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**CAN CHANGES IN COVER CROP MANAGEMENT AFFECT SOYBEAN  
PRODUCTIVITY IN THE UNITED STATES? A SYSTEMATIC REVIEW AND  
META-ANALYSIS**

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*Magister Scientiae*

**RIO VERDE**  
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## SUMMARY

LIST OF TABLES.....	iv
LIST OF FIGURES.....	v
RESUMO.....	vii
ABSTRACT.....	viii
1 INTRODUCTION.....	1
2 LITERATURE REVIEW.....	2
2.1. Soybean cultivation.....	2
2.2. Challenges in soybean production.....	3
2.3. Regenerative agriculture.....	4
2.3.1. Cover crops.....	5
2.4. Agroclimatology in the united states in soybean-producing regions.....	7
2.5. Challenges between climate and cover crop implementation.....	8
3 MATERIALS AND METHODS.....	9
3.1 Protocols and general design.....	9
3.2 Literature search.....	10
3.3 Database screening.....	12
3.4 Data extraction procedure.....	14
3.5 Statistical analysis.....	15
4 RESULTS.....	17
4.1 General effects of adopting cover crops on soybean yield.....	17
4.2 Effects of termination time of cover crops on soybean yield.....	19
5 DISCUSSION.....	29
5.1 General effects of adopting cover crops on soybean yield in the midwest, northeast and south regions.....	29
5.2 Effects of planting and termination time of cover crops on soybean yield.....	30
6 CONCLUSIONS.....	33
REFERENCES.....	34
ANEXO.....	40

## LIST OF TABLES

TABLE 1	Configuration of string terms and results obtained for each database.....	11
TABLE 2	Model parameters (Degrees of Freedom - df, Akaike Information Criterion - AIC, Bayesian Information Criterion - BIC, Log-Likelihood - logLik, Likelihood Ratio - L.Ratio) and analysis of variance between univariate and additive effects or interaction models for accumulated precipitation and soil pH.....	28

## LIST OF FIGURES

FIGURE 1	ROSES diagram referring to the stages of searching, sorting and critically evaluating the files. OATD means Open Access Theses and Dissertations	14
FIGURE 2	Meta-analysis for effects of different cover crop families on log-ratio soybean yield, stratified by region (Midwest, Northeast, South). The solid vertical line marks the null effect point (log-ratio = 0). The blue line and shadow represent global mean effect and confidence interval. The $\chi^2$ , $I^2$ , and $\tau^2$ values indicate heterogeneity between studies in each region. Weight common and weight random represent the weights assigned to each study in fixed-effect and random-effect models, respectively.....	18
FIGURE 3	Meta-analysis for effects of different cover crop termination dates on log-ratio soybean yield. The red vertical line marks the null effect point (log-ratio = 0). n = number of observations. Highlighted in blue were significant at p-value < 0.05. <sup>1</sup> Test for residual heterogeneity. <sup>2</sup> Test of moderators.....	20
FIGURE 4	Meta-analysis for effects of different termination dates (y-axis) and soybean planting moments (after, before or during cover crop termination) on log-ratio soybean yield. The red vertical line marks the null effect point (log-ratio = 0). n = number of observations. Highlighted in blue were significant at p-value < 0.05. <sup>1</sup> Test for residual heterogeneity. <sup>2</sup> Test of moderators.....	21
FIGURE 5	Meta-analysis for effects of different termination dates (y-axis) and termination method of cover crops on log-ratio soybean yield. The red vertical line marks the null effect point (log-ratio = 0). n = number of observations. Highlighted in blue were significant at p-value < 0.05. <sup>1</sup> Test for residual heterogeneity. <sup>2</sup> Test of moderators.....	23
FIGURE 6	Meta-analysis for effects of different termination dates (y-axis) and maturity group of planted soybeans on log-ratio soybean yield. The red vertical line marks the null effect point (log-ratio = 0). n = number of observations. Highlighted in blue were significant at p-value < 0.05. <sup>1</sup> Test for residual heterogeneity. <sup>2</sup> Test of moderators.....	24

FIGURE 7	Linear mixed-effects model between accumulated cover crop biomass and soil proprieties on the log-ratio of soybean yield. Model parameters and their significance level are shown in blue color in the lower right corner in each graph. Others termination dates did not show sufficient data for analysis.....	26
FIGURE 8	Linear mixed-effects model between cumulative precipitation and the log-ratio of soybean yield for each termination date in the midwest, northeast and south. Model parameters and their significance level are shown in blue color in the lower right corner in each graph. Others termination dates did not show sufficient data for analysis.....	27
FIGURE 9	Linear mixed-effects model for integration between cumulative precipitation and soil pH (B) on log-ratio of soybean yield.....	27

## RESUMO

MUNIZ, C. R, UniRV – Universidade de Rio Verde, dezembro de 2025. **Mudanças no manejo das culturas de cobertura podem afetar a produtividade da soja nos Estados Unidos? Uma revisão sistemática e meta-análise.** Orientador: Prof. Dr. Matheus de Freitas Souza.

As plantas de cobertura (PC) têm sido cada vez mais adotadas nos Estados Unidos devido aos seus potenciais benefícios, como melhoria na retenção de nutrientes, estabilidade do solo e controle de plantas daninhas. No entanto, a influência do manejo das PC na produtividade da soja permanece incerta, com resultados variados na literatura. Este estudo investigou o efeito do momento e método de dessecação das PC, família de PC, grupo de maturação da soja e atributos do solo na produtividade da soja por meio de uma revisão sistemática e meta-análise de 51 estudos conduzidos nos EUA. A meta-análise com os dados da região Meio-Oeste mostrou efeitos variados conforme a família da PC: a família *Poaceae* (como o centeio) reduziu a produtividade da soja em comparação aos tratamentos sem PC, enquanto as leguminosas aumentaram a produtividade em até 22,4%. No Sul, o efeito geral das PC foi neutro. A alta heterogeneidade entre os estudos ( $I^2 = 98,8\%$ ) sugere que condições locais específicas são cruciais para o sucesso das práticas com PC. A dessecação das PC em meados de abril geralmente resultou em maior produtividade da soja, com ganhos de até 12% em comparação com áreas sem PC, especialmente para grupos de maturidade precoce (I a III). Entretanto, dessecações no final de abril e em maio reduziram a produtividade em até 4,5% para os grupos de maturidade IV e V, associadas à competição por água e atrasos no plantio. Além disso, o método de dessecação influenciou significativamente os resultados: a dessecação química em meados de abril aumentou a produtividade em 38% em comparação a áreas sem o uso de plantas de cobertura, enquanto métodos mecânicos anularam esse efeito. O modelo multivariado indicou efeitos significativos da precipitação acumulada e do pH do solo, que influenciam diretamente os resultados de produtividade. Esses achados destacam a importância de ajustar o momento e o método de dessecação das plantas de cobertura, considerando as condições ambientais regionais, para maximizar os benefícios das PC na produtividade da soja.

**Palavras-chave:** *Glycine max* L, manejo de dessecação, grupo de maturidade, produtividade.

## ABSTRACT

MUNIZ, C. R, UniRV – University of Rio Verde, december 2025. **Can changes in cover crop management affect soybean productivity in the United States? A systematic review and meta-analysis.** Advisor: Prof. Dr. Matheus de Freitas Souza.

Cover crops (CC) have been increasingly adopted in the United States due to their potential benefits, such as improved nutrient retention, soil stability, and weed control. However, the influence of CC management on soybean yield remains uncertain, with varied results in the literature. This study investigated the effect of the timing and method of termination of CC, CC family, soybean maturation group and soil attributes on soybean yield through a systematic review and meta-analysis of 51 studies conducted in the USA. The meta-analysis with data from the Midwest region showed varied effects according to the CC family: the *Poaceae* family (such as rye) reduced soybean yield compared to treatments without CC, while legumes increased yield by up to 22.4%. In the South, the overall CC effect was neutral. The high heterogeneity between the studies ( $I^2 = 98.8\%$ ) suggests that specific local conditions are crucial for the success of CC practices. The desiccation of BW in mid-April generally resulted in higher soybean yield, with gains of up to 12% compared to areas without BW, especially for early maturity groups (I to III). However, desiccations at the end of April and in May reduced productivity by up to 4.5% for maturity groups IV and V, associated with competition for water and delays in planting. In addition, the desiccation method significantly influenced the results: chemical desiccation in mid-April increased productivity by 38% compared to areas without the use of cover crops, while mechanical methods nullified this effect. The multivariate model indicated significant effects of accumulated precipitation and soil pH, which directly influence yield results. These findings highlight the importance of adjusting the timing and method of desiccation of cover crops, considering regional environmental conditions, to maximize the benefits of CP on soybean yield.

**Keywords:** *Glycine max* L, termination management, maturity group, yield.

## 1 INTRODUCTION

Soybean plays a crucial role in the economy and industry of the US, being one of the most significant agricultural crops in terms of production, exportation, and socioeconomic impact. Between 2002 and 2022, soybean-grown area increased by 18%, a growth rate faster than that of corn-planted due to the rising soybean demand as a protein source for livestock feed and for biofuel production, both domestically and internationally (Vaiknoras and Hubbs, 2022).

In the US, soybean yield has increased through various innovations and agricultural practices, including the use of high-yielding resistant seed varieties, innovative agricultural methods, and enhanced processing techniques (Deepak et al., 2023). Apart from increased yield, sustainability of management practices is an important issue. Use of cover crops can increase formation of stable carbon pools (Kallenbach et al., 2016), the uptake of nitrogen by plants, enhance nitrogen retention and availability in the soil (Lewis et al., 2023), contribute to improved soil aggregate stability and infiltration rates and reduced erosion (Garcia et al., 2019) and suppress weed seed germination (Gerhards and Schappert, 2020).

The area of US cropland dedicated to cover crops increased by 17 percent from 2017 to 2022, rising from 6,228,630.48 to 7,279,041.04 hectares, according to data from the recently published Census of Agriculture. Despite the increase of cover crop use, this represents just 4.7 percent of the total cropland in 2022 (NASS, 2024). This low adoption can be explained in part by the variable effects observed on soybean yield studies. For example, multi-species cover crops such as rye (*Secale cereale*), oats (*Avena sativa*), radish (*Raphanus sativus*), red clover (*Trifolium pratense*), and hairy vetch (*Vicia villosa*). have not always resulted in increased soybean yield compared to areas without this practice (Tyson et al., 2018). Another study showed that a four-year wheat-corn-soybean rotation with cereal rye, wheat and crimson clover as cover crops (planted in the fall and terminated in the spring) caused negative effects on economic profitability during the first two years but positive effects in the fourth year (Zhen et al., 2019). Additionally, cover crops with tillage reduced nitrogen leaching rates from cropland soils but also decreased the yield of the following maize and wheat, except for soybean which showed a positive response to cover crop practices (Jens et al., 2022).

Overall, the impact of cover crops on soybean yield can be negligible or positive depending on specific agricultural practices. Cover crop termination time is an important management practice which can affect soybean planting date. Delays in the cover crop termination period have delayed soybean planting and this fact has been correlated with a

reduction in crop yield. Tyson et al. (2018) and Liebert et al. (2023) reported that the delay in soybean planting due to the termination of the cover crop is the main factor linked to lower grain yield.

In the literature, there are variable results about the effect of cover crop termination timing on soybean yield and a knowledge gap still exists. A systematic review and meta-analysis about how cover crop species, termination timing, and soybean planting date affect soybean yield can allow for a better understanding of the potential benefits and challenges associated with cover crop adoption in soybean production compared to areas without cover crop use. Our objectives were to evaluate the effect of cover crops on soybean yield across different US regions (Midwest, Northeast, and South) and how different cover crop families (Poaceae, Fabaceae, Brassicaceae, and mixes), cover crop termination dates and methods, soybean maturity group, soil pH, soil texture, cumulative precipitation and average temperature interact and affect soybean yield.

## **2 LITERATURE REVIEW**

### **2.1 Soybean cultivation**

Historical evidence suggests that soybean (*Glycine max* L.) cultivation began in northern China around 1700–1100 BC. In the United States, records date back to the 18th century, with the first introduction of the crop in Georgia around 1765, aimed at margarine and oil production, where it was processed (Hamza, 2024). However, its cultivation remained incipient until the early 20th century, when researchers such as William Morse and George W. Carver began to investigate its nutritional, agronomic, and industrial value. Morse led expeditions to Asia to collect germplasm and founded the American Soybean Association in 1920 (Farm Doc Daily, 2023). During World War II, soybean was consolidated as a strategic crop due to shortages of vegetable oils and animal protein, driving its expansion in the U.S. Midwest. Mechanization, genetic advances, and the institutionalization of government support for research and production consolidated the United States as the world's leading producer and exporter of the oilseed throughout the 20th century (NC Soybean Producers Association, 2023).

Currently, soybean is considered one of the main agricultural commodities, standing out for its high yield per cultivated area and added value as a source of protein and vegetable oil. It

is an important crop in the global agri-industrial context, particularly relevant to the economy of the United States and several developing countries (FAO, 2021). Between 2002 and 2022, the soybean planted area in the United States grew by 18%, mainly driven by the increasing demand for protein for animal feed and the use of the oilseed in biofuel production (Vaiknoras & Hubbs, 2023). Soybean production in the United States in 2024 is estimated at approximately 118.84 million tons, representing about 28% of global production and consolidating the country as the second largest producer of the oilseed (USDA, 2025).

It is estimated that approximately 70% of soybeans cultivated in the country are destined for feed formulations for poultry, swine, and cattle sectors, in addition to its consolidated role in the national energy matrix through biodiesel (United Soybean Board, 2023). Soybean plays a central role by providing an affordable and sustainable source of high-quality protein. Its composition, with protein content ranging between 38% and 45% and about 20% oil, makes it a strategic resource for human and animal nutrition, especially in countries with limited access to animal-based products (Sustainable Nutrition Initiative, 2023).

## **2.2 Challenges in soybean production**

Despite the large volume of soybeans produced in the United States, several challenges limit productivity growth in a sustainable and economically viable manner. Among the main constraints are phytosanitary factors, such as the increasing incidence of root pathogens (*Phytophthora sojae*, *Fusarium* spp., and *Rhizoctonia solani*), nematodes such as *Heterodera glycines*, and foliar diseases including powdery mildew, brown spot, and Asian soybean rust, which directly affect yield and crop stability (Allen et al., 2017). The growing resistance of some of these pests and diseases to conventional chemical treatments has required the intensive use of pesticides, raising production costs and intensifying environmental impacts.

In addition to diseases, pest pressure also represents a growing phytosanitary challenge. Species such as the brown stink bug (*Euschistus heros*), the soybean looper (*Chrysodeixis includens*), and the two-spotted spider mite (*Tetranychus urticae*) have required intensive insecticide use, contributing to the emergence of resistant populations and disrupting ecological balance in soybean fields (Venugopal; Dunn; Lamp, 2025).

The reliance on transgenic cultivars and the continuous use of broad-spectrum herbicides, such as glyphosate, have promoted the selection of resistant biotypes among major weed species such as *Amaranthus palmeri* and *Conyza canadensis*, requiring more diversified integrated management strategies (Norsworthy, 2025). Moreover, weed competition can cause

highly significant yield losses. Estimates from Embrapa suggest that without effective management, losses may exceed 90%; under standard control practices, average grain yield reduction range from 13% to 15% (Embrapa, 2023; Fundação Meridional, 2023). Specific studies also reveal more extreme scenarios: in maize, *Amaranthus palmeri* can reduce yields by 31% to 57% under high-density conditions (Zhang et al., 2025); species related to *Conyza canadensis*, such as *C. bonariensis*, can cause yield losses ranging from 1.4% to 25.9%, and up to 13% reduction with only one plant per square meter (Younis et al., 2025). In other crops, such as beans and sugar beet, losses may reach up to 70% (WSSA, 2019), while in potato, average losses of 44% have already been reported (Knezevic et al., 2020).

Alongside phytosanitary problems, producers also face agronomic challenges associated with climate variability and soil degradation. Extreme weather events, such as prolonged droughts, excessive rainfall, or sudden temperature fluctuations, have become more frequent and unpredictable, compromising crop establishment, biological nitrogen fixation, and reproductive development (Koch, 2025). Soil compaction, caused by intensive management and machinery traffic, also hinders root growth and nutrient uptake. These factors demand the improvement of conservation practices and the use of technologies adapted to regional edaphoclimatic conditions, highlighting the importance of integrating tools such as precision agriculture, diversification of production systems, and the strategic use of cover crops (Derpsch; Friedrich, 2025).

### **2.3 Regenerative agriculture**

According to LaCanne and Lundgren (2018), regenerative agriculture is a system of agricultural principles and practices that aims to increase biodiversity, enrich soils, improve the water cycle, strengthen the resilience of agricultural ecosystems, and enhance ecosystem services, while simultaneously sequestering carbon in the soil and reducing dependence on external inputs. Regenerative agriculture emerges as a promising technological and ecological paradigm, integrating principles of ecosystem functionality restoration into agricultural systems.

This approach is based on the adoption of practices such as diversified crop rotation, permanent soil cover, reduced mechanical tillage, crop-livestock integration, and, most importantly, the use of cover crops (Gerhards & Schappert, 2020). These strategies are designed to conserve natural resources, increase climate resilience, and promote functional biodiversity in agricultural environments.

Studies indicate that regenerative systems provide substantial improvements in the physical, chemical, and biological quality of soils. Among the practices that drive the regeneration of agricultural systems and create favorable conditions for greater crop resilience, the use of cover crops has been widely studied across different production systems. Numerous studies have reported benefits such as greater structural stability, increased organic matter, improved water infiltration rates, enhanced nutrient cycling efficiency, and greater carbon sequestration in agricultural fields after cover crop implementation (Garcia et al., 2019; Kallenbach et al., 2016). Crops such as rye (*Secale cereale* L.), oats (*Avena sativa* L.), forage radish (*Raphanus sativus* L.), red clover (*Trifolium pratense* L.), and hairy vetch (*Vicia villosa* Roth.) have proven effective in suppressing weeds and improving nitrogen availability for subsequent crops (Golden et al., 2023). Nevertheless, the adoption of such practices remains incipient in the United States, covering only 4.7% of total cropland in 2022 (USDA, 2022), which reflects resistance stemming from economic uncertainty associated with the agroecological transition.

### **2.3.1 Cover crops**

Cover crops play a central role in promoting soil health and building more resilient farming systems. Among their main benefits is the diversity of root architectures, which promotes the physical rotation of root exploration zones and improves soil structure. The continuous presence of living roots in the soil stimulates the activity of mesofauna and soil microbiota through root exudation, creating a favorable environment for the multiplication of beneficial microorganisms and the balance of the soil microbiome (Tiemann et al., 2015). This synergistic interaction between roots and microorganisms contributes to the formation of stable aggregates and to the accumulation of carbon in more stable fractions of soil organic matter, favoring long-term carbon sequestration (Poeplau & Don, 2015).

The carbon sequestration promoted by agricultural practices such as the use of cover crops has significant implications not only for soil health but also for climate change mitigation. By capturing atmospheric carbon dioxide through photosynthesis and converting this carbon into plant biomass and soil organic matter, cover crops help stabilize carbon in humic fractions. This process reduces greenhouse gas concentrations in the atmosphere, enhances the resilience of agroecosystems, and improves soil physicochemical properties such as water-holding capacity, structure, and fertility (Lal, 2004; Poeplau & Don, 2015).

The interaction between cover crops and arbuscular mycorrhizal fungi (AMF) establishes beneficial symbioses with the roots of crops such as soybean. These fungi promote increased nutrient uptake, especially phosphorus, while also contributing to tolerance against abiotic stresses such as drought and salinity. Cover crops maintain an active root system in the soil during the off-season, supporting the persistence and development of mycorrhizal hyphal networks. This contributes to faster and more efficient colonization of the roots of subsequent crops, strengthening the beneficial soil microbiome and promoting greater sustainability in production systems (Kabir, 2005; Bender et al., 2016).

Cover crops also play a relevant role in soil nitrogen dynamics. Legumes such as vetch (*Vicia* spp.) and clover (*Trifolium* spp.) fix atmospheric nitrogen biologically, while grasses such as rye (*Secale cereale* L.) and oats (*Avena sativa* L.) recycle nutrients, particularly in systems with high leaching potential. The decomposition of cover crop biomass contributes to the gradual release of nutrients, increasing nitrogen availability in the soybean rhizosphere while reducing losses through volatilization and leaching (Quemada et al., 2013).

The adoption of cover crops is also an effective tool in weed management, both through resource competition and the release of allelopathic compounds. Species such as rye (*Secale cereale* L.) and black oat (*Avena strigosa* Schreb.) have a high soil-covering capacity and rapid biomass production, which reduces light incidence on the soil and limits the germination of light-sensitive weed seeds. In addition, certain secondary metabolites released by the roots and residues of these plants can inhibit the growth of invasive seedlings, providing an additional suppressive effect (Teasdale et al., 2007). Reducing weed pressure contributes to lower herbicide dependence, mitigating the risk of selecting resistant biotypes and promoting greater agricultural sustainability.

Effects related to increased biological control of soil pathogens, such as phytopathogenic fungi and nematodes, are also a focus of studies involving cover crops. Species such as sunn hemp (*Crotalaria* spp.), black oat (*Avena strigosa*), and pearl millet (*Pennisetum glaucum*) have demonstrated the ability to reduce populations of plant-parasitic nematodes, such as *Meloidogyne* spp. and *Heterodera glycines*, through the release of bioactive compounds and disruption of their life cycles. Furthermore, promoting a more diverse and active soil microbiota stimulates natural antagonisms that inhibit the proliferation of pathogens such as *Rhizoctonia solani*, *Fusarium* spp., and *Sclerotinia sclerotiorum*. The incorporation of cover crop biomass also increases the availability of organic substrates that favor beneficial microorganisms, such as antagonistic bacteria and fungi, strengthening the soil's suppressive mechanisms (Wang et al., 2021; Dias-Arieira et al., 2013).

Another important benefit, often underestimated, is the increase in water infiltration and retention in the soil promoted by cover crops. The roots of these species improve soil porosity and pore continuity, facilitating water penetration and reducing surface runoff. This effect is particularly relevant in regions with extreme weather events, as it helps reduce water erosion and increases water availability for cash crops during drought periods. In addition, the vegetative cover and plant residues on the soil act as a physical barrier against the direct impact of raindrops and reduce evaporation, promoting greater water conservation in the system (Blanco-Canqui et al., 2015).

### **2.3.2. Cover crop termination management in the United States**

In general, cover crop termination management in the United States is a widely studied practice integrated into soybean production systems, particularly under no-till and conservation agriculture systems. The primary objective of termination is to interrupt cover crop growth at an appropriate time to minimize competition for resources such as water, nutrients, and light, while preserving soil-related benefits, including erosion control, weed suppression, and improvements in soil structure. The literature indicates that the effects of cover crops on soybean yield are highly dependent on the termination method, termination timing, cover crop species, and regional edaphoclimatic conditions, especially water availability and soil temperature (Mirsky et al., 2013; Acharya et al., 2022).

Chemical termination is the most widely adopted method in the United States due to its operational efficiency and management flexibility. Glyphosate is the most commonly used herbicide, applied alone or in combination with other active ingredients such as 2,4-D or dicamba, depending on the cover crop species and developmental stage. Studies indicate that chemical termination performed two to four weeks prior to soybean planting generally reduces the risk of water and temperature competition and promotes early crop establishment (Mirsky et al., 2012; Reberg-Horton et al., 2012). However, termination efficacy may decline when cover crops reach advanced growth stages or experience stress conditions, requiring higher application rates or herbicide mixtures, which raises environmental concerns and increases the risk of herbicide-resistant weed populations (Norsworthy et al., 2012).

Mechanical termination, most commonly performed using a roller-crimper, is more prevalent in organic or low-input production systems. This method is highly dependent on the phenological stage of the cover crop and is most effective when species such as cereal rye reach flowering or early grain development stages. Although mechanical termination can provide

high biomass production and effective weed suppression, several studies report that this practice may delay soil warming and soybean emergence, particularly in cooler regions such as the U.S. Midwest, potentially leading to yield reductions compared to chemical termination (Reberg-Horton et al., 2012; Mirsky et al., 2013).

Termination timing is considered one of the most critical factors for the success of cover crop-based systems. Early termination, typically conducted in early spring, tends to reduce biomass accumulation but minimizes competition for water and allows timely soybean planting. In contrast, late termination increases residue production and weed suppression potential but is frequently associated with soybean yield reductions, especially under water-limited conditions or in soils with low water-holding capacity (Ruis et al., 2019; Acharya et al., 2022). The literature suggests that the optimal termination window varies across regions, being more restrictive in cooler climates and more flexible in the southern United States.

In U.S. production systems, soybean planting in the presence of cover crops may occur before, during, or after termination, depending on the management strategy. Planting after termination is the most conservative and widely recommended approach, as it reduces competition risks and facilitates crop establishment. “Planting green,” defined as planting soybean before or during cover crop termination, has been adopted by some producers to extend operational windows and maximize cover crop biomass production. However, studies indicate that this practice may result in uneven emergence and yield reductions, particularly when grass cover crops are used and under water-limited environments (Mirsky et al., 2013; Quinn et al., 2020). Therefore, successful soybean planting relative to cover crop management requires careful coordination among species selection, termination method, and environmental conditions.

#### **2.4 Agroclimatology in the United States in Soybean-Producing Regions**

The climatic diversity of the United States is a key factor in the variability of agricultural practices across the country. From the perspective of soybean production, this variability presents both challenges and opportunities depending on the region. Soybean cultivation is concentrated in Midwestern states such as Iowa, Illinois, Indiana, Minnesota, Ohio, and Nebraska — accounting for more than 80% of national production (USDA, 2023).

The predominant climate in this region is humid continental, with harsh winters, frozen soil, and hot, rainy summers. These conditions favor soybean growth between May and September, but make the start of planting highly dependent on the timing of soil thaw and the

ability to manage soil moisture. The optimal planting period, from late April to early June, is considered critical to ensure productivity. Late planting reduces the number of days available for vegetative growth and increases crop exposure to heat stress during grain filling (MOURTZINIS et al., 2015; HATFIELD et al., 2011).

In more northern regions, such as North Dakota, South Dakota, and Minnesota, the growing season is shorter due to lower solar radiation and the risk of early frosts. In these areas, the use of cultivars with earlier maturity groups (00 to I) is necessary for the crop to complete its cycle before autumn arrives (FEHR; CAVINESS, 1977). In contrast, in southern states like Missouri, Arkansas, and Mississippi, the growing season can be longer, favoring the use of later-maturing cultivars (groups IV to VI), provided they are managed properly to avoid losses from excessive heat and drought during grain filling (BOARD; HARVILLE, 1992).

Photoperiod, latitude, and classification into maturity groups pose additional challenges for soybean adaptation in different regions of the country. At higher latitudes, such as in northern states (Dakotas, Minnesota), the shorter growing season and limited daylight hours necessitate the use of early-maturing cultivars, which may restrict yield potential (FEHR; CAVINESS, 1977; BOARD; HARVILLE, 1992). Conversely, in southern U.S. regions, adequate photoperiod combined with greater thermal availability favors the use of longer-maturity cultivars, while also increasing plant exposure to prolonged heat and water stress. (BOARD; HARVILLE, 1992).

Beyond latitude and photoperiod, extreme weather events significantly affect crop success. Spring floods, mid-season heatwaves, and prolonged droughts at the end of the cycle are becoming increasingly frequent, partly due to climate change. For example, in 2019, heavy rainfall from April to June delayed soybean planting in more than 20% of the planned Midwestern area, compromising national productivity (USDA, 2020).

Global warming has altered precipitation and temperature patterns across various U.S. regions. The increased frequency of hotter summers, combined with greater variability in rainfall distribution, has required new adaptation strategies, such as the use of cultivars tolerant to heat and water stress, conservation management practices, and integration with cover crops (USDA CLIMATE HUBS, 2024; KASPAR; SINGER, 2011).

In this context, agroclimatic zoning emerges as an essential tool to guide decisions regarding planting time, cultivar selection, and soil management practices. Precision agriculture, combined with real-time climate data, is increasingly used to mitigate risks associated with climatic instability.

## 2.5 Challenges between Climate and Cover Crop Implementation

Despite the widely documented benefits of cover crops, their adoption in the United States remains limited. Data from the 2022 Agricultural Census indicate that only about 4.7% of the total area planted with annual crops used some form of cover crop during the off-season. This low adoption can be attributed to factors such as perceived risk regarding impacts on the main crop's productivity, the additional cost of implementation, the lack of region-specific technical guidance, and uncertainty regarding short-term economic returns. Furthermore, many farmers face practical challenges related to mechanization and proper management of cover crop biomass. Developing public incentive policies, alongside applied research and technical training, will be essential to expand the scale and effectiveness of these sustainable practices in the medium and long term.

The transition from late winter to early spring is characterized by thawing and excessive moisture, which limits machinery access and timely crop establishment (NIELSEN; VIGIL, 2010). Late termination of cover crops can result in conflicts with soybean planting, negatively impacting productivity (Tyson et al., 2018). The planting window is short and often challenged by delays in cover crop desiccation, extreme weather events, and interannual variations that affect the predictability of field operations (NIELSEN; VIGIL, 2010; USDA NRCS, 2022).

These factors also influence the choice and management of cover crops: species that require vernalization or cannot tolerate cold temperatures may struggle to establish before soybean planting, especially when the interval between the previous crop's harvest and soybean planting is short (KASPAR; SINGER, 2011; USDA MIDWEST COVER CROPS COUNCIL, 2023). Thus, the complexity of the U.S. climate demands region-specific management strategies that consider agroclimatic zoning, seasonal dynamics, and integration between main crops and cover crops (USDA CLIMATE HUBS, 2024; ALLEN et al., 2011).

As a result, farmers face a trade-off between environmental gains and production stability. Empirical evidence indicates that, although regenerative practices may reduce initial yields—particularly in the first two years of adoption—their beneficial effects become more evident in the medium and long term, resulting in increased profitability, yield stabilization under water stress, and improvement of soil properties (Zhen et al., 2019; Jens et al., 2022). The lack of region-specific technical recommendations and the variability of results obtained in different edaphoclimatic contexts create a knowledge gap that limits widespread adoption.

Consolidating understanding of the agronomic effects of cover crops and regenerative practices—considering variables such as climate, soil, species used, and management

methods—is crucial to support public policies and guide farmer decision-making. Clarifying these relationships could facilitate the transition to more resilient, productive, and environmentally sustainable agricultural systems in the United States.

### **3 MATERIALS AND METHODS**

#### **3.1 Protocols and general design**

This study was based on a systematic review approach to synthesize scientific literature obtained from various databases. The methodology was designed following the Collaboration for Environmental Evidence (CEE, 2018) protocol, adopting inclusion criteria that cover study selection, data extraction, filtering and synthesis of relevant information.

The main question of this systematic review was: “Can changes in cover crop termination timing reduce soybean yield?”. Based on this question, we followed the PICO (Population, Intervention, Comparator, and Outcome) methodology—Population (soybean), Intervention (time to terminate the cover crop), Comparator (differences between areas with and without cover crop coverage and between cover crop species), and Outcome (soybean grain yield)—to identify the studies (Guyatt et al., 1992).

#### **3.2 Literature search**

Six databases were used to retrieve literature published in international academic journals. The databases used were Scopus, Web of Science, Willey Online Library and National Agricultural Library – USDA (AGRICOLA). For searching grey literature, the Open Access Theses and Dissertations (<https://oatd.org/>) search engine was used to consult published theses and dissertations. The search period established for all databases was between 2013 and 2024, which reflect contemporary agricultural practices and capture recent climatic variations, ensuring the scientific relevance and accuracy of the results. The search in the databases was carried out until March 29, 2024. The string terms used to query the database are listed in Table 1. The string terms were the same for all databases, only the insertion structure has been changed in order to attempt the search criteria for each database.

TABLE 1 - Configuration of string terms and results obtained for each database

Database	String terms arrangement	Results
Scopus	TITLE-ABS-KEY ( ( soybean OR "glycine max" ) AND ( "planting green" OR "termination timing" OR "timing of termination" OR "optimal termination" OR "timing strategies" OR "termination practices" OR "crop termination" OR "cover crop" OR "cover cropping" OR "interseeded cover crop" OR "overseeded* cover crop" OR "cover crop biomass" OR "cover crop biomass accumulation" OR "cover crop establishment" OR "cover crop benefits" OR "cover cropping" OR "soil protection" OR "soil enrichment" OR "green manure" OR "crop rotation") AND ( "soybean yield" OR "soybean production" OR "yield improvement" OR "crop yield" OR "soybean farming" OR "harvest yield" OR "yield factors" OR "growth" OR "development" OR "soybean development" OR "soybean growth" ) ) AND PUBYEAR > 2013 AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE , "ar" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) ) AND ( LIMIT-TO ( AFFILCOUNTRY , "United States" ) )	442
Web of Science (Core Collection and CAB Abstracts)	((ALL=(soybean OR glycine max)) AND ALL=("planting green" OR "termination timing" OR "timing of termination" OR "optimal termination" OR "timing strategies" OR "termination practices" OR "crop termination" OR "cover crop" OR "cover cropping" OR "interseeded cover crop" OR "overseeded* cover crop" OR "cover crop biomass" OR "cover crop biomass accumulation" OR "cover crop establishment" OR "cover crop benefits" OR "cover cropping" OR "soil protection" OR "soil enrichment" OR "green manure" OR "crop rotation")) AND ALL=("soybean yield" OR "soybean production" OR "yield improvement" OR "crop yield" OR "soybean farming" OR "harvest yield" OR "yield factors" OR "growth" OR "development" OR "soybean development" OR "soybean growth")) AND PY=(2013-2024) and Article (Document Types) and English (Languages) and USA (Countries/Regions)	549
Wiley Online Library	"(soybean OR "glycine max") AND ("planting green" OR "termination timing" OR "timing of termination" OR "optimal termination" OR "timing strategies" OR "termination practices" OR "crop termination" OR "cover crop" OR "cover cropping" OR "interseeded cover crop" OR "overseeded* cover crop" OR "cover crop biomass" OR "cover crop biomass accumulation" OR "cover crop establishment" OR "cover crop benefits" OR "cover cropping" OR "soil protection" OR "soil enrichment" OR "green manure" OR "crop rotation") AND ("soybean yield" OR "soybean production" OR "yield improvement" OR "crop yield" OR "soybean farming" OR "harvest yield" OR "yield factors" OR "growth" OR "development" OR "soybean development" OR "soybean growth") anywhere and "united states" OR US OR USA OR "united states of america" in Author Affiliation	404
AGRICOLA	"(soybean OR "glycine max") AND ("planting green" OR "termination timing" OR "timing of termination" OR "optimal termination" OR "timing strategies" OR "termination practices" OR "crop termination" OR "cover crop" OR "cover cropping" OR "interseeded cover crop" OR "overseeded* cover crop" OR "cover crop biomass" OR "cover crop biomass accumulation" OR "cover crop establishment" OR "cover crop benefits" OR "cover cropping" OR "soil protection" OR "soil enrichment" OR "green manure" OR "crop rotation") AND ("soybean yield" OR "soybean production" OR "yield improvement" OR "crop yield" OR "soybean farming" OR "harvest yield" OR "yield factors" OR "growth" OR "development" OR "soybean development" OR "soybean growth") anywhere and "english" in Language	583
Open Access Theses and Dissertations (OATD)	TITLE-ABS-KEY ( ( soybean OR "glycine max" ) AND ( "planting green" OR "termination timing" OR "timing of termination" OR "optimal termination" OR "timing strategies" OR "termination practices" OR "crop termination" OR "cover crop" OR "cover cropping" OR "interseeded cover crop" OR "overseeded* cover crop" OR "cover crop biomass" OR "cover crop biomass accumulation" OR "cover crop establishment" OR "cover crop benefits" OR "cover cropping" OR "soil protection" OR "soil enrichment" OR "green manure" OR "crop rotation") AND ( "soybean yield" OR "soybean production" OR "yield improvement" OR "crop yield" OR "soybean farming" OR "harvest yield" OR "yield factors" OR "growth" OR "development" OR "soybean development" OR "soybean growth" ) ) AND PUBYEAR > 1973 AND PUBYEAR < 2025 AND ( LIMIT-TO ( DOCTYPE , "ar" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) ) AND ( LIMIT-TO ( AFFILCOUNTRY , "United States" ) )	197

The search results were exported in each database in .RIS format (see Supplementary files S1). The .RIS files were imported into the Rayyan platform (Mourad Ouzzani et al., 2016). The Rayyan® platform was used for initial screening of studies of interest, helping to identify duplicate results obtained between the databases. The total number of files filtered by the database was equal to 2175. The first screening was carried out to remove duplicate files obtained from the databases. The software detected 730 possible duplicate files based on the degree of similarity for title, abstract, authors and affiliations. After manual checking, a total of 730 files were considered duplicates, with 1445 unique files remaining in the database.

### **3.3 Database screening**

The first stage was carried out on the Rayyan® platform and the criteria used to exclude studies were: (1) literature reviews, opinion studies or any publication that does not include primary data; (2) studies that did not evaluate soybean yield. This first step allowed the faster exclusion of studies without relevant information to answer the main question of this review.

The search returned across all databases returned 2175 results (Table 1). After the first screening stage, a second screening was carried out to select studies containing more specific information for subsequent analysis and discussion. The criteria adopted at this stage to exclude studies were: (1) studies that reported only the average, not showing additional statistics such as standard error, standard deviation, confidence interval or least statistical difference; (2) studies that reported results illustrated by conceptual figures/graphs without numerical values; (3) studies that reported only indirect effects of cover crops on soybean or soils (e.g., soybean growth or development and soil proprieties changes as chemical, biological or physical parameters); (4) studies that analyzed only treatments with the presence of cover crops, without a control (no cover crop); (5) studies conducted outside the US (7); studies without primary experimental data. Studies that met at least one of these criteria were excluded at this stage. Some of them did not clearly present the information necessary for inclusion or exclusion in the abstract. These studies were included for later consideration when consulting the article in its entirety. In this way, the authors ensured that all studies with information relating to the focus of the study were included without bias.

The results obtained in each completed stage are shown as a ROSES diagram in Figure 1. The Rayyan platform performed as a good alternative for removing duplicate studies. The automatic removal option based on criteria (in the case of this review: exact similarity for the title and similarity above 90% for abstract and authors) allowed the correct removal of all 730

duplicated files, even after manual checking. Thereby, a total of 1445 studies were included for next steps of screening. After screening, 363 files considering the criteria of the first and second stages were included for the third stage, discarding 1812 files that contained at least one exclusion criterion.

The third screening phase was characterized by the thorough collection of data that were used for meta-analysis. The inclusion or exclusion criteria for studies was based on the presence of all information considered essential for carrying out the meta-analysis. The data considered essential for the studies were: (1) cover crop (no cover crops should be referred to as control), (2) cover crop planting date, (3) cover crop termination date, (4) growing region, (5) number of replicates, (6) soybean yield mean and (7) statistical parameters as standard error (se) or standard deviation (sd) or confidence interval (CI) or least significant difference (lsd). These data allowed the investigation of the main and secondary question raised by this systematic review.

After the third screening stage, 160 files were included for data extraction, while 2,015 were excluded after duplicate checks and screenings. Specifically, 1,017 studies were excluded based on population criteria, 1,005 due to outcome criteria, and 761 for study design issues, including unclear experimental designs and inadequate control groups. Additionally, 96 studies were excluded for being conducted outside the US, 15 for publication type, two for lacking soybean or cover crop planting data, 15 for not involving cover crops, and one for being an abstract. Ultimately, 51 studies that provided average soybean yield, standard deviation data, termination times, and treatment comparisons were selected for the meta-analysis.

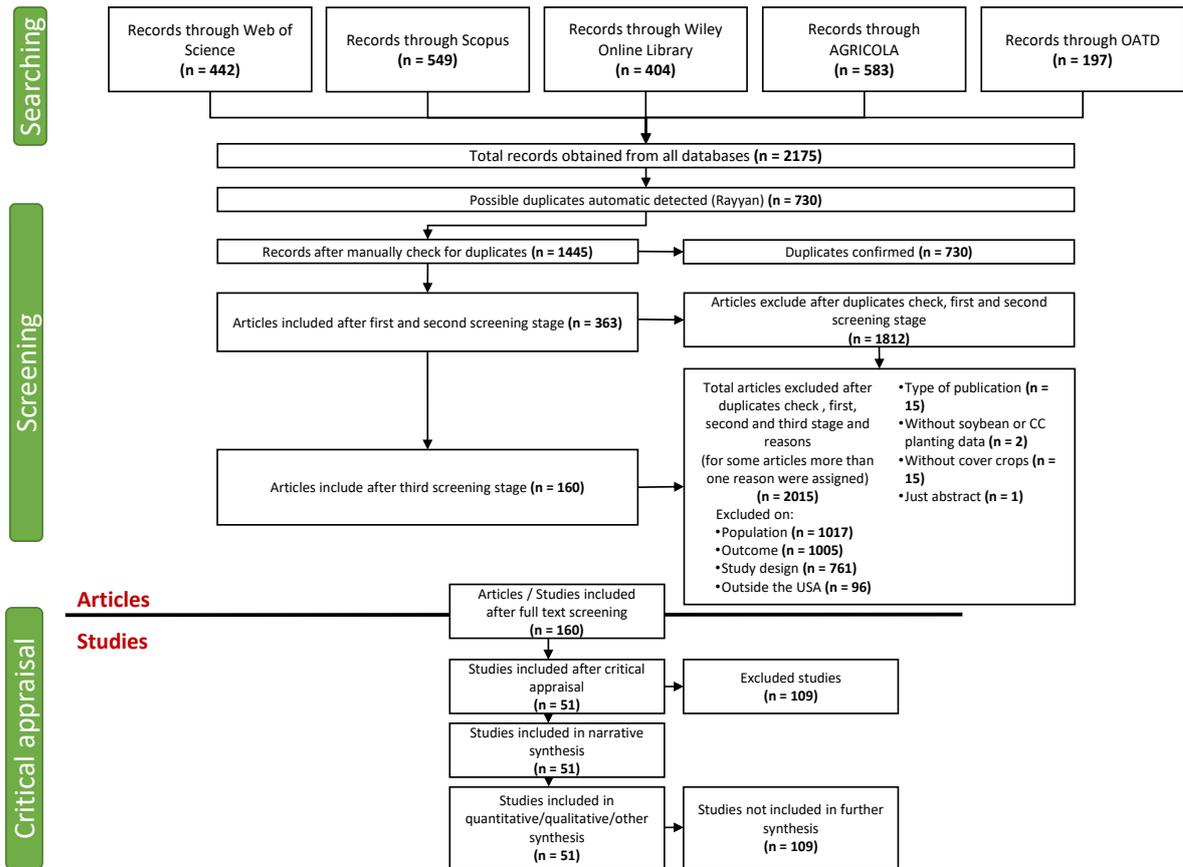


FIGURE 1 - ROSES diagram referring to the stages of searching, sorting and critically evaluating the files. OATD means Open Access Theses and Dissertations.

### 3.4 Data extraction procedure

The data were extracted from the papers using Rayyan platform. The papers can be consulted in Supplementary Files S1. All data collected from the studies were organized in Structured Query Language (SQL), arranged in columns (variables) and lines (attributes), as set out in Supplementary Files S1.

For the third stage of screening and thorough data collection, the SCISPACE<sup>®</sup> system was used to assist users in obtaining data. The selected studies were downloaded in full and imported through SCISPACE<sup>®</sup>. The copilot function of SCISPACE<sup>®</sup> was used to filter data of interest, optimizing users' search time in this third stage. To extract quantitative values from graphical representations in the selected studies, ImageJ<sup>®</sup> software was utilized (Schneider et al., 2012). Data points were extracted by using the Point tool or Polygon tool to mark the relevant points on the graph. For example, in bar charts representing soybean yield, the heights of the bars were measured against the y-axis to obtain individual yield values, which were then averaged to determine mean yield. The lengths of error bars were measured to determine

standard error or standard deviation. In graphs depicting temperature and precipitation over time, data points corresponding to each time interval were marked and measured to create time series datasets. Derived values such as averages, standard errors, and standard deviations were calculated using R<sup>®</sup>, version 4.0.2 (R Core Team, 2021) and Excel.

Each step of the data extraction process, including scale setting and point measurement, was carefully documented to ensure reproducibility and accuracy. By employing ImageJ, quantitative data were effectively extracted from graphical figures, facilitating their inclusion in the systematic review and enhancing the utilization of valuable information presented in non-tabular formats.

### 3.5 Statistical analysis

First, to investigate the impact of cover crops on soybean yield, it was conducted meta-analysis. The data were grouped by study, year, and planting region (region in which the experiment was conducted) to ensure that comparisons were made within similar experimental conditions. For each combination of study, year, and region, was extracted the yield, standard deviation, and the number of replicates referring to the control group (areas without cover crops). For studies with standard error, confidence interval or minimum significant difference data, calculations were performed to obtain the value corresponding to the standard deviation. Then, these values were propagated across all corresponding observations within each group using the fill function to ensure that the comparisons with the control group were correctly associated.

For each observation that included a cover crop, was calculated the log-ratio between the soybean yield of the treatment with cover crop and without cover crop, according to the Equation 1:

$$\text{Equation 1: } \log - \text{ratio}_{\text{yield}} = \log \left( \frac{\text{With cover crop}}{\text{Without cover crop}} \right)$$

The standard error of the log-ratio was calculated considering the standard deviations and the number of replicates for both the treatments and the control, using the following Equation 2:

$$\text{Equation 2: } SE_{\log\text{-ratio}} = \sqrt{\left(\frac{SD_{\text{with CC}}^2}{n_{\text{with CC}} * yield_{\text{with CC}}^2}\right) + \left(\frac{SD_{\text{without CC}}^2}{n_{\text{without CC}} * yield_{\text{without CC}}^2}\right)}$$

Where:

$SE_{\log\text{-ratio}}$  is the standard error of the log-ratio.

$SD_{\text{with CC}}$  is the standard deviation of the yield in areas with cover crops.

$n_{\text{with CC}}$  is the number of replicates in the cover crop group.

$SD_{\text{without CC}}$  is the standard deviation of the yield in the control group.

$n_{\text{without CC}}$  is the number of replicates in the control group

The variance of the log-ratio was obtained as the square of the calculated standard error:

$$\text{Variance}_{\log\text{-ratio}} = SE_{\log\text{-ratio}}^2$$

All analysis were conducted using R<sup>®</sup>, version 4.0.2 (R Core Team, 2021). A multivariate meta-analysis was conducted to assess the effects of studies, cover crop planting time and cover crop classes on soybean yield, applying the same analysis pattern across different regional subgroups. The metafor package in R was used to fit random-effects models via `rma` and `rma.mv` (Viechtbauer, 2010), accounting for study-specific variances and moderators (e.g., planting time). Study and year of study were treated as random effects, for different moderator variables assessed in each subgroup. The `dplyr` package was used for data preprocessing, while `ggplot2` (Wickham, H 2016) generated Forest Plot and Funnel Plot graphs, allowing for visualization of effect estimates, confidence intervals, and statistical significance.

For regression analysis between independent continuous variables and  $\log\text{-ratio}_{\text{yield}}$ , random effects nested by study and year of experiment was used to adjust the models using the `nlme` package in R (Pinheiro and Bates, 2024). The analysis was replicated for several variables and subgroups, such as different regions, termination times and their interaction with continuous variables (cover crop biomass, precipitation, temperature, among others), using linear regression to identify their relationships with the logarithmic ratio of soybean yield. The coefficients (intercept and slope), p-values and the conditional  $R^2$  (which considers fixed and random effects) were extracted from the models. The results were visualized through regression plots using the `ggplot2` package. The graphs displayed model coefficients (intercept and slope),  $R^2$  and p-values for parameter of model.

## 4 RESULTS

### 4.1 General effects of adopting cover crops on soybean yield

The random effects model (RE Model) indicates a null global effect (-0.01, 95% confidence interval [0.05, 0.02]), suggesting that, across all studies, the intervention or studied variable does not have a significant effect on the soybean yield (Supplementary file S2). The confidence intervals for most studies cross the no effect line (log-ratio of 0), indicating no significant effect on soybean yield.

The influence analysis of each study showed that most studies did not significantly affect the overall effect (Supplementary file S2). Studies 1 and 101, showed values for the *r*student test higher than the thresholds -2 or 2, suggesting that they can be considered outliers. The remaining studies, despite having greater weight in the analyses as indicated by the Cook's distance values, did not exceed the limits for the *r*student test (Supplementary file S3A). The funnel analysis indicates that most studies presented a standard error close to the upper end of the triangle, that is, these standard errors generated by the model estimates were low. Furthermore, there was no strong asymmetric distribution between negative and positive cases for the studied effect (Supplementary file S3B). These results suggest that the potential for bias in the analysis for the collected studies can be considered low.

Figure 2 shows the subgroup meta-analysis for cover crop families in the regions where the studies were conducted (Midwest, Northeast, and South). In the **Midwest region**, the highest number of observations was collected for the *Poaceae* family (n = 231), followed by *Brassicaceae* (n = 138), *mix* (n = 159), and *Fabaceae* (n = 22). The overall effect for the Midwest was -0.0605 (-0.0894 to -0.0317), associated with extremely high heterogeneity,  $I^2 = 98$ . The  $\tau^2$  and  $\chi^2$  values were 0.0097 and 189.14 ( $p < 0.001$ ), respectively, indicating significant variability between studies. The *Brassicaceae*, *mix* and *Fabaceae* showed a positive effect for yield log-ratio, while *Poaceae* had a negative for this variable. For *Fabaceae*, the effect size for yield log-ratio was equal to 0.23, that is, the presence of these species increased soybean yield by 22.4% on average for the studies collected in this region.

In the Northeast region, the results at the family level were similar to the species level since only cereal rye and *mix* were evaluated. In the **South region**, 96 cases were analyzed, with the highest number of observations for the *Poaceae* family (n = 52), followed by *mix* (n = 30) and *Fabaceae* (n = 14). The overall effect estimate was close to zero, with a value of -

0.0119 (-0.0606 to 0.0368). Heterogeneity was moderate, with  $I^2 = 72\%$ , and the  $\tau^2$  and  $\chi^2$  values were 0.0010 and 7.2 ( $p$ -value = 0.03). The no-significant effect for  $\chi^2$  and moderate heterogeneity indicate that there is null global effect for yield log-ratio due cover crops use compared to control. However, there is some variation among the cases, specifically for Poaceae. For this family a positive effect was observed, even though low (0.01), for yield log-ratio.

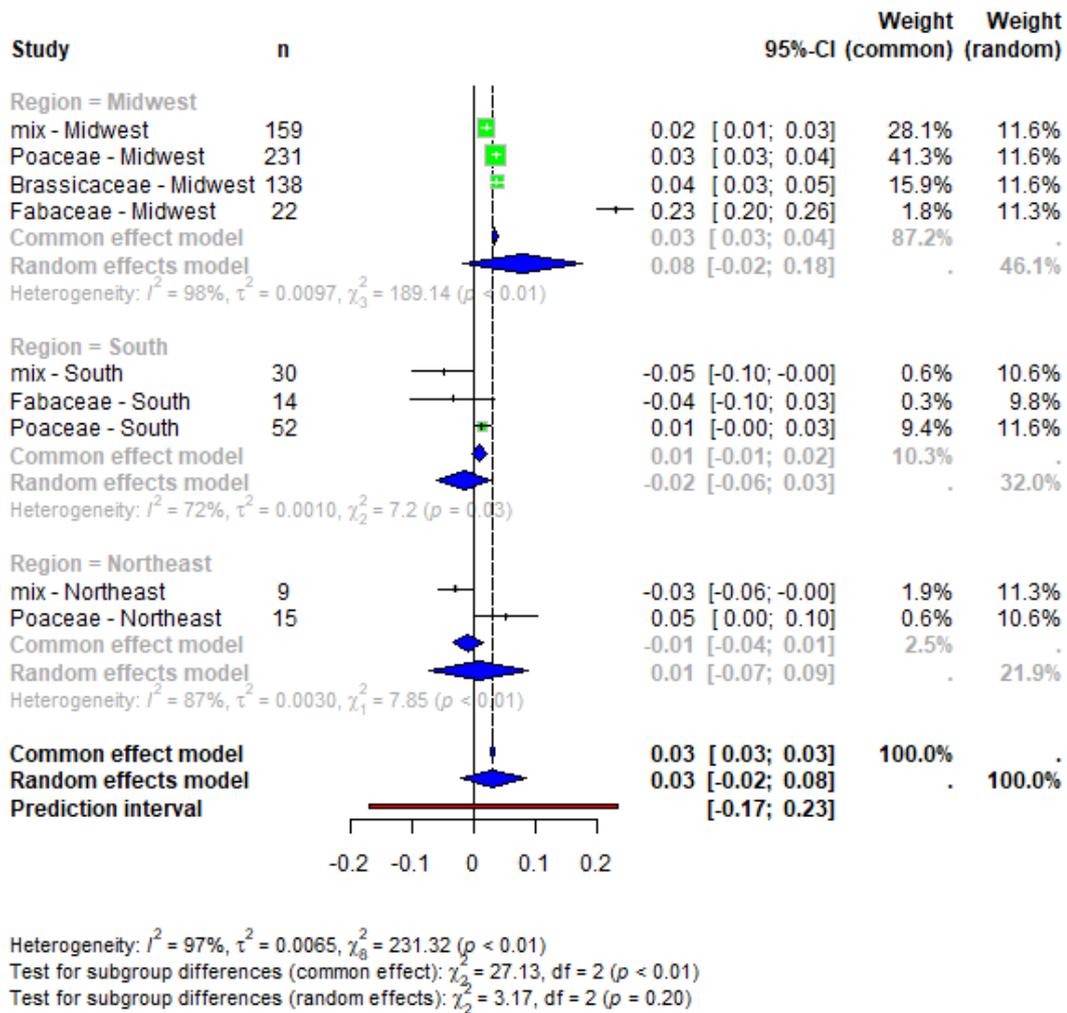


FIGURE 2 - Meta-analysis for effects of different cover crop families on log-ratio soybean yield, stratified by region (Midwest, Northeast, South). The solid vertical line marks the null effect point (log-ratio = 0). The blue line and shadow represent global mean effect and confidence interval. The  $\chi^2$ ,  $I^2$ , and  $\tau^2$  values indicate heterogeneity between studies in each region. Weight common and weight random represent the weights assigned to each study in fixed-effect and random-effect models, respectively.

## 4.2 Effects of termination time of cover crops on soybean yield

No case as for the CCs termination time, considering different moderators that will be presented below, presents a strong influence on the results, indicating that the results obtained are not biased due to the weight of one possible case over the other (Supplementary file S4 to S7). The results of the multivariate meta-analysis using the restricted maximum likelihood method indicate significant residual heterogeneity among the cover crop termination dates of the collected studies (Figure 3). The test for residual heterogeneity showed a QE value of 4656 ( $p < 0.0001$ ), suggesting substantial variability in the observed effects among the cover crop termination dates. The moderators' test also revealed a significant influence of these factors on the overall results ( $QM = 170$ ;  $df = 10$ ;  $p < 0.0001$ ), highlighting the importance of the factors included in the model to explain part of the variation between studies (Figure 3).

Significant effects were observed in several termination date classes of cover crops on the log-ratio of soybean yield. The mid-Apr class showed a positive effect (estimate = 0.114; 95% CI = 0.077 to 0.151;  $p < 0.0001$ ). The termination dates late-Apr and late-May showed significant negative effects, with estimates of -0.046 (95% CI = -0.078 to -0.013;  $p$ -value = 0.006) and -0.041 (95% CI = -0.077 to -0.005;  $p$ -value = 0.028), respectively. Other termination dates, such as early-Apr (estimate = 0.072; 95% CI = -0.001 to 0.145) and mid-Mar (estimate = -0.093; 95% CI = -0.202 to 0.016), showed trends but were not statistically significant considering a  $p$ -value  $< 0.05$ . The remaining dates, including early-Jun, mid-Jun, late-Mar, early-May, and mid-May did not show significant effects, with  $p$ -values greater than 0.1.

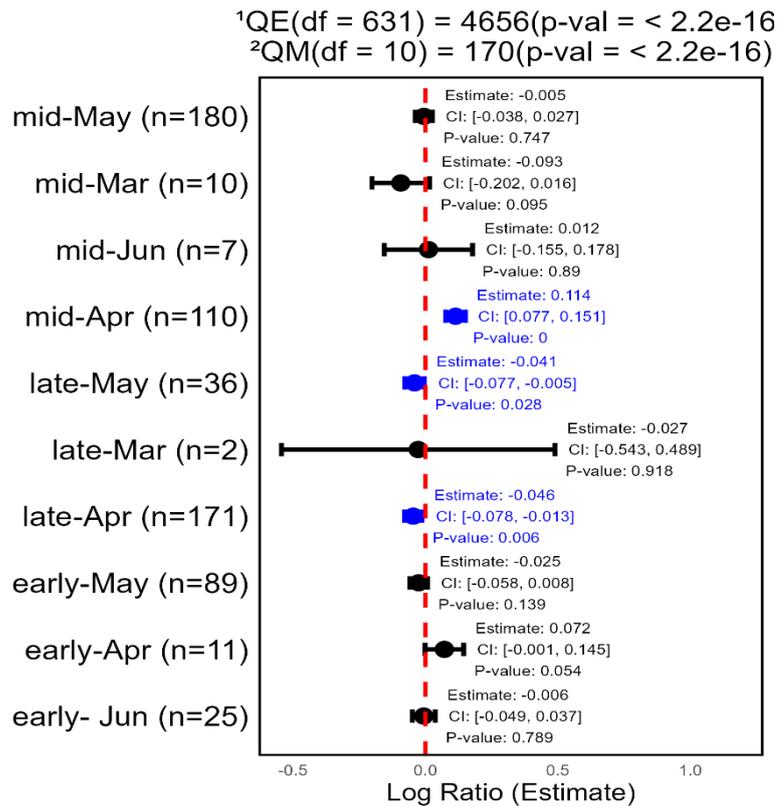


FIGURE 3 - Meta-analysis for effects of different cover crop termination dates on log-ratio soybean yield. The red vertical line marks the null effect point (log-ratio = 0). n = number of observations. Highlighted in blue were significant at p-value < 0.05. <sup>1</sup>Test for residual heterogeneity. <sup>2</sup>Test of moderators.

When considering planting date after cover crop termination, the test for residual heterogeneity showed a QE value of 3533 ( $p < 0.0001$ ; Figure 4), suggesting that substantial variability still exists in the effects observed among the different termination dates. The test for moderators also revealed a significant influence of these factors on the overall results (QM = 173;  $df = 10$ ;  $p < 0.0001$ ) (Figure 4). For conditions where soybeans were planted after the termination of the cover crop, significant effects for some termination dates were observed. The mid-Apr class showed a positive effect, with a significant increase (estimate = 0.113; 95% CI = 0.08 to 0.147;  $p < 0.0001$ ). The late-Apr class showed a significant negative effect, with an estimate of -0.041 (95% CI = -0.07 to -0.012;  $p$ -value = 0.0051), while the late-May class also showed a significant reduction in yield, with an estimate of -0.042 (95% CI = -0.082 to -0.002;  $p$ -value = 0.039).

Other termination periods, such as early-Jun, mid-Jun, late-Mar and mid-May did not show statistically significant effects ( $p$ -value > 0.05), although some trends were observed. The mid-May class, for example, showed a slight negative trend, but it was not statistically significant considering  $p < 0.05$ , with  $p$ -value = 0.062.

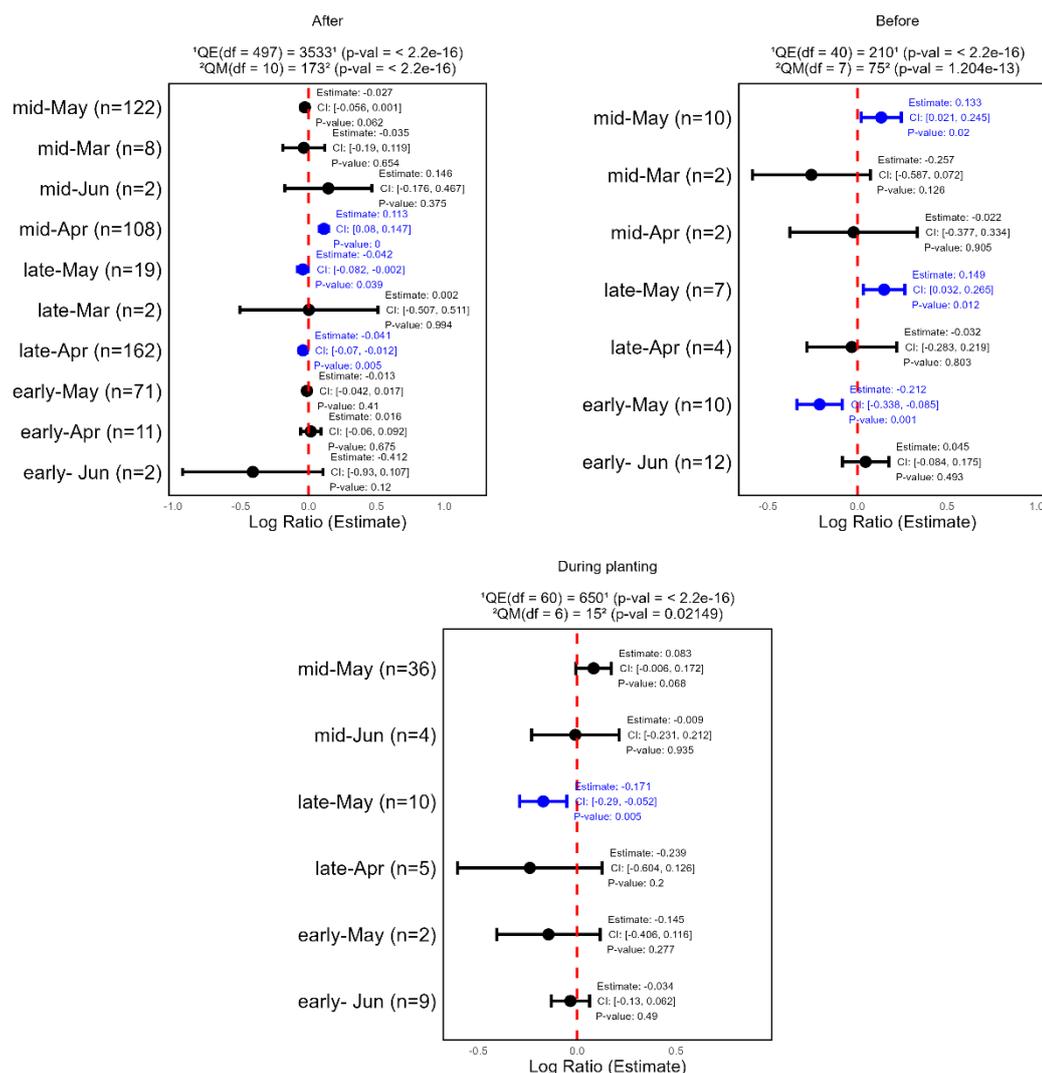


FIGURE 4 - Meta-analysis for effects of different termination dates (y-axis) and soybean planting moments (after, before or during cover crop termination) on log-ratio soybean yield. The red vertical line marks the null effect point (log-ratio = 0). n = number of observations. Highlighted in blue were significant at p-value < 0.05. <sup>1</sup>Test for residual heterogeneity. <sup>2</sup>Test of moderators.

When considering planting date before cover crop termination, the test for residual heterogeneity showed a QE value of 210 ( $p < 0.0001$ ), and the test for moderators also revealed a significant influence of these factors on the overall results ( $QM = 75$ ;  $p < 0.0001$ ). Some termination dates showed significant effects on the log-ratio of soybean yield (Figure 4). The termination date early-May showed a significant negative effect, with an estimate of -0.212 (95% CI = -0.338 to -0.085;  $p$ -value = 0.001). On the other hand, the termination dates late-May and mid-May demonstrated significant positive effects, with estimates of 0.149 (95% CI = 0.032 to 0.265;  $p$ -value = 0.012) and 0.133 (95% CI = 0.021 to 0.245;  $p$ -value = 0.02),

respectively. Other termination dates, such as late-Apr, early-Jun and mid-Mar did not show statistically significant effects, with p-values above 0.05.

When considering planting date during cover crop termination, the test for residual heterogeneity showed a QE value of 650 ( $p < 0.0001$ ). The test for moderators revealed a significant influence of these factors on the overall results ( $QM = 15$ ;  $p$ -value = 0.01), suggesting that for conditions where soybeans were planted simultaneously with the termination of the cover crop, there were significant effects for some termination dates (Figure 4). The late-May termination date showed a significant negative effect, with an estimate of -0.171 (95% CI = -0.29 to -0.052;  $p$ -value = 0.005), indicating a reduction in soybean yield compared to the control. Other termination dates, such as late-Apr (estimate = -0.239; 95% CI = -0.604 to 0.126;  $p$ -value = 0.20) and mid-May (estimate = 0.083; 95% CI = -0.006 to 0.172;  $p$ -value = 0.068), showed trends, but the effects were not statistically significant considering a  $p$ -value  $< 0.05$ . The remaining termination dates, such as early-Jun, mid-Jun and early-May did not show statistically significant effects, with  $p$ -values greater than 0.05.

The test for residual heterogeneity for conditions where the cover crop was terminated by chemical, harrowing, mowing, and roller-crimper methods showed QE values of 4114, 162, 22, and 105, all significant ( $p < 0.0001$ ). The tests of moderators also indicated that, for each termination method, the termination dates significantly affected the overall results ( $QM$  values = 167, 17, 1.0, 9, respectively;  $p$ -value  $< 0.05$ ) (Figure 5).

Some cover crop termination dates using chemical termination showed significant effects on the log-ratio of soybean yield. The mid-Apr date showed a significant positive effect (estimate = 0.143; 95% CI = 0.102 to 0.184;  $p < 0.0001$ ), while late-Apr showed a significant negative effect (estimate = -0.042; 95% CI = -0.077 to -0.006;  $p$ -value = 0.021). Other termination dates, such as late-May (estimate = -0.033;  $p$ -value = 0.100) and mid-Mar (estimate = -0.087;  $p$ -value = 0.123), showed only trends but no statistically significant effects. The early-Jun and mid-Jun did not show statistically significant effects, with  $p$ -value  $> 0.05$ .

For the harrowing and mowing termination methods, none of the termination dates showed statistically significant effects on the log-ratio of soybean yield. The roller-crimper termination method resulted in a negative effect on the log-ratio of soybean yield when the cover crop was terminated in late-May, with an estimate of -0.158 (95% CI = -0.275 to -0.042;  $p$ -value = 0.001), with no effects for the other dates.

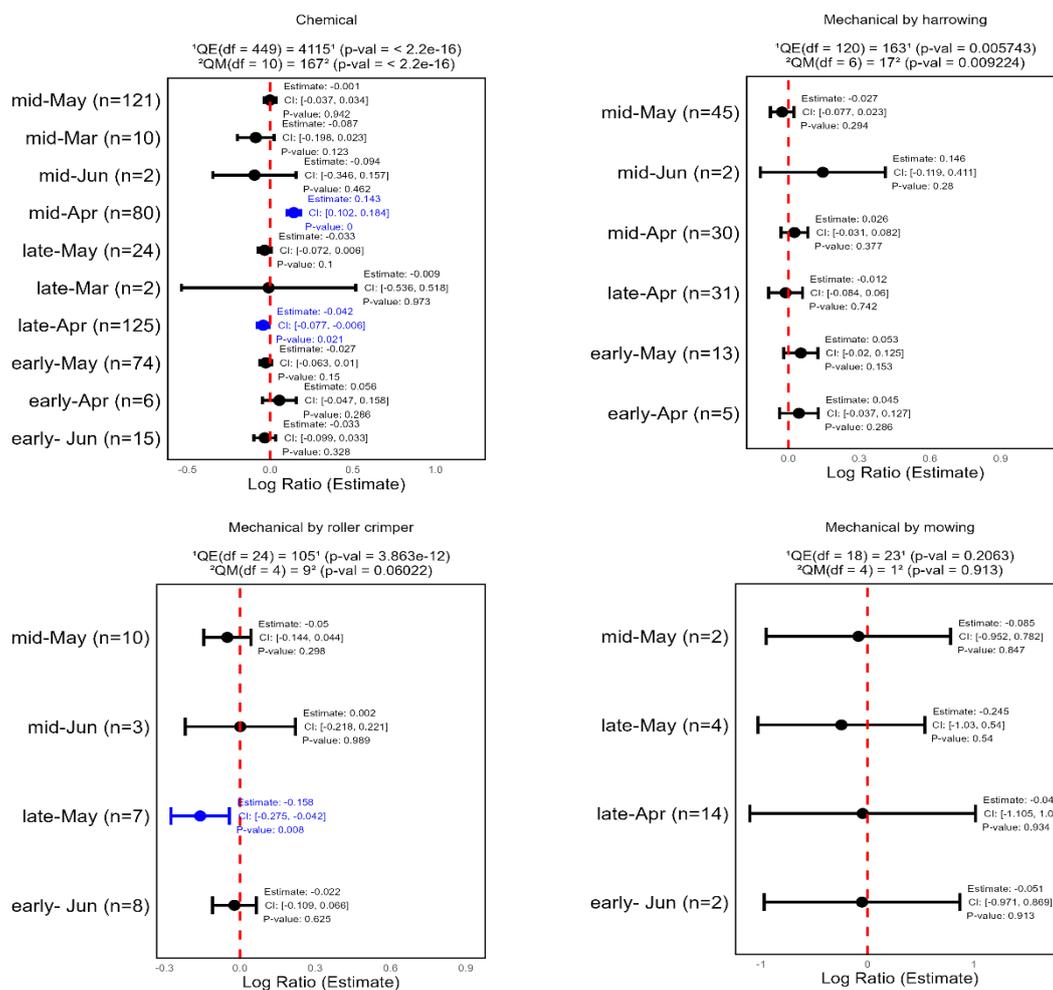


FIGURE 5 - Meta-analysis for effects of different termination dates (y-axis) and termination method of cover crops on log-ratio soybean yield. The red vertical line marks the null effect point (log-ratio = 0). n = number of observations. Highlighted in blue were significant at p-value < 0.05. <sup>1</sup>Test for residual heterogeneity. <sup>2</sup>Test of moderators.

The test for residual heterogeneity considering different soybean maturity group showed QE values of 514, 1072, 1559, 42 and 256 for I, II, III, IV and V maturity group, all significant (p < 0.0001; Figure 6). The tests of moderators also indicated that, for I, III, IV and V maturity group, the termination dates significantly affected the overall results (p-value < 0.05). For II maturity group, a significant effect for moderators was observed only for p < 0.10.

For soybeans in maturity group III, cover crop termination in mid-April had a positive effect on the log-ratio of soybean yield (estimate = 0.278; 95% CI = 0.106 to 0.450; p-value = 0.002). For other dates, a null effect was observed, with confidence intervals crossing the line corresponding to a log-ratio of 0. Soybean cultivars in maturity group IV exhibited negative effects when the cover crop was terminated in late-April (estimate = -0.191; 95% CI = -0.345 to -0.037; p-value = 0.015), with null effects for other termination dates. For maturity group V, a

positive effect was observed for early-May (estimate = 0.065; 95% CI = 0.01 to 0.12; p-value = 0.02) and a negative effect for mid-May (estimate = -0.068; 95% CI = -0.103 to -0.032; p-value = 0.001). Other dates showed null effects. For group II, termination in early-May showed a negative effect for the log-ratio of soybean yield, with an estimate of -0.067 (95% CI = -0.131 to -0.004; p-value = 0.039).

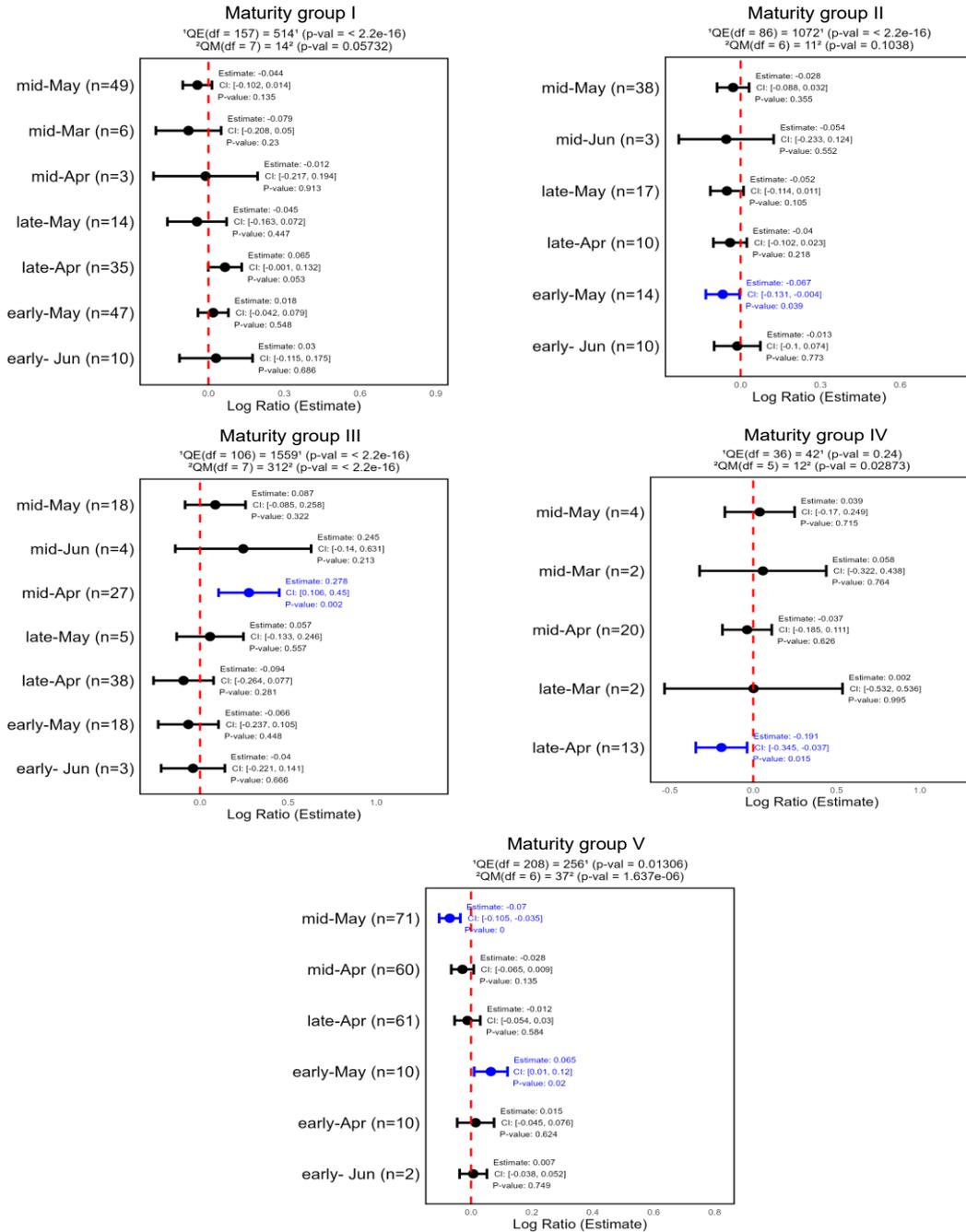


FIGURE 5 - Meta-analysis for effects of different termination dates (y-axis) and maturity group of planted soybeans on log-ratio soybean yield. The red vertical line marks the null effect point (log-ratio = 0). n = number of observations. Highlighted in blue were significant at p-value < 0.05. <sup>1</sup>Test for residual heterogeneity. <sup>2</sup>Test of moderators.

Cover crop biomass did not have a significant impact on soybean yield (Figure 7). The biomass coefficient value was very small and non-significant:  $\approx 0$  (p-value = 0.83). This suggests that increased cover crop biomass was not strongly associated with changes in the log-ratio of soybean yield. A similar pattern was observed for the clay, sand, silt, and organic matter content, with no significant effects in the linear model parameters (p-value > 0.05) (Figure 7).

The relationship between soil pH and the log-ratio of soybean yield showed a significant effect, with an estimated slope and coefficient of -0.0408 (p-value = 0.0112). The intercept was also a significant parameter for this relationship (0.2483, p-value = 0.0204). The coefficient of determination ( $R^2$ ) for the linear model between soil pH and the log-ratio of yield was 0.35.

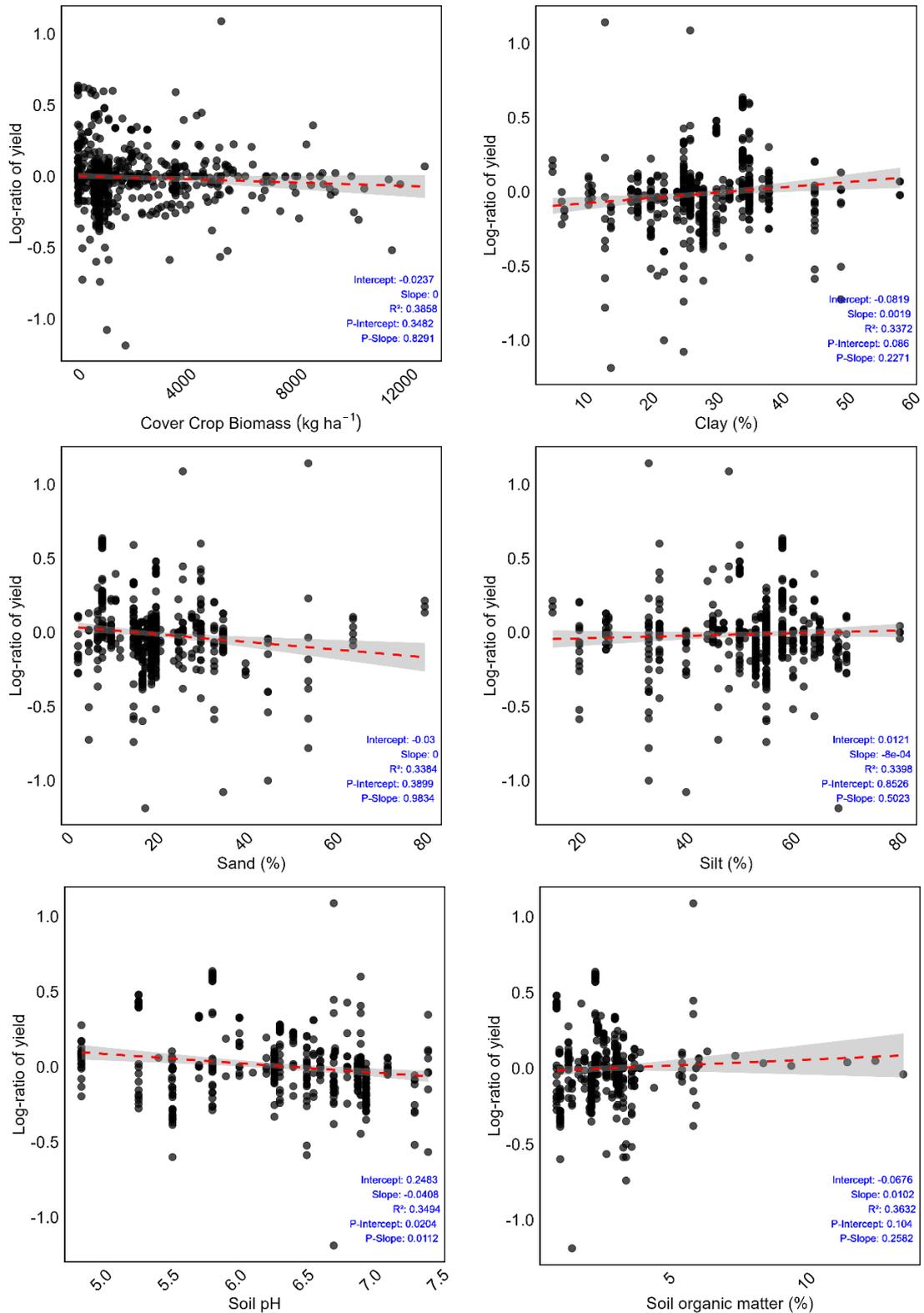


FIGURE 7 - Linear mixed-effects model between accumulated cover crop biomass and soil proprieties on the log-ratio of soybean yield. Model parameters and their significance level are shown in blue color in the lower right corner in each graph. Others termination dates did not show sufficient data for analysis.

Cumulative precipitation did not have a significant impact on the log-ratio of soybean yield, although a trend was observed (Figure 8). The estimated coefficient was 0.0001 (p-value = 0.0939). The intercept was significant, with a value of -0.1107 (p-value = 0.0203). The relationship between mean temperature and the log-ratio of yield was not significant, with a coefficient of 0.0048 (p-value = 0.2643) and an intercept of -0.0827 (p-value = 0.1489).

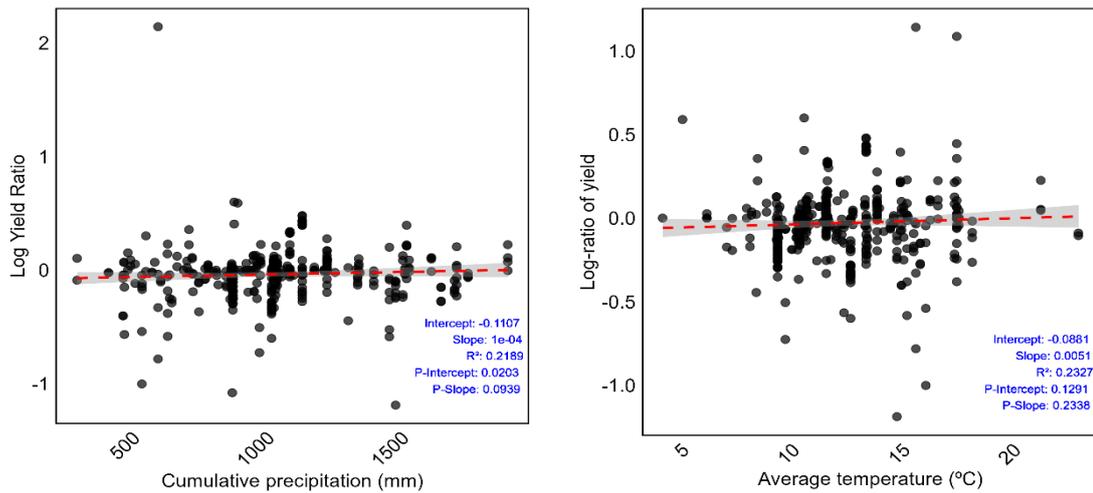


FIGURE 8 - Linear mixed-effects model between cumulative precipitation and the log-ratio of soybean yield for each termination date in the midwest, northeast and south. Model parameters and their significance level are shown in blue color in the lower right corner in each graph. Others termination dates did not show sufficient data for analysis.

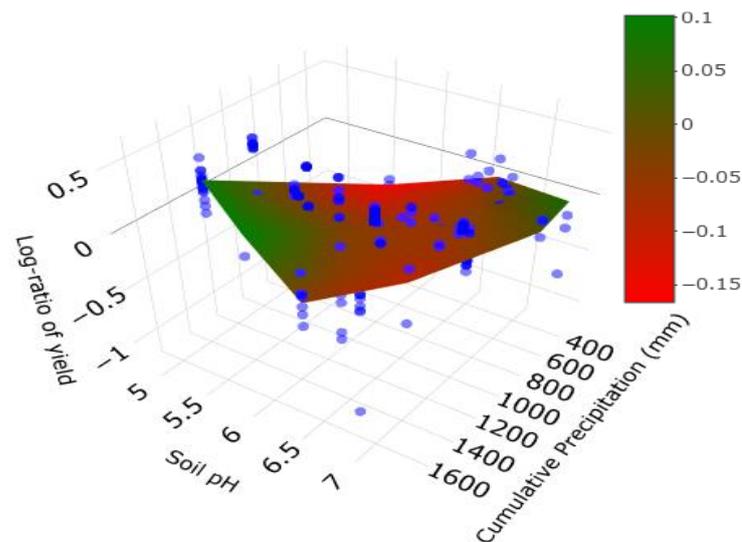


FIGURE 9 - Linear mixed-effects model for integration between cumulative precipitation and soil pH (B) on log-ratio of soybean yield.

The comparison of models showed a significant difference when interactions between cumulative precipitation and soil pH were added (Figure 9 and Table 2). The model with interaction had an AIC value of -210.3 and a log-likelihood of 112.2, with a p-value of 0.0020 compared to univariate models, which had AIC equal to -201.9 and -204.7 for Precipitation and Soil pH, indicating that the interaction between precipitation and soil pH significantly improves the model's fit. The additive model between cumulative precipitation and soil pH was not significant (p-value = 0.09) compared to the both univariate models.

In the model evaluating the interaction between cumulative precipitation and pH, both factors were significant. Cumulative precipitation had a slope coefficient of 0.0021 (p-value = 0.0021), while soil pH showed a slope coefficient of 0.3165 (p-value = 0.0063). The interaction between cumulative precipitation and pH was also significant, with a slope coefficient of -0.0003258 (p-value = 0.0021).

TABLE 2 - Model parameters (Degrees of Freedom - df, Akaike Information Criterion - AIC, Bayesian Information Criterion - BIC, Log-Likelihood - logLik, Likelihood Ratio - L.Ratio) and analysis of variance between univariate and additive effects or interaction models for accumulated precipitation and soil pH

Random effects:						
Formula: ~1   study						
(Intercept)						
StdDev: 0.02						
Formula: ~1   Years_2 in study						
(Intercept) Residual						
StdDev: 0.10						
Fixed effects: Log-ratio of yield ~ Culmulative precipitation * pH						
Parameters	Value	Std.Error	t-value	p-value	R <sup>2</sup>	
(Intercept)	-2.14	0.77	-2.79	0.01		
Culmulative precipitation	0.00	0.002	3.10	0.00	0.52	
Soil pH	0.32	0.11	2.75	0.01		
Culmulative precipitation/pH	0.00	0.0003	-3.10	0.00		
Analysis of variance						
Model	df	AIC	BIC	logLik	L.Ratio	p-value (Precipitation/Soil pH)
Precipitation	5	-201.9	-182.9	105.9		
Soil pH	5	-204.7	-185.7	107.3		
Precipitation + Soil pH	6	-202.8	-180.0	107.4	2.9	0.09/0.09
Precipitation * Soil pH	7	-210.3	-183.7	112.1	9.5	0.002/0.001

df = Degrees of Freedom, AIC = Akaike Information Criterion, BIC = Bayesian Information Criterion, logLik = Log-Likelihood, L.Ratio = Likelihood Ratio.

## 5 DISCUSSION

### 5.1 General effects of adopting cover crops on soybean yield in the midwest, northeast and south regions

Although the non-significant result for the overall effect of cover crop use on soybean yield obtained by meta-analysis, recent studies indicate that a positive impact of cover crops can be better observed in diversified rotation systems and under specific management conditions. For example, rotation with corn, combined with the use of cover crops, demonstrated an approximate 10% increase in soybean yield, while proper nutrient management and mitigation of water stress can contribute to greater yield stability (Mazzilli & Ernst, 2023; Weber et al., 2023).

The significant variability among studies in each region suggests the importance of considering subgroups, such as cover crop type, management practices, and crop rotation, to better understand the conditions in which cover crops are most effective. More detailed and stratified analyses are necessary to identify sources of heterogeneity and to provide more accurate management recommendations (Strock et al., 2023).

Even with the stratification of the meta-analysis by cover crop species and region, the results indicate that the effect of cover crops on soybean yield remains highly variable. This lack of a significant overall estimate for the Midwest region reflects not only the inherent heterogeneity of cropping systems but also the complex interaction between management practices and specific environmental conditions (Eckert, 2023). This suggests that local factors, such as soil type and climatic conditions, may still be moderating the effectiveness of cover crops, limiting the generalization of results for this region.

The South region showed a null overall effect, indicating that cover crops, while contributing to soil health and other agronomic benefits, did not result in consistent greater yield compared to the control. This could be related to less diversified management practices or the predominance of cover crop species with neutral effects on yield (Roesch-McNally et al., 2018; Plastina et al., 2020). Meanwhile, the Northeast region, which also showed no significant effect, highlights the need to consider more contextual factors when evaluating cover crop performance, such as selecting species better adapted to local conditions.

The analysis at the class and family levels revealed that Poaceae species tend to have negative effects, while broadleaf species demonstrated more positive effects. However, it is

crucial to emphasize that within Poaceae there are significant differences: while species like rye showed a positive effect on soybean yield, others, such as barley (*Hordeum vulgare*) e oats (*Avena sativa*), pulled the results down due to extreme negative values. Removing these extreme cases shifted the log-ratio yield effect above the null, suggesting that cover crop species choice may play a role in yield outcomes. However, achieving substantial increases in soybean yield likely depends on an interplay of factors beyond species selection, including specific management practices, environmental conditions, and other system-level decisions (Buxton et al., 2023).

## 5.2 Effects of planting and termination time of cover crops on soybean yield

The effect of cover crop termination timing on soybean yield showed that earlier termination generally achieved greater yields, while later termination can reduce productivity. Specifically, the "mid-Apr" class resulted in an approximate 12% greater yield compared to the control, aligning with the literature, which emphasizes that early termination supports soybean productivity (Acharya et al., 2019; Rankoth et al., 2021). Conversely, later termination periods, such as "late-Apr" and "late-May," showed yield reductions between 2.73% and 9.01%. Soil moisture conditions and precipitation may be key factors in soybean response across the termination timings. In "late-Apr" and "late-May," planted soybeans could experience lower soil moisture, impairing their initial establishment. Termination in June, however, coincided with a phase of greater water availability due to the accumulation of precipitation after the beginning of spring, providing better initial growth conditions for soybean. Despite fluctuations between years and regions, according to Boyer et al. (2023), for planting in June, there is a greater regularity of rainfall, with a tendency for excessive rainfall events across the country. On the contrary, for mid-May, the lack of rain has been the limiting factor for planting. This rainfall behavior illustrates how the termination of cover crops in June may have favored the performance of soybeans under cover crops, especially due to the ability of the crop residues of the cover crop to retain soil moisture.

When soybeans were planted before cover crop termination, later termination, especially in mid-May, showed yield increases up to 29%, whereas early May termination led to a 16% yield reduction due to water competition. These observations align with studies suggesting that prolonged cover crop presence may lead to water competition and operational challenges, particularly under non-irrigated conditions (Reed et al., 2019; Mirsky et al., 2012). In cases of simultaneous termination and soybean planting, only "late-May" led to yield

reductions, suggesting that optimal termination timing depends not only on the date but also on regional climate conditions, underscoring the importance of tailored adjustments to maximize productivity (Silva et al., 2024).

The method and timing of cover crop termination significantly influenced soybean yield. Herbicide termination in "mid-Apr" boosted soybean yield by 38% compared to control areas, while termination by harrowing nullified this effect. Herbicide termination at this time likely retained more soil mulch, benefiting moisture retention, temperature stability, beneficial microbiota, and weed control. For maturity group III, "mid-Apr" termination increased yield by over 10.6% compared to areas without cover crop use, likely due to optimal soil preparation and moisture balance at this stage in mid-latitude regions like the US Midwest, aligning well with vegetative growth requirements before flowering (Campos et al., 2024).

In maturity group IV, "late-Apr" termination had a negative yield effect by 3.7%, suggesting this timing may miss the ideal planting window (Colet et al., 2023; Siler and Singh, 2023). Group V showed positive effects with "early-May" termination, increasing yields by 15% as cover crop biomass enhanced nutrient availability. However, "mid-May" termination reduced yield by 3.2%, likely due to shortened reproductive time, indicating that while group V allows planting flexibility, overly delayed termination can hinder yield.

Among the soil parameters collected from the database, only soil pH showed a significant interaction with the log-ratio of yield. This significant effect of pH increased when the average precipitation level was considered in the model. The negative slope between soil pH and the log-ratio indicates that the difference in yield between areas with and without cover crops is smaller at higher pH levels, reaching null values for the log-ratio at an estimated pH of 6.05. The positive intercept for this relationship also suggests that in soils with lower pH, there is a tendency for positive effects from adopting cover crops compared to areas without this practice, for grain yield. However, despite this significant effect, the precise relationship between the pH and log-ratio of yield is limited due to the moderate importance suggested by the coefficient of determination value of model, even for the model that include the interaction between soil pH and precipitation on the log-ratio of yield ( $R^2 = 0.52$ ).

The low value for  $R^2$  suggests that other factors related to environmental conditions and management practices should also be considered to better understand the yield differences between areas with and without cover crops. These other effects linked to the yield response of soybeans probably did not allow the identification of a general correlation between the levels of clay, sand, silt, organic matter and accumulated biomass of the cover crop with soybean yield in systems with and without the use of cover crops.

Although the slope for the linear model between cumulative precipitation and the log-ratio of yield did not reach significance for  $p < 0.05$ , when the soil pH was added, a significant effect was detected for slope (0.002 and  $p$ -value = 0.002). This suggests that the adoption of cover crops tends to result in a positive effect compared to areas without this practice as cumulative precipitation increases, mainly for conditions where there is a lower soil pH. This is because the interactive model for precipitation \* soil pH showed a significant negative value for slope, i.e., the higher the soil pH, the lower the positive effect of precipitation on the log-ratio of soybean productivity, and vice versa. Thus, the adoption of cover crops tends to increase soybean productivity compared to areas without this agricultural practice under conditions of higher precipitation and lower soil pH. According to the model, conditions with accumulated annual precipitation between 1100 and 1300 mm are sufficient to allow higher yields for areas with CC than without CC, but for soil pH between 5 and 6, respectively.

The observation that low precipitation reduces soybean productivity in areas with cover crops compared to those without is supported by findings in recent research. In the study by Sanyal et al. (2023), the authors suggest that while cover crops may offer various benefits, such as weed suppression or erosion control, their impact on yield can be heavily influenced by hydroclimatology, particularly in regions with lower precipitation. Sanyal et al (2023) found that cover crops did not improve soil health significantly, as potentially mineralizable nitrogen, permanganate oxidizable carbon, soil respiration, soil microbial biomass, soil organic matter and other basic soil properties (pH, electrical conductivity, etc.). The authors attributed this effect due to plots had healthy soils (long-term no-till was practiced, high SOM levels  $>30$  g kg<sup>-1</sup>). However, in this study, the hydroclimatic conditions played a crucial role in determining yield outcomes. In areas where water availability is limited, cover crops can exacerbate water competition, reducing the amount of soil moisture available for the soybean crop. This effect is particularly pronounced in dry conditions, where the benefits of cover crops may be offset by the competition for limited water resources between the cover crop and the primary cash crop, in this case, soybean. This may also explain negative effects observed for some termination dates of cover crops already mentioned previously.

When precipitation is low, the cover crops continue to absorb water, which could otherwise be available for soybeans during their critical early development stages (Garba et al., 2022; Kasper et al., 2022; Whippon et al., 2024). This aligns with our observation of reduced soybean yield in cover crop fields during periods of low rainfall compared areas without cover crops. Sanyal et al. argue that hydroclimatology—the relationship between climate, hydrology, and crop performance—should guide decisions on cover crop management, particularly in

regions prone to water stress. Their findings suggest that under low rainfall conditions, the adoption of cover crops without adequate moisture may lead to yield losses, contradicting the intended benefits of cover cropping in improving overall farm productivity.

Higher soil pH may make some nutrients important for soybean growth unavailable, mainly micronutrients due to precipitation at more alkaline pH (Liu et al., 2022; Hartemink and Barrow, 2023). This may be intensified in conditions where the cover crop extracts some of these nutrients, reducing the amount of this resource for soybeans. Even though the cover crop may exert nutrient cycling in the long term, in the short term this limitation may be reducing soybean productivity. The effect of pH is probably minimized by increased rainfall, because it favors greater absorption of nutrients from the soil due to higher moisture content. Consequently, the other beneficial effects on the system provided by CCs may be resulting in increased productivity of soybeans purchased in areas without CCs.

## **6 CONCLUSIONS**

Cover crops can improve soil quality over time. However, the results of this meta-analysis shows that their effect on subsequent cash crops is not well-established. Also, the results in this study highlight the complexity of interactions between cover crops, environmental factors, and soybean yield. While mid-April termination consistently correlated with yield increases, mainly for early-maturity groups. Late termination tends to reduce yields, particularly for later-maturity groups. The increases of precipitation levels generally enhance yield in cover-cropped areas; however, elevated soil pH conditions negatively moderates this effect. These results highlight the importance of adjusting cover crop practices, such as termination timing and soil management, to optimize yield benefits under varying environmental conditions.

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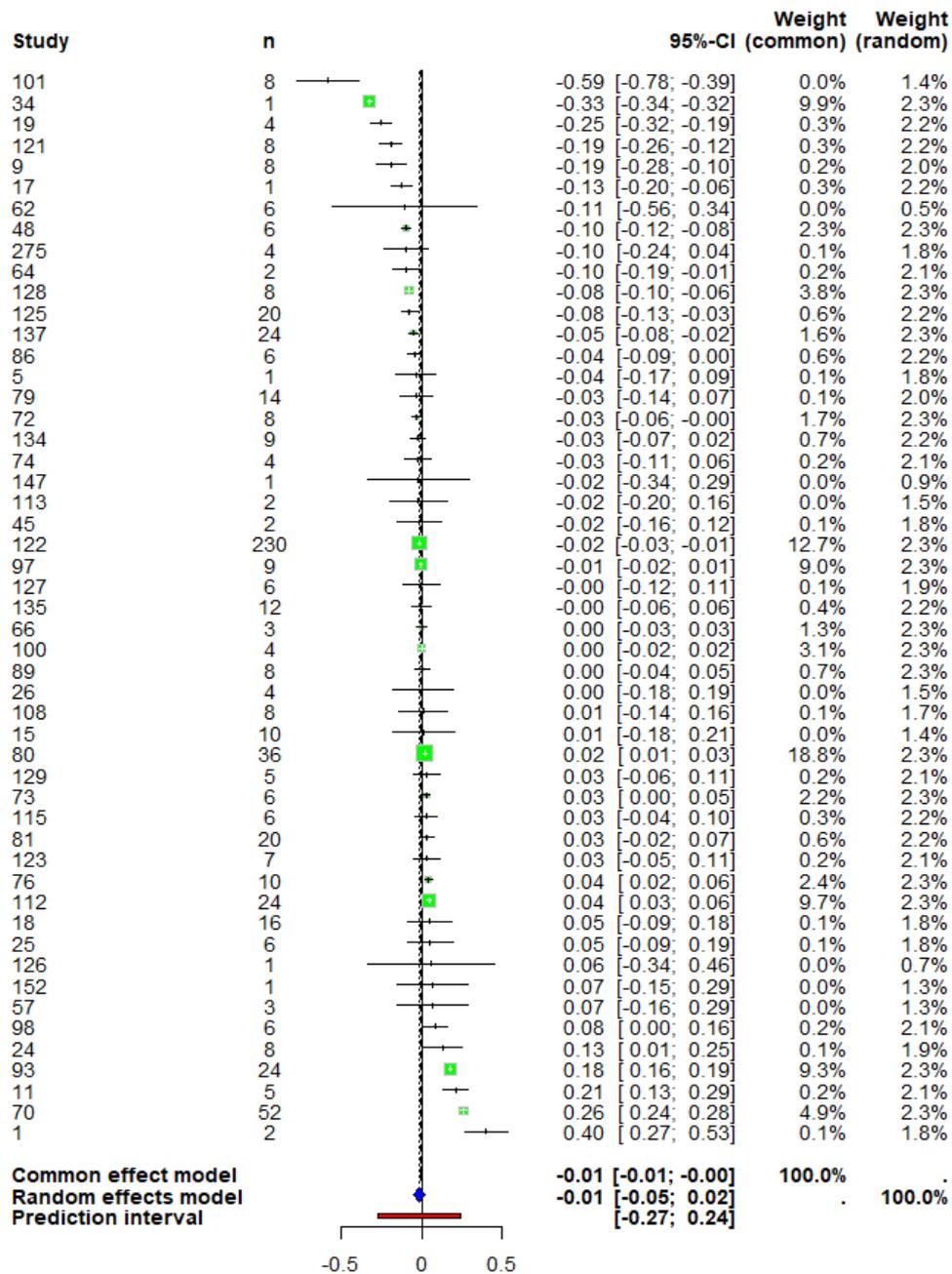
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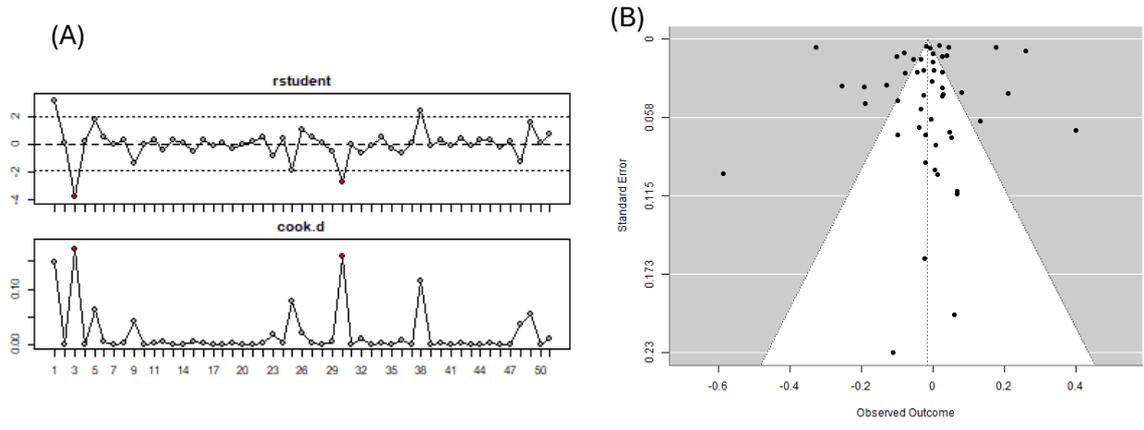
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## **ANEXOS**

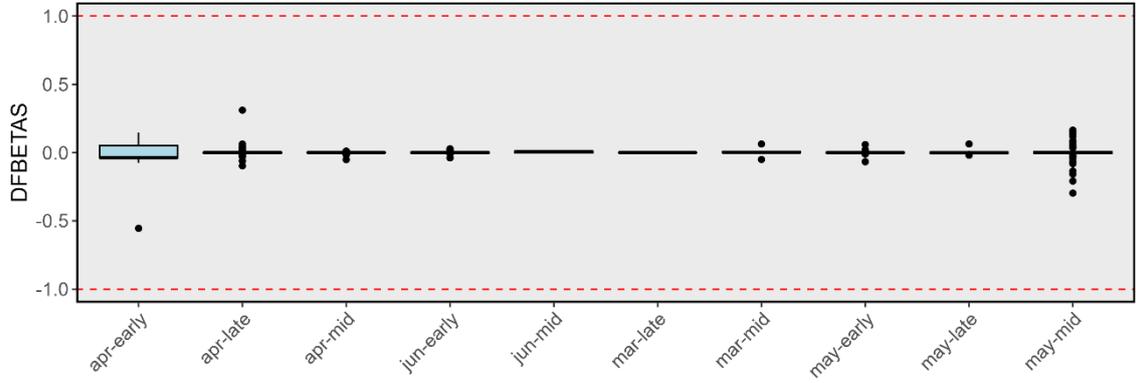


Heterogeneity:  $I^2 = 99\%$ ,  $\tau^2 = 0.0159$ ,  $\chi^2_{50} = 5135.25$  ( $p = 0$ )  
 Test for overall effect (common effect):  $z^2 = -2.99$  ( $p < 0.01$ )  
 Test for overall effect (random effects):  $z = -0.74$  ( $p = 0.46$ )

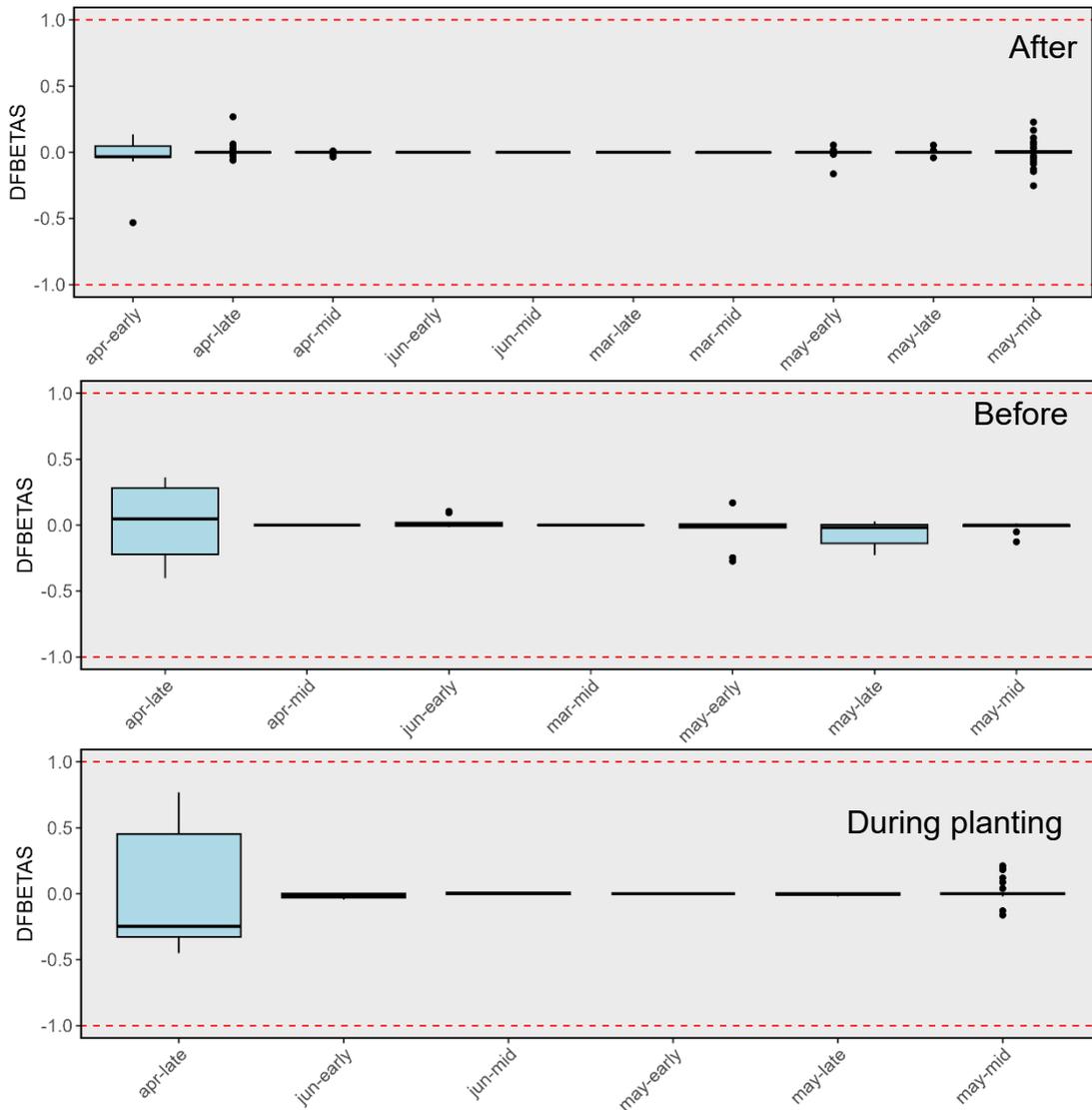
**Supplementary file S2.** Forest plot presenting the log-ratios of the estimated effects of 51 individual studies on the variable of interest, along with their respective 95% confidence intervals. The dotted vertical line indicates the no-effect point (log-ratio = 0). The blue diamond at the bottom represents the overall effect estimate based on the random-effects model. The Q-value and degrees of freedom (df) indicate that the variability among studies is statistically significant ( $Q = 5134.90$ ,  $df = 50$ ,  $p < 0.001$ ).



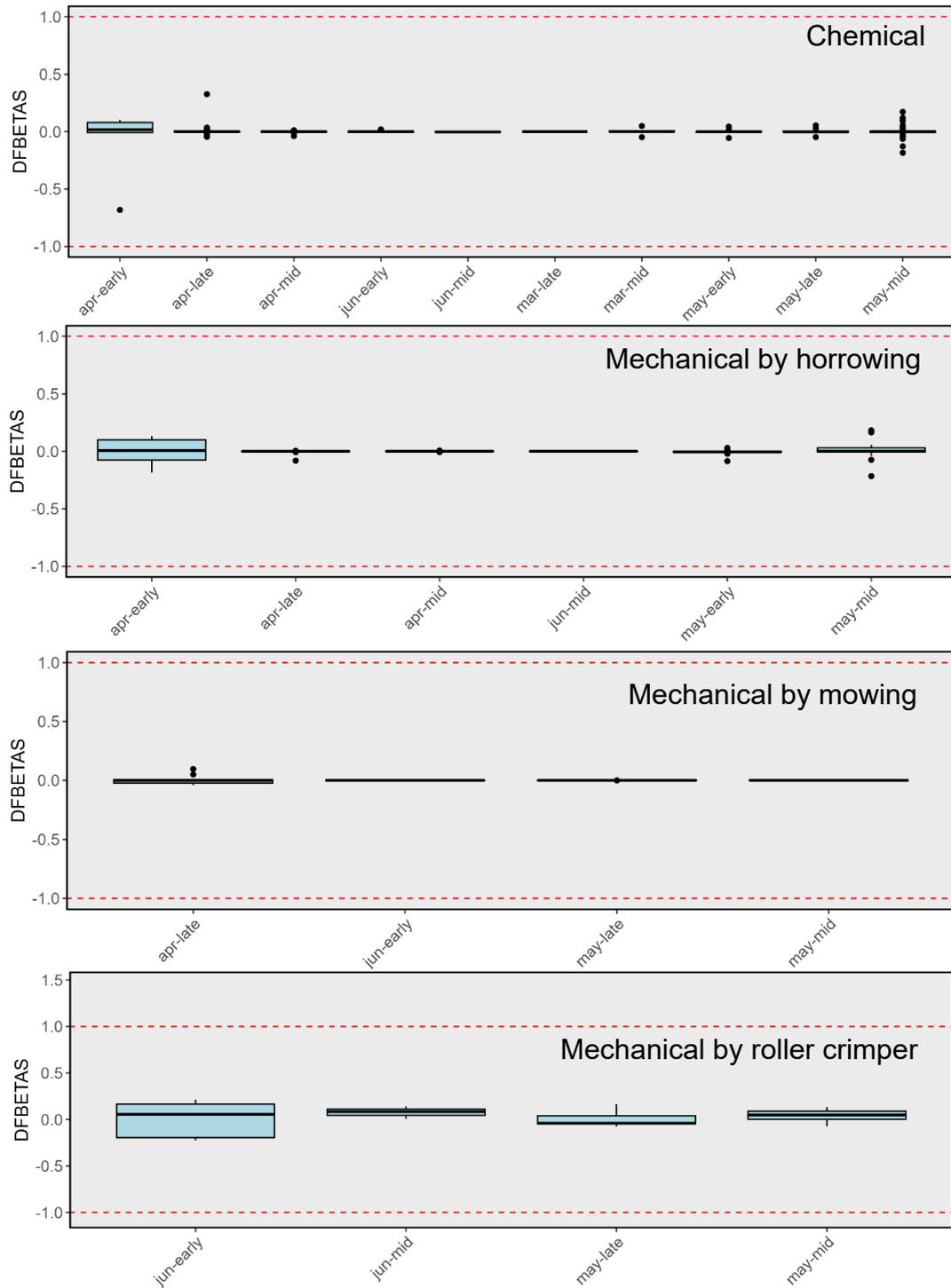
**Supplementary file S3.** Influence analyses and funnel plot for the studies included in the meta-analysis. Values outside the range  $[-2, 2]$  indicate studies with large deviations from the fitted model by *rstudent*.



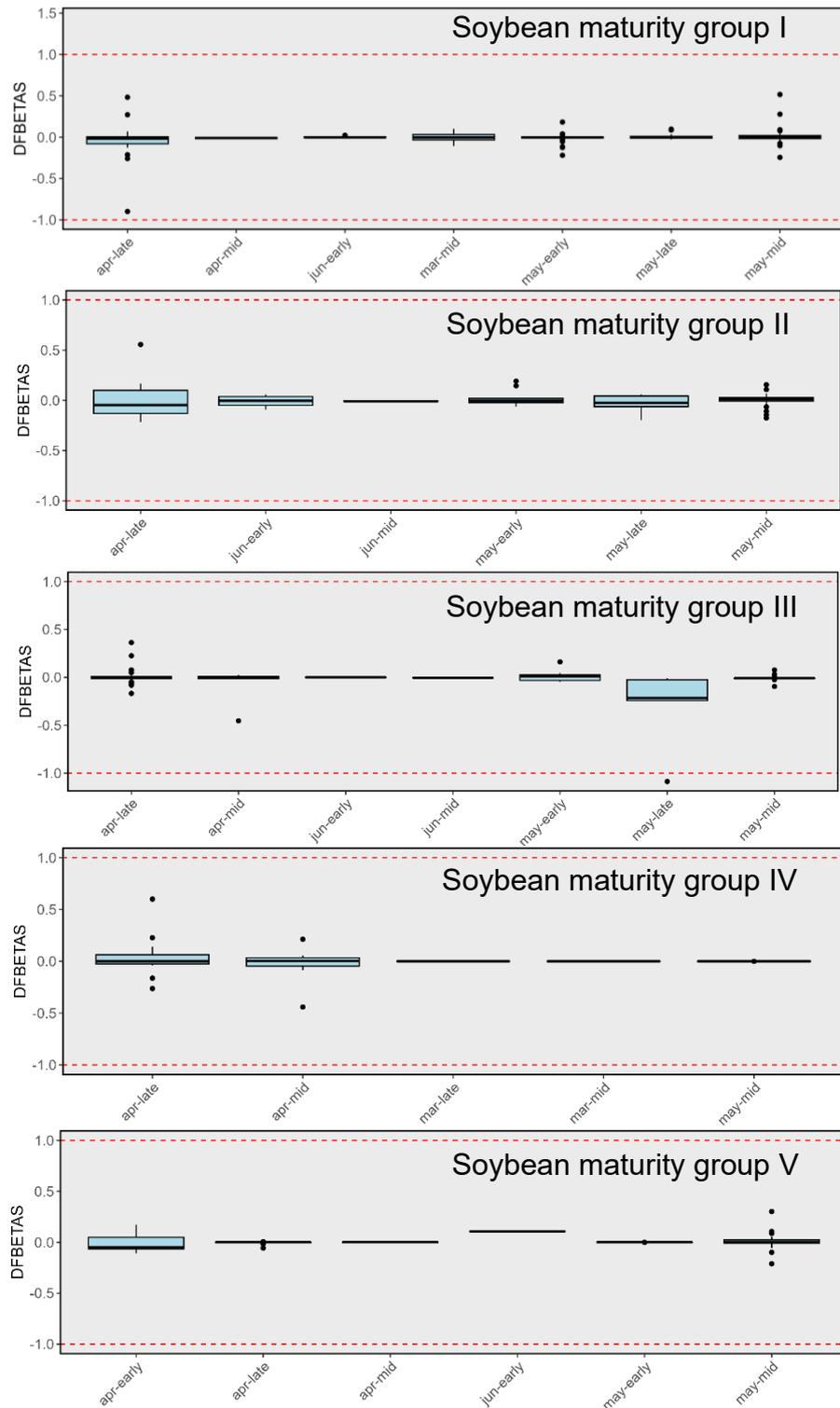
**Supplementary file S4.** Influence analyses for the termination dates cases included in the meta-analysis. Values outside the range  $[-1, 1]$  indicate studies with large deviations from the fitted model by *rstudent*.



**Supplementary file S5.** Influence analyses for the termination dates cases considering soybean planting after, before and during cover crop termination included in the meta-analysis. Values outside the range [-1, 1] indicate studies with large deviations from the fitted model by rstudent.



**Supplementary file S6.** Influence analyses for the termination dates cases considering termination method of cover crop included in the meta-analysis. Values outside the range [-1, 1] indicate studies with large deviations from the fitted model by rstudent.



**Supplementary file S7.** Influence analyses for the termination dates cases considering soybean maturity group included in the meta-analysis. Values outside the range [-1, 1] indicate studies with large deviations from the fitted model by rstudent.