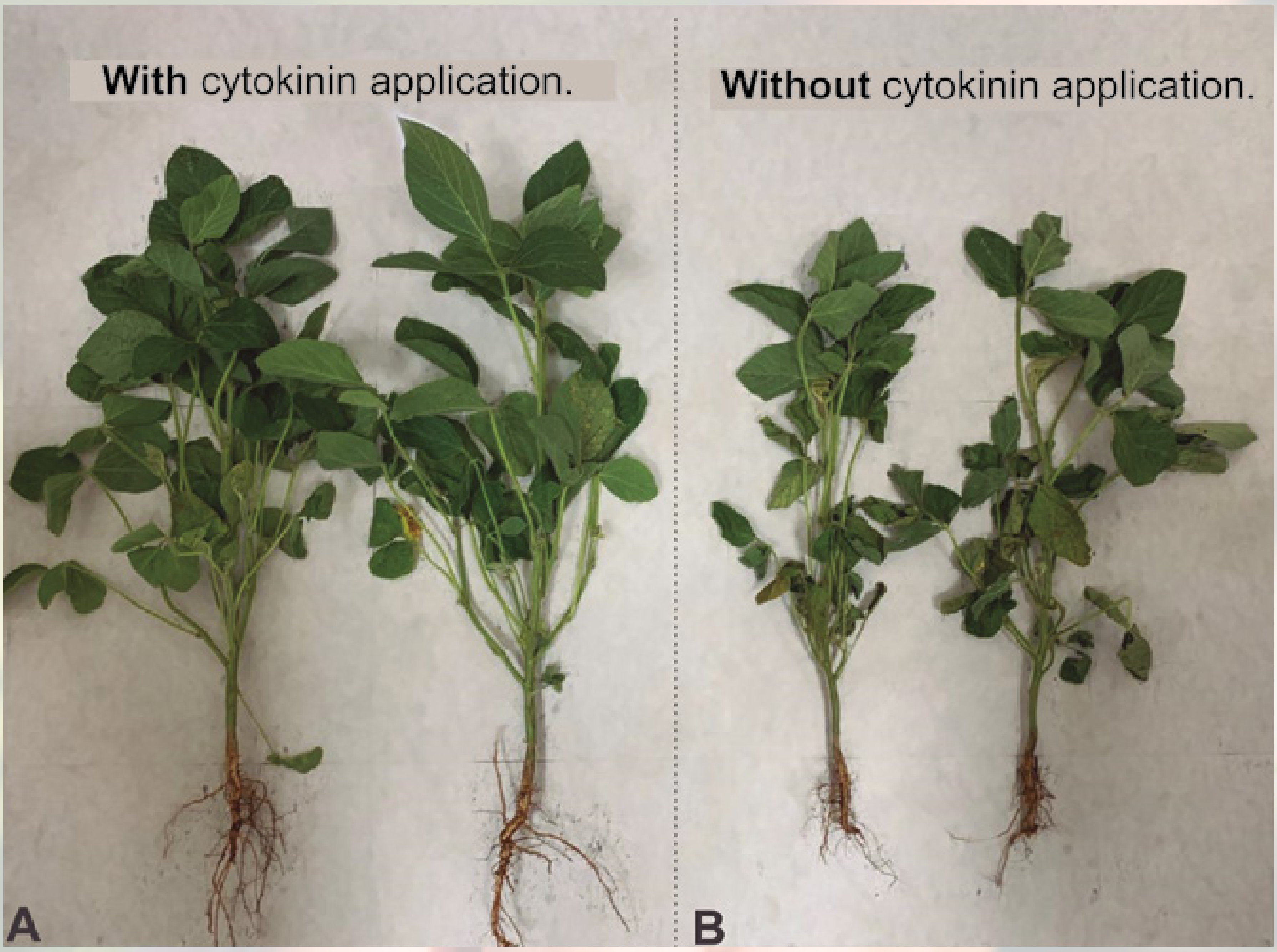

Figure 4.1.3.1. Soybean plants at the V5 stage with (Panel A) and without (Panel B) cytokinin application.

Cytokinins are also linked to vegetable attachment (Kokubum, 2010). As Figure 4.1.3.2 illustrates, there is a high concentration of cytokinin at the beginning of flowering, coinciding with the highest likelihood of a flower developing into a vegetable (Carlson, 1987). This suggests a potential role for cytokinins in promoting fruit set.

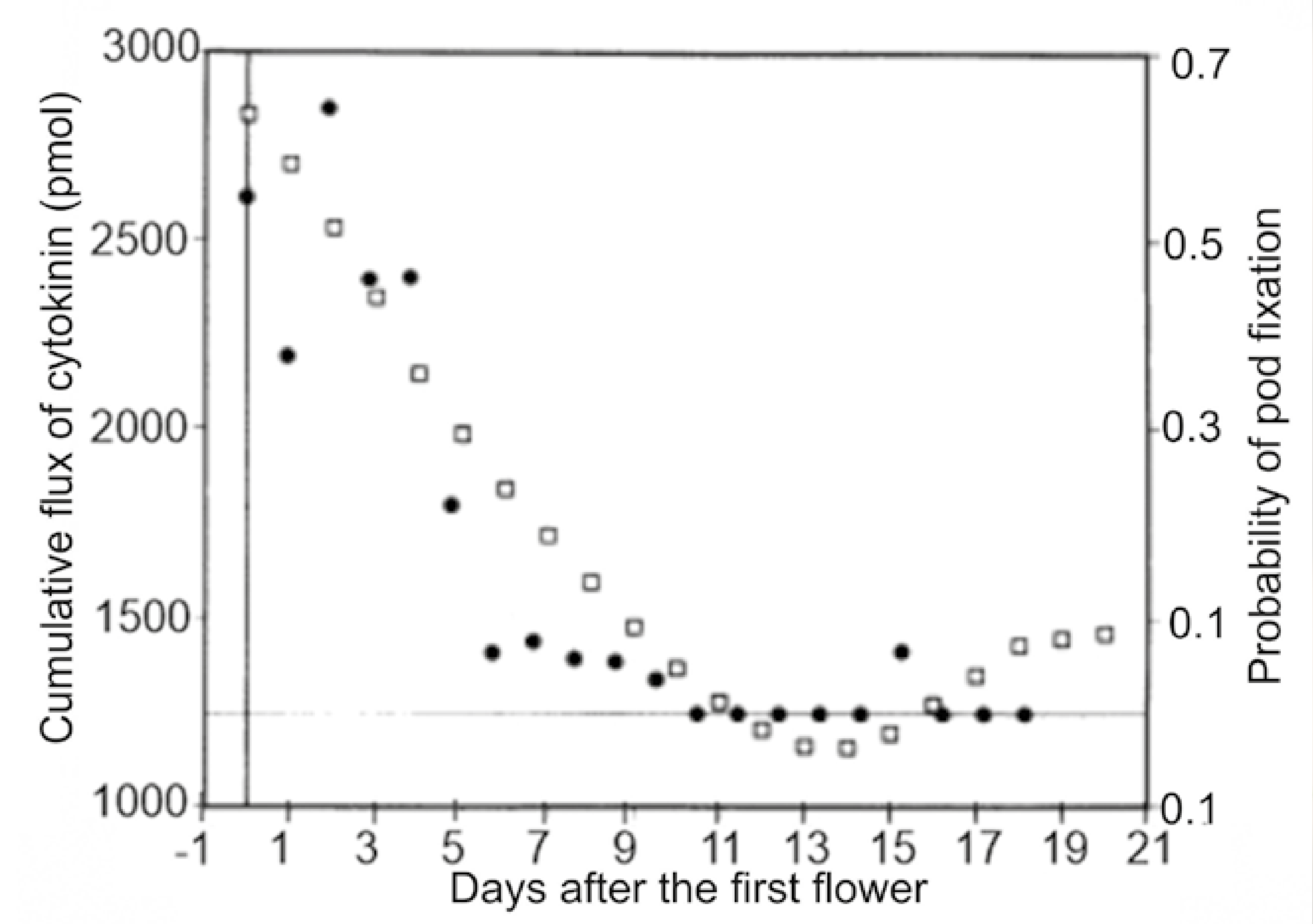

Figure 4.1.3.2. Relationship between the probability of flower initiation in legumes reaching maturity and the cumulative flux of cytokinin from the roots during reproductive development. Adapted from Carlson et al., 1987.

4.1.4. Ethylene (ET)

Ethylene, a gaseous phytohormone, is known for its involvement in plant stress responses, in addition to its roles in germination, fruit ripening, and organ abscission (Kläy et al., 2014). Ethylene production is more active in the meristematic regions and plant nodes. Various stresses, including injury, water deficiency, cold temperatures, and flooding, can induce ethylene biosynthesis (Taiz & Zeiger, 2009). Auxin also plays a regulatory role, with its application promoting an increase in ethylene levels within plants.

HaHB4® technology is a transgenic soybean event called HB4IND-00410-5. This event was generated through Agrobacterium-mediated transformation and contains the HaHB4® transcription factor gene variant from sunflower. HaHB4® belongs to the HD-Zip I class of genes, which are primarily involved in plant responses to abiotic stress (non-living environmental factors) like water deficit, salt exposure, and herbivory. They help plants tolerate these stresses by regulating processes like abscisic acid and ethylene signaling, photosynthesis, and repair of mechanical damage. Field trials showed that HaHB4® expression slightly delayed the soybean plants' maturation but also increased grain yield due to an increase in the number of seeds per plant, even though individual grain weight was slightly reduced (Ribichich et al., 2020). The average yield gain was 4%, with even greater increases (up to 10.5%) observed in hot and dry environments (Ribichich et al., 2020).

4.1.5. Gibberellin (GA)

Gibberellins are essential plant hormones for many developmental processes in plants, including seed germination, stem elongation, leaf expansion, trichome development, pollen maturation, and flowering induction (Achard & Genschik, 2009). GA was first identified in the pathogenic fungus *Gibberella fujikuroi* in rice culture, causing excessive elongation of infected plants (Yabuta, 1938).

Gibberellins induce the synthesis of hydrolytic enzymes that degrade the nutrient reserves accumulated in the endosperm (embryo) as the germination process occurs, making carbohydrates and energy available to sustain seedling growth. They also act in overcoming the mechanical resistance of the seed coat by weakening the tissues around the radicle (Taiz & Zeiger, 2013). Biosynthesis is related to strict genetic, environmental, and developmental control. For example, photoperiod and temperature can alter the gene transcription of gibberellin biosynthesis enzymes. The application of commercial gibberellin-based products in the vegetative phase aims to stimulate branching and increase the leaf area index, being recommended for situations where the crop has undergone stress (cold, intoxications).

Commercial Formulations Associated with Biofertilizers
Humic Substances (HS)

Humic substances (HS) are natural constituents of soil organic matter, resulting from the decomposition of plant, animal, and microbial residues, and the metabolic activity of soil microorganisms (Perminova et al., 2019). HS are categorized according to their molecular weights and solubility into humins, humic acids, and fulvic acids. These compounds exhibit a complex dynamic of association and dissociation in supramolecular colloids, influenced by plant roots through the release of protons and exudates (Du Jardin, 2015). Humic substances can be used to increase their cation exchange capacity (CEC), with a preference for use in areas with low CEC and organic matter. Humic substances improve nutrient absorption by the root system by promoting growth through the regulation of hormonal balance, increased respiration, and invertase activity (Jindo et al., 2012). Thus, the use of humic substances aims to improve soil conditions for root development, which can result in higher productivity depending on the characteristics and management of the crop.

Amino Acids

Amino acids are obtained by chemical and enzymatic hydrolysis of proteins from plant (sugarcane) or animal (animal leather) sources, forming compound or isolated amino acids (Calvo et al., 2014; Halpern et al., 2015). Amino acids are naturally produced by plants, where the base structure has a central carbon attached to an amine group (NH_2) and a carboxyl group (COOH). The location and size of the amino acid structure form variations, where for plants twenty basic variations are necessary for proper growth and development, namely: glycine, alanine, serine, cysteine, tyrosine, arginine, aspartic acid, glutamic acid, histidine, asparagine, glutamine, proline, phenylalanine, valine, tryptophan, threonine, lysine, leucine, isoleucine, and methionine.

Amino acids have direct effects on the absorption and assimilation of nitrogen (N) by plants and are related to nodulation.

Some amino acids, such as proline, act on the mobility and acquisition of micronutrients and also have a chelating effect to protect plants against heavy metals. Glutathione (a molecule composed of the amino acids glutamic acid, cysteine, and glycine), glycine, betaine, and proline act as non-enzymatic antioxidants, removing reactive oxygen species and potentially mitigating moderate environmental stresses such as thermal and saline stress (Colla et al., 2014), with the greatest effect from applications preceding the stress.

Seaweed Extracts

Seaweed consists of micro and macronutrients, sterols, nitrogen-containing compounds, and hormones, and is used to promote plant growth (Khan et al., 2009). Many of these compounds are unique to their seaweed source, explaining the growing interest of the scientific community and industry in these taxonomic groups. Most of the species used belong to the phylum of brown algae, with *Ascophyllum*, *Fucus*, and *Laminaria* being the main genera found. Commercially, seaweed is used in seed treatments to accelerate germination and plant establishment due to hormonal effects. Cytokinins, auxins, abscisic acid, gibberellins, and other hormone-like compounds have been identified in seaweed extracts (Craigie, 2011; Wally et al., 2013).

Chitosan and Biopolymers

Chitosan is a form of the biopolymer chitin. The physiological effects of chitosan on plants are due to its ability to bind to cellular components such as the plasma membrane, cell wall constituents, receptors, and plant defense elicitors (El Hadrami et al., 2010; Hadwiger, 2013). Consequently, chitosan has been developed over the years focusing on protecting plants against fungal pathogens and providing tolerance to abiotic stresses (drought, salinity, cold stress) by inducing stomatal closure through an ABA-dependent mechanism (Iriti et al., 2009).

Opportunities and Challenges

Biofertilizers face inherent challenges in new technologies, whether scientific, technical, or regulatory. In the scientific field, the main challenge is the complexity of the physiological effects of biofertilizers. Many of these responses affect primary metabolism, growth, and development, specific processes with multiple metabolic pathways in plant organisms, and their response depends on the environment. Often the use of biofertilizers shows genotypic changes (gene expression) in plants in the laboratory but does not express phenotypic (structural change in the plant) changes in the field. In the technical field, there are difficulties in how to monitor crops to decide whether to apply, when, and how to apply biofertilizers. Abiotic stresses and micronutrient deficiencies are difficult to identify and evaluate for defining quantitative criteria for decision-making on biofertilizer application. Despite everything, the need to make agricultural production more sustainable due to climatic and economic fluctuations drives the biofertilizer market, which emerges as a new strategy for mitigating stresses in soybean crops.

5. Soybean Sowing Season

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Kelin Pribs Bexaira; Cristian Savegnago; Leonardo Silva Paula; Marcos Dalla Nora;
Edgardo Santiago Arevalo; María Soledad Armoa Báez; Luciano Zucuni Pes;
Nereu Augusto Streck; Cleber Alberto Maus; Geter Alves Machado;
Mateus Possebon Bortoluzzi; Leonardo Munari; Daniel Andrei Robe Fonseca;
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Darci Francisco Uhry Junior; Camille Flores Soares; Paula de Souza Cardoso;
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The soybean sowing season should be defined based on knowledge of the environment, genetics, phenology, and management characteristics of each field and/or farm. In defining the soybean sowing season, there is a pattern of climatic characteristics that provide higher yields and/or lower risk of losses. This chapter will address some management factors that characterize the sowing seasons to achieve high yields and minimize the risk of yield loss.

The yield potential of the soybean crop can be defined as the maximum yield achievable per unit area of a given cultivar in an adapted environment without limitations from nutrients, weeds, pests, and diseases (Evans, 1993). In irrigated environments, it is assumed that the plant grows without water stress; therefore, the growth rate is defined only by temperature, solar radiation, atmospheric CO_2, and genetic characteristics. In non-irrigated environments, water becomes a limiting factor for yield potential, being referred to as water-limited yield potential (Van Ittersum et al., 2013). The easiest and most efficient way to modify the growing environment during soybean cultivation is through the sowing season because to achieve yields close to the crop's yield potential, it is necessary to adjust the sowing season so that the best environmental conditions coincide with the most sensitive phases of its development.

The soybean cultivars currently sown require between 650 and 800 mm to achieve high yields, with rainfall and/or irrigation needing to be well-distributed throughout the development cycle, especially during the reproductive phase (Zanon et al., 2016a; Monteiro, 2009). Without water restriction, the pod formation and grain filling period should coincide with the period of the longest photoperiod (Figure 5.1) and, consequently, the highest photothermal coefficient (See item 2.5).

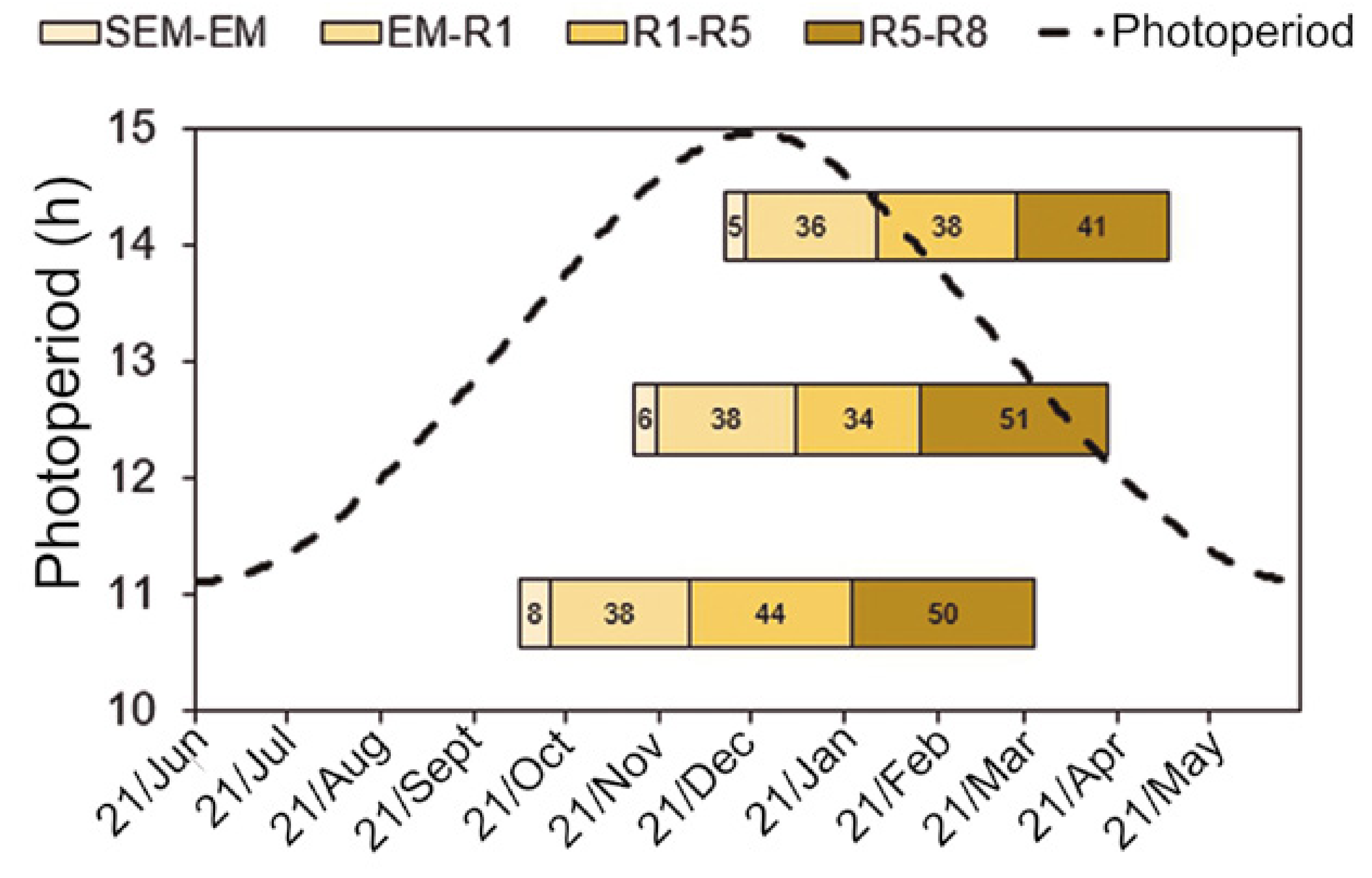

Figure 5.1 Phenological stages of soybeans in relation to photoperiod in sowings of 15/10, 15/11, and 15/12 in southern Brazil. The cycle duration is based on the optimal agronomic cycle for each sowing date (item 1.6.1).

5.1.1. Sowing time to reach high yield in Brazil

Using mathematical models, the GYGA Brazil team (www.yieldgap.org/brazil) employed the CROPGRO soybean model in the DSSAT platform v. 4.7 (Hoogenboom et al., 2004) to simulate daily soybean sowings, from October 1st to December 31st, for Brazil's soy-producing regions (Hoogenboom et al., 2004). This data allowed them to define the achievable yield potential, the period when this potential can be reached, and the date at which yield reduction due to delayed seeding begins.

According to the analysis, Brazil can be divided into 5 yield potential zones, determined by latitude and the impact of delayed sowing on yield potential in each location (Figure 5.1.1.1). The first zone includes the states of Pará, Piauí, Maranhão, and northern Tocantins. Here, yield potential can reach 5.7 ton ha^{-1} (ha), with a reduction of 20 kg ha^{-1} per day^{-1} for sowings after November 18th. The second zone encompasses the center and north of Mato Grosso, south of Tocantins, north of Goiás and Bahia. This zone has a yield potential ranging from 5.7 to 6.1 tons ha^{-1}, and a yield reduction of 27 to 29 kg ha^{-1} per day^{-1} for sowings after November 6th and November 16th, respectively. The third zone includes the south of Mato Grosso, south of Goiás, north of Mato Grosso do Sul, north of São Paulo, and Minas Gerais. This zone's yield potential ranges from 6.1 to 6.7 tons ha^{-1}, with yield reduction starting at 33 to 37 kg ha^{-1} per day^{-1} for sowings after November 3rd to 15th, respectively.The fourth region encompasses the south of Mato Grosso do Sul, south of São Paulo, north of Santa Catarina and Paraná. Yield potential here ranges from 6.7 to 7.2 ton ha^{-1} (ha), with a potential yield loss of 39 to 42 kilograms per hectare per day (kg ha^{-1} day^{-1}) for plantings carried out from November 27th to October 31st (later plantings experiencing greater losses). The fifth region comprehend comprises Rio Grande do Sul . Yield potential here varies from 6.5 to 7.2 ton ha^{-1}, with a potential yield reduction of 37 to 39 kg ha^{-1} day^{-1} for plantings done between October 23rd and November 4th.

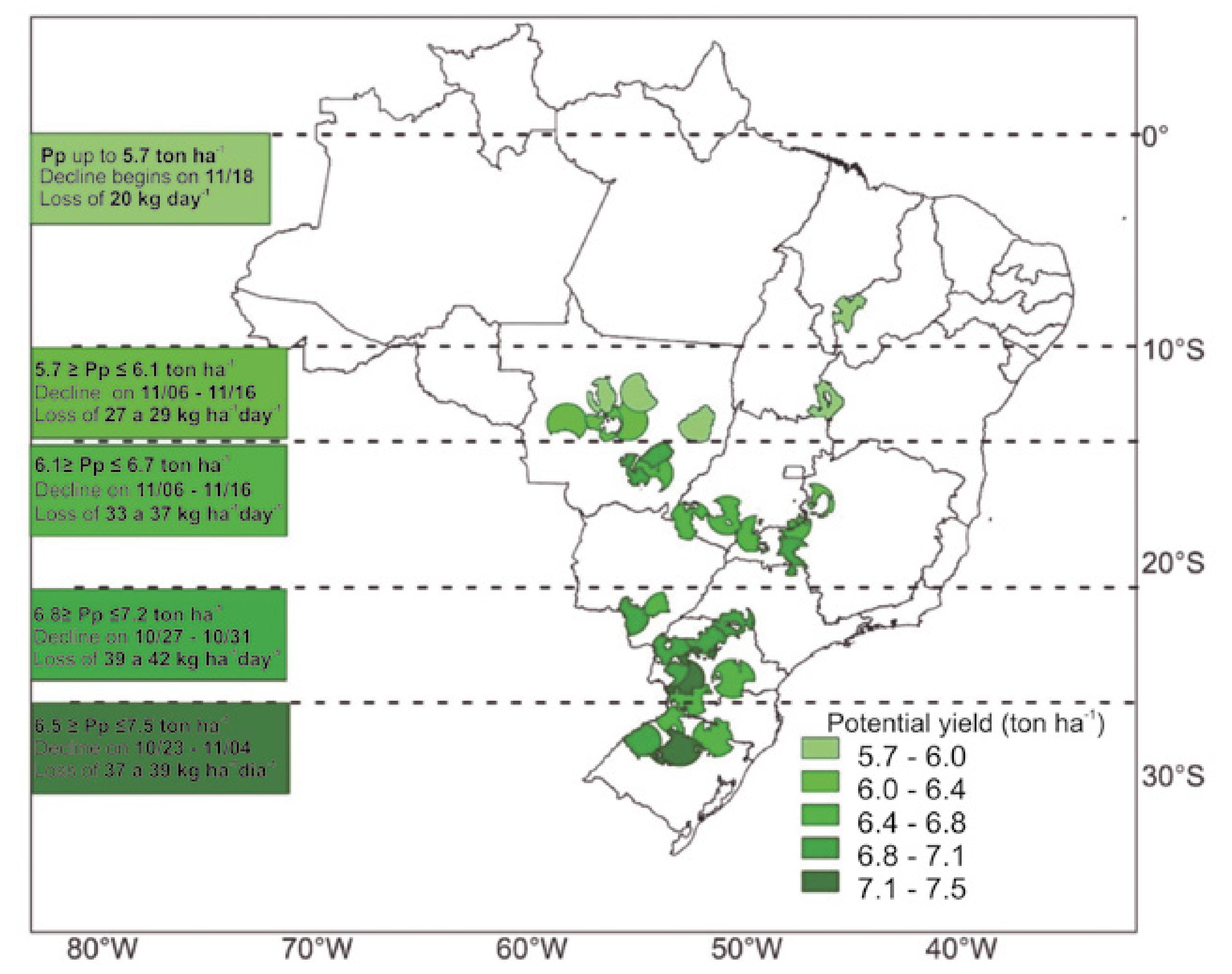

Figure 5.1.1.1. Soybean yield potential (kg/ha) and the onset of yield decline, along with daily yield reduction (kg/ha/day), analyzed across five latitude bands in Brazil. Source: www.yieldgap.org/Brazil.

From this analysis, yield potential in Brazil reveals two key trends. First, a positive correlation exists between yield potential and latitude. Soybeans planted further south benefit from longer days and increased solar radiation during their development period, likely contributing to higher yields. Second, there's a greater potential yield loss with delayed sowing in regions with higher yield potential. This is evident in the fifth region compared to the fourth. The variation in yield potential within the fifth region is likely due to the influence of higher temperatures, such as those experienced in the northwest regions of Rio Grande do Sul.

5.1.2. Sowing time to reach yield potential by maturity group in Southern Brazil – A case study with soybean crops

In southern Brazil's subtropical environment, experiments with and without irrigation have shown that the yield potential of soybeans can be achieved with plantings up to November 4th, after which there is a daily yield reduction of 26 kg ha^{-1} (Zanon et al., 2016a) (Figure 5.1.2.1 A).

The experimentally determined YP (6 tons ha^{-1}) differs from the model-predicted YP (7 tons ha^{-1}). This is because growers don't always optimize all aspects of their production systems, and economic feasibility limits the adoption of practices suggested by models. As a result, models tend to simulate higher yield potential than achieved in experiments. Consequently, the yield loss estimated by experiments due to delayed sowing (26 kg ha^{-1} day^{-1}) is lower than the loss predicted by models (37 kg ha^{-1} day^{-1}).

The cumulative probability function of yield was calculated for three sowing dates in Rio Grande do Sul (RS): before October 31st, November 1st to November 30th, and after December 1st (Figure 5.1.2.1 B). The vertical line indicates the probabilities of achieving yields below or above 3 tons ha^{-1}. The probability analysis shows a 80% chance of achieve yield equal to or greater than 3 ton ha^{-1} in sowings up to 10/30, while in sowings from of 01/12 the probability is 42%.

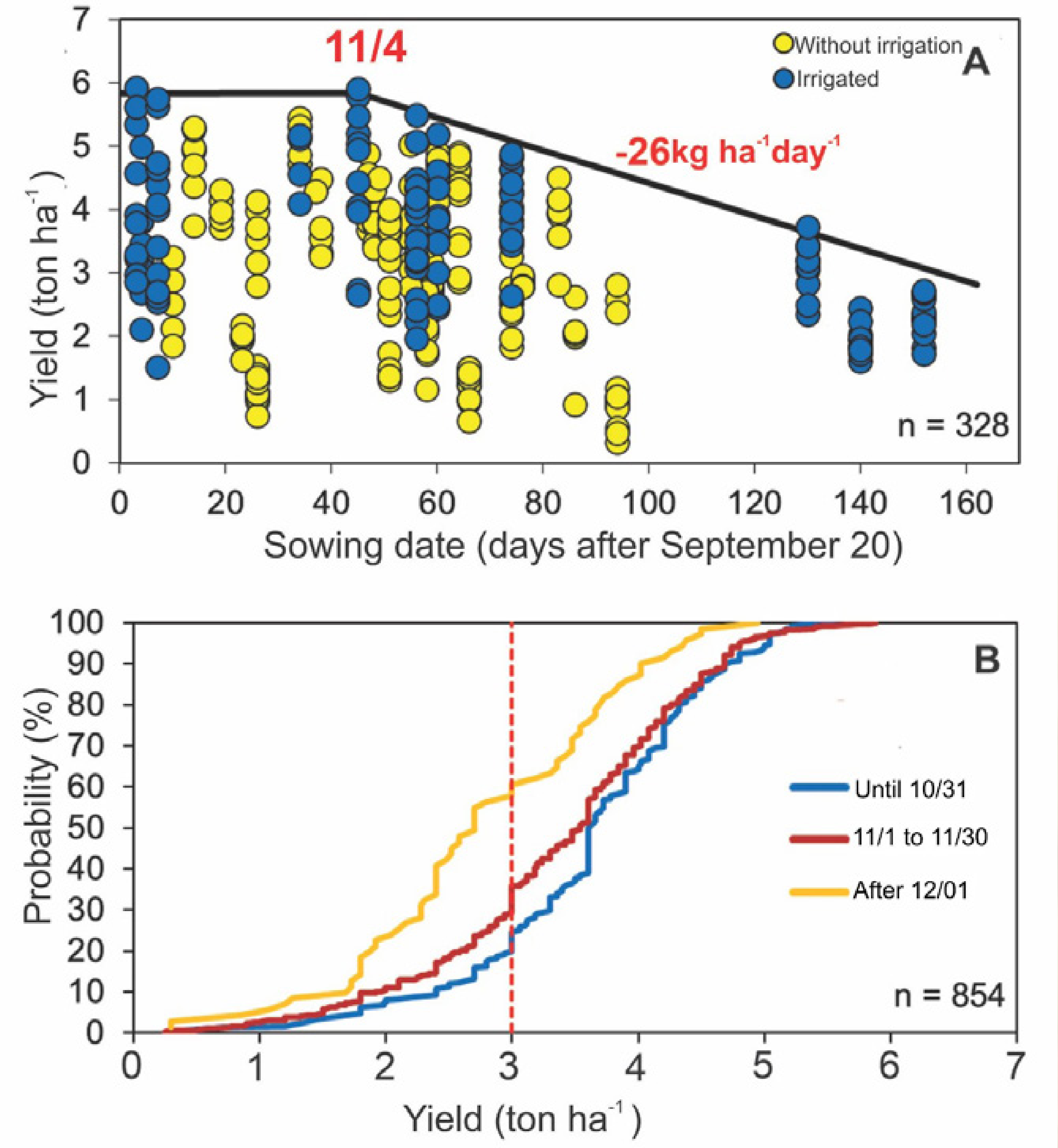

Figure 5.1.2.1. Relationship between grain yield and growing season sowing time (expressed in days after September 20th) for crops of irrigated soybean (blue circle) and rainfed (yellow circle) during four harvests (2011/2012, 2012/2013, 2013/2014 and 2014/2015) (A), and analysis of probability for productivity of 3 ton ha^{-1} (red line) as a function of sowing date (B) in southern Brazil. Solid line indicates the function limit (y = 5842) before November 4th; (y = 5842 – 0.026x) after November 4th. Source: Zanon et al. (2016a).

The reduction in yield potential due to delayed sowing varies based on the maturity group (MG) used by the producer. Different intensity levels and sowing periods lead to varied outcomes. Cultivars with MG ≤ 5.5 (Figure 5.1.2.2 A) exhibit a higher yield potential (6 tons ha^{-1}) but have a more limited ideal sowing window, from September 20th to November 3rd. Beyond November 3rd, the yield potential of these cultivars decreases by 30 kg ha^{-1} per day. For cultivars with MG between 5.6 and 6.4 (Figure 5.1.2.2 B), the sowing season to achieve maximum yield extends until November 15th. However, the yield potential reduces by 25 kg ha^{-1} per day for sowings after November 15th. Cultivars with MG ≥ 6.5 (Figure 5.1.2.2 C) maintain their yield potential until November 20th, with a reduction of 25 kg ha^{-1} per day thereafter. Understanding the response of different MGs across a broad range of sowing times, particularly in southern Brazil, allows for the strategic positioning of soybean cultivars based on specific Genotype x Environment x Management x Producer (G x H x M x P) interactions. This approach helps reduce the yield gap without increasing soybean production costs.

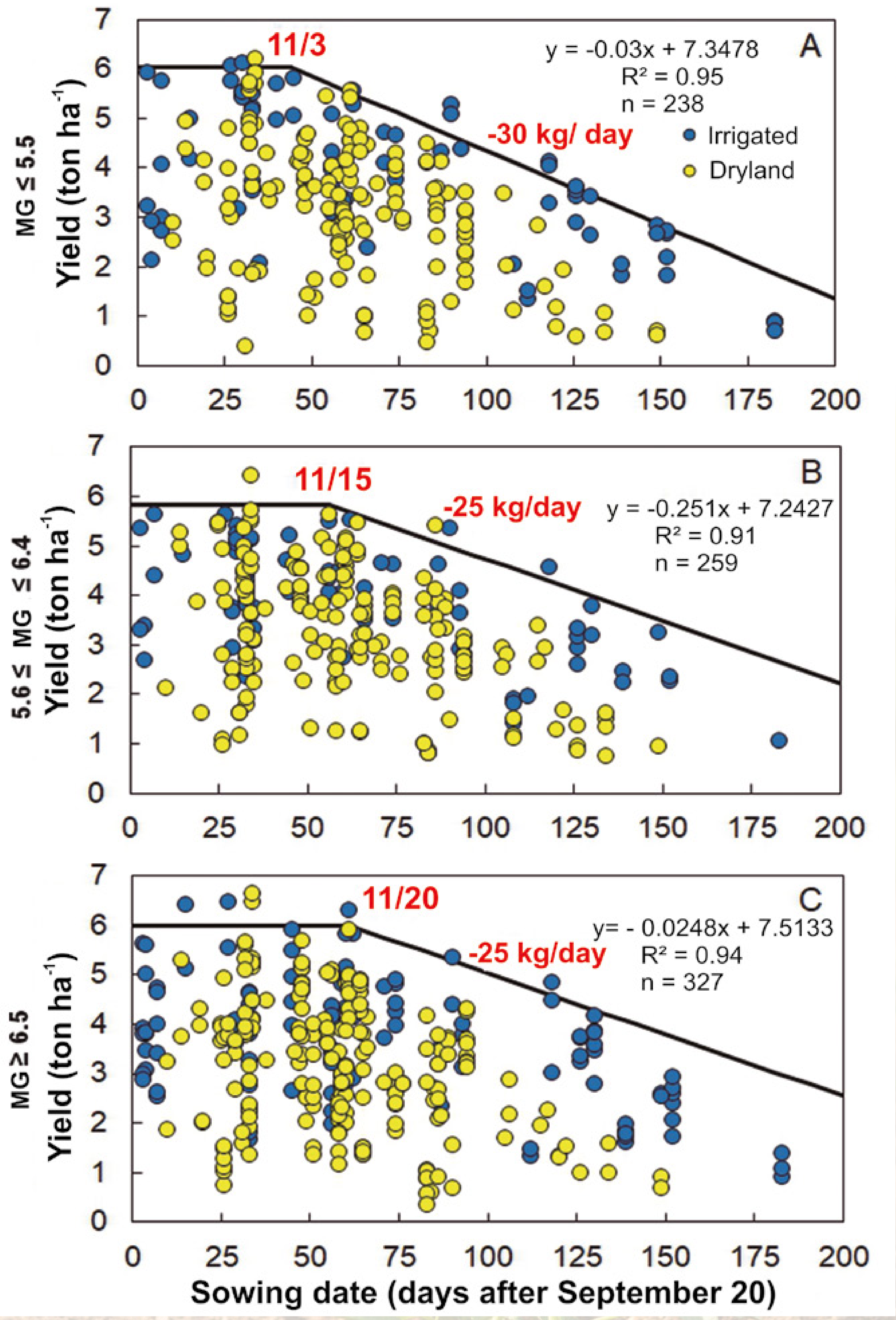

Figure 5.1.2.2 Soybean yield (ton ha^{-1}) in southern Brazil in relation to the sowing time (days after September 20th) for different ranges from MG. MGs ≤ 5.5 (A), MGs 5.6 to 6.4 (B), and MG ≥ 6.5 (C). Blue circles represent experiments with irrigation, while yellow circles represent experiments without irrigation. The black solid line represents the threshold function. Adapted from Tagliapietra et al., 2021.

5.2. Sowing time to minimize the risks of yield loss

Sowing time is a crucial factor used to assess the risk of yield loss due to climatic factors, with rainfall being the meteorological element most associated with decreased grain productivity in soybean crops (Sentelhas et al., 2015). The two critical stages of development during which water deficit poses a significant risk to soybean productivity are germination/emergence and flowering/grain filling. Water deficit during germination/emergence reduces plant density per square meter, particularly affecting seeds with low vigor. On the other hand, water deficit during flowering/grain filling triggers physiological changes in the plant, such as stomatal closure, leaf curling, premature shedding of leaves and flowers, and abortion of pods, ultimately leading to reduced grain yield (Tagliapietra et al., 2021).

Given that sowing time is the management factor that most impacts the soybean growth environment and, consequently, grain yield, Brazil annually determines and updates the Agricultural Zoning of Climate Risk (ZARC). ZARC aims to advise farmers on the optimal crop establishment timing for each region based on the historical climate data, predicting the likelihood of adverse weather conditions. Compliance with ZARC guidelines is necessary to qualify for rural insurance and participate in the Agricultural Activity Guarantee Program (PROAGRO). Farmers who do not adhere to ZARC recommendations risk having their claims denied in case of crop failure or other accidents.

The Agricultural Zoning of Climate Risk (ZARC) for soybean crops determines the optimal period for sowing at a municipal level based on several parameters, including the “Satisfaction Index of Water Requirement” (ISNA) and thermal limits that define risk levels at 20% (satisfied in 80% of years), 30% (satisfied in 70% of years), and 40% (satisfied in 60% of years). The ISNA represents the water consumption by the plant relative to its maximum potential consumption without water restrictions.

The analysis involves a crop balance model that considers climate, soil, and plant factors:

a) Rainfall: Historical daily data spanning at least 15 years from available weather stations are used.

b) Potential evapotranspiration: Estimated for ten-day periods using climatological data from available stations in the state.

c) Phenological phases of the crop: The crop cycle is divided into four stages—germination/emergence, growth/development, flowering/grain filling, and physiological maturation—based on cultivar maturity group (MG), sowing date, and region, with cycles ranging from 100 to 180 days.

d) Crop coefficient (Kc): Data obtained from experiments and literature (Kc initial = 0.35, Kc mid = 1.15, Kc end = 0.50).

e) Maximum soil water availability: Estimated based on root depth and soil type (Types 1, 2, and 3 with water storage capacities of 35, 55, and 75 mm, respectively).

The ZARC zoning considers an ISNA greater than 0.60 during the germination/emergence phase. During flowering and grain filling, the ISNA is adjusted variably (0.50 to 0.65) based on sowing time and region.

Lavoura na Fazenda Primavera (Lorivan Formighieri), em Alegrete, no Rio Grande do Sul, Brasil com produtividade de 3720 kg ha^{-1}, safra 2020/21.

5.3. Sowing time aiming at intensification sustainable production system

Increasing yield at the system level of cultivation is an important strategy to enhance overall production systems, aiming to maximize productivity while optimizing individual crop yields (Andrade et al., 2015). In environments where growing two crops per year is restricted, crop rotation becomes a sustainable intensification strategy, allowing for optimal soybean productivity by planting at the ideal time. In regions with long growing seasons that permit two harvests per year, there is an opportunity to improve natural resource efficiency and increase total system productivity (tonnes per hectare) (Guilpart et al., 2017).

Expanding the number of crops in the same area is a key agricultural practice for boosting production. Sustainable intensification through crop diversification not only increases grain productivity per unit area but also enhances soil physical and chemical properties, potentially reducing production costs (Carauta et al., 2017). However, choosing between one or two grain harvests in the same area requires comprehensive knowledge of the crop requirements and resource availability in each environment. Often, the longer duration of one crop delays the subsequent crop, potentially affecting its yield. Thus, the challenge lies in maximizing the production potential of crop sequences.

In most of the Center-West of Brazil, production system intensification involves planting soybeans (after fallow periods in September and October), followed by corn planting (after soybean harvest in January and February) (Figure 5.3.1). In this setup, soybeans have their most demanding phase coinciding with the period of maximum environmental resource availability. However, using soybean cultivars with shorter cycles (95 to 110 days) may reduce their productivity compared to cultivars with longer cycles exceeding 110 days. Nonetheless, shorter soybean cycles are essential for enabling the subsequent planting of corn or cotton, thereby enhancing the productive potential of the cropping system (soybean-corn) compared to growing only soybeans or corn (Battisti et al., 2020; Ribeiro et al., 2020; Pereira Filho & Borghi, 2020).

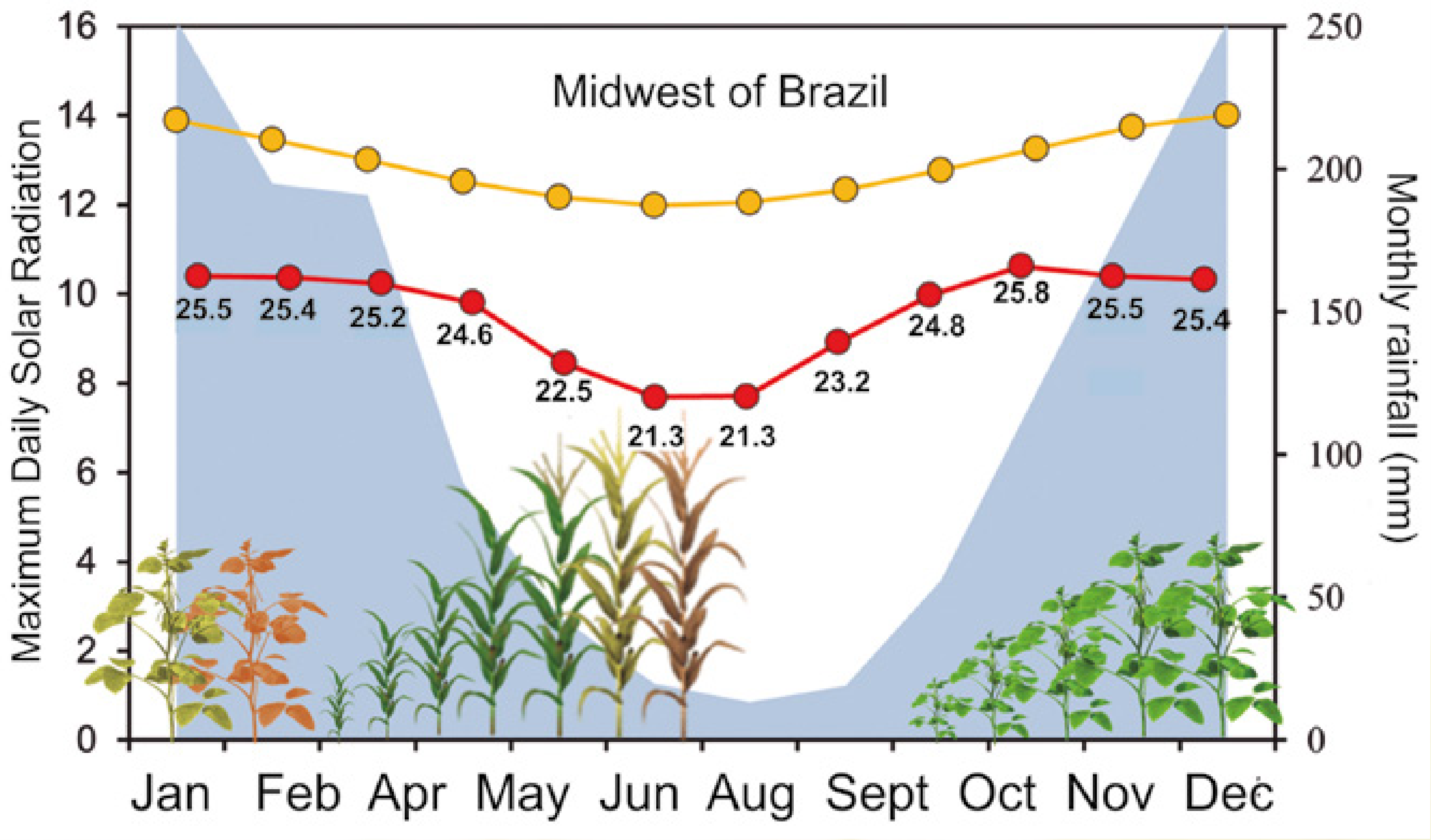

Figure 5.3.1. Illustration of the production system in the Midwest of Brazil showing maximum daily solar brightness (hours, y-axis - line and yellow circle), average temperature (°C, red line and circle) and monthly rainfall (mm, secondary y-axis - area in blue).

In certain regions of southern Brazil, such as the western part of Santa Catarina (SC) and the northwest of Rio Grande do Sul (RS), soybeans are planted after corn harvest between January and February (see Figure 5.3.2). Unlike the Midwest, the annual variation in photoperiod and lower temperatures in August and September (cold months with shorter days) typically prevent soybean planting during this period. Consequently, producers opt to plant corn as the first crop (from August to January) followed by soybeans (January to May).

The reduced availability of solar radiation and shorter daylight hours for soybeans planted as a second crop can decrease its productivity potential (Zanon et al., 2015), although it provides better conditions for corn planted as the first crop (Ribeiro et al., 2020) (see Figure 5.3.3). Despite the benefits of this cropping system, intensification also brings increased risks. In the Midwest, there is a heightened risk of water deficits for corn during grain filling, while in the south, there is a greater risk of frost during the initial development of corn planted at the end of July. For soybeans, the greatest risk of frost occurs towards the end of the development cycle in May (Nóia Junior et al., 2020).

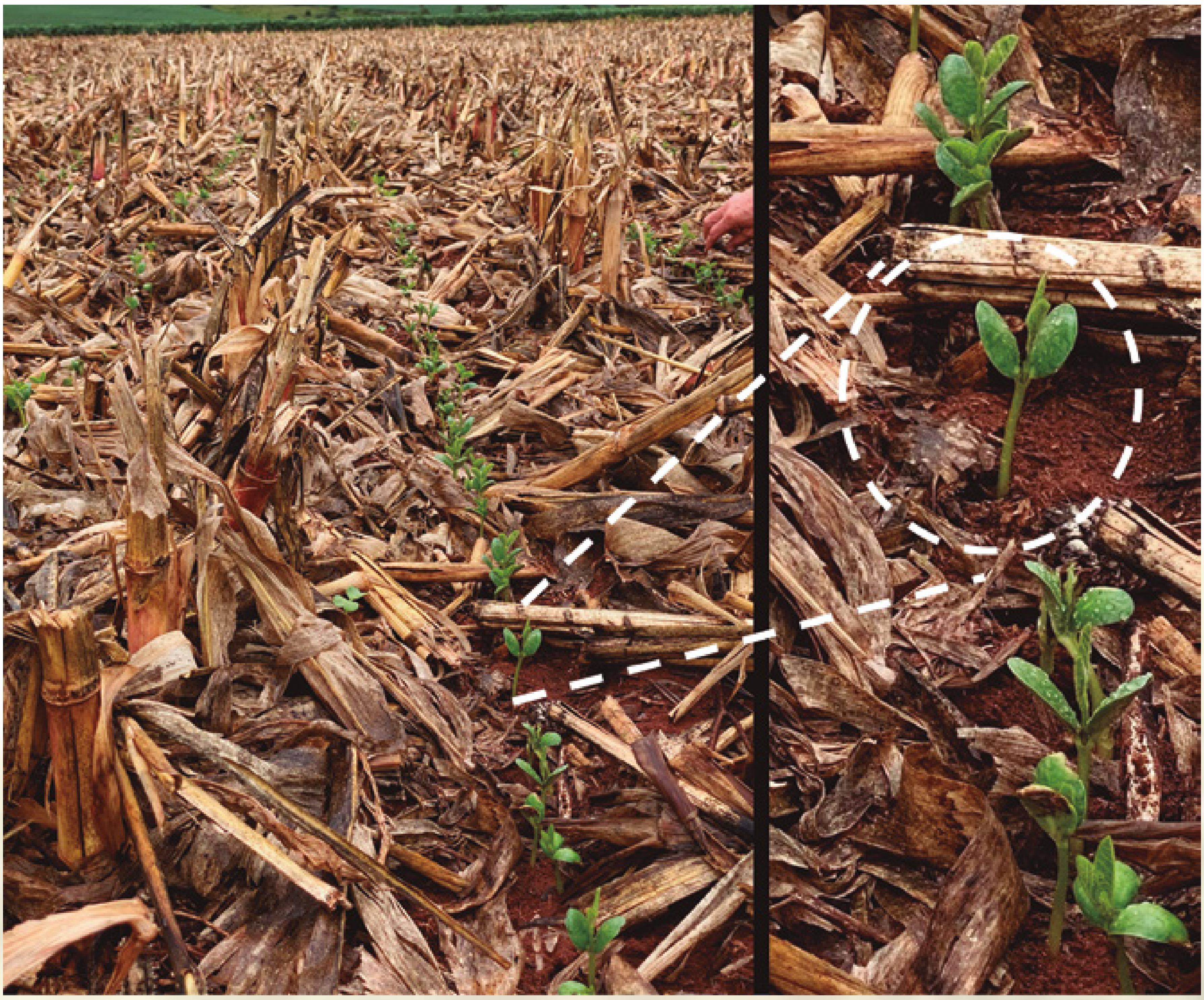

Figure 5.3.2. Eleven-day-old soybeans, sown on January 17th, after corn harvest, in Júlio de Castilhos, Rio Grande do Sul, Brazil, yield of 3360 kg ha^{-1}, in the 2020/21 harvest. Courtesy: Letícia Miranda Cechin.

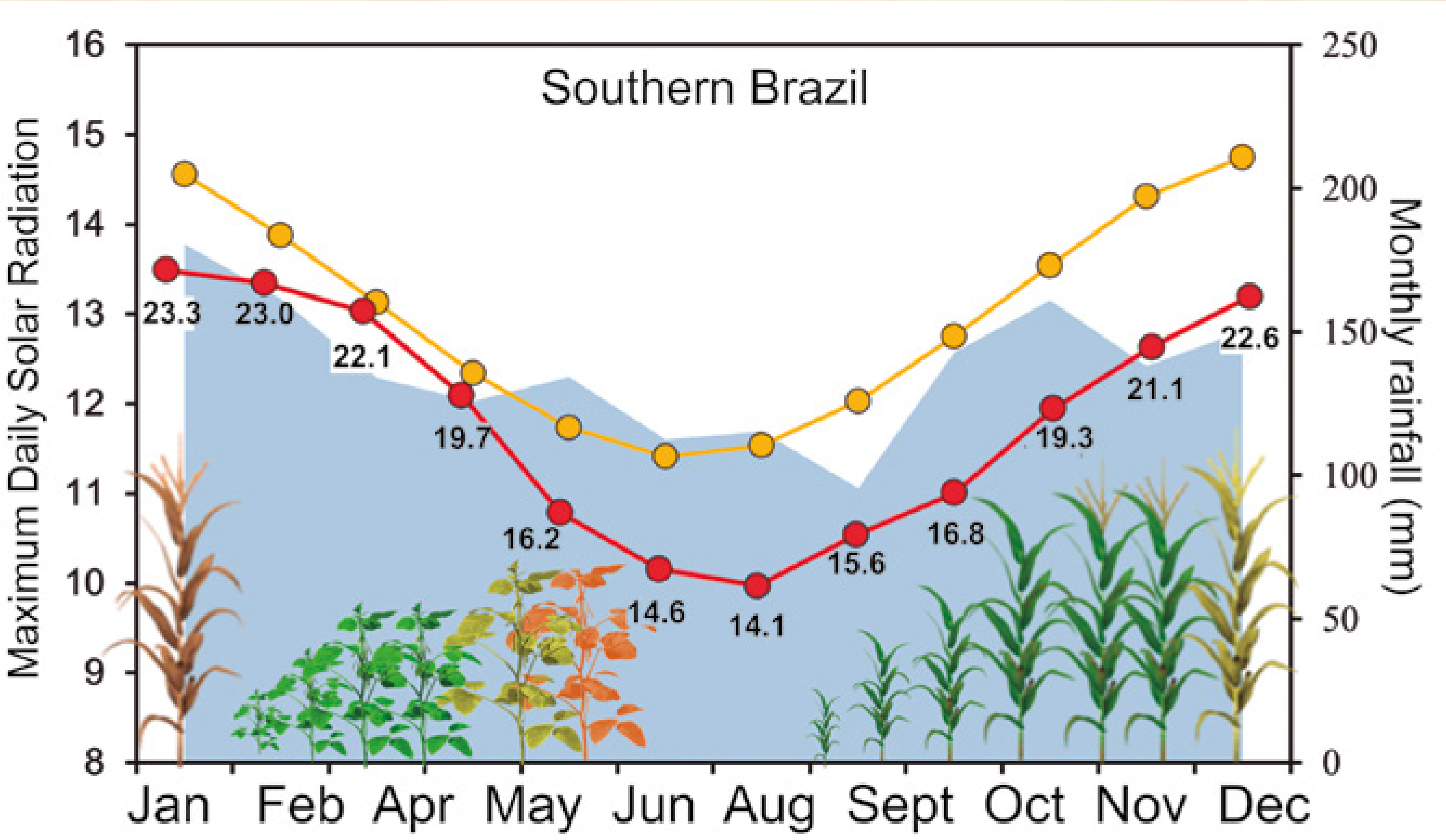

Figure 5.3.3. Illustration of the production system in southern Brazil. Shine daily solar maximum (hours, y-axis - line and yellow circle), temperature average (°C, red line and circle) and monthly rainfall (mm, y-axis secondary - area in blue).

One of the established production systems in the southern region of Brazil is the rice-soybean rotation system in flooded areas. In this system, the development of soybeans is constrained by the hydromorphic characteristics of the soil and the intensive soil preparation required for irrigated rice cultivation, leading to soil compaction that reduces water infiltration rate and soil aeration, which is detrimental to soybean root development (Theisen et al., 2017). Besides the risk of excess water, there is also a significant risk of water deficit due to the low soil water storage capacity, with water limitation occurring in this system approximately 56% of the time over the last fifteen years (2005 to 2020) (Ribas et al., 2021).

To mitigate the risks of water deficit or excess in lowland areas affected by the ENSO phenomenon (La Niña = higher risk of water deficit, El Niño = higher risk of water excess), adjusting the sowing season is an option (Bueno et al., 2020; Sartori et al., 2016a, Sartori et al., 2016b; Nóia Júnior et al., 2020). Soybeans sown before October 15th in lowland areas are at a high risk of water excess during early development due to lower evapotranspiration demand and higher precipitation events (Bortoluzzi et al., 2020). October is typically the month with the highest rainfall in the South of Brazil.

Despite these challenges, production costs and labor requirements are respectively 30% and 27% lower in the soybean-rice rotation system compared to the traditional rice-rice system (Ribas et al., 2021). The cost savings in the soy-rice system outweigh the lower yield and gross revenue compared to the rice-rice system (Ribas et al., 2021). Additionally, this system can be further intensified through the use of a furrow/ridge cultivation system, which facilitates drainage by directing water flow through furrows (Cassol et al., 2020) (Figure 5.3.4). In addition to irrigating the crop during water deficit periods, the implementation of the furrow/ridge system during periods of higher rainfall volumes allows for drainage and increased soil aeration in the surface layer (Gubiani et al., 2018; Sartori et al., 2015).

Figure 5.3.4. Polytube irrigation system. Courtesy: Geovano Parcianello, Alegrete, Rio Grande do Sul, Brazil.

Despite the risks and increased complexity, managing rural properties based on a systems approach enhances sustainability by reducing environmental impact, lowering costs, and increasing profits, particularly when considering gross energy production rather than just grain production. Gross energy production yield is higher in environments with two harvests compared to single-crop environments (Battisti et al., 2020). Therefore, the key challenge is to maximize successive crop production in environments capable of supporting two harvests, while recognizing that the productivity of each crop depends on the performance and management of the preceding crop.

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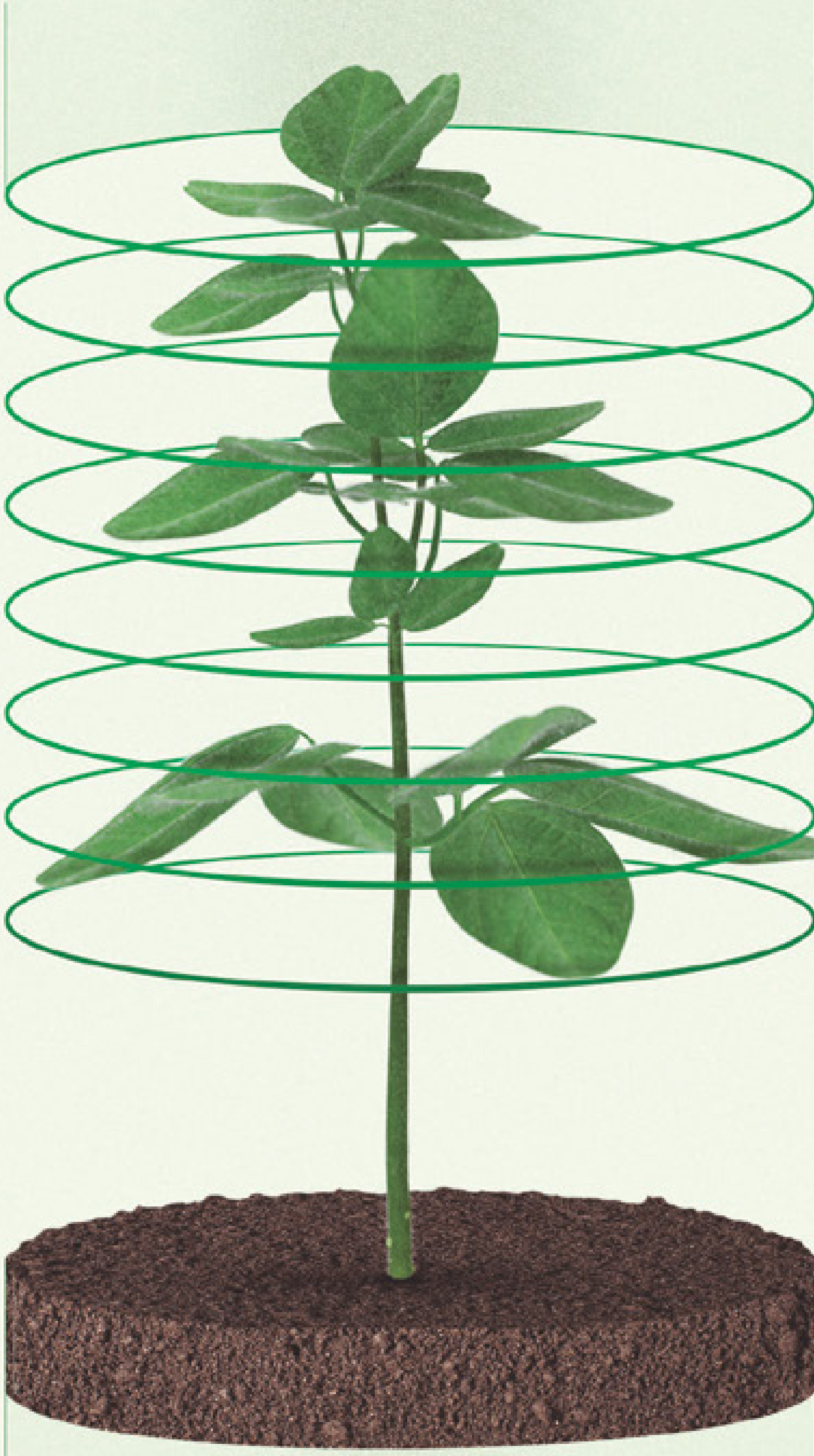

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6. Soybean yield potential and gaps

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Statistics project that by 2050, the world population will approach 10 billion inhabitants, necessitating a 50% to 70% increase in agricultural production to meet the growing food demand. To achieve this, it is imperative to identify the yield potential (YP) of agricultural crops to predict the potential increase in food production globally, focusing on vertical productivity gains without expanding into less suitable or higher-risk areas that threaten biodiversity (FAO & DWFI, 2015).

A critical scientific question researchers are addressing worldwide is whether sustainable food production for 10 billion people by 2050 is achievable while ensuring global food security. In this context, Brazil plays a crucial role as a major producer and exporter, particularly with soybean cultivation. The most extensive agronomic initiative for estimating the yield potential of agricultural products worldwide is the Global Yield Gap Atlas (GYGA - www.yieldgap.org). This project, endorsed by the scientific community (Grassini et al., 2014; Van Bussel et al., 2015; Van Wart et al., 2013; de Groot et al., 2017; Marin et al., 2016; Aramburu Merlos et al., 2015; Wolf et al., 2015), has assessed over 15 crops in 70 countries.

Yield potential (YP) refers to the yield achievable by a cultivar under optimal conditions without limitations in water, nutrients, or biotic stresses (diseases, pests, and weeds). The growth rate of the plant or crop is primarily determined by intercepted solar radiation, temperature, atmospheric CO_2 levels, and genetic traits (Evans, 1993; Van Ittersum & Rabbinge, 1997). Potential water-limited yield (YW) is similar to YP but additionally considers water availability and soil characteristics impacting water storage capacity, influencing crop yield potential (Van Ittersum et al., 2013; FAO & DWFI, 2015) (see Figure 6.1).

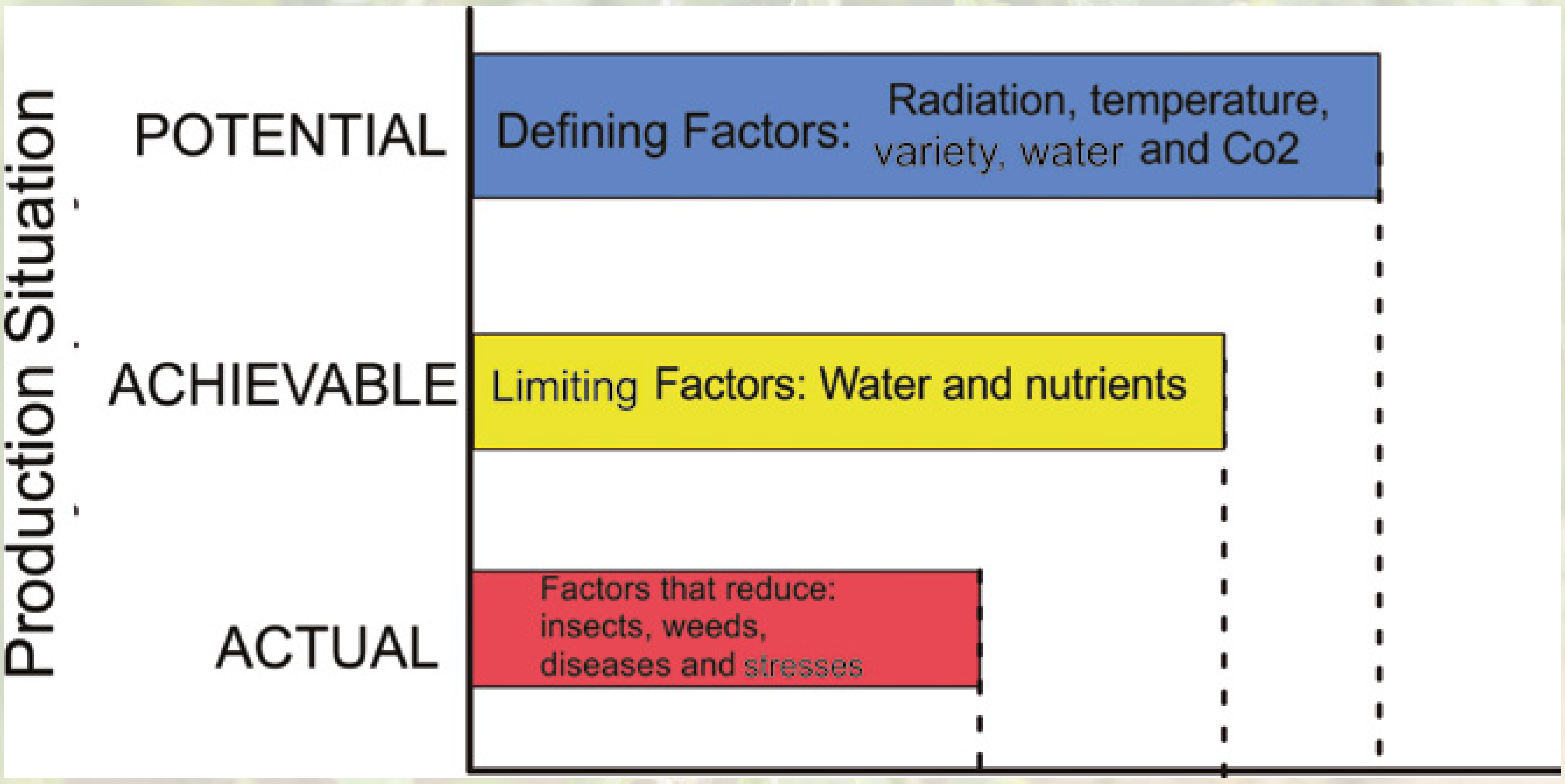


Figure 6.1 Factors that define the yield potential of a crop, including limitations to potential yield and factors that reduce actual yield relative to production level and conditions.

Understanding the yield potential (YP) and potential water-limited yield (YW) across different climatic regions and soil characteristics enables producers to efficiently plan their crop management strategies. By adjusting resource investments to achieve yields close to 80% of YP (for irrigated areas) or YW (for rainfed areas), producers can maximize resource use efficiency, profitability, and sustainability of the production system (Van Ittersum and Rabbinge, 1997) (see Figure 6.2). To estimate the potential growth of soybean production in Brazil within current arable areas, only a small fraction—11% of 200 evaluated areas (covering crop years from 2014/15 to 2016/17) under the Maximum Yield Challenge initiated by the Soja Brasil Strategic Committee—achieved yields exceeding 80% of YW (Battisti et al., 2018).

This information underscores the importance of optimizing crop management practices based on YP and YW assessments to enhance agricultural productivity and sustainability, particularly in regions with diverse climatic and soil conditions. Achieving yields close to the maximum potential represents a significant opportunity for improving food security and meeting future global food demands efficiently.

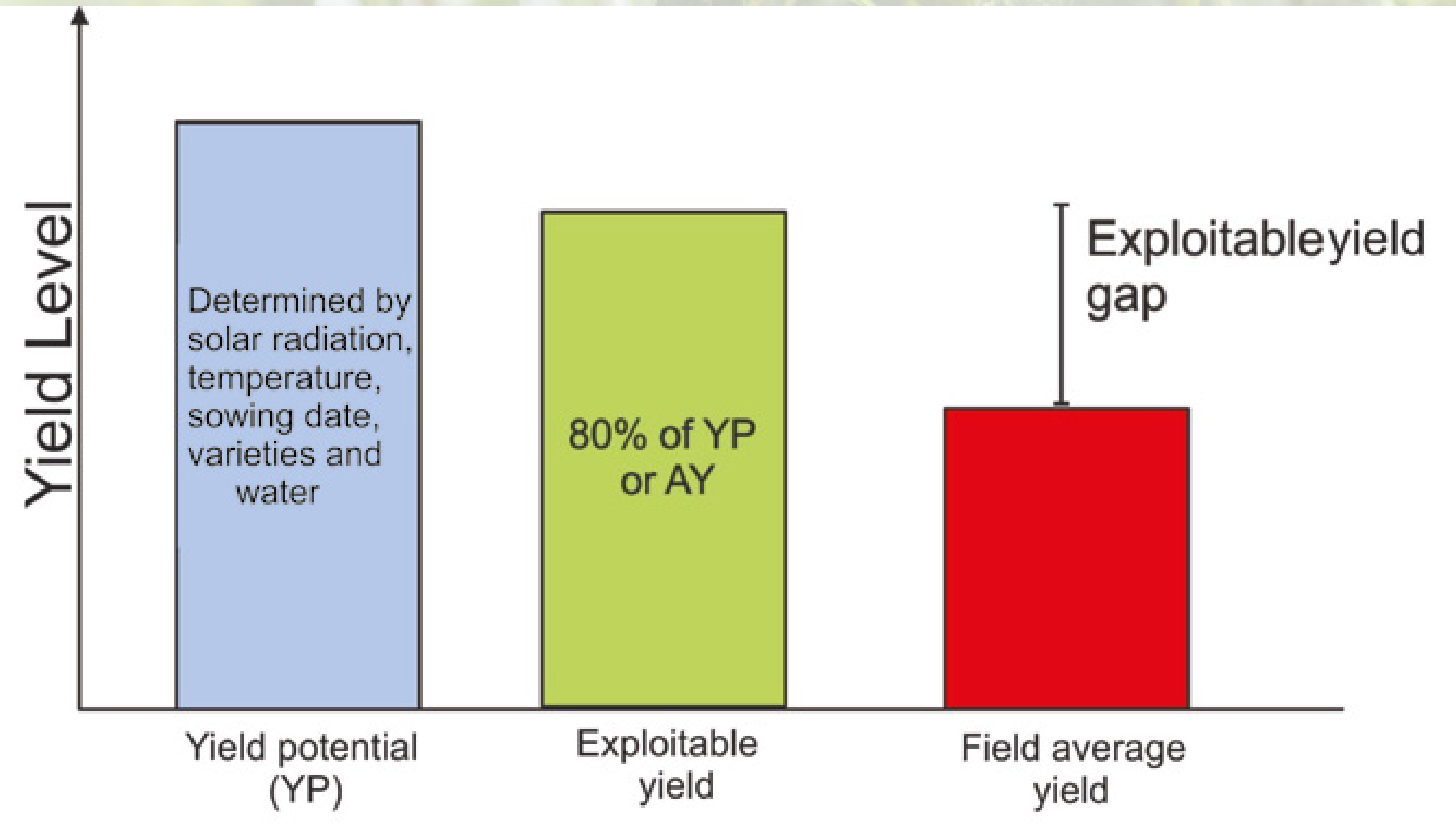


Figure 6.2. Relationship between the different levels of yield: potential, exploitable and current average of crops.

6.1. Soy yield potential and yield gaps in Brazil

To calculate the yield potential (YP) and potential water-limited yield (YW), a process-based ecophysiological model (refer to Chapter 7) was used and calibrated for all of Brazil. This model leveraged the best available data on soybean harvested areas, meteorological conditions, actual productivity, and farming practices at regional and national levels. Additionally, similar climatic regions and soil characteristics were identified to extrapolate and compare results with analogous regions worldwide, drawing from works such as those by Edreira et al. (2017) for the United States and Merlos et al. (2015) for Argentina.

In Brazil, the YP ranged from 5.7 to 7.5 ton ha^{-1}, with the highest value observed in Cruz Alta, Rio Grande do Sul (located at a lower latitude), and the lowest in Baixa Grande do Ribeiro, Piauí (at a higher latitude). Generally, there is a YP gradient in Brazil from south to north, with lower values found in northern Brazil (refer to Figure 6.1.1). The highest YP values are associated with higher latitudes, a relationship explained by the photothermal coefficient (see item 2.5). Adjustments to the maturity group and sowing date can enhance productive potential regionally, aligning the peak leaf area with the period of maximum solar radiation availability, typically occurring at the end of December. This strategic alignment optimizes crop performance and yield potential across diverse geographic and climatic conditions in Brazil.

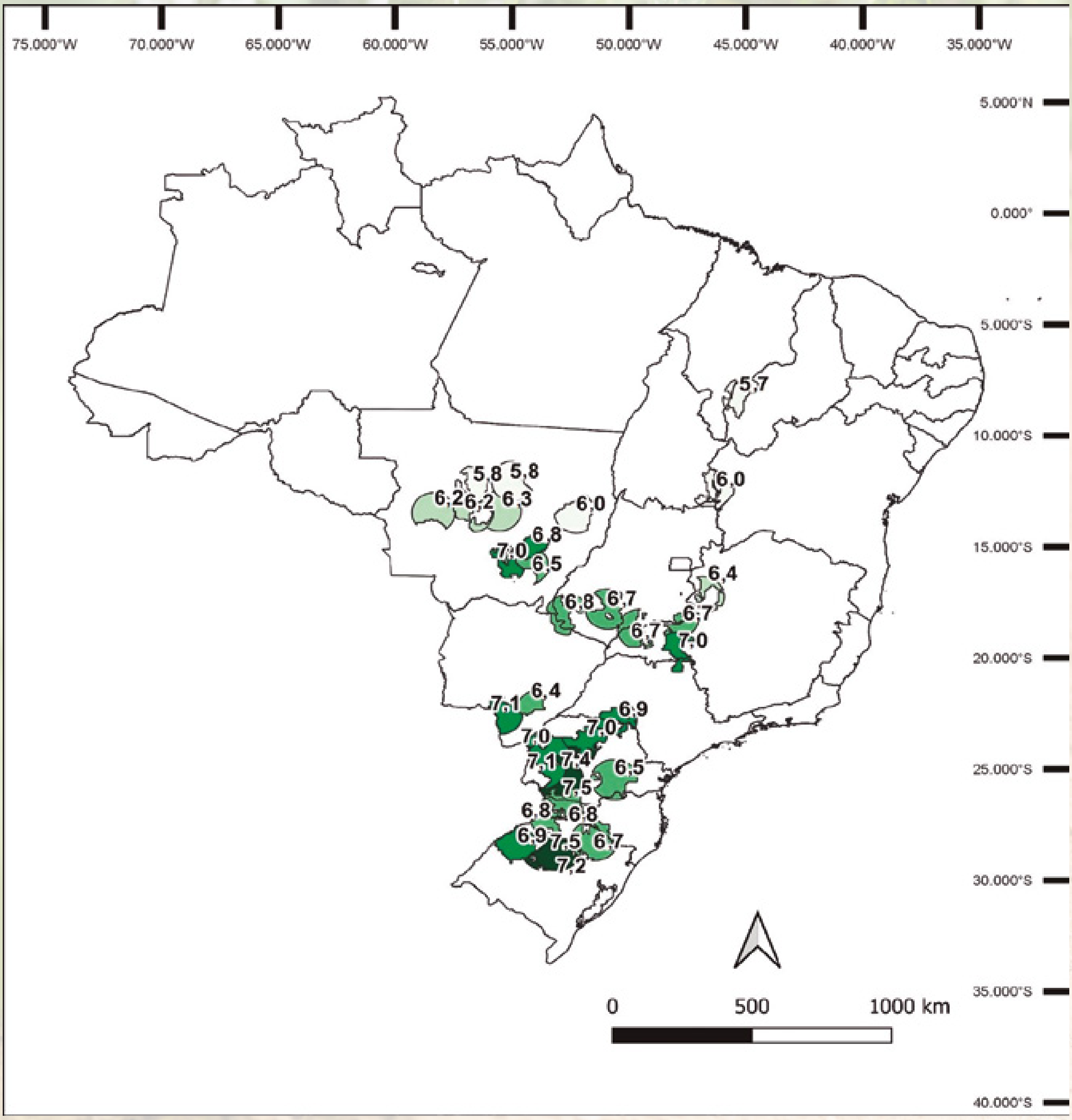


Figure 6.1.1. Yield potential, in ton ha^{-1}, (YP) of soybeans in Brazil. The presented PP value for each region represents the 20-year average (2000-2020). These estimates were conducted by the Brazil GYGA Team (www.yieldgap.org/brazil).

The potential water-limited yield (YW) ranged from 3.1 to 6.9 ton ha^{-1}, with the highest value observed in Campo Verde (Mato Grosso, Brazil) and the lowest in São Luiz Gonzaga (Rio Grande do Sul, Brazil) (refer to Figure 6.1.2). Unlike YP, YW values demonstrate a reduction in yield with increasing latitude, indicating a gradient of YW in Brazil from North to South, with lower values found in southern Brazil. This variation is attributed to the different water regimes across Brazil. In the Midwest, a monsoon regime prevails, characterized by regular precipitation during the summer when crops are cultivated. Conversely, the southern region experiences an isoigro regime, with precipitation distributed throughout the year. However, this region is more susceptible to droughts due to meteorological phenomena like ENSO (Arsego et al., 2018). The irregular distribution of precipitation, particularly in Rio Grande do Sul, where most years witness precipitation exceeding 600 mm during the rainy season, impacts soybean crop growth. The irregular distribution of precipitation throughout the growing cycle contributes to reduced YW (see item 2.1.1). This analysis underscores the importance of understanding regional water regimes and their impact on crop productivity. Strategies to optimize water use and mitigate the effects of irregular precipitation are essential for enhancing agricultural productivity and resilience, particularly in regions susceptible to climatic variability.

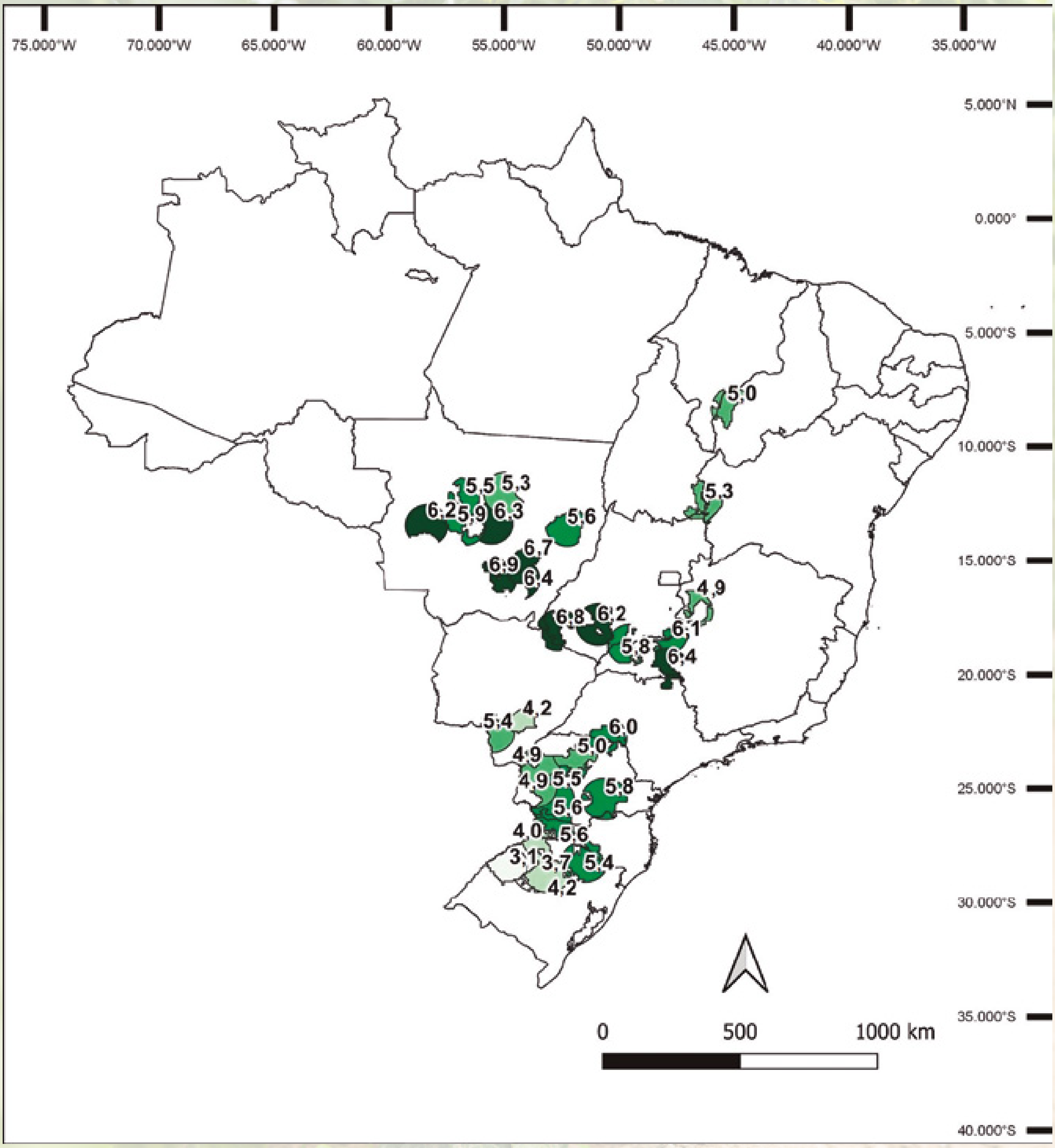


Figure 6.1.2. Water-limited yield potential (YW), in ton ha^{-1}, of soybeans in Brazil. The YW value presented for each region represents the 20-year average (2000-2020). These estimates were conducted by the Brazil GYGA Team (www.yieldgap.org/brazil).

The average yield (AY) shows little variation between the locations evaluated in Brazil. The lowest yield occurred in São Luiz Gonzaga (RS) at 2.3 ton ha^{-1}, while the highest yield was in Irati (PR) at 3.3 ton ha^{-1} during the period from 2000 to 2020 (Figure 6.1.3). These values are similar to the average soybean yield of 2.9 ton ha^{-1} obtained over the last 20 years (2000/01 to 2020/21) in Brazil, according to surveys by the National Company for Food Supply (CONAB - https://www.conab.gov.br/).

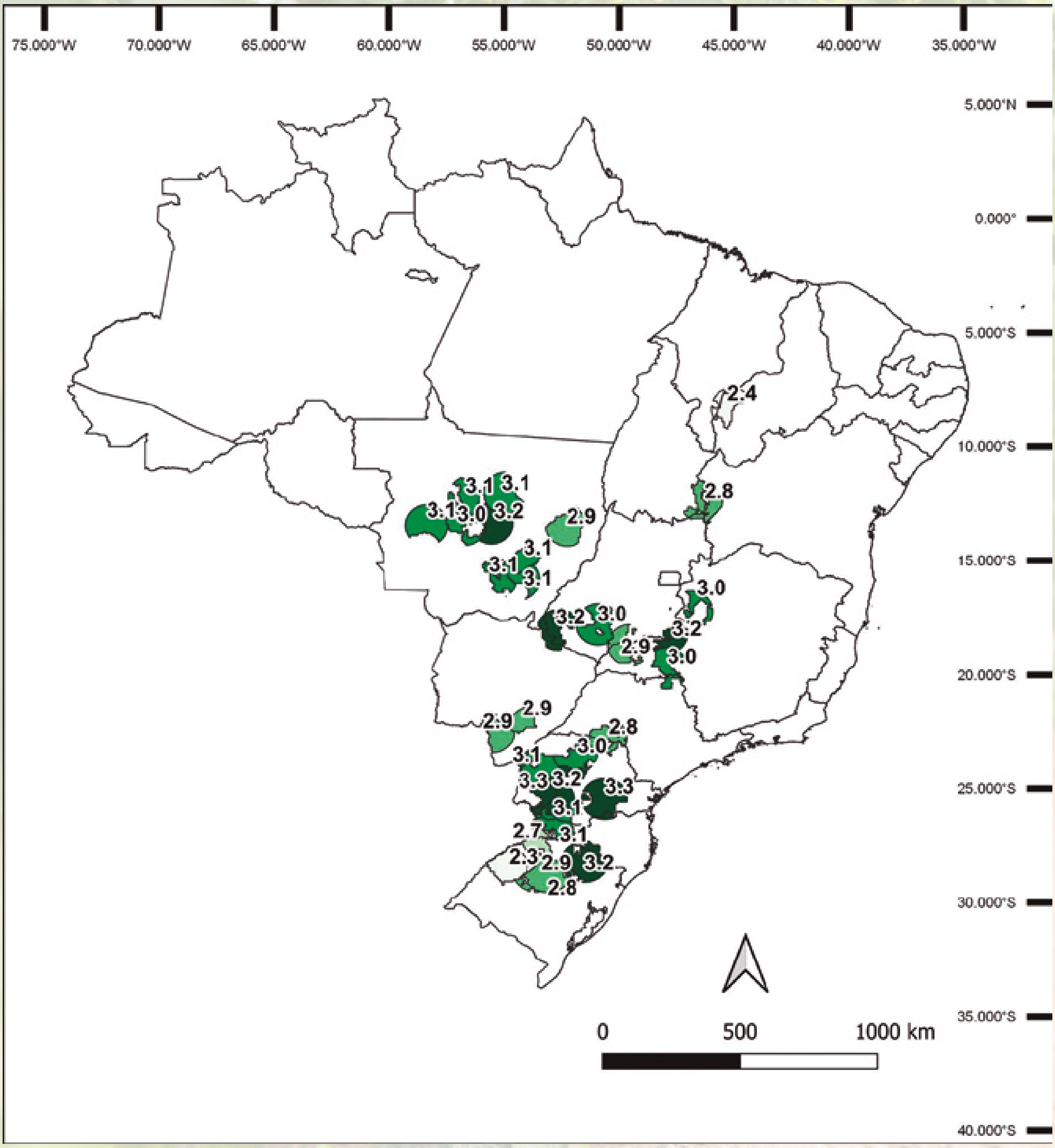


Figure 6.1.3. Average yield (AY), in ton ha^{-1}, of soybeans in Brazil. The AY value presented for each region represents the 20-year average (2000-2020). These estimates were conducted by the Brazil GYGA Team (www.yieldgap.org/brazil).

Figure 6.1.4 illustrates the water yield gap (LA = YP - YW) shown as the blue area of the graph, and the water gap management productivity (LM = YW - AY) represented by the green area of the graph. The water productivity gap is 1.2 ton ha^{-1} (ton ha^{-1}), which corresponds to the water deficit resulting from low precipitation or poor distribution of precipitation in Brazil (Figure 6.1.5). This gap varies significantly, reaching 3.8 ton ha^{-1} in Cruz Alta (RS) due to higher YP (greater solar radiation and less cloud cover), while in some areas of Mato Grosso and Goiás, the water gap is less than 0.1 ton ha^{-1}, indicating minimal water deficit throughout the soybean cycle. The average yield gap management in Brazil is 2.5 ton ha^{-1} (Figure 6.1.5), reflecting the management practices adopted by producers. For example, Campo Verde (Mato Grosso) exhibits the highest LM at 3.8 ton ha^{-1}, indicating significant potential for improvement in water management, while Cruz Alta (Rio Grande do Sul) shows the lowest LM with a loss of 0.8 ton ha^{-1}.

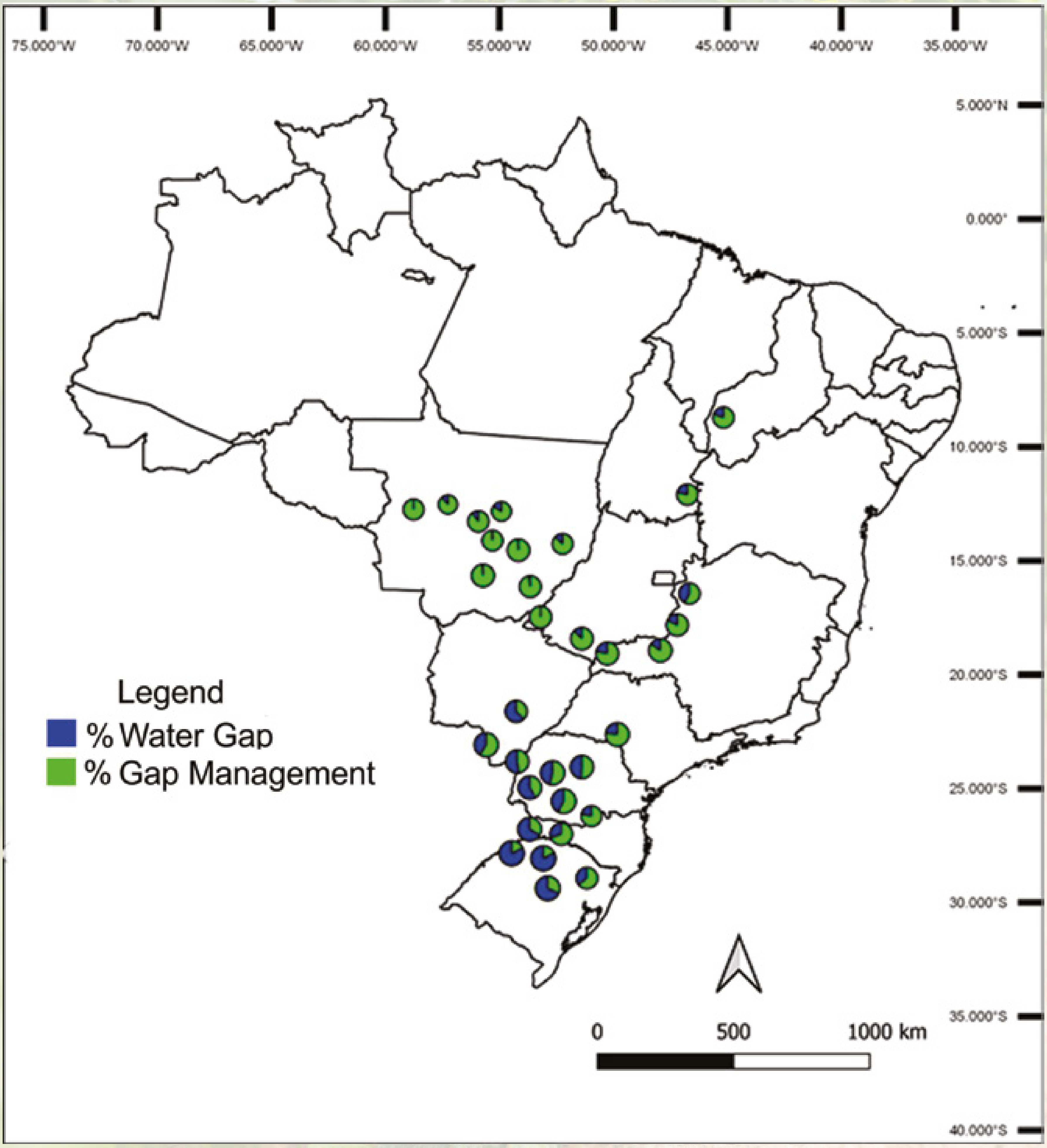


Figure 6.1.4. The soybean yield gaps in Brazil are represented by the size of the pie charts, with divisions into yield gaps caused by management (GM - green color) and water deficit (WG - blue color). These estimates were conducted by the Brazil GYGA Team (www.yieldgap.org/brazil).

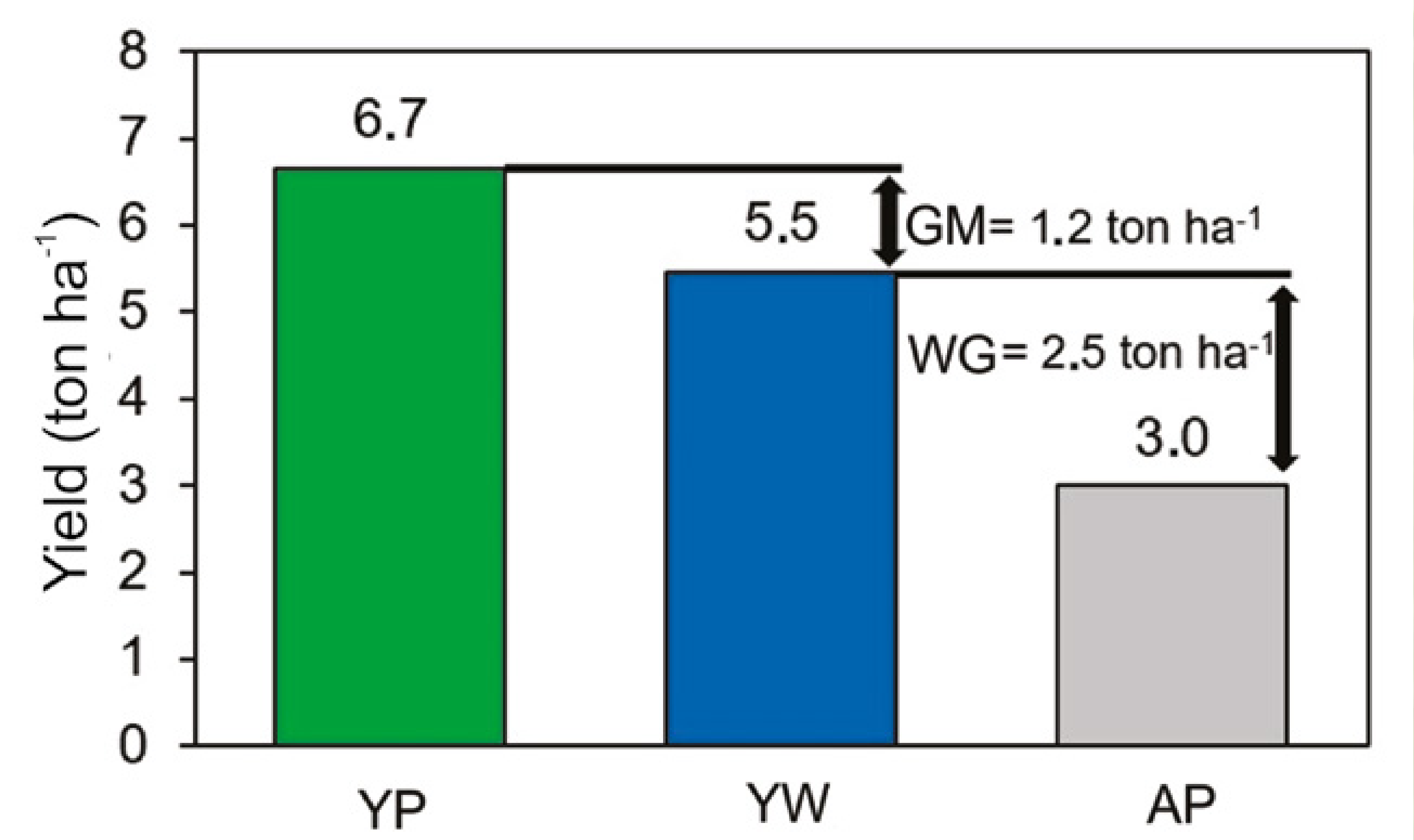


Figure 6.1.5. The yield potential (YP), water-limited yield potential (YW), average productivity (AP), management gap (GM), and water gap (WG) in soybean in Brazil. These estimates were conducted by the Brazil GYGA Team (www.yieldgap.org/brazil).

Considering the national average of evaluated locations in Brazil, the yield gap attributed to management practices is estimated at 2.5 ton ha^{-1}. In this context, achieving 80% of the potential water-limited yield (YW) through improved management practices could add an additional 1.4 ton ha^{-1}. This improvement has the potential to increase the national average yield by 46%, equivalent to producing an additional 54 million tons of soybeans (refer to Figure 6.1.5). This substantial yield increase would be comparable to expanding the cultivated area by 18 million hectares. However, such expansion can be avoided by embracing the principles of sustainable agricultural intensification, focusing on optimizing existing land use through improved management practices rather than expanding into new areas.

6.2. Potential and yield gaps in Rio Grande do Sul - A case study with soybean crops

After conducting a comprehensive analysis, it is crucial to consider the specific characteristics of each region in Brazil. Rio Grande do Sul (RS) contributes approximately 17% of Brazil's soybean production (CONAB, 2022). Over recent years, genetic enhancements and improvements in management practices adopted by producers have led to a 20% increase in average soybean yield in RS, comparing the five-year average yield from 2010-2014 to the period of 2015-2019. Analyzing the annual rate of increase in crop yield, we estimate that 45.4 kg ha^{-1} per year improvement is attributed to advancements in crop management practices. From 2005 to 2021, the annual contribution to increased yield in RS was distributed as follows: 42% attributed to genetic improvement, 46% to management practices, and 13% to environmental factors (refer to Figure 6.2.1). Despite these improvements, the average productivity in RS remains around 3.0 ton ha^{-1}, which is significantly lower than the average productivity achieved in experimental settings (6.0 ton ha^{-1}) and in crops evaluated in competitions like the Soybean Money Maker Championship (Zanon et al., 2016a; Tagliapietra et al., 2018; Ribeiro et al., 2021). This discrepancy underscores the potential for further enhancing soybean productivity in RS through continued investment in genetic improvement and advanced management practices. Bridging the gap between experimental yields and on-farm productivity is essential for maximizing agricultural potential and meeting increasing demand sustainably.

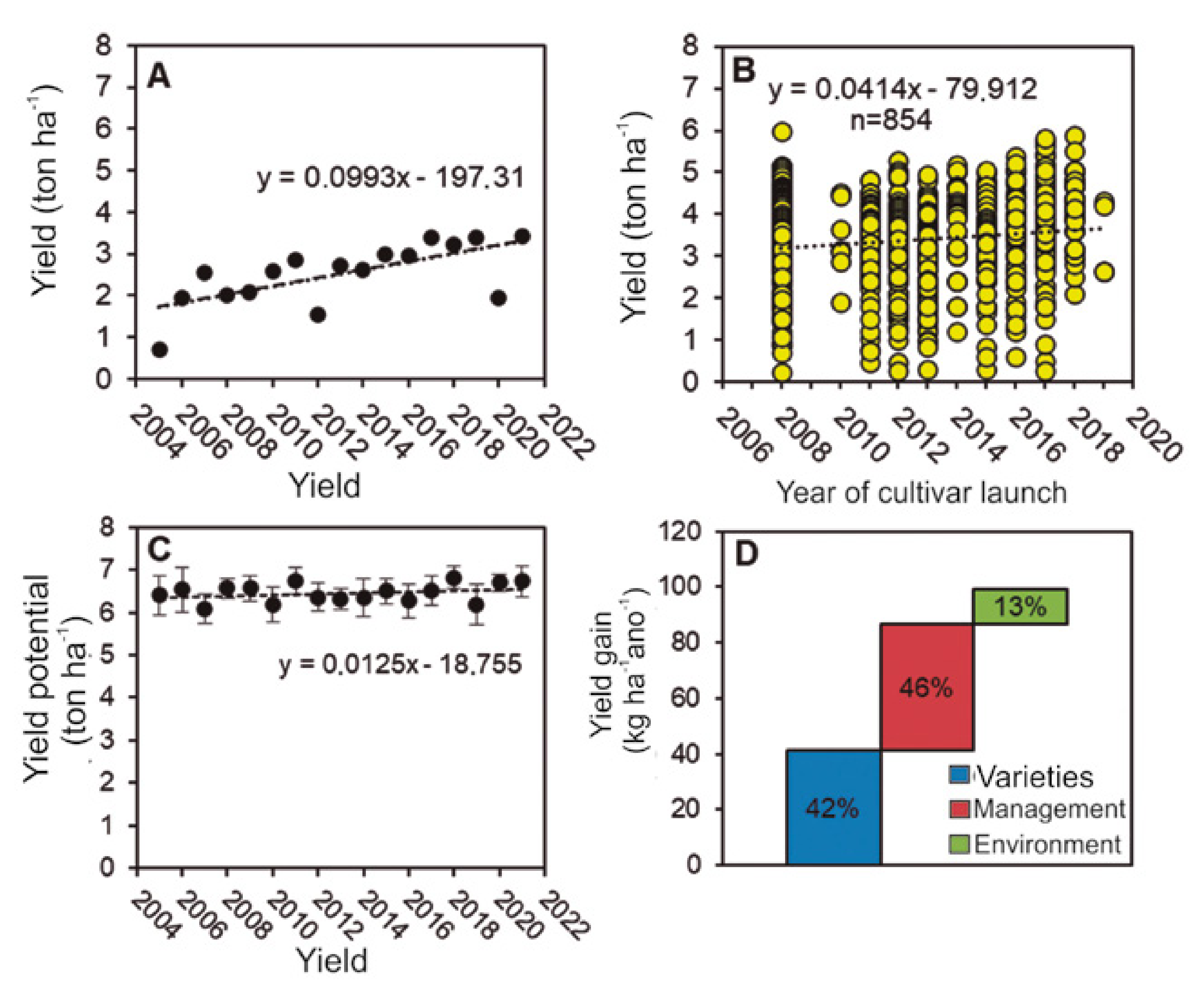


Figure 6.2.1. Average yield in Rio Grande do Sul according to IBGE official statistics from 2004/05 to 2020/21 (A), genetic gain estimated by yield database and year of cultivar release (B), average yield potential estimated by CSM-CROPGRO Soybean model for Rio Grande do Sul from 2004/05 to 2020/21 (C) and factors of contribution (management, genetic improvement and environment) to the annual yield increment in Rio Grande do Sul (D).

The yield potential (YP) of soybeans in Rio Grande do Sul (RS) ranged from 6.1 to 7.2 ton ha^{-1} (Figure 6.2.2 A). The highest YP was observed in region II (7.2 ton ha^{-1}), located in the Center-North region of RS, with sowings typically done in the second half of October. Lower YP values were observed in regions VI (6.1 ton ha^{-1}, VIII (6.1 ton ha^{-1}), and IX (6.2 ton ha^{-1}, which collectively represent 12% of the total soybean cultivated area in RS. These regions with lower YP are characterized by lower solar radiation, higher average temperatures, and a lower photothermal coefficient (Zanon et al., 2016). These environmental factors contribute to reduced yield potential and highlight the importance of selecting appropriate sowing times and management practices to optimize soybean productivity in different regions of Rio Grande do Sul.

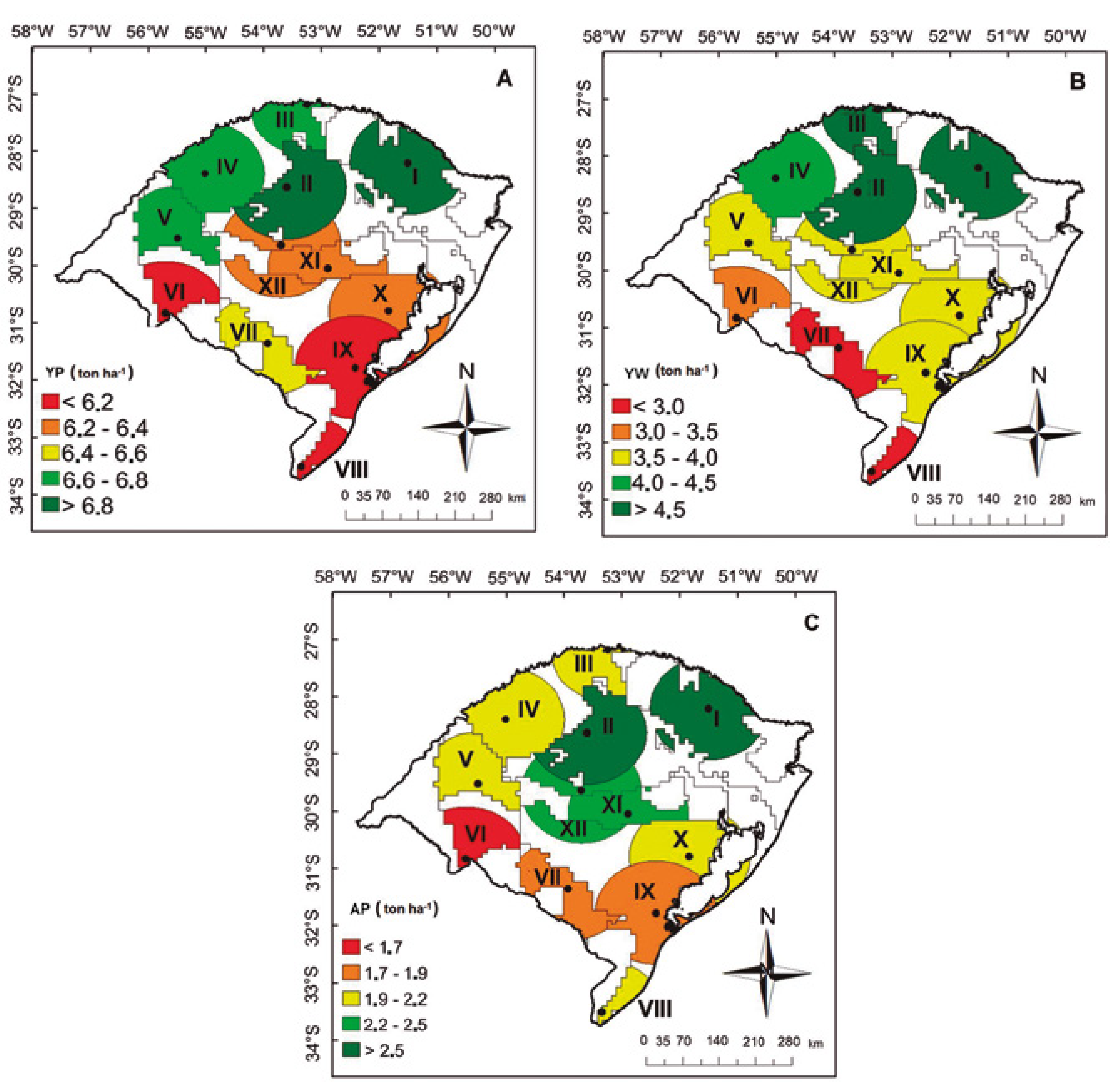


Figure 6.2.2. Yield potential (YP) (Panel A), water-limited yield potential (YW) (Panel B), and actual soybean yield (15-year average, 2004-2019) (Panel C) in twelve regions of Rio Grande do Sul, Brazil.

The potential water-limited yield (YW) exhibited significant variation between regions in Rio Grande do Sul, ranging from 2.5 to 5.1 ton ha^{-1}, as depicted in Figure 6.2.2 B. The Northern regions (I to IV) demonstrated higher YW, attributed to a greater quantity and historically better distribution of precipitation during the growing seasons, as well as the predominance of Oxisols characterized by deep soils with greater water storage capacity, allowing plants to withstand longer periods of water deficit (Streck et al., 2008). These findings are consistent with those of Battisti et al. (2017), who observed yield gains of up to 300 kg ha^{-1} in soils with deeper rooting profiles.

The average yield (AY) over 15 years (2004 – 2019) in Rio Grande do Sul varied between regions, ranging from 1.7 to 2.8 ton ha^{-1} (Figure 6.2.2 C). This trend mirrors that of YW, with regions I, II, and XII exhibiting the highest AYs (2.8, 2.6, and 2.4 ton ha^{-1}, respectively). These regions typically receive around 600 mm of accumulated rainfall, a value deemed sufficient for achieving high yields according to studies by Zanon et al. (2016) in RS and Grassini et al. (2015b) in Nebraska, USA. However, adequate distribution of this precipitation throughout the growth season and sufficient soil water storage capacity (AWS) are critical to prevent water limitations in soybean crops. Conversely, regions III, IV, and V also experience similar accumulated precipitation close to 600 mm but with greater variability during the growing season. Regions VI, VII, and IX exhibit lower YP and smaller precipitation volumes (~400 mm), coupled with shallow soils characterized by low water storage capacity (Streck et al., 2008).

Understanding the yield potential (YP), potential water-limited yield (YW), and average yield (AY) of different regions allows for the identification of yield gaps in Rio Grande do Sul (Figure 6.2.4), aiding in the understanding of factors contributing to yield losses. Notably, a substantial yield gap exists, ranging from 60% (Region I) to 73% (Region VI) (Figure 6.2.3 A), underscoring the importance of addressing specific agronomic challenges to optimize soybean productivity across different regions. To decompose this yield gap into water-limited yield gap (WG) and genetic potential yield gap (GM), it was observed that water deficit caused a loss of 26% and 62% (equivalent to 1.8 to 4.1 ton ha^{-1}), respectively (Figure 6.2.3 B). The southern half of Rio Grande do Sul (regions V to XII) exhibited the highest water-limited yield gap (WG) due to irregular distribution of precipitation during the growth season and soil characteristics, notably low water storage capacity in the soil. This analysis highlights the significant impact of water deficit on soybean yield in these regions, underscoring the importance of targeted management strategies and technological advancements to mitigate yield losses associated with environmental challenges, particularly water availability and distribution during critical growth stages.

Addressing these factors is essential for narrowing the yield gap and optimizing soybean production in Rio Grande do Sul.

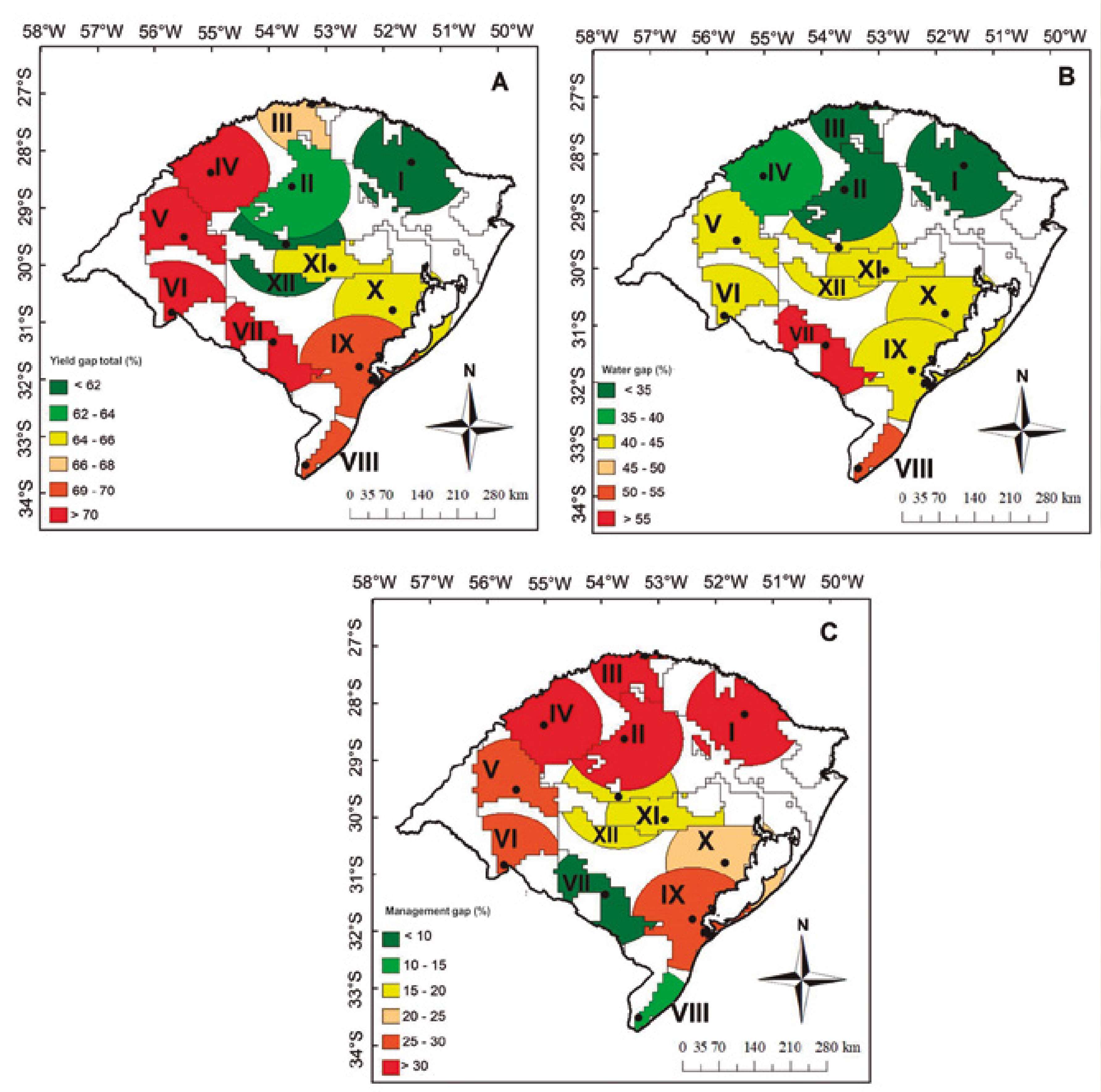


Figure 6.2.3. Yield gap (YG) (Panel A), water gap (WG) (Panel B), and management gap (GM) (Panel C) in soybean production (expressed as a percentage) in different regions of Rio Grande do Sul, Brazil.

The genetic potential yield gap (GM) showed less variation, ranging from 9% to 39% of the yield potential (YP), equivalent to 0.6 to 2.7 ton ha^{-1} (Figure 6.2.3 C). Regions I to IV exhibited the largest gaps, ranging from 31% to 39%, primarily due to the smaller average yields (AY) of these regions compared to others (Figure 6.2.1 C). These findings suggest that larger productivity gaps attributed to management occur in areas with better climatic conditions, particularly in terms of water availability. This highlights the importance of minimizing losses, especially in regions with higher productive potential, by optimizing management practices. Moreover, there is a clear need for soy consultants and producers to accurately assess yield potential (for irrigated crops) or potential limited by water availability (for dryland crops) and identify yield gaps at the crop level. This diagnostic approach allows for more informed and sustainable decision-making regarding management practices, ultimately optimizing productivity and narrowing the yield gap in soybean production systems (Van Oort et al., 2017).

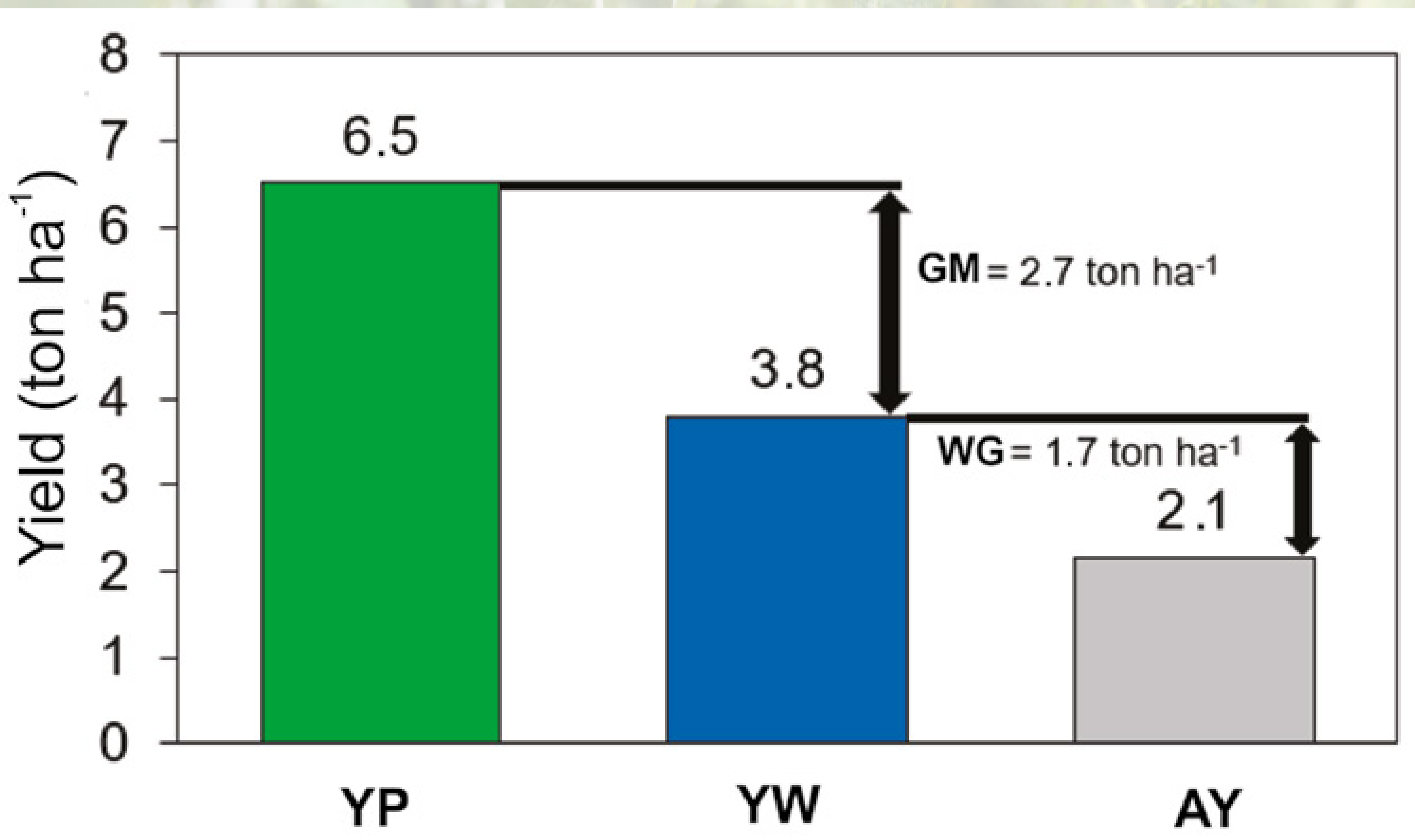


Figure 6.2.4. Yield Potential (YP), Water-Limited Yield (YW), Actual Yield (AY), Management Gap (GM), and Water Gap (WG) in soybean production for Rio Grande do Sul.

6.2.1. Factors causing yield gaps in soybean crops in Rio Grande do Sul

The analysis of management practices across 349 crops over three agricultural years (2016-2019) identified key variables that potentially explain yield gaps in Rio Grande do Sul. A regression tree analysis was conducted, dividing yields into high and low categories, with five variables explaining 61% of high yields and 22% of low yields (Figure 6.2.1.1). These variables are: (i) sowing date, (ii) final plant density, (iii) number of fungicide applications, (iv) maturation group of cultivars and (v) base fertilization.

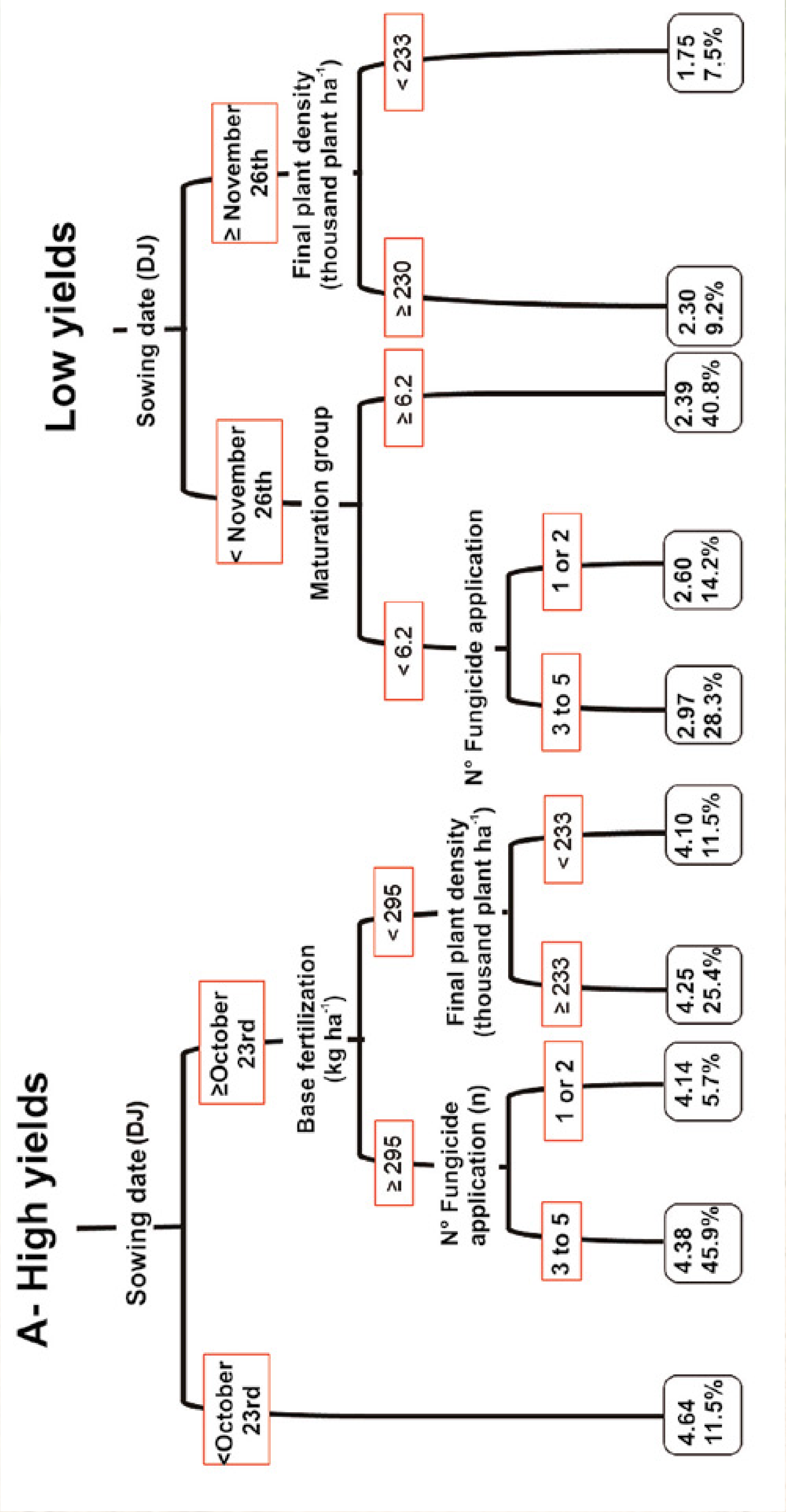
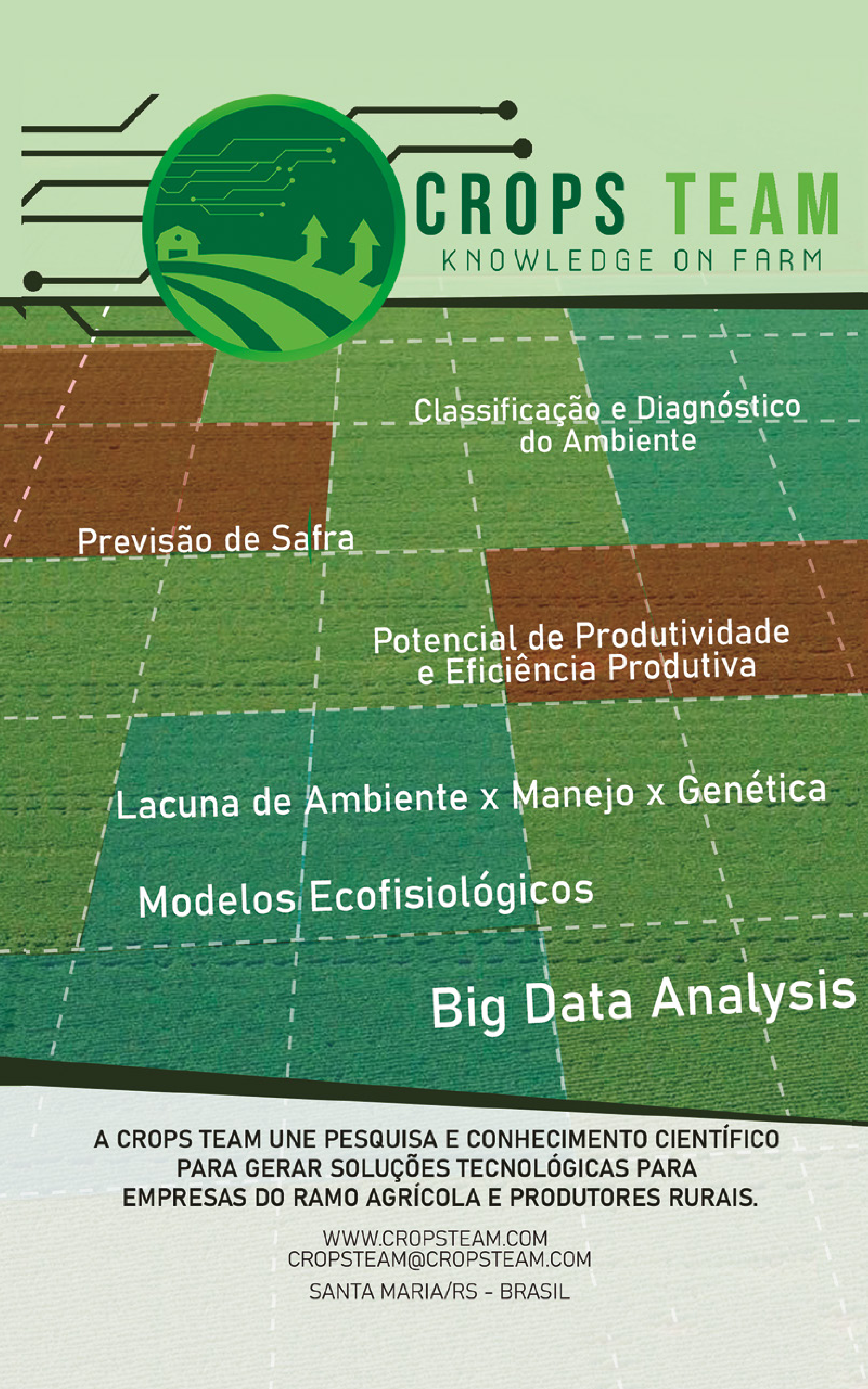


Figure 6.2.1.1. Regression tree demonstrating sources of variation in soybean grain yield due to biophysical and management factors. The boxes in the tree represent split nodes, with smaller boxes at the bottom representing terminal nodes. Within each terminal node, values indicate the average grain production (in ton ha^{-1} at 13% moisture) and the percentage of observations in that node. Panel (A) shows high yields (upper tertile), while panel (B) shows low yields (lower tertile).

The sowing date emerged as the most critical factor influencing soybean yields in Rio Grande do Sul. Earlier sowings (before October 23rd) led to higher yields (4.6 ton ha^{-1}), particularly when using early-maturing cultivars (MG 5.8), benefiting from a higher photothermal coefficient during this period. Conversely, for sowings after October 23rd, achieving high yields (4.4 ton ha^{-1}) depended on applying substantial base fertilization (> 295 kg ha^{-1}) and conducting 3 to 5 fungicide applications, which helped prevent yield losses due to diseases like Phakopsora pachyrhizi (Asian rust). In situations where base fertilization was less than 295 kg ha^{-1}, final plant density became critical, with high-yield crops (4.3 ton ha^{-1}) associated with plant densities exceeding 233 thousand plants ha^{-1}. For crops sown later (after November 26th), higher yields (3.0 ton ha^{-1}) were achieved by using cultivars with MG < 6.2, applying 3 to 5 fungicide applications, and maintaining plant densities above 233 thousand plants ha^{-1}.

These strategies resulted in productivity gains compared to crops with fewer fungicide applications or cultivars with MG ≥ 6.2. Overall, the most favorable yields, even among lower productivity levels, were observed with sowings conducted early in the recommended period (October and November) using earlier-maturing cultivars. In late sowings (December), maximizing plant density became crucial due to reduced vegetative phase and leaf area index, allowing for greater interception of solar radiation and consequently higher yields.



7. Digital Ecophysiology

Michel Rocha da Silva; Rafael Batista; Eduardo Lago Tagliapietra; José Eduardo Minussi Winck; Alexandre Ferigolo Alves; Guilherme Guerin Munareto; Anderson Haas Poersch; Bruna San Martin Rolim Ribeiro; Cesar Eugênio Quintero; Gean Leonardo Richter; Darlan Scapini Balest; Victoria Brittes Inklman; Renan Augusto Schneider; Kelin Pribs Bexaira; Cristian Savegnago; Leonardo Silva Paula; Marcos Dalla Nora; Edgardo Santiago Arevalo; María Soledad Armoa Báez; Luciano Zucuni Pes; Nereu Augusto Streck; Santiago Vianna Cuadra; Ivan Rodrigues De Almeida; Romulo Pulcinelli Benedetti; Alencar Junior Zanon

The concept of “Digital Ecophysiology” extends the principles of traditional ecophysiology to the realm of Agriculture 4.0, emphasizing the use of technologies and digital tools to understand and quantify the interactions between plants and their environment. This field aims to represent, translate, and simplify the complex interactions that influence plant growth and development, enabling more informed and sustainable management practices. Digital Ecophysiology leverages advancements in technology to enhance the efficiency and precision of agricultural decision-making. By integrating data from various sources, such as sensors, satellite imagery, weather forecasts, and crop models, this approach provides insights into the physiological processes of plants and their responses to environmental conditions. These insights can be instrumental in optimizing resource use, improving productivity, and minimizing environmental impacts. The adoption of Digital Ecophysiology is essential for modern agriculture, empowering producers and agronomists to make data-driven decisions that optimize input use while promoting economic and environmental sustainability. This chapter will explore the historical evolution of Digital Ecophysiology, key mathematical models, digital tools, and their practical applications on farms. Through this exploration, stakeholders can gain a deeper understanding of how technology is reshaping agriculture and driving the transition towards more efficient and sustainable practices.

7.1. History and origin of digital ecophysiology

Digital ecophysiology traces its roots back to the mid-20th century, coinciding with significant developments in mathematical modeling applied to agriculture. Earl Heady's pioneering work in the late 1950s focused on developing mathematical equations to understand the economic implications of agricultural decisions, providing tools for rural producers to make informed choices. The emergence of ecological modeling gained momentum through initiatives like the International Biological Program (IBP) in the 1960s. This program catalyzed the development of ecological mathematical models to simulate interactions within ecosystems, including dynamics involving forage and grazing by cattle. This early work laid a foundation for understanding the complex interplay between ecological factors and agricultural systems. Simultaneously, agricultural modeling began to evolve with contributions from scientists worldwide, supported by governments and institutions seeking to advance agricultural understanding (Jones et al., 2016).

Notable contributions include physicist de Wit's seminal work at Wageningen University, where he explored the relationship between transpiration and crop biomass production under varying water availability. Additionally, chemical engineer Duncan's work at the University of Kentucky in 1967 introduced a model for simulating photosynthesis in plant communities, further advancing the understanding of plant physiology within agricultural contexts. These foundational works from the Netherlands and the United States established these countries as centers for agricultural modeling expertise. Agricultural models, characterized by sets of mathematical equations, provide a means to describe and predict the complex interactions within the soil-plant-atmosphere system.

These models are crucial for assessing how different management practices impact agricultural productivity and sustainability, forming the basis for digital ecophysiology—an evolving field that leverages technology to enhance the precision and efficiency of agricultural management.

In the era of Agriculture 4.0, agricultural models are integral to digital ecophysiology, facilitating decision-making and management of crops by capturing the interactions among genotype, environment, management practices, and producers within various production systems. These models encompass a range of types that estimate crop growth, development, and yield, broadly classified into empirical, physiological-mathematical, and mechanistic categories. Empirical Models: These models establish straightforward relationships between crop productivity and meteorological variables without delving into underlying physiological processes. They are characterized by simplicity and directness in their approach.

Physiological-Mathematical Models: This category involves mathematical equations that elucidate specific physiological processes of plants. These models delve deeper into plant biology and provide more nuanced insights compared to empirical models.

Mechanistic Models: Representing the most complex type, mechanistic models meticulously describe the intricate processes involved in biomass production within the soil-plant-atmosphere continuum. They aim to simulate and integrate numerous physiological and environmental factors affecting crop growth and development.

The complexity of models used in digital ecophysiology varies based on the number and sophistication of simulated processes. As depicted in Figures 7.1.1 and 7.1.2, this spectrum of models spans from relatively simple empirical relationships to more intricate physiological and mechanistic representations. Each type of model offers unique advantages and trade-offs, providing valuable tools for optimizing agricultural management practices and enhancing sustainability in the context of modern precision agriculture and Agriculture 4.0 initiatives.

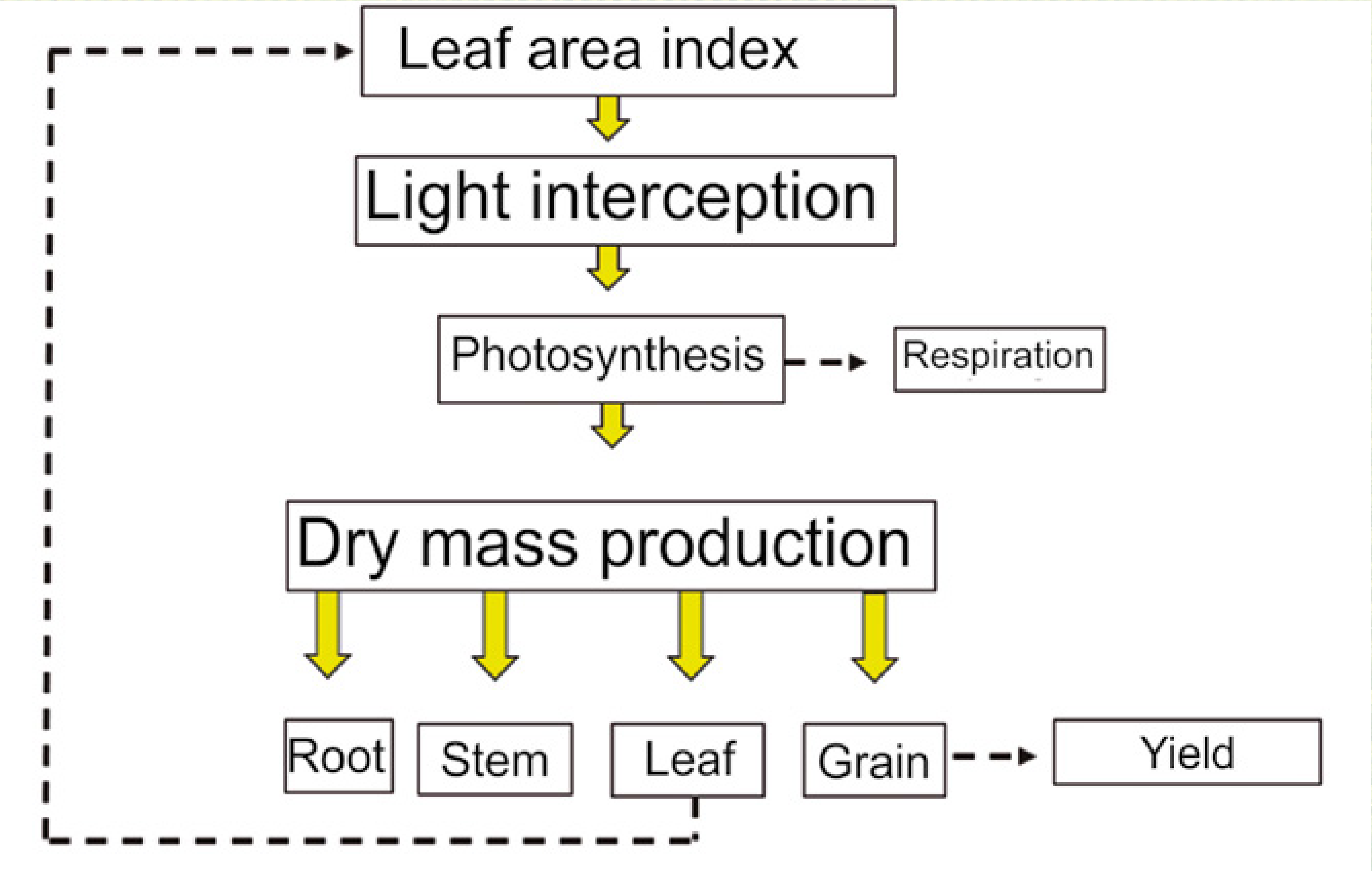


Figure 7.1.1. Schematic representation of a simulation model of crop growth. The model simulates the production of photoassimilates using factors such as leaf area, solar radiation interception, and photosynthetic rate. It is a component of a larger mechanistic model that integrates simulation of phenology, water balance, and nitrogen dynamics. The model combines these elements to predict crop growth and development under varying environmental conditions and management practices.

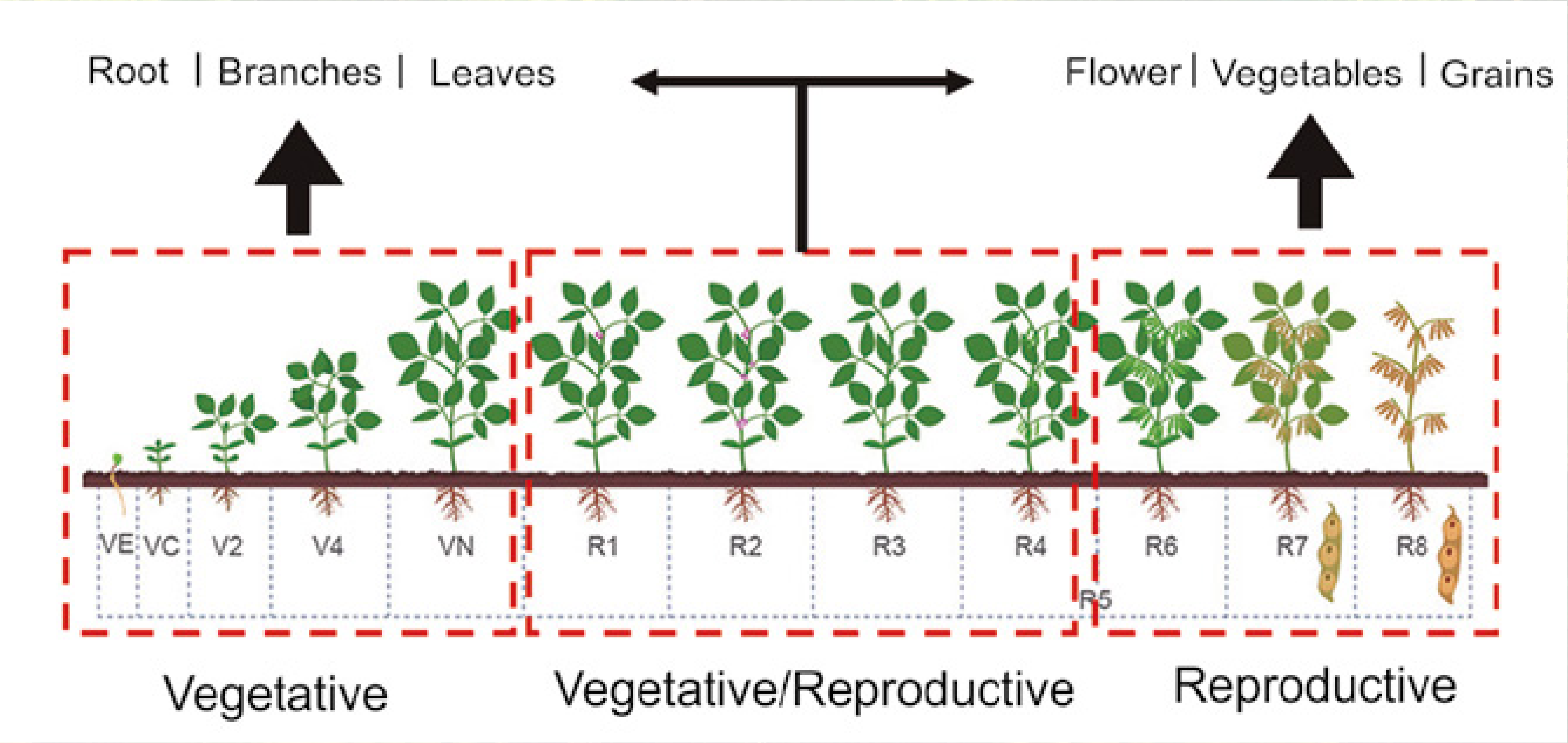


Figure 7.1.2. Biomass partition by the soybean crop as a function of the development stage. This relationship can be utilized to construct digital ecophysiological models, wherein the stages of development are simulated based on air temperature and photoperiod. From this estimate, the pathway of photoassimilates produced can be delineated by equations until reaching productivity at the end of the development cycle.

Complex ecophysiological models describe processes on smaller time scales, including instantaneous photosynthesis, transpiration processes, and nutrient supply at hourly and daily intervals. These models require a large number of parameters and detailed information, which may not always be readily available for consistent calibration, such as spatial variations in the relationship between soil water and water potential. In contrast, less complex models employ simple functions to represent complex processes, such as the relationship between intercepted energy using the leaf area of the plant and the efficiency of radiation use (a measure of biomass produced per unit of intercepted radiation - MJ m^{-2} day^{-1}). The choice of relationships to represent processes is one of the main reasons why multiple models have been developed for the same crop, livestock, and agricultural systems. As a result, ecophysiological models vary in complexity and precision levels when predicting the crop cycle and yield (Jones et al., 2016). Below are some of the main ecophysiological models developed for soybeans.

7.2. Mathematical models in soybean culture

For the soybean crop, there are several mathematical models that simulate the physical, chemical, and biological processes in the plant as a function of climate, soil, and crop management. The main simulation models for soybean cultivation include: the SOYBEAN model, the GLYCIM model, the SOYCROS model, the CROPGRO–SOYBEAN model, the APSIM model, the MONICA model, the WOFOST model, and the SOYDEV and SOYSIM models (Sinclair, 1986; Acock & Acock, 1991; Penning de Vries et al., 1992; Boote et al., 1998; Holzworth et al., 2018; Wu et al., 2019; Nendel et al., 2011; Battisti et al., 2017; Brisson et al., 1998; Setiyono et al., 2007; 2010).

The SOYBEAN model is probably the simplest, requiring only a few cultivar-specific features, while the WOFOST model is a generic and mechanistic model of crop growth, but it still necessitates genotype-specific calibrations (Sinclair, 1986; Brisson et al., 1998). The CROPGRO–SOYBEAN model, available on the DSSAT platform, is a process-based model that requires many specific genotype parameters, with each cultivar represented by 18 parameters (Boote et al., 1998). Since new soybean cultivars are released annually, cultivar-specific parameters can quickly become outdated, necessitating new calibrations and adjustments (Figure 7.2.1).

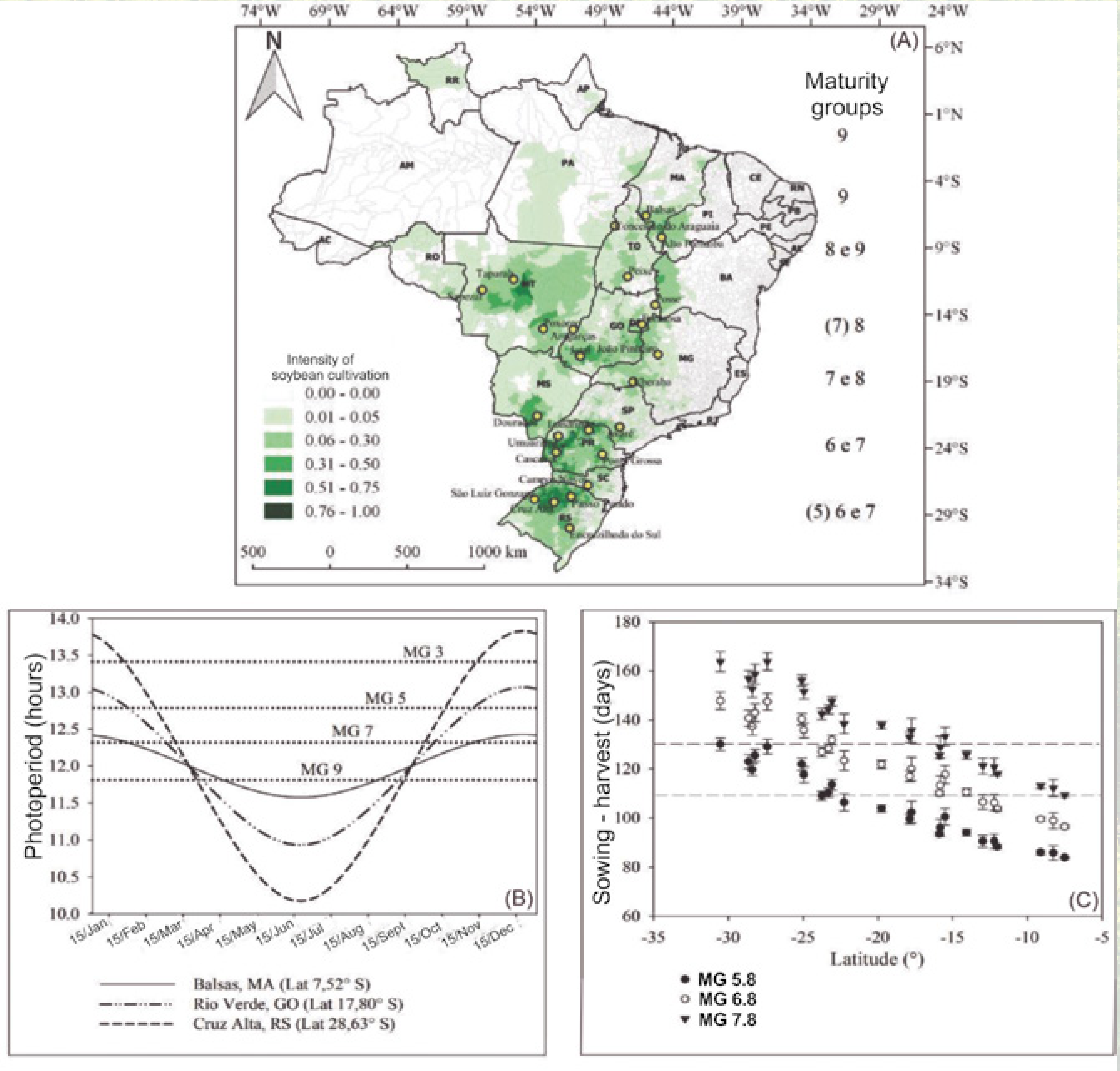


Figure 7.2.1. Maturity groups of soybean cultivars used in Brazil and the intensity of soybean cultivation (A), depending on the latitude of the region of cultivation (Adapted from EMBRAPA, 2011; IBGE, 2016), photoperiod at throughout the year to Balsas, MA, Rio Verde, GO and Cruz Alta, RS, with the critical photoperiod values for maturation groups (MG) 3 (13.4 hours), 5 (12.8 hours), 7 (12.3 hours) and 9 (11.9 hours) (B) (Boote et al., 2003), and cycle length for maturation group 5.8, 6.8 and 7.8 in function of cultivation latitude (C) based on highlighted locations (A) using the CROPGRO–SOYBEAN ecophysiological model.

SOYSIM is a dynamic model based on processes for soy that requires fewer genotype-specific parameters compared to the CROPPROSOYBEAN model (Setiyono et al., 2010; Cera et al., 2017). SOYSIM combines state-of-the-art approaches to various processes such as photosynthesis, biomass accumulation, and partitioning, along with innovative components like SOYDEV, which encapsulates current knowledge on soybean development stages in response to environmental factors (Setiyono et al., 2007).

The Australian APSIM platform encompasses multiple crops, serving as a mechanistic model for simulating development and growth based on climate, soil, plant, and management models. One significant advantage of APSIM is its flexibility, allowing users to add or adjust equations to tailor simulations to specific management scenarios (Holzworth et al., 2018; Wu et al., 2019; Nendel et al., 2011). On the other hand, the MONICA model (Model for Carbon and Nitrogen Simulation) focuses on processes related to carbon and nitrogen balance in the soil, integrating crop development and growth (Holzworth et al., 2018; Wu et al., 2019; Nendel et al., 2011).

The selection and use of digital ecophysiological models depend on objectives, familiarity with the tools, and assessment of simulation accuracy—whether the model adequately represents crop reality. In some cases, combining multiple models can yield superior performance in simulating productivity. For example, Battisti et al. (2017) evaluated five ecophysiological models and found that combining their average yield simulations produced the best results across diverse production environments.

Simpler ecophysiological models can also be effective for on-farm soybean management. For instance, producers can establish relationships between precipitation during the reproductive phase and soybean yield using field data (Fendrich, 2003). Another straightforward approach is linking sowing dates with maturity groups based on historical data, incorporating temperature and photoperiod relationships (Rodrigues et al., 2001). Modern tools like Best Cultivar provide readily accessible digital ecophysiology resources, aiding producers in determining optimal sowing times for different soybean cultivars in specific production environments (Android: https://play.google.com/store/apps/details?id=br.cropsteam.bestcultivar, iOS: https://apps.apple.com/br/app/best-cultivar/id1583524475). It's essential to highlight that producer experience and knowledge play pivotal roles in maximizing the efficiency of digital ecophysiology for decision--making and production enhancement.

7.3. Uses of mathematical models

Mathematical models represent a cutting-edge tool in agricultural science for enhancing soybean crop efficiency worldwide. Practical applications of mathematical models in soybean cultivation include:

1) Guidance for Crop Management Practices: Mathematical models are employed to define optimal management strategies for specific crops or production systems. For instance, Battisti & Sentelhas (2014) determined the best sowing season for soybean crops by integrating yield simulations with economic modeling, identifying dates with positive economic returns in at least 80% of years. Another advantage is the integration of various factors such as cultivar selection, weather forecasts (e.g., El Niño), sowing dates, nitrogen fertilization, and profitability into decision-making processes. An example of this approach is seen in the work conducted in Australia by Zheng et al. (2018), who defined optimal strategies for wheat production by considering these factors (Streck et al., 2003a, 2003b). Using models helps to understand genotype × environment interactions, enabling the identification of optimal placement for each maturity group (MG), among other applications.

2) Support for Genetic Enhancement Programs: Mathematical models play a crucial role in supporting planning and decision-making to enhance genetic efficiency, resulting in the selection of superior genotypes adapted to various environmental conditions. For instance, an innovative study by Messina et al. (2006) involved calibrating an ecophysiological model based on gene analysis of soybean genotypes, focusing on phenological cycles and phases. This calibration allowed testing under different environmental conditions using the model, thereby identifying locations with the greatest potential for adapting to new materials. Furthermore, data from cultivar trials can assess cultivar adaptability in different environments. For example, Battisti & Sentelhas (2015) evaluated 101 soybean cultivars across five seasons at various locations in the Center-South of Brazil, classifying cultivars based on water deficit tolerance. The study revealed a 10% difference in yield potential reduction between the most and least tolerant cultivars under a 40% water deficit (Banterng et al., 2006).

3) Determining Yield Potential and Gaps: The objective is to define the maximum achievable yield for a given crop, considering several environmental factors, to quantify production intensification capacity and ensure food security (Grassini et al., 2015a). The Global Yield Gap Atlas (GYGA – www.yieldgap.org) utilizes simulation models to evaluate productivity potentials and identify sources of productivity loss, categorized as climatic (e.g., water deficit) or management-related losses. For soybeans, GYGA indicates a potential rainfed productivity of 5400 kg ha^{-1} for Brazil, compared to the national average of 3000 kg ha^{-1}, representing a management-related yield reduction of 2400 kg ha^{-1}. This suggests that improved management practices could increase soybean production in Brazil by 80% without expanding cultivated areas, with variations ranging from 28% to 123% across regions, such as Cruz Alta, RS, and Campo Verde, MT.

4) Assessing Impacts and Mitigation Strategies for Climate Change: The goal is to evaluate climate change impacts on agricultural production and identify adaptation strategies to mitigate negative effects. Battisti et al. (2018) observed a reduction in soybean yield with rising air temperatures using four growth simulation models in the Center-South region of Brazil. On average, the models predicted a decrease from 66 sc ha^{-1} to 42 sc ha^{-1} with a 6°C increase in mean air temperature (Fig. 7.3.1 A), while an increase in CO_2 concentration from 380 to 780 ppm led to an increase from 50 to 80 sc ha^{-1} (Fig. 7.3.1 B). Based on climate forecasts and soybean physiological traits, the authors identified advantageous physiological characteristics for future soybean cultivars, including a deep root system and reduced sensitivity to water deficit, resulting in an almost 9% increase in total production under climate change scenarios (Battisti et al., 2017).

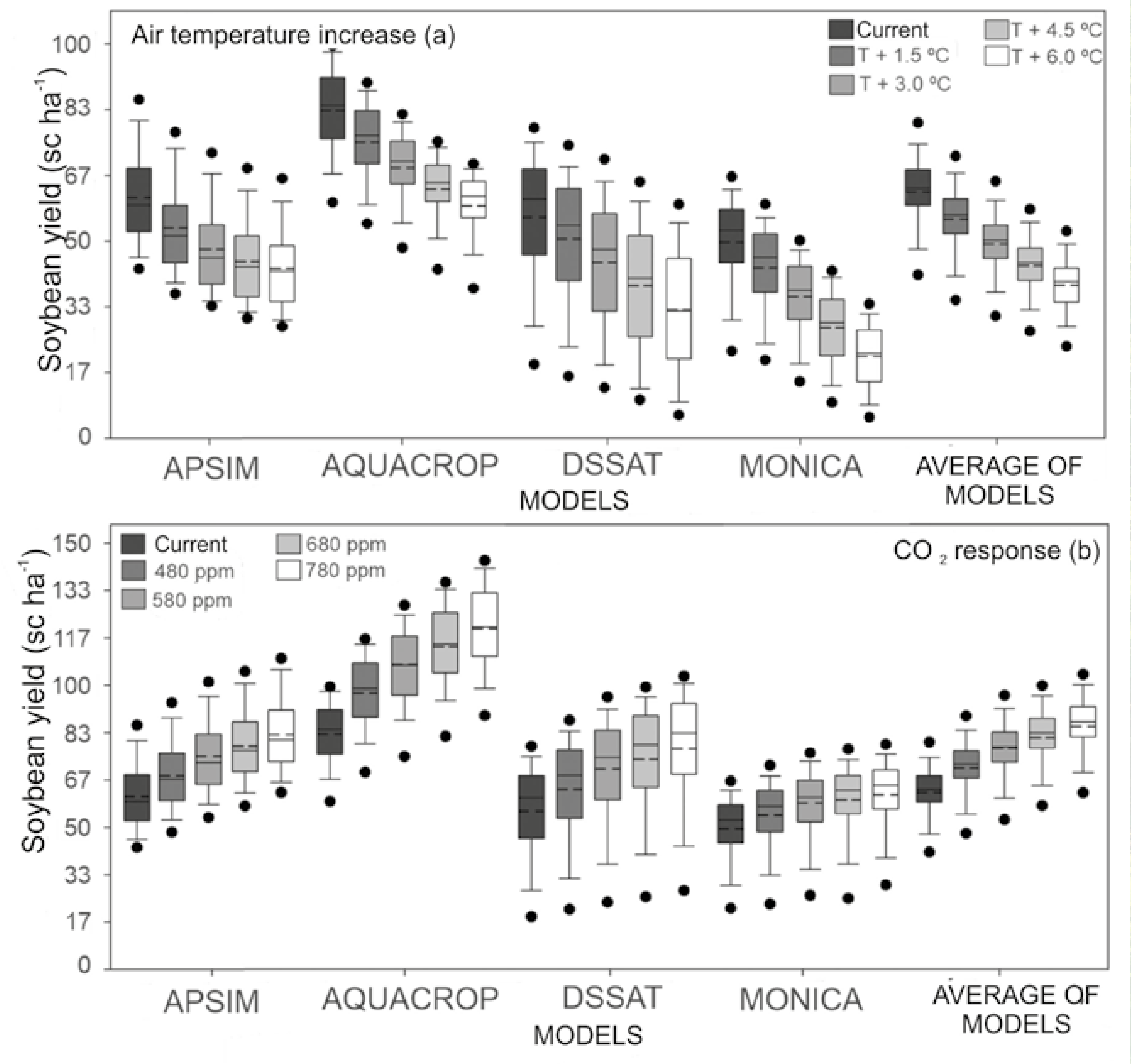


Figure 7.3.1. Evaluation of soybean yield response to air temperature increase (a) and CO_2 (b) obtained with four models of yield simulation and the average of the models for the Center- Southern Brazil (Battisti et al., 2018). This analysis reveals the yield variation over 55 simulation seasons (shown as dispersion bars) and the effects of increasing air temperature by up to 6°C compared to current climatic conditions. The increase in air temperature resulted in yield reduction, whereas the increase in CO_2 had a positive effect on yield.

5) Strategies for Intensifying Production Systems: The aim is to evaluate optimal crop combinations to intensify production systems, whether to increase food production or enhance sustainability by mitigating climate change impacts on productivity. Battisti et al. (2020) evaluated the safrinha soy-corn production system in central Brazil using a growth simulation model to assess economic profitability and food production (energy and protein). The study found that the soy-corn association with early sowing resulted in greater profitability for rural producers. However, delayed soybean sowing reduced profitability, rendering the system economically unviable. Overall, the soy-corn safrinha system produced more raw energy during most of the sowing season compared to single-crop systems.

6) Estimating Plant Development and Growth: This involves simulating and defining the occurrence of crop phenological phases, biomass accumulation, and productivity based on environmental conditions such as climate, soil, cultivar, and various management practices (e.g., sowing date, irrigation, fertilization). Ribas et al. (2016) used a model to estimate dry matter accumulation and productivity of rice hybrids, while Silva et al. (2016) employed numerical modeling to forecast irrigated rice crop outcomes in Rio Grande do Sul state.

7) Climate Risk Assessment and Regional Classification: This aims to assess climate risks and identify regions with better adaptability to different crops. In Brazil, a key digital ecophysiology tool used for this purpose is climatic risk zoning, developed by EMBRAPA and mandated by the Ministry of Agriculture, Livestock, and Supply. This zoning aims to identify ow climate risk locations and sowing dates for specific crops, considering extremes of air temperature and water deficit during critical crop phases. For soybeans, suitable sowing dates require meeting at least 50% of evapotranspiration demand during the reproductive phase, with zoning indicating suitable dates/locations with three risk levels (60%, 70%, and 80% of years meeting demand). Figure 7.3.2 illustrates an example screen from the ZARC – Plantio Certo application showing climate risk zoning results for corn cultivation in General Carneiro, MT, highlighting days with risk levels (20%, 30%, and 40% loss) for late-cycle cultivars on sandy soil (blue, green, and orange, respectively).

armazenamento de água no solo: média no decêndio

Legenda: risco até 20% 30% 40% Sem Indic.

Ciclo da planta: 1 (precoce), 2 (médio), 3 (tardio) P (perene), S (semiperene)

Solo: 1 (arenoso), 2 (textura média), 3 (argiloso)

Legenda: armazenamento de água no solo (%)

< 10	50 -| 60
10 -| 20	60 -| 70
20 -| 30	70 -| 80
30 -| 40	80 -| 90
40 -| 50	90 -|100

O número dentro do círculo indica a fase fenológica estimada: (1) semeadura e estabelecimento, (2) vegetativo, (3) floração e formação da produção e (4) maturação

Figure 7.3.2. The application screen for agricultural zoning is a digital tool developed by EMBRAPA in collaboration with the Ministry of Agriculture, Livestock, and Supply. This tool illustrates the risk of productivity loss based on ten-day sowing periods, with a 20% risk from September 21st to December 20th, a 30% risk from December 21st to 31st, and a 40% risk from September 11th to 20th during the corn harvest in General Carneiro, MT. Additionally, the tool provides information on soil water storage throughout the year.

8) Sustainable Pest and Disease Control: Mathematical models are used to predict the occurrence of pests and diseases and assess their impact on crop yield. Del Ponte et al. (2006) developed a severity estimation model for Asian rust (*Phakopsora pachyrhizi*) with low complexity. This model estimated Asian rust severity based on accumulated precipitation during the evaluation period (see Figure 7.3.3). The model's simplicity was advantageous because it did not rely on air temperature as a limiting factor for disease development, and additional data on disease inoculum were not necessary for prediction. This model allows for estimating the optimal time for disease management interventions and helps avoid unnecessary applications during periods of low disease pressure.

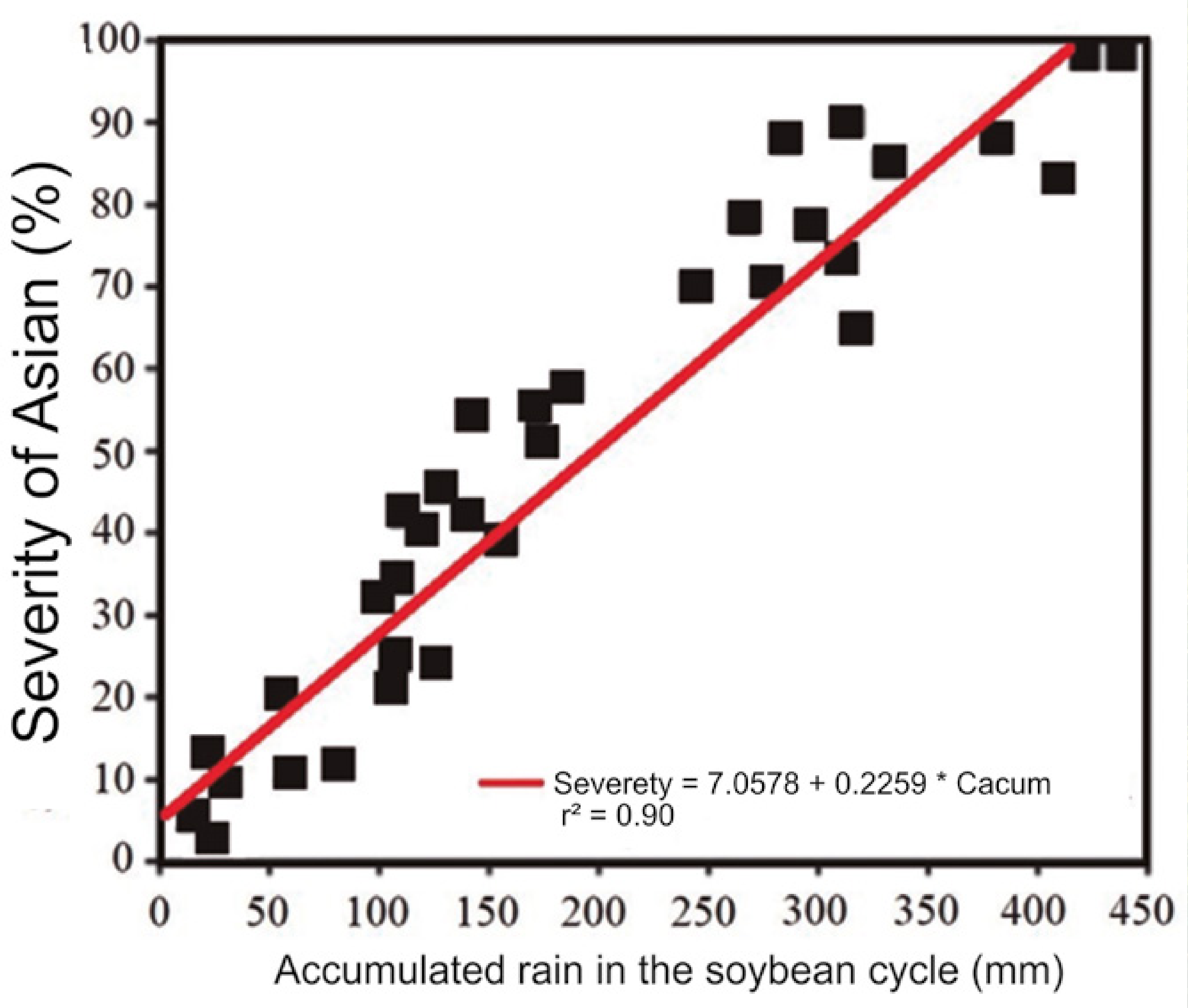


Figure 7.3.3. The relationship between accumulated precipitation during the soybean cycle and the severity of Asian rust is depicted in a simple model. This model allows for the estimation of rust severity based on accumulated precipitation (CAcum) during the specific cycle or period of interest. By evaluating the disease pressure on the crop, this model assists in making decisions regarding disease control strategies. Adapted from Del Ponte et al. (2006).

The FieldCrops team is developing a process-based model to enhance disease management in soybeans and rice, with the goal of providing more precise, accurate, and profitable disease management solutions for producers. The model's development began with experiments conducted by the team, which revealed varied responses to fungicide applications across different sites. Figure 7.3.4 illustrates the response to fungicide application on soybeans in Alegrete, RS during the 2019/2020 harvest, where fungicide application did not impact productivity. Contrastingly, in Tupanciretã, RS during the 2018/2019 harvest (Figure 7.3.5), fungicide application increased yield and profitability for producers. The results are presented as relative productivity to facilitate comparisons between experiments, with the yield reference set as the one with the highest number of fungicide applications in both trials.

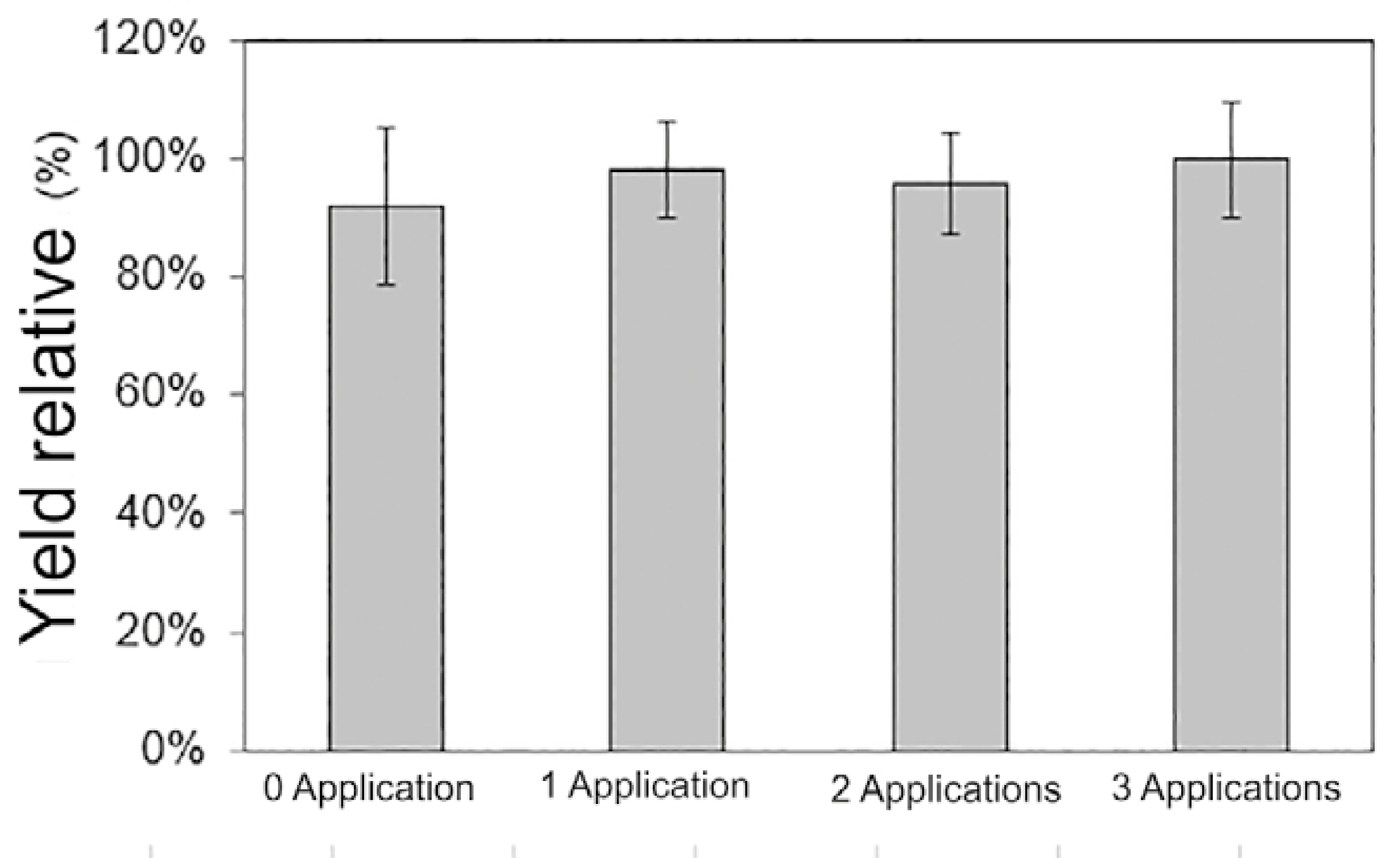


Figure 7.3.4 Soybean yield relative to the number of fungicide applications (yield of treatment with X applications compared to yield of treatment with 3 applications) in Alegrete, Rio Grande do Sul, Brazil.

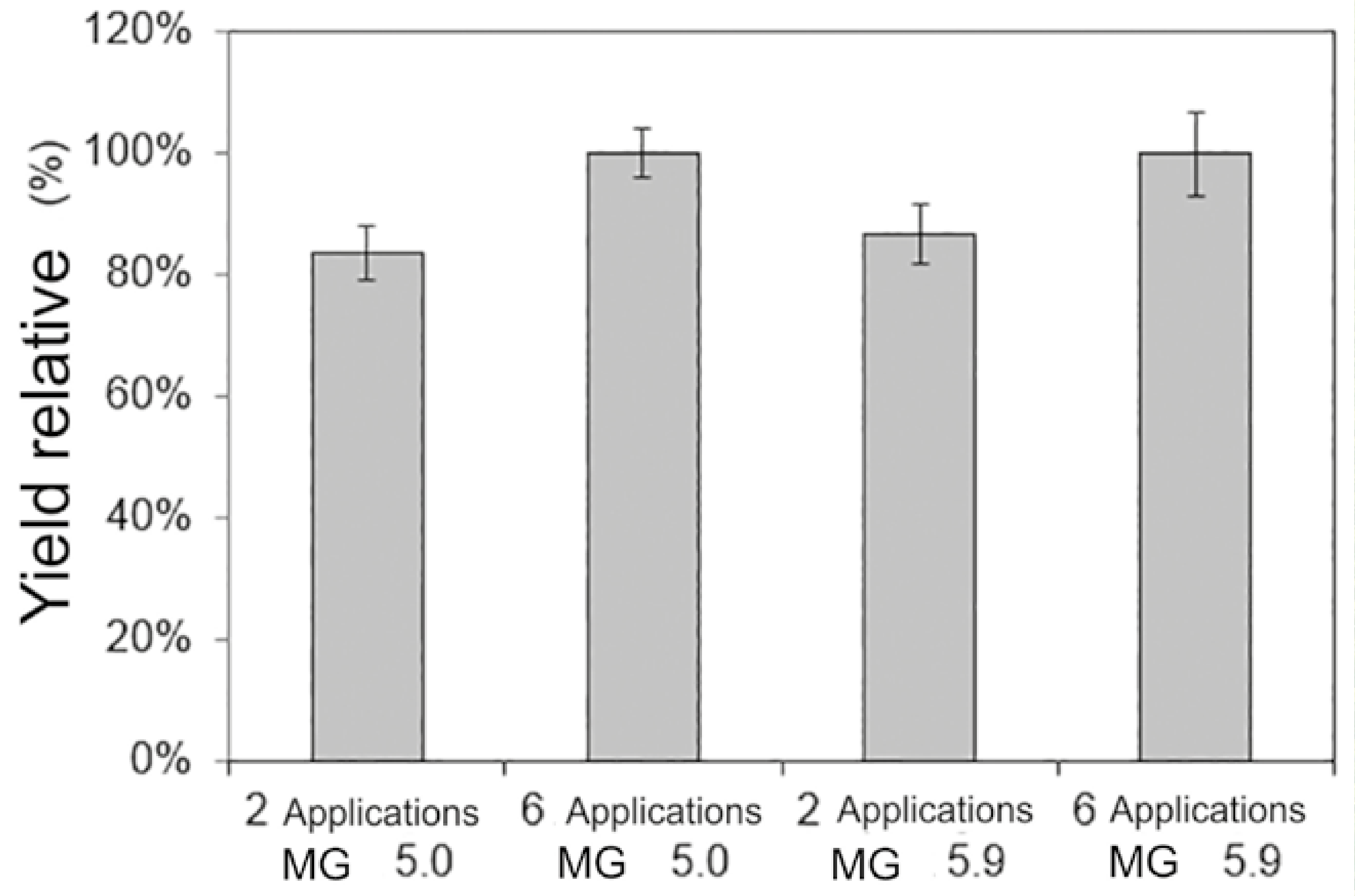


Figure 7.3.5. Soybean yield relative to the number of fungicide applications (yield of treatment with X applications compared to yield of treatment with 3 applications) in Tupanciretã, Rio Grande do Sul, Brazil.

The use of mathematical models in agriculture is becoming a global trend, reaching rural producers to assist in planning and decision-making. This generation of information works in two directions: on-farm data collection, such as monitoring rainfall, which is then processed into models to generate applied agricultural information. Additionally, these models serve as valuable tools to guide investments and public policies aimed at promoting agricultural sustainability within regions.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The Soybean Money Maker Championship aims to stimulate sustainable and profitable soybean production in Brazil.

8. The sustainability revolution in the soybean field

Bruna San Martin Rolim Ribeiro; Eduardo Lago Tagliapietra; Jose Eduardo Minussi Winck; Michel Rocha da Silva; Alexandre Ferigolo Alves; Guilherme Guerin Munareto; Anderson Haas Poersch; Cesar Eugênio Quintero; Gean Leonardo Richter; Darlan Scapini Balest; Victoria Brittes Inklman; Renan Augusto Schneider; Kelin Pribs Bexaira; Cristian Savegnago; Leonardo Silva Paula; Marcos Dalla Nora; Edgardo Santiago Arevalo; María Soledad Armoa Báez; Luciano Zucuni Pes; Nereu Augusto Streck; Paulo Ivonir Gubiani; Rodrigo Pivoto Mulazzani; Emerson Jose Goin; Yuri Gross; Luciano Carmona; Rodrigo Bega; Daniel Debona; Gregori da Encarnação Ferrão; Luís Henrique Loose; Kaleb Emanoel Ferreira do Amaral; Renan Buque Pardinho; Paula Dalla Vecchia; Julio Viégas; Alencar Junior Zanon

The primary challenge facing humanity is to increase food production by 50% to 70% by 2050. To achieve this, revolutionizing agriculture requires evolution and transformation. Therefore, maximizing yield on every arable hectare through sustainable intensification is the main objective of all actions undertaken by the FieldCrops Team. In line with this objective, the FieldCrops Team initiated the Kick off of the Soybean Money Maker Championship, which classifies soybean crops based on production sustainability and aims to understand the interaction between genetics, environment, management, and producers (Figure 8.1).

The term sustainability refers to the process of gradually improving efficiency in the use of resources to meet present needs without compromising the ability of future generations to meet their own needs. The sustainability of a crop is achieved through the adoption of good management practices that allow ecosystems to achieve higher yields with less environmental impact, greater profitability, and an improved quality of life for producers. In this way, maintaining or improving the foundation of natural resources, reducing dependency on non-renewable resources, fosters adaptability, resilience, and social equality.

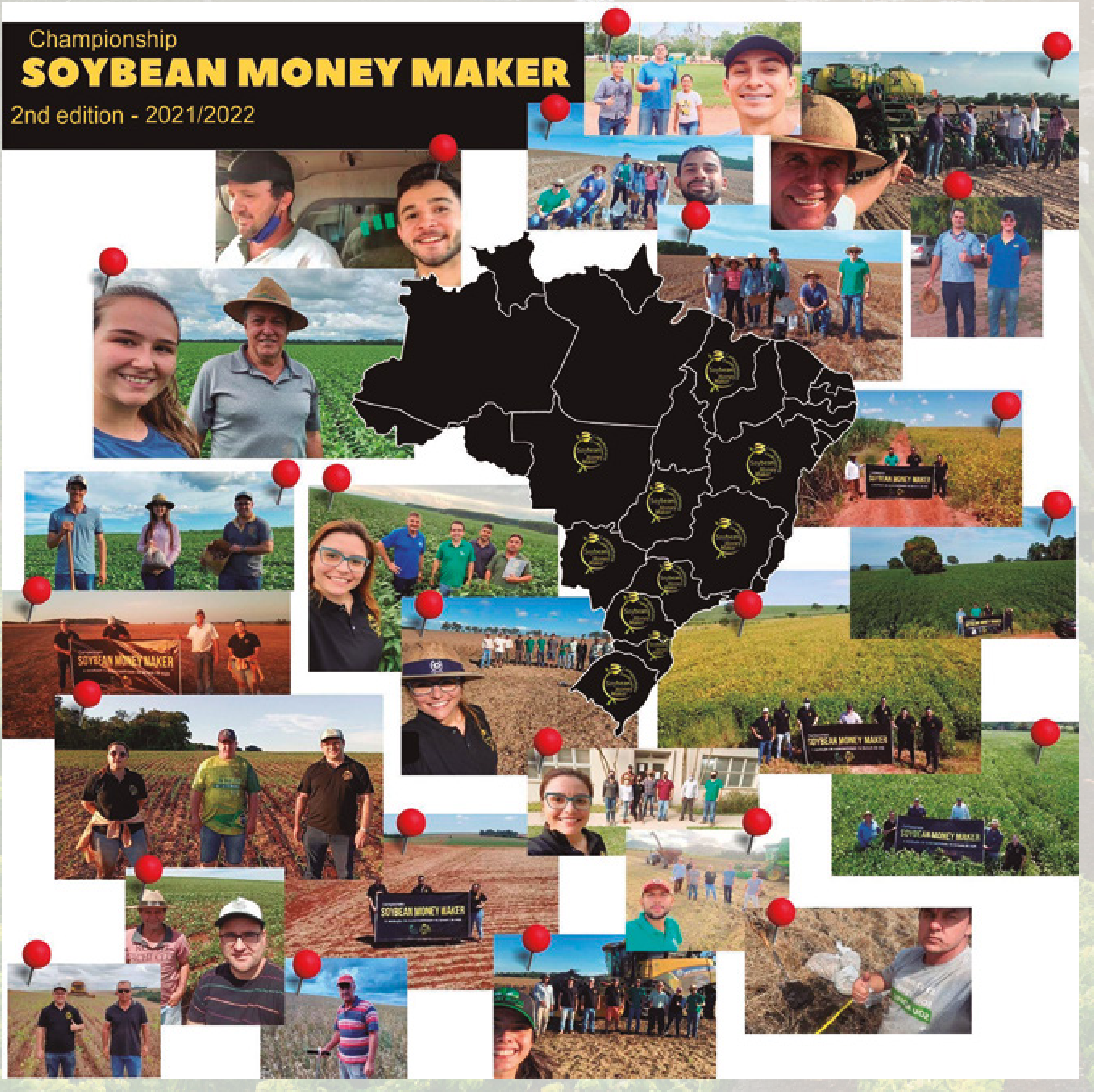


Figure 8.1. Representation of the scope of the 2nd edition of the Soybean Money Maker Championship 2021/2022 crop, with 10 states and 52 crops soy farms in Brazil.

8.1. How to measure sustainability in Soy crops?

The sustainability of a soybean crop can be assessed using three levels of indicators: environmental, social, and economic. When selecting indicators to evaluate crops, it is essential that the indicator provides clear information to guide actions and enable producers to achieve a higher level of sustainability (Maul et al., 2008; Pannell & Glenn, 2000). For example, Cassman & Grassini (2021) indicate that efficiency in the use of natural resources and inputs is the best metric to measure the sustainability of a crop (Figure 8.1.1).

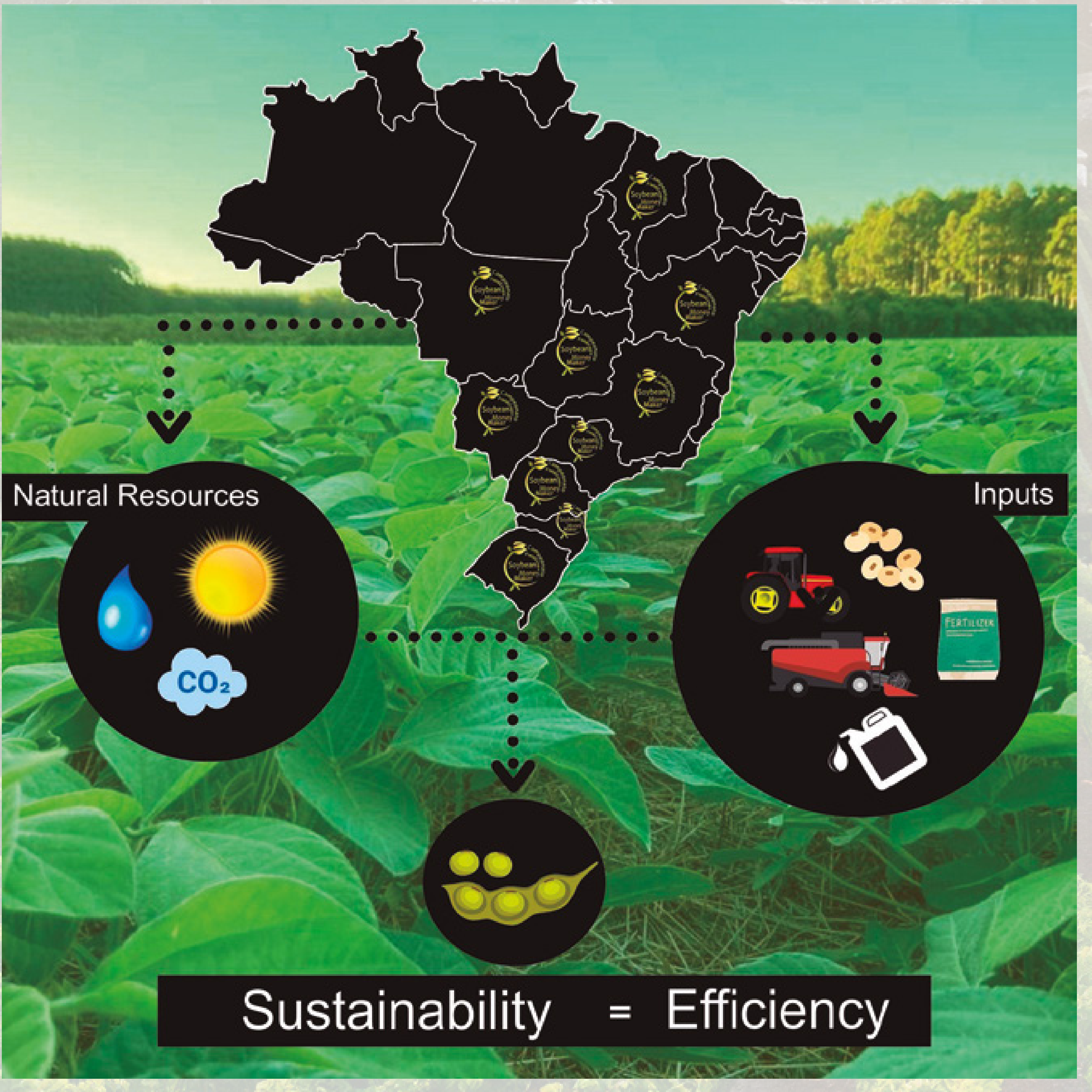
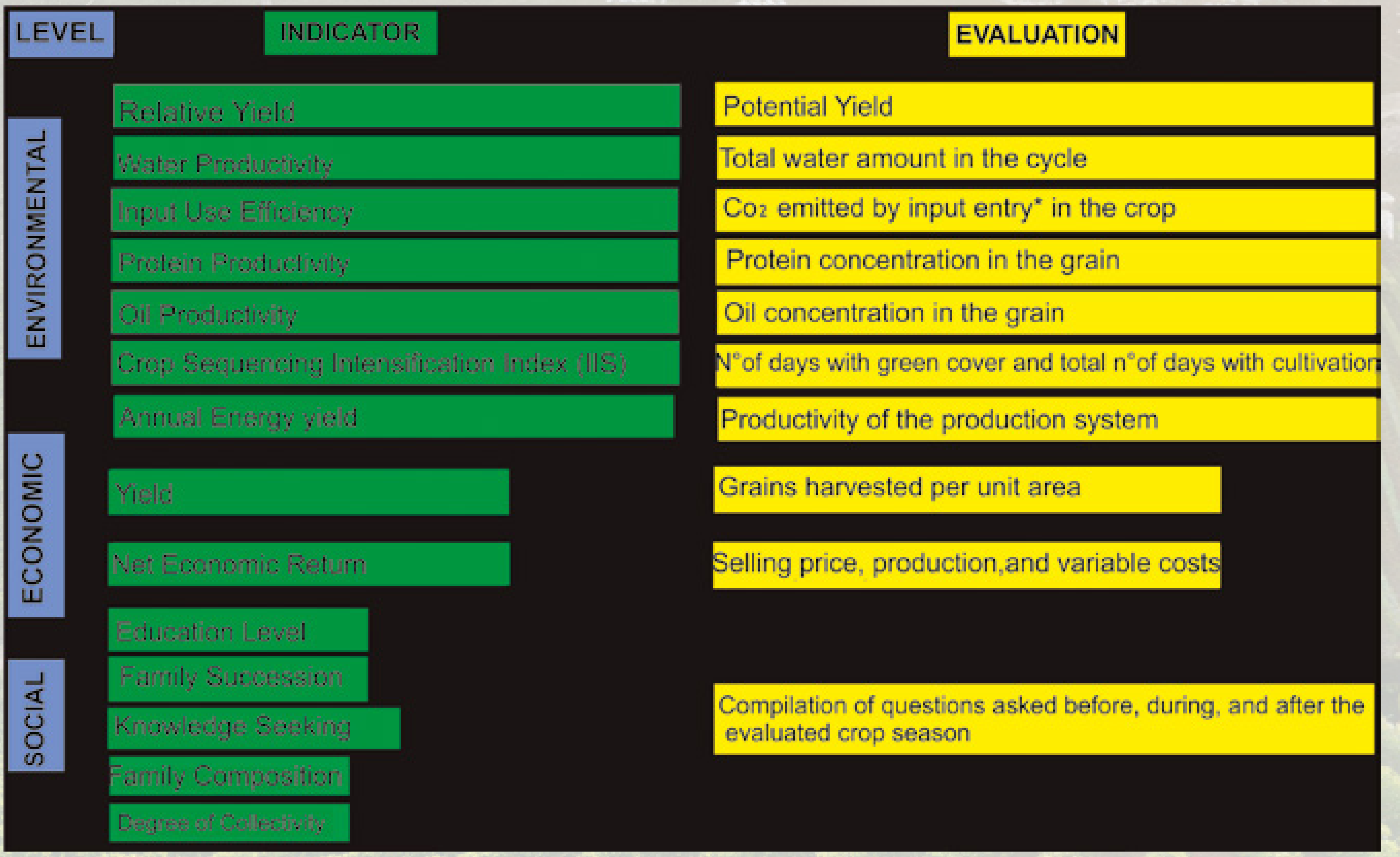


Figure 8.1.1. Scheme with the main factors considered for determining the sustainability of soy crops in the Soybean Money Maker Championship.

Indicators to quantify environmental, economic, and social sustainability selected in the Soybean Money Maker Championship are depicted in Figure 8.1.2. To access information on crop management, each producer answers a sequence of questions about the management of the area entered in the championship (date of sowing, amount of fertilizer, name and quantity of products used, etc.) and variable costs (seed, pesticides, and fertilizer). Thus, it is possible to identify the level of sustainability of crops.



LEVEL	INDICATOR	EVALUATION
ENVIRONMENTAL	Relative Yield	Potential Yield
	Water Productivity	Total water amount in the cycle
	Input Use Efficiency	Co_2 emitted by input entry* in the crop
	Protein Productivity	Protein concentration in the grain
	Oil Productivity	Oil concentration in the grain
	Crop Sequencing Intensification Index (IIS)	N°of days with green cover and total n°of days with cultivation
	Annual Energy yield	Productivity of the production system
ECONOMIC	Yield	Grains harvested per unit area
	Net Economic Return	Selling price, production,and variable costs
SOCIAL	Education Level	Compilation of questions asked before, during, and after the evaluated crop season
	Family Succession	
	Knowledge Seeking	
	Family Composition	
	Degree of Collectivity	

Figure 8.1.2. Conceptual framework for assessing sustainability in soybean production at social, environmental, and economic levels in crops of the Soybean Money Maker Championship.

Soybean crop from the Soybean Money Maker Championship at Bartz Farm in Camaquã, Rio Grande do Sul, Brazil, with a yield of 5,402 kg ha^{-1} in the 2020/21 season.

8.2. Application of sustainability indicators in soybean crops

The first and most important indicator specific to the Soybean Money Maker Championship is the estimation of yield potential (YP) and yield potential limited by water (YW) for each crop. This estimation is carried out by mathematical models based on processes that are validated for combinations of environmental factors (such as solar radiation, temperature, and CO_2) and soil characteristics that represent soybean cultivation in Brazil. Determining the YP for each crop allows for comparisons between championship crops and crops from other regions of the world using a standardized, non-empirical methodology (see Figure 8.2.1). This approach enables the definition of relative yield compared to YP (determined by cultivar, solar radiation, temperature, and CO_2) for irrigated crops and YW (imposed by the cultivar, solar radiation, temperature, CO_2, and precipitation) for rainfed crops, providing insights into the productive efficiency of each crop.

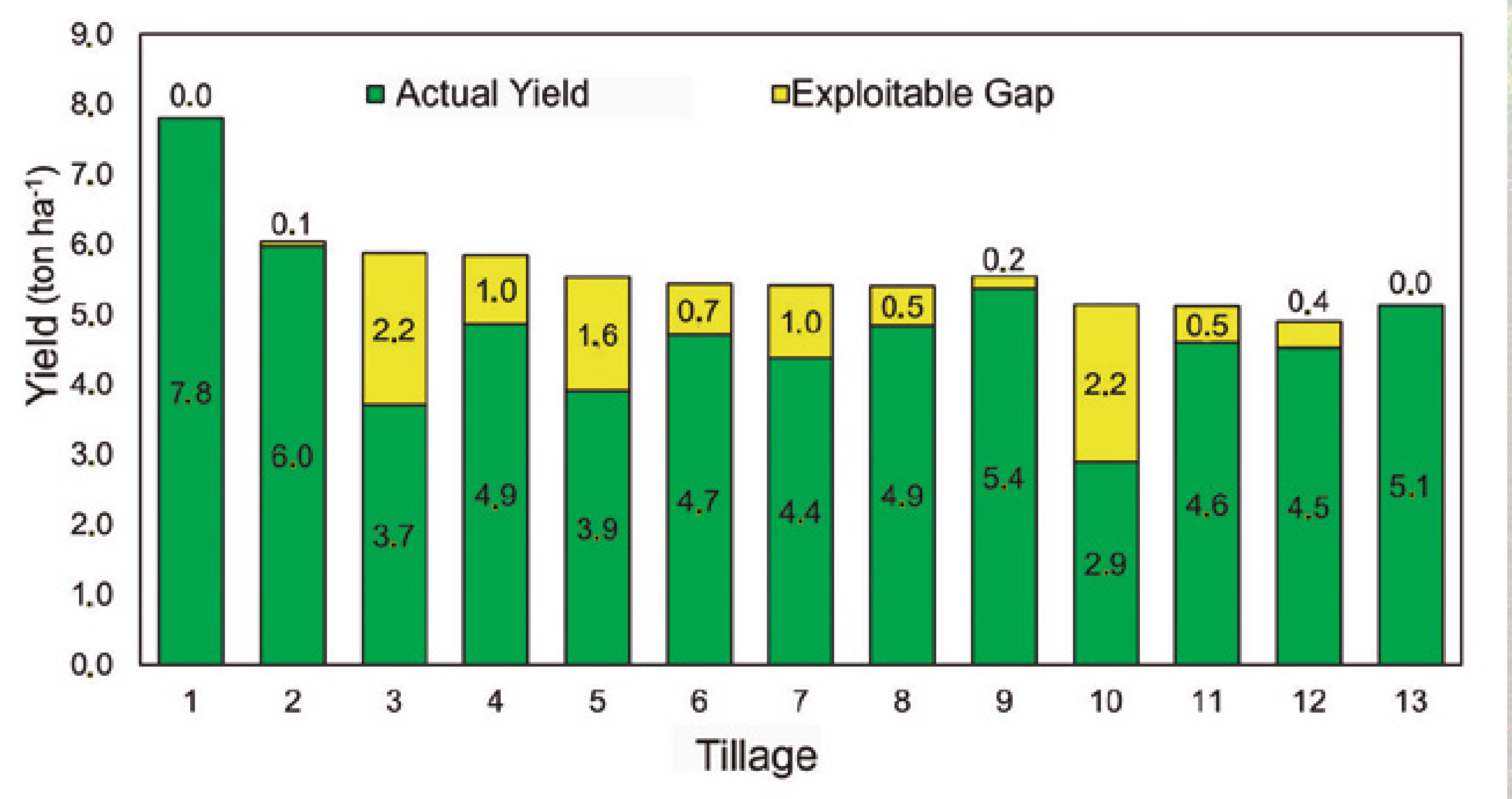


Figure 8.2.1. Yield actual (green - values determined in the field with harvest monitoring) and exploitable gap (yellow - calculated considering that each field can reach 80% of its yield potential) for 13 soybean fields in Brazil. *1 bag of soybeans is equivalent to 60 kg of soybeans.

Achieving 80% of the yield potential (referred to as the “exploitable gap” in Figure 8.2.1) is the target aimed at reducing the yield gap for producers with adequate access to inputs, markets, and extension services. In the 2020/21 harvest of the Soybean Money Maker Championship (Figure 8.4), 30% of the participating crops (crops 1, 2, 9, and 13) reached this target by achieving 80% of the yield potential. These successful crops utilized cultivars that were well-suited to the sowing date and optimized natural resource availability, thereby ensuring the crop’s potential was maximized throughout its critical stages. Water productivity efficiency indicates the use of water, specifically how many kilograms of soy can be produced with one millimeter of water in each crop. Water productivity values above 9 kg mm^{-1} signify excellent efficiency in crop management practices (Zanon et al., 2016). In the Soybean Money Maker Championship, water productivity is evaluated based on precipitation and irrigation during the soybean cycle, soil water storage capacity, and grain yield. During the 2020/21 harvest, among the thirteen evaluated crops, only four did not achieve water productivity efficiency of 9 kg mm^{-1} (field 3, 7, 11, and 12), despite having total water availability (rainfall + irrigation) exceeding 800 mm throughout the development cycle. In these cases, other management factors were limiting the achievement of greater water use efficiency. Field with higher water productivity values (>9 kg mm^{-1}) averaged 424 mm of water and achieved 94% productivity efficiency. However, in cases like field 13, low water use efficiency values may be more attributed to excessive precipitation and soils with low water storage capacity rather than overall productivity efficiency (see Figure 8.2.2).

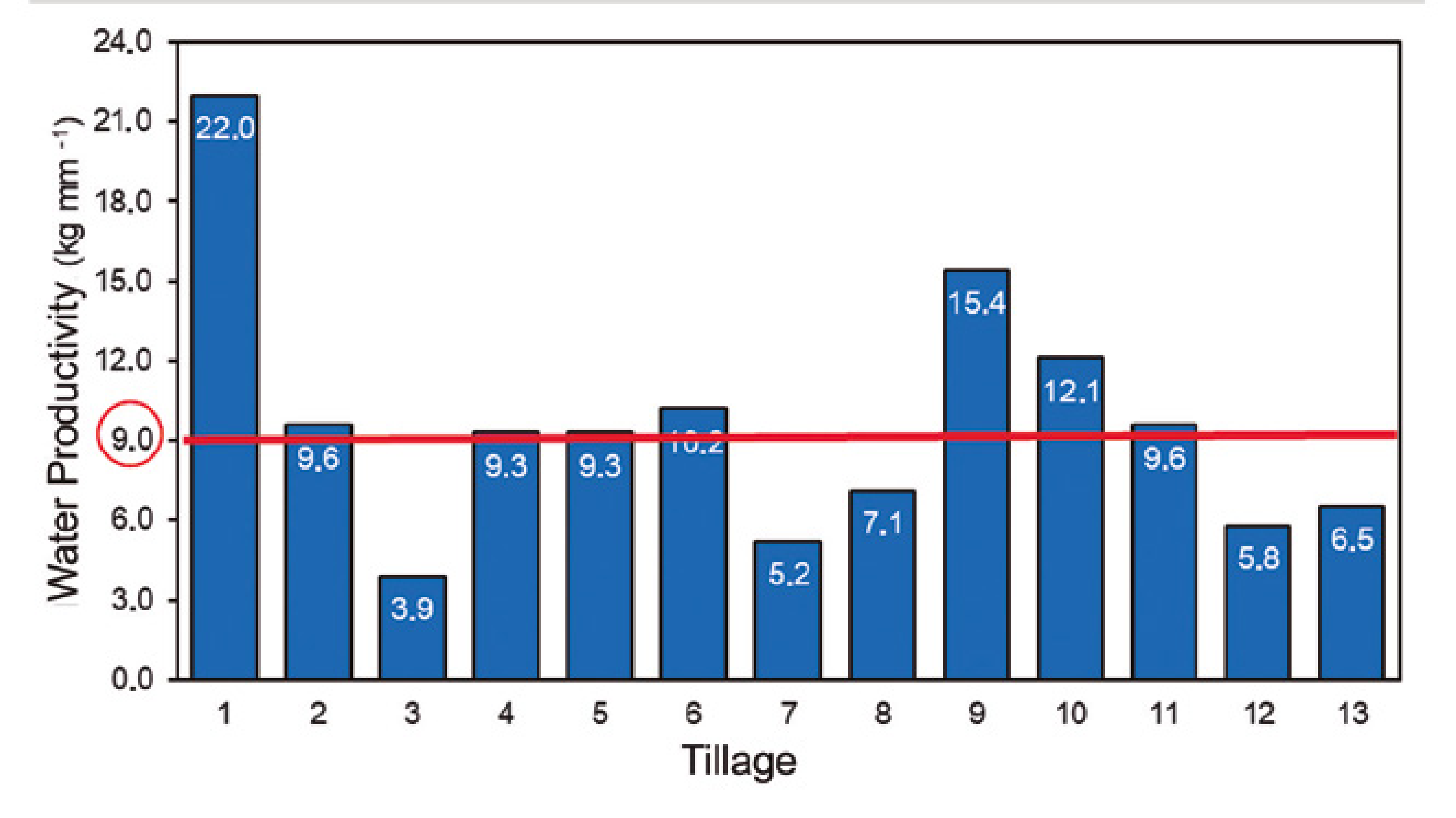


Figure 8.2.2. Water productivity in 13 soy fields in the Soybean Money Maker Championship in Brazil.

The efficiency in the use of inputs (EUI) in the crops of the Soybean Money Maker Championship was defined by the amount of grain produced per kilogram of CO_2 emitted equivalent (CO_{2e}). EUI was calculated based on the total CO_2 emissions resulting from management practices used in the crop, including seed usage, fertilization operations, pesticide applications, and others. Reference values for this indicator have not yet been established, and one of the proposals of the Soybean Money Maker Championship is to define these reference values based on crop data. During the 2020/21 harvest, the average EUI across thirteen crops was determined to be 13.5 kg of soybeans per kilogram of CO_{2e} emitted (Figure 8.2.3). Given the scarcity of studies in Brazil addressing this topic, information from the Soybean Money Maker Championship that links EUI, CO_2 emissions, and management practices can serve as a valuable reference for future policies related to carbon sequestration, as well as for the generation and commercialization of carbon credits. These efforts are based on ecophysiological indicators, such as efficiency in the use of inputs, to promote sustainability and reduce environmental impact in agriculture.

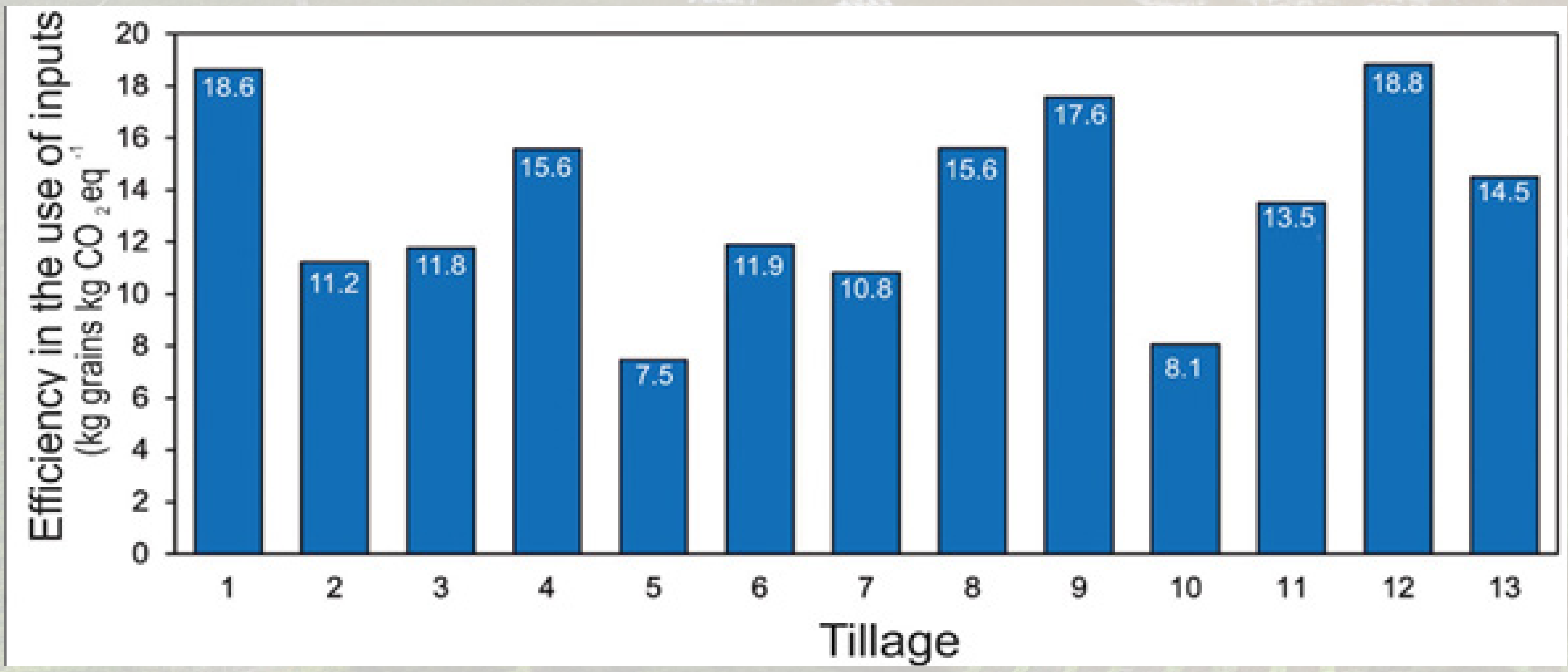


Figure 8.2.3. Efficiency in the use of inputs in 13 soybean crops in the Soybean Money Maker Championship in Brazil.

In addition to quantitative indicators, the Soybean Money Maker Championship evaluates qualitative information of soybean crops by quantifying oil content and grain protein. The use of qualitative indicators for soybean commercialization is a global trend, pioneered by the North American market and expected to expand to Latin American countries. At the farm level, the interactions between genetics (G), environment (W), and management (M) influence the levels of nutrients, proteins, and lipids in soybeans.

In the fields evaluated during the 2020/21 season of the Soybean Money Maker Championship, the average protein content was 33.2% with an average deviation of 1%, and the average oil content was 21.6% with an average deviation of 0.8% (Figure 8.2.4). These qualitative indicators provide valuable information for understanding crop quality and market suitability, enhancing the value proposition for soybean producers.

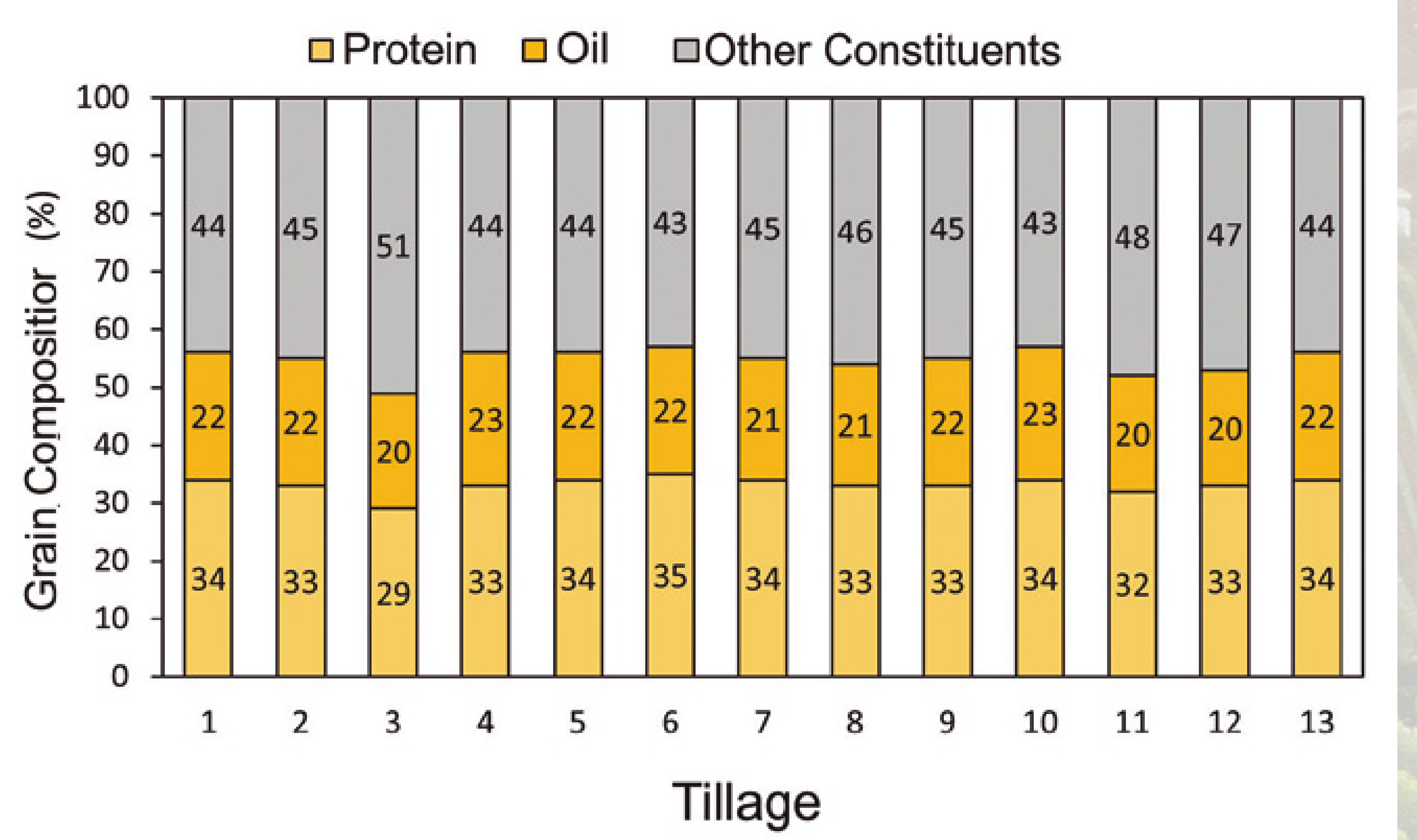


Figure 8.2.4. The composition of soybeans, including oil content and protein, determined in 13 soybean crops of the Soybean Money Maker Championship in Brazil using Nira®.

The average protein productivity was 1.6 ton ha^{-1} with an average deviation of 0.26 ton ha^{-1}, and the average oil productivity was 1.1 ton ha^{-1} with an average deviation of 0.24 ton ha^{-1} (Figure 8.2.5). The Soybean Money Maker Championship provides both qualitative and quantitative data to assist in defining management practices that maximize the sustainability of soybean crops and production systems, aligned with the production of quality food. It's important to highlight the interest of export traders and soybean processing industries in the composition of the grain, as it impacts the production of by-products and their operating costs. In the near future, soybean prices may be influenced by their oil and protein concentration, reflecting the growing importance of quality parameters in the soybean market.

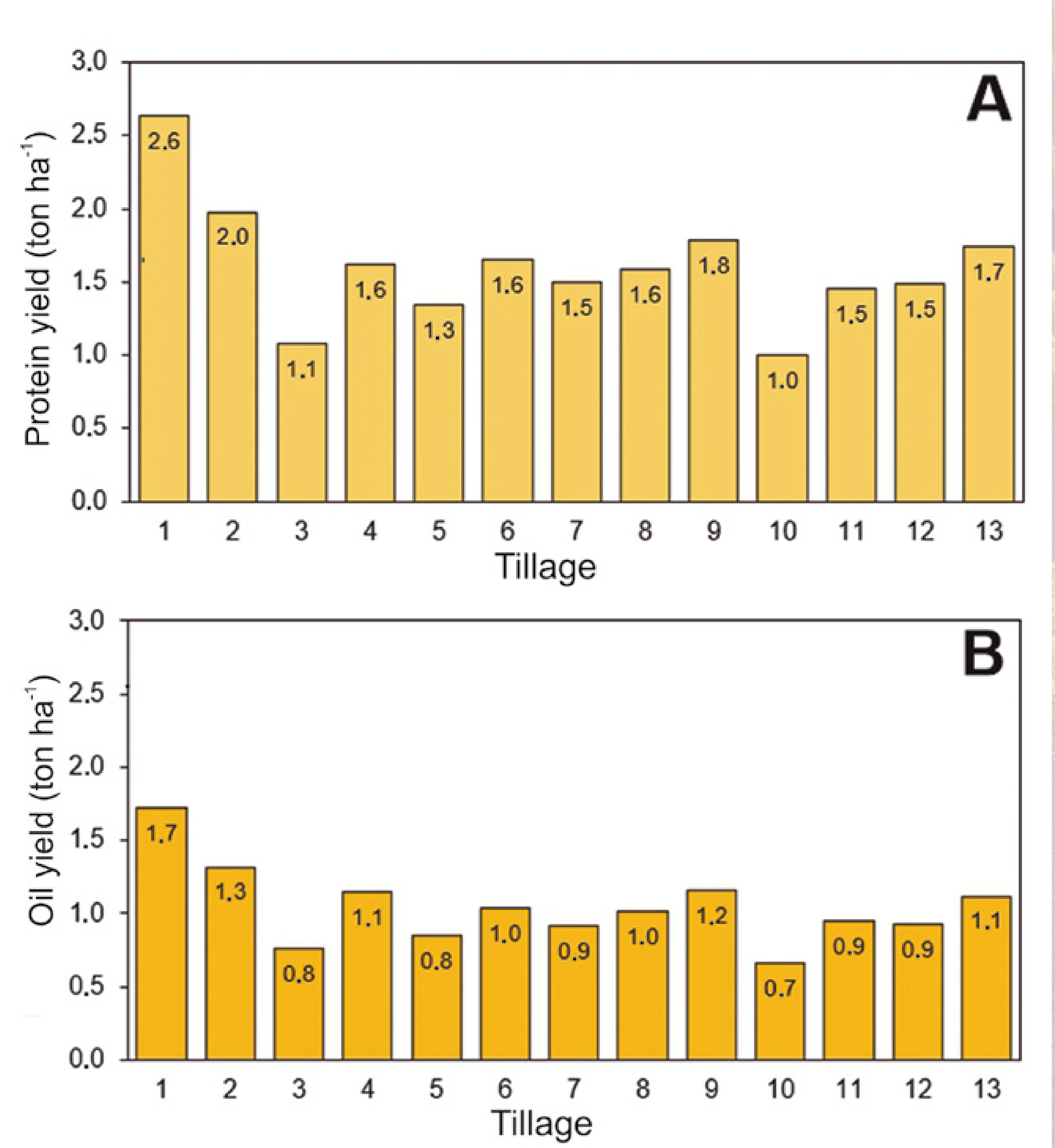


Figure 8.2.5. Protein (A) and oil (B) productivity of 13 crops of Soybean Money Maker Championship in Brazil.

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. Visão:
Evoluir na diversificação e integração de culturas, sendo referência em irrigação e digitalização das atividades, buscando a máxima eficiência dos processos e reconhecida pelo bem-estar dos colaboradores e respeito ao meio ambiente, investindo continuamente nas pessoas.

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9. The steps of a profitable and sustainable soybean crop

José Eduardo Minussi Winck; Eduardo Lago Tagliapietra; Michel Rocha da Silva; Alexandre Ferigolo Alves; Guilherme Guerin Munareto; Anderson Haas Poersch; Bruna San Martin Rolim Ribeiro; Cesar Eugênio Quintero; Gean Leonardo Richter; Darlan Scapini Balest; Victoria Brittes Inklman; Renan Augusto Schneider; Kelin Pribs Bexaira; Cristian Savegnago; Leonardo Silva Paula; Marcos Dalla Nora; Edgardo Santiago Arevalo; María Soledad Armoa Báez; Luciano Zucuni Pes; Nereu Augusto Streck; Alencar Junior Zanon

The yield of a crop primarily depends on the availability of basic inputs for photosynthesis. Factors such as the concentration of CO_2, solar radiation, and air temperature are uncontrollable environmental variables influenced by seasonal variations. However, annual variations in photoperiod, solar radiation, and temperature, along with the choice of cultivar (MG), allow adjustments of critical phenological stages to coincide with periods of optimal environmental resource availability. The availability of these resources, or limitations caused by water, nutrients, and plant density, determine the potential and achievable yield of the crop. Conversely, factors that reduce yield, such as weeds, pests, diseases, thermal stresses, and salinity, impact the actual yield of the crop (Figure 9.1). Effective crop management strategies are essential to minimize the effects of yield-reducing factors.

Agriculture is a dynamic activity characterized by unique biophysical and socioeconomic factors for each crop. Therefore, proposing standardized “recipes” or “technological packages” for achieving sustainable intensification in farming is not aligned with the principles of Agriculture 4.0, which emphasize tailored solutions based on local conditions and data-driven insights. However, we can prioritize assisting the world’s soy producers by identifying factors that limit yield, providing technical support to guide investments and enhance the efficiency of soybean production.

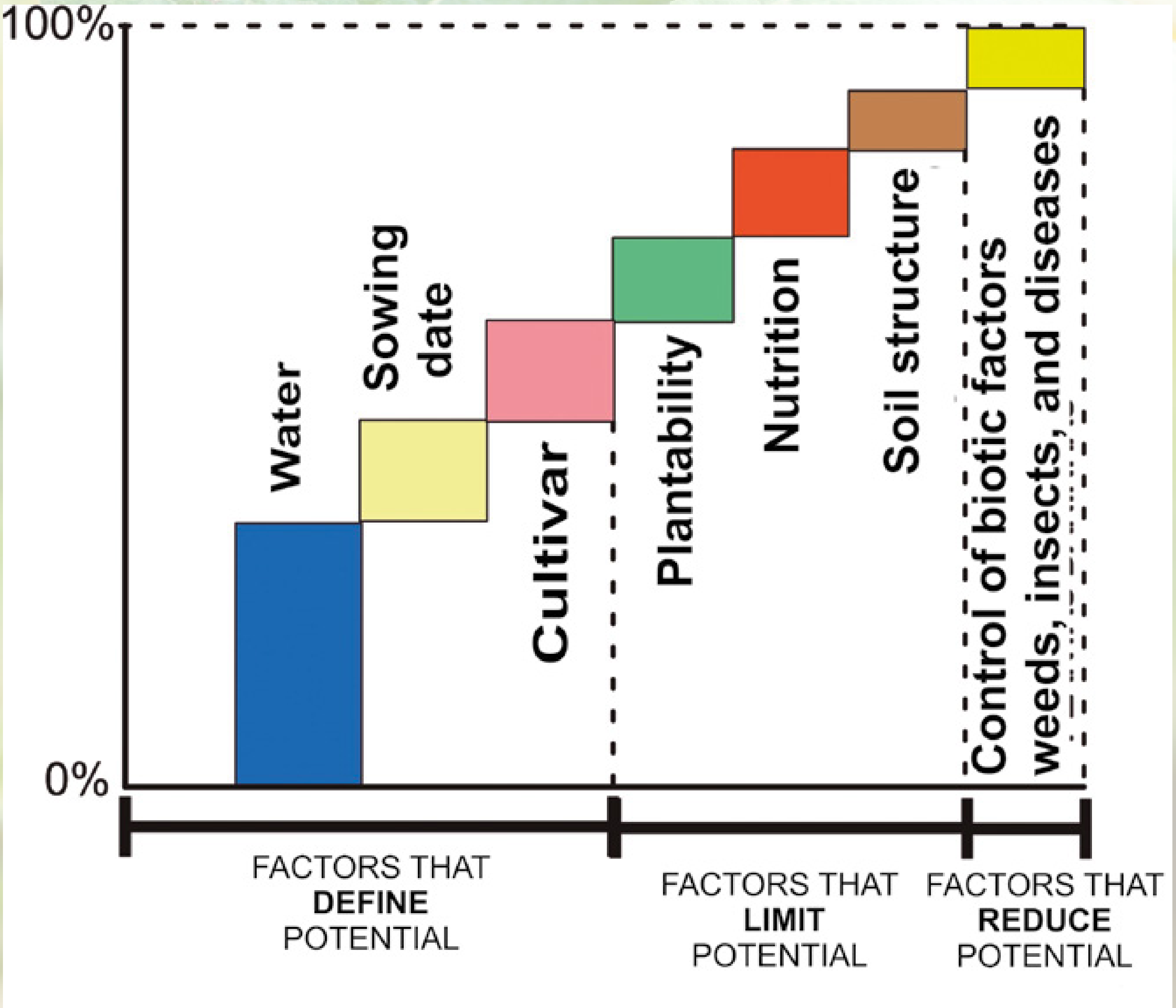


Figure 9.1. Factors that define, limit, and reduce the potential for soybean yield in order of importance.

To achieve a profitable and sustainable crop, two steps are essential: 1) identifying the yield potential of the crop; and 2) pinpointing the constraints that contribute to the yield gap. These estimates provide crucial insights into the potential for increasing crop production through improvements in agricultural systems and property management (Devkota et al., 2015). Decomposing yield gaps into their constituents is crucial because it allows for the evaluation and quantification of the impact of fundamental management practices, such as sowing timing, soil amendment, crop rotation, optimal plant density, etc., on soybean productivity. Moreover, factors that limit productivity vary in terms of investment costs, risk levels, and favorable adoption conditions, including market integration levels in the region (Shiferaw et al., 2009). All these factors are influenced by the heterogeneity associated with biophysical, socioeconomic, and ecological aspects of production environments (Beddow et al., 2015).

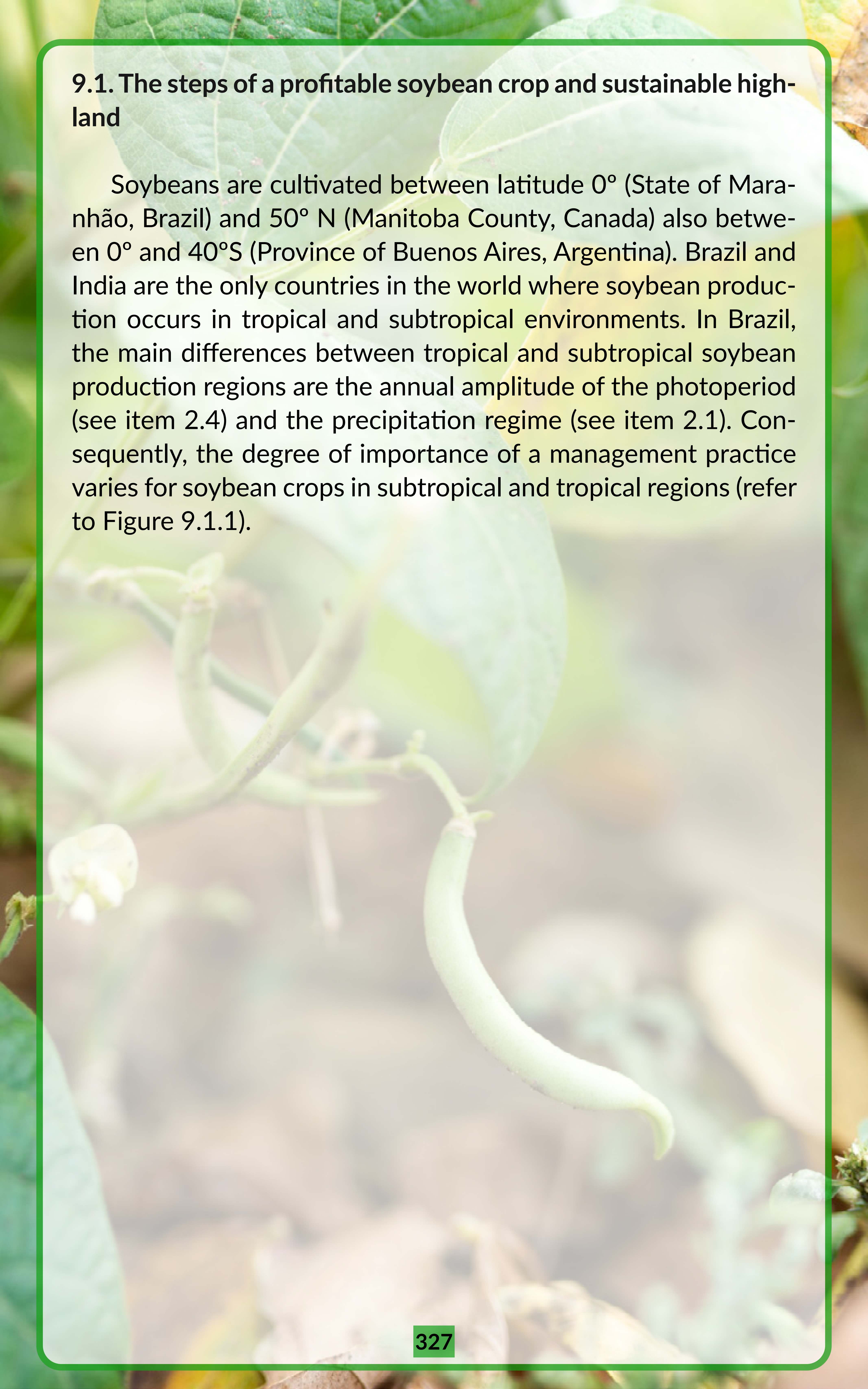
This chapter underscores the key points addressed in this book for soybean producers across different production environments: 1) maximizing profitability in high-altitude tropical soybean environments; 2) optimizing tillage practices for tall subtropical soybean environments; and 3) achieving high yields in lowland soybean environments, considering factors such as productivity potential, crop response to productivity, and implementation costs associated with specific management practices.

Field of the Soybean Money Maker Championship at Agropecuária Parcianello, in Alegrete, Rio Grande do Sul, Brazil with yield of 5988 kg ha^{-1} in the 2020/21 season.

Field of the Soybean Money Maker Championship at the Luis Freire farm, in Luis Eduardo Magalhães, in Bahia, Brazil with yield of 5220 kg ha^{-1}, 2021/22 season.

9.1. The steps of a profitable soybean crop and sustainable highland

Soybeans are cultivated between latitude 0° (State of Maranhão, Brazil) and 50° N (Manitoba County, Canada) also between 0° and 40°S (Province of Buenos Aires, Argentina). Brazil and India are the only countries in the world where soybean production occurs in tropical and subtropical environments. In Brazil, the main differences between tropical and subtropical soybean production regions are the annual amplitude of the photoperiod (see item 2.4) and the precipitation regime (see item 2.1). Consequently, the degree of importance of a management practice varies for soybean crops in subtropical and tropical regions (refer to Figure 9.1.1).



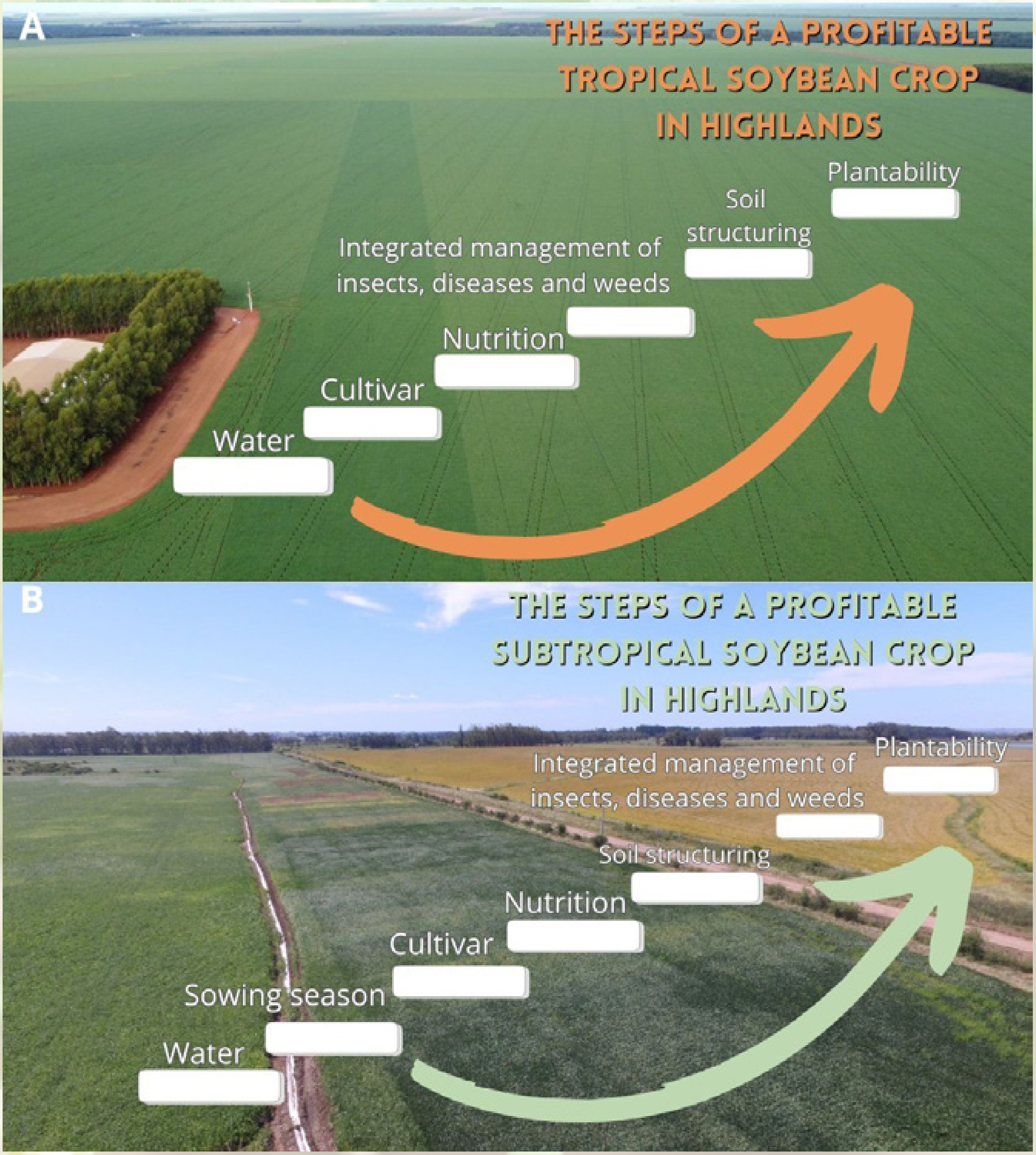


Figure 9.1.1. Factors for building high yield crops of tropical (A) and subtropical (B) soybeans.

The water available during the crop cycle is an important factor in defining the achievable yield potential. In subtropical environments (southern Brazil, Uruguay, and the Pampas region in Argentina), the precipitation regime is greatly influenced by the ENSO phenomenon (see item 2.1.2.1), which commonly results in water deficits during the development cycle due to uneven precipitation distribution (refer to item 2.1.2). In case the southern region of Brazil, the yield gap due to water deficiency accounts for approximately 60% of the total yield gap. In tropical environments, the uniform distribution of precipitation reduces the water gap, representing only 20% of the total gap in that environment. Therefore, soybean irrigation is much more relevant in subtropical regions of Brazil compared to tropical regions (source: www.yieldgap.org/brazil). However, investments in irrigation are justified in tropical regions like the Central West and Matopiba due to adaptations in the production system (e.g., second harvest corn). Water is crucial in the Midwest due to its role in determining the soybean sowing season, which is triggered by the onset of the rainy season (refer to item 5).

In tropical soybean production, the cultivar factor becomes more relevant compared to subtropical regions, which have a broader sowing window (refer to item 1.6). In southern Brazil, the sowing season is crucial for aligning the period of higher photothermal coefficient with the R3-R7 growth stages, according to the maturity group (MG) of the cultivar (refer to items 1.5 and 2.5).

Nutrition (refer to item 3) is another limiting factor of yield potential, influenced by water availability, sowing date, and genetic potential. Plant nutrition involves ensuring the availability of essential nutrients and preventing the immobilization of toxic elements. The relationship between soil pH and productivity indicates a negative linear trend with decreasing pH (refer to item 3.1). Yield losses due to low pH are attributed to the immobilization of essential elements and toxicity caused by H+, Al, and Mn. Additionally, soil fertilization with corrected pH should consider the existing nutrient levels and the expected yield.

In subtropical regions, low temperatures during winter interrupt the life cycles of certain pests and diseases, or at least reduce their population growth rate. Conversely, in tropical environments characterized by high temperatures and frequent rainfall, conditions are more conducive to the multiplication of fungi and insects, resulting in greater pressure from pests and diseases on tropical soybean crops. In subtropical crops, however, emphasis is placed on chemical, physical, and biological soil structuring rather than solely relying on pest, disease, and weed control. Soil structure is closely related to water retention capacity, nutrient availability, and root exploitable depth (refer to item 2.1.1.1). This factor is particularly important in environments with greater limitations.

The plantability factor (refer to item 1.9) involves plant distribution, row spacing, and plant density. Regardless of the environment, errors in plantability can limit yield potential by reducing radiation use efficiency.

9.2. The steps of a profitable soybean crop and sustainable lowland

An emerging production system in southern Brazil involves cultivating soybeans in lowland areas in rotation with irrigated rice. In these areas, the factors that limit yields differ from those in upland soybean areas. Common challenges include the presence of compacted subsurface layers, low hydraulic conductivity, limited water storage capacity, and low soil pH. Identifying these limiting factors in new production systems is crucial for directing efforts and investments towards achieving profitable crops.

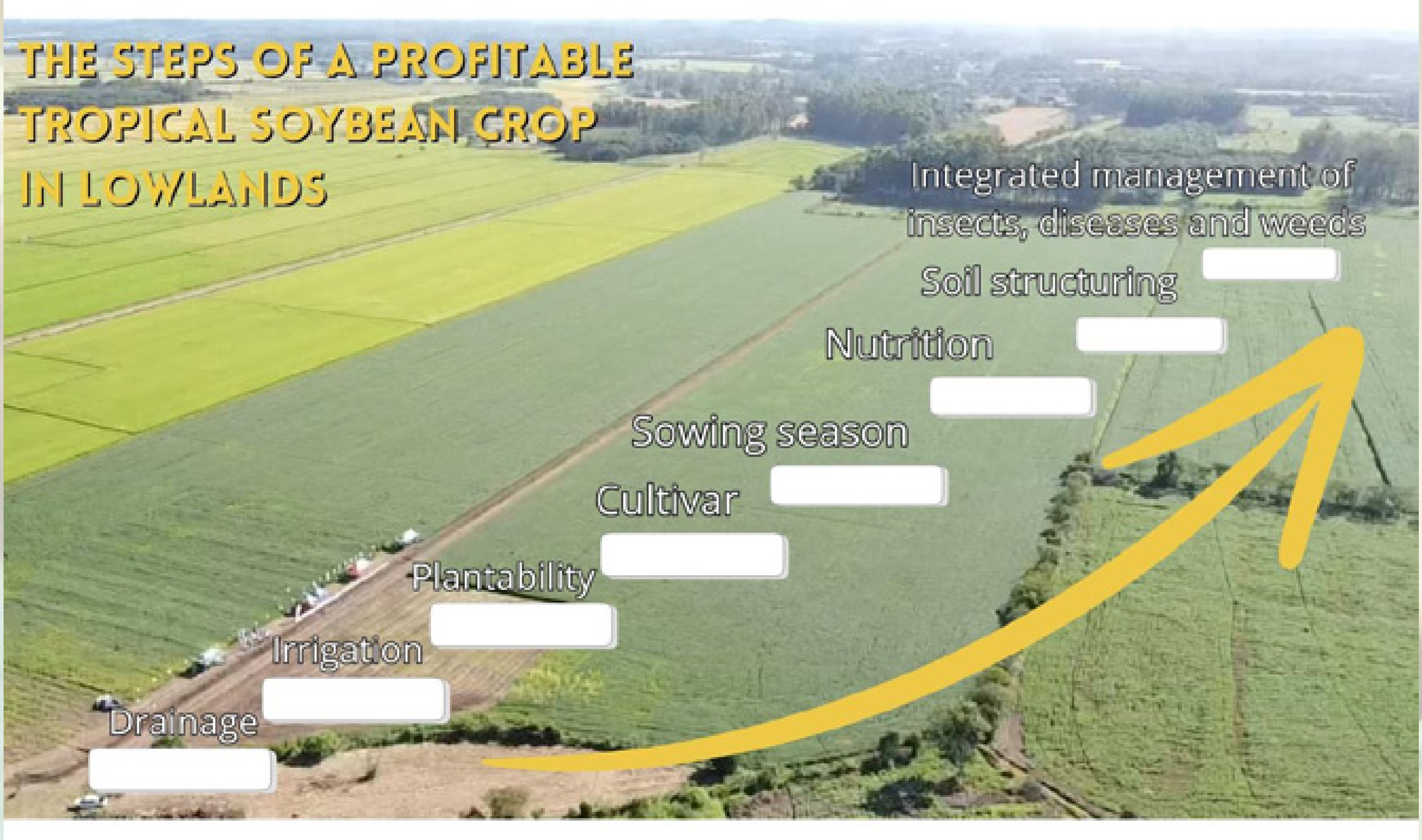


Figure 9.2.1. Factors for achieving high-yield soybean crops in lowland environments or within irrigated rice production systems.

The differences in edaphic characteristics of lowlands necessitate adaptive management that prioritizes factors which may be less significant in highland areas. Lowland environments are prone to water excess in the soil, which can negatively impact soybean productivity. To minimize these effects, several strategies for drainage can be implemented. These include constructing main and secondary drains to facilitate rapid rainwater drainage, scarification to break up compacted subsurface layers (Figure 9.2.2), planting soybeans in microridges (Figure 9.2.3), or using mechanisms attached to the seeder to break up compacted surface soil layers. These measures collectively aim to mitigate the occurrence or intensity of water excess and improve soybean productivity in lowland environments.

Figure 9.2.2. Soil profile in a lowland area with a compacted layer from 15 to 30 cm deep in Cacequi, Rio Grande do Sul, Brazil. Courtesy: Bruna Pinto Ramos.

Figure 9.2.3. Soybean sowing in microbed in Pelotas, Rio Grande do Sul, Brazil. Courtesy: Pedro de Souza.

Despite the recurrence of excess water in lowland areas, a soybean crop grown in this environment often goes through periods of water deficiency in the same growing season due to the soil's low water storage capacity and low effective root depth. Water supplementation for soybeans in lowlands typically occurs through furrow irrigation or "bathing" (flooding the area). However, during soil preparation and implementation of irrigation furrows, it is necessary to make them in the direction of the slope of the area, so that water drainage occurs quickly (does not last for a period longer than 24 hours) to avoid excess water in the soil.

The third principle for achieving a profitable soybean crop in lowlands is the plantability of the crop, which determines the density of plants. The most common soils found in lowland systems are classified as planosols, neosols, organosols, glysols, chernosols, vertisol, plinthosol, and spodosol. In these soil types, factors such as water excess, surface encrustation, and soil diseases hinder seedling emergence and can cause seed and adult plant mortality, resulting in gaps in the crop. The naturally poor drainage, high density, low total porosity, presence of a subsurface layer with low permeability, and flat to gently wavy relief create an anaerobic environment that hinders seed germination. Processes for ensuring good plantability involve advanced soil preparation (including drainage, loosening, and leveling), desiccation to create a clean sowing environment, using high-quality seeds, ensuring appropriate soil moisture at sowing, and considering environmental conditions post-sowing. It is essential for producers to conduct a historical diagnosis of the area to anticipate potential seed density adjustments due to plant mortality during the growing season, primarily caused by soil diseases such as *Rhizoctonia solani*, *Fusarium solani*, and *Phytophthora sojae*.

The fourth principle involves the choice of cultivar for lowland environments. When selecting cultivars for lowlands, certain characteristics must be considered, including tolerance to water excess, tolerance to soil diseases mentioned above, root aggressiveness and branching ability, and a cycle greater than 130 days. In well-established lowland crops with efficient drainage, irrigation, and corrected pH, cultivars with a cycle longer than 120 days can be chosen.

Unlike highland areas, sowing time is less critical in lowlands due to climate risks associated with sowings at the beginning of October (the month with the highest precipitation in southern Brazil). However, optimal plant establishment and the highest yields in experiments have been achieved with sowings conducted in the second half of October and the first half of November (Figure 9.2.4).

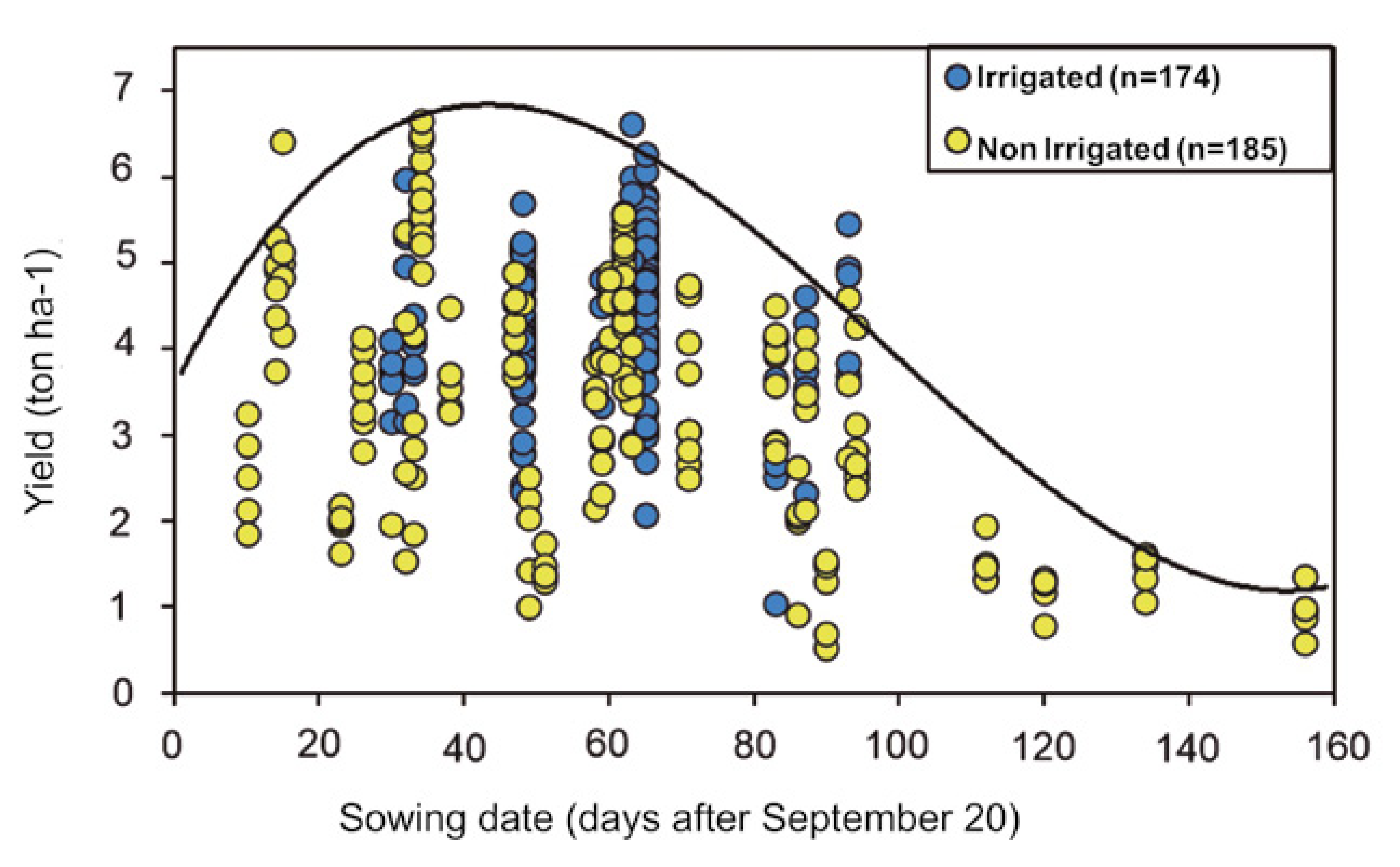


Figure 9.2.4. Relationship between soybean yield (ton ha^{-1}) and sowing date (days after September 20th) for soybean experiments in rotation with lowland rice in Rio Grande do Sul, Brazil. Blue circles represent experiments with supplemental irrigation and yellow circles stands to experiments without supplemental irrigation. The solid line shows the upper limit function.

Plant nutrition is the sixth principle for achieving profitable farming in lowlands. Liming is not a common practice for flood-irrigated rice production because once the water recedes and enters the soil surface, the action of water naturally raises the pH of the soil, ensuring good nutrient availability for rice plants. However, for soybean crops to achieve optimal development and growth, soils should ideally have a pH between 5.5 to 6.5. This pH range allows for better availability and uptake of required nutrients by soybean plants. Item 3 provides details on adjusting soil conditions and meeting the nutritional requirements of soybean plants to achieve high yields.

Soil compaction is a significant limiting factor for crops in lowland areas. The continuous use of harrows for rice sowing over several years leads to the formation of a compacted layer just below the soil surface, typically between 10 to 15 cm deep, known as the 'plow pan'. This physical barrier restricts root growth in soybean plants, hinders water storage and drainage, and can increase susceptibility to root diseases. To mitigate the effects of compaction, subsoiling actions are recommended to break up this layer. If subsoiling is not feasible, using deep furrowing tools during sowing at depths of 15 to 20 cm is advised. Additionally, adopting a furrow-ridge planting strategy can improve soil aeration and facilitate deeper root penetration by plants.

Weed management in lowland areas is also critical; integrating soybeans into lowland rotations with rice provides a profitable alternative and supports integrated weed management practices in rice crops. Areas of the first year of soybean cultivation commonly present high incidence of weeds such as *Echinochloa crusgalli*, *Oryza sativa* and *Eleusine indica*. Pre-planting desiccation and use of selective pre-emergent herbicides are practices for eliminating the vegetation present in the crop before sowing. This initial control can be done with the application of more products that act on the plants to be controlled.

Field of the Eckert Family Soybean Money Maker Championship, in Tapes, Rio Grande do Sul, Brazil with a yield of 7800 kg ha^{-1} in the 2020/21 season.

Final Considerations

The increase in soybean yield worldwide is driven by economic growth in the world's most populous countries, increasing demand for energy, and the high profitability of soybean cultivation. Increasing yield is the most feasible alternative to meet the growing demand and enhance profitability for producers. Therefore, it is essential to determine the yield potential of soy farming and identify key economically viable investments for producers. Management practices that aim to standardize knowledge across different environments without considering environmental specificity and cultivar interactions underscore the need for more efficient studies exploring soybean crop ecophysiology.

In this book, we compile 13 years of research conducted by the FieldCrops Team aimed at adjusting ecophysiological parameters of soybeans to specific environments and management practices tailored to each region. Our goal is to reduce the productivity gap observed on farms. Understanding the growth and development of soybean plants allows us to optimize management practices to coincide with critical phases of crop development under ideal environmental conditions

This effort highlights the importance of sustainability in modern agriculture, which hinges on the rational use of inputs and natural resources, particularly through increasing soybean yield. In this book, we provide detailed insights into the phenological, physiological, and morphological events of the soybean plant influenced by environmental interactions, genetics, management practices, and producer decisions that contribute to achieving high yields. These insights should serve as a valuable reference for producers, technicians, consultants, and academia seeking to implement management practices aimed at sustainable soybean production.

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