Nativa, Cuiabá, v. 14, n. 3, e21128, 2026.
Pesquisas Agrárias e Ambientais
DOI: https://doi.org/10.31413/nat.v14i3.21128
ISSN: 2318-7670

Boron nutrition and herbicide strategies in managing glyphosate-resistant Palmer amaranth in Roundup Ready® alfalfa

Rogerio FURLAN JUNIOR [1], Thomas MUELLER [1], Lawrence STECKEL [1], Renata Nave OAKES [1], Bruno CARNEIRO E PEDREIRA *[1]

[1] University of Tennessee, Knoxville, USA.
*E-mail: pedreira@utk.edu

Submitted on: 02/20/2026; Accepted on: 05/18/2026; Published on: 08/05/2026.

ABSTRACT: Alfalfa (*Medicago sativa* L.) is one of the most economically valuable forage crops worldwide, due to its high nutritive value and adaptability to diverse climates. However, its agronomic potential depends on proper soil fertility and weed control. Alfalfa production requires substantial inputs of macronutrients and boron, which is often the only micronutrient routinely recommended, yet often overlooked. Boron deficiency is common on coarse-textured, high-pH soils and under dry conditions, reducing regrowth vigor, stand persistence, and the crop's ability to compete with weeds. The adoption of Roundup Ready® (RR) alfalfa initially simplified weed control, but repeated glyphosate use on resistant crops has selected for resistant weed biotypes, such as glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson). Alternative herbicidal options, including PPO inhibitors and paraquat, can provide effective Palmer amaranth control but are constrained by crop safety, application timing, environmental conditions, or regulatory concerns. This review aimed to consolidate existing research on boron fertility, herbicide options, and Palmer amaranth biology to clarify how these factors are related, and to guide integrated management strategies for productive and more sustainable alfalfa systems.
Keywords: weed control; hay; legume; herbicide; resistance.

Nutrição com boro e uso de herbicidas no manejo do *Amaranthus palmeri* resistente ao glifosato em alfalfa RR

RESUMO: A alfafa (*Medicago sativa* L.) é uma das culturas forrageiras de maior valor econômico no mundo, devido ao seu elevado valor nutritivo e à adaptabilidade a diferentes condições edafoclimáticas. No entanto, seu potencial agronômico depende da fertilidade do solo e do controle eficiente de plantas daninhas. A produção de alfafa exige aportes substanciais de macronutrientes e de boro, o único micronutriente recomendado rotineiramente e, ainda assim, frequentemente negligenciado. A deficiência de boro é comum em solos de textura arenosa, com pH elevado e sob condições de seca, e reduz o vigor de rebrotação, a persistência do estande e a capacidade da cultura de competir com plantas daninhas. A adoção da alfafa Roundup Ready® (resistente ao glifosato) inicialmente simplificou o controle de plantas daninhas; contudo, o uso repetido de glifosato em culturas resistentes selecionou biótipos resistentes, como o caruru-gigante resistente ao glifosato (*Amaranthus palmeri* S. Watson). Opções herbicidas alternativas, incluindo inibidores da protox e do paraquat, podem proporcionar controle eficaz da daninha, porém são limitadas pela seletividade à cultura, pelo momento de aplicação, pelas condições ambientais ou por restrições regulatórias. Esta revisão teve como objetivo consolidar as pesquisas existentes sobre fertilidade com boro, opções herbicidas e biologia do caruru-gigante, a fim de compreender como esses fatores se relacionam e orientar estratégias de manejo integrado para sistemas de produção de alfafa mais produtivos e sustentáveis.
Palavras-chave: caruru-gigante; feno; legume; herbicida; forragem.

1. INTRODUCTION

Alfalfa is one of the most valuable forage crops in the world; it is high in nutritive value, and it is mostly used in the form of hay (UNDERSANDER et al., 2021). Still, its performance depends on the effective management of two major constraints: soil fertility and weed control. Because alfalfa and hay operations require high inputs to replenish phosphorus (P), potassium (K), sulfur (S), and boron (B), fertility often represents the highest variable cost in hay systems. Boron is a required micronutrient for eudicotyledonous plants (RENGEL et al., 2022); its deficiency reduces crop regrowth vigor and competitiveness against weeds. This relationship demonstrates that fertility is not only important for forage production but also for the crop's competitiveness against weeds (STORKEY et al., 2021).

Weed management in alfalfa became significantly simpler with the introduction of Roundup Ready® technology, resulting in glyphosate-resistant alfalfa. However, the extensive and repeated use of this technology in other glyphosate-resistant cropping systems ultimately resulted in the selection and spread of glyphosate-resistant weeds (ORLOFF et al., 2011). As glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson) became the most troublesome weed in alfalfa hayfields in a survey led by the Weed Science Society of America (GETTS, 2022), alongside its multiple resistance cases reported in the U.S. (SCHWARTZ-LAZARO et al., 2017), it forces growers to integrate control methods and not rely solely on herbicides.

Integrating fertility management (boron) and diversified herbicide programs are essential for maintaining a competitive alfalfa plant population and limiting selection pressure for weed resistance (LITTLE et al., 2021). Understanding how these factors interact is fundamental for developing sustainable strategies that enhance alfalfa productivity while mitigating the growing challenge of glyphosate-resistant Palmer amaranth.

2. MATERIAL AND METHODS

This literature review was conducted through a bibliographic survey using major scientific databases, including Google Scholar, Web of Science, and Scopus. Keywords in both English were employed, such as "alfalfa," "boron," "fertility," "glyphosate-resistant Palmer amaranth," "weed management," and "Roundup Ready alfalfa," combined using Boolean operators (AND, OR). Peer-reviewed research and extension publications from the past 20 years were prioritized and comprise the majority of the references cited, while seminal, review, and foundational studies relevant to the biological and agronomic context were also included. Publications were initially screened based on title and abstract, followed by full-text evaluation to ensure thematic relevance, methodological consistency, and contribution to understanding the interactions among alfalfa hayfields, herbicide management, and the biology of Palmer amaranth.

Studies were included if they: (i) primarily focused on alfalfa production for animal use as hay, baleage, or grazing; (ii) addressed at least one of the following topics: glyphosate-resistant alfalfa, soil fertility with emphasis on boron, weed management in alfalfa, weed management in glyphosate-resistant crops, or glyphosate-resistant Palmer amaranth; (iii) consisted of peer-reviewed research articles, extension publications or bulletins, or review articles; and (iv) were published in English.

Studies were excluded if they: (i) did not report agronomically relevant field or greenhouse data; (ii) focused on crops unrelated to alfalfa or forage production, or on weed species unrelated to alfalfa production or Palmer amaranth; or (iii) were non-peer-reviewed opinion pieces, editorials, or non-scholarly reports lacking affiliation with a recognized research or extension institution. A total of 94 references met these criteria and were included in this review.

3. LITERATURE REVIEW

3.1. Alfalfa

Alfalfa (*Medicago sativa* L.) is a perennial herbaceous plant in the Fabaceae family, originally from Asia (Wang; Şakiroğlu, 2021), that is widely adapted across various regions of the world and suitable for a wide range of soil and climatic conditions, making it the most valuable forage crop grown worldwide. One of the most important characteristics of alfalfa is its high nutritive value as an animal feed, being an excellent source of vitamins and able to provide more digestible energy and protein per hectare than most forage crops, with crude protein ranging from 18 to 25%. The alfalfa's high nutritive value, combined with substantial forage accumulation, makes it an excellent forage for high-demand animals, such as cattle and horses. For example, over 50% of dairy farms utilize alfalfa as the majority of their feed ration (GILLESPIE, 2023).

Occasionally referred to as the "Queen of the forages", alfalfa can be harvested for up to 4 or 5 years before stand degradation. Because alfalfa exhibits autotoxicity, thin or weak stands are difficult to renovate, and producers frequently switch to other crops after 2–3 years. This contrasts with cool-season grasses like tall fescue, which are commonly reseeded (BALL et al., 2014; UNDERSANDER et al., 2021). Therefore, the establishment period is essential to the success of the crop and the operation's profitability.

Most of the alfalfa grown is destined for conservation as hay, an operation with high nutrient removal and very limited nutrient cycling. To achieve forage accumulation with high nutritive value, soil fertility augmentation is required, as fertilization can alter its chemical composition and growth (CAPSTAFF et al., 2018). Earlier work has reported that forage accumulation, alfalfa seed yield, and nutrient uptake increase significantly with proper fertilization (P, K, S, and 2 kg ha^{-1} B) for four years (MALHI, 2011). However, applying nutrients in quantities greater than required usually results in nutrient luxury consumption, impacting the economic viability of the operation and environmental issues, such as nutrient losses due to leaching, which can lead to watershed eutrophication (HUSSAIN et al., 2021).

Soil fertility is among the largest variable costs associated with alfalfa hay production. Alfalfa has high P and K requirements for forage production and stand persistence (JUNGERS et al., 2019), and frequently responds to sulfur when soils are deficient. Sulfur deficiency became more common as reduced-sulfur diesel has lowered atmospheric sulfur deposition (FEINBERG et al., 2021). Alfalfa also requires frequent lime inputs, since high pH is a requirement for the crop's success, as low pH is detrimental for *rhizobia* nodule formation (FERGUSON et al., 2013). Beyond its requirements for a high pH and adequate macronutrients, alfalfa also has a relatively high boron demand, with typical recommendations ranging from 2 to 4 kg B ha^{-1} year being common (BEEGLE, 2025). In contrast, micronutrient applications are rarely required in grass hay production systems.

Pesticides are also a big part of the expenses in an alfalfa operation, whether for insect control (SHI et al., 2025) or weed control. Although some alfalfa has been modified to resist glyphosate for weed control, glyphosate-resistant Palmer amaranth was identified as the most troublesome weed in alfalfa fields in 2019 (GETTS, 2022). Palmer amaranth has developed resistance around the world to the majority of labeled herbicides for use in alfalfa, glyphosate, ALS-inhibitors, and some PPO-inhibitors (SCHWARTZ-LAZARO et al., 2017; STECKEL, 2009).

3.2. Importance of boron fertilization in alfalfa

Boron is the most required micronutrient for eudicotyledonous plants. Along with its postulated roles are sugar transport, phenol metabolism, indole acetic acid metabolism, respiration, RNA metabolism, carbohydrate metabolism, cell wall structure, lignification, and cell wall synthesis (RENGEL et al., 2022). The large number of processes involving the nutrient can lead to a cascade effect in case of deficiency (LOOMIS et al., 1992).

Boron is typically the only micronutrient recommended in alfalfa fertility programs. Response to fertilization is strongly influenced by soil texture; sandy soils retain boron poorly, and are aggravated by high pH from excessive liming (RENGEL et al., 2022), common scenarios on alfalfa fields, due to the legume's requirement on high pH (6.5 to 7.0) and good drainage, conditions typically found in sandy to silt-loam textures, resulting in an environment prone to boron deficiency (UNDERSANDER et al., 2016). Boron deficiency in alfalfa, often called "yellow-top", first appears as yellowing of young leaves with interveinal reddening. As it worsens, internodes shorten, plants become rosetted and crumpled, and the apical meristem may die (DAVIS et al., 1999). In addition, micronutrient uptake is mainly driven by mass flow, which is highly dependent on soil water content, making it a limiting factor under dry soil conditions (MATTIELLO et al., 2009; PUTNAM, 2021; SHORROCKS, 1997; TUCKER et al., 2024).

Studies have sought to understand the need for boron in alfalfa since the 1970s. Miller & Smith found that boron application to the soil resulted in increased tissue boron concentrations, which were proportional to the application rate (MILLER et al., 1977). This suggests that alfalfa efficiently uptakes the nutrient, potentially to the point of luxury consumption, where it would absorb more than it strictly needs for optimal growth. Luxury consumption can have several reasons, such as opportunistic icons consumption, competitive advantage, stress preparation, impaired metabolic regulation, or genetic predisposition (DE MAZANCOURT et al., 2012). However, the phenomena and their relationship to boron in alfalfa have yet to be studied.

In the literature, alfalfa's response to boron remains controversial. Positive results have been reported, such as a 13% increase in forage accumulation in Idaho (USA) with 1.1 kg B ha^{-1} in a soil with low B concentration (MAHLER et al., 2009) a 47% increase in forage accumulation when 6 kg B ha^{-1} were applied in a soil with low boron concentration in Oregon (DREGNE et al., 1942), and end of yellowing symptoms when compared with the control along with a 16% increase in forage accumulation when 2.5 kg B ha^{-1} were applied in a soil with low B concentration in Connecticut (BROWN et al., 1940; BROWN et al., 1946). In contrast, no difference was observed in forage accumulation when applying 2.3 kg B ha^{-1} in Montana (SAPKOTA et al., 2018), but there was an increase in petiole mass and no increase in forage accumulation in Ohio (RAZMJOO et al., 1997) and New York (CHANDLER et al., 1946) when applying 2 and 4.9 kg B ha^{-1}, respectively.

3.3. Roundup Ready alfalfa and glyphosate

Roundup Ready® (Bayer Crop Sciences) alfalfa was the first perennial forage crop to be developed with a genetically modified trait, conferring the plant's resistance to glyphosate. Glyphosate binds to the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS). In Roundup Ready® alfalfa, a glyphosate-tolerant form of EPSPS was introduced into the resistant alfalfa genome via genetic engineering using an agrobacterium-mediated transformation (UNDERSANDER et al., 2009). The transformed enzyme is similar to the regular one but has reduced glyphosate affinity. Glyphosate inhibits EPSPS, blocking the conversion of shikimate-3-phosphate and phosphoenolpyruvate to EPSP, leading to the accumulation of shikimate-3-phosphate and free shikimate and preventing the synthesis of the aromatic amino acids tryptophan, phenylalanine, and tyrosine downstream of EPSPS (DUKE et al., 2008). Visible plant injury and death typically develop over 1 to 3 weeks as the shikimate pathway remains blocked (POWLES et al., 2006). Glyphosate is a nonselective herbicide across susceptible monocots and dicots (GROSSMANN, 2010) and remains the only commercially used EPSPS-targeting herbicide (DUKE et al., 2008).

The technology provides more flexibility in weed management in the hayfield because, unlike other herbicides regularly used in conventional alfalfa fields, glyphosate causes minimal to no injury to Roundup Ready® alfalfa. It also does not need to be applied during alfalfa dormant periods, before a certain plant size or height, or before new leaves are produced after harvest (WILSON, 1994).

In addition, because glyphosate is a broad-spectrum herbicide, the need for separate applications targeting broadleaf weeds with 2,4-DB and grasses with clethodim or sethoxydim, for instance, is eliminated; one single glyphosate application reduces operational costs and time and diminishes drift potential (VAN DEYNZE et al., 2004). Furthermore, glyphosate has a low acute toxicity to mammals (oral LD50 of 5,600 mg kg^{-1}). It is one of the least dangerous pesticides used in agriculture and is not persistent in soil, as once in the soil, it adheres to soil particles and breaks down due to microbial activity (GURETZKY et al., 2004).

The adoption of the Roundup Ready technology has raised some concerns. Even in regular alfalfa hayfields, stand thinning over time is expected due to alfalfa autotoxicity in the short term and allelopathy in the long term (HEDGE et al., 1990). Although 5 to 10% of the Roundup Ready® alfalfa plants could potentially be susceptible to glyphosate, studies have shown that even across a wide range of seeding rates (16.8 to 29 kg ha^{-1}) with labeled glyphosate doses, the killed plants had no significant effect on stand density (HALL et al., 2008). Thus, further concerns about the adoption of glyphosate-treated genetically engineered alfalfa were unfounded.

In terms of carbohydrates, protein, neutral and acid detergent fiber, fat, lignin, calcium, copper, iron, manganese, phosphorus, potassium, sodium, and zinc, there was no significant difference between conventional and Roundup Ready® alfalfa (STECKEL et al., 2007). At a 40% inclusion rate, Roundup Ready® and conventional alfalfa produced no differences in feed intake, feed efficiency, milk production, or milk composition in lactating cows (COMBS et al., 2008). These nutritional equivalences indicate that the Roundup Ready® trait alters herbicide tolerance, not plant composition or nutritive value.

The release of glyphosate-resistant crops simplified weed management in the first years on the market. The major benefits are flexible application timing, minimal damage in resistant crops, excellent weed control, and reduced tillage. Before the release of glyphosate-resistant crops, soybean farmers normally used almost 10 different herbicidal modes of action (GREEN, 2009). However, repeated glyphosate use in Roundup Ready crops without rotation with other herbicide modes of action led to the selection of resistant weeds, making the challenge of weed control even worse before the adoption of glyphosate-resistant crops (HEAP, 2014; POWLES et al., 2010).

3.4. Palmer amaranth

Native to the southwestern United States, Palmer amaranth is a broadleaf, herbaceous, warm-season annual plant well known for its rapid growth and opportunistic nature. One of its most important characteristics is the C_4 photosynthetic pathway, which confers greater drought tolerance and faster growth than most crops with which it competes. Although it is found in a different habitat from its native one, it has been reported in the southeastern U.S. for at least 100 years (WARD et al., 2013). Its damage is not only confined to the United States (RANDELL-SINGLETON et al., 2024) but also in Canada, Mexico, Europe (MATZRAFI et al., 2025), and South America (ROBERTS et al., 2022). Given its rapid and aggressive growth and potential, the weed poses a serious threat to major summer field crops, causing significant production losses even at low populations (WARD et al., 2013). The losses are not limited to direct impacts of plant competition, such as reduced forage production, but also to longer harvest times and crop quality losses (BASINGER et al., 2019). This includes possible toxicity when ingested by mammals (CLODE et al., 1987).

Even though it has been widely characterized as one of the most troublesome weeds in the world, it was originally considered a useful plant, which brings back the definition of a weed as "a plant out of place" (BOURGEOIS et al., 2019). Native North American tribes used the plant as food, eating seeds and leaves with meat. Beyond human consumption, *Amaranth* spp. are often used as grain or forage for cattle, chickens, pigs, and rabbits in extensive conditions (PEIRETTI, 2018; STECKEL, 2007). However, Palmer amaranth's characteristic of accumulating toxic compounds for livestock, such as nitrates and oxalates, makes it an undesirable plant in modern and intensive livestock systems. The potential for nitrate poisoning increases when the plant is under high N fertilization and dry conditions, often observed in hay systems during dry summers (BURROWS et al., 2012; O'HARA et al., 1975).

Given that Palmer amaranth requires cross-pollination between male and female plants and its prolificacy, Palmer amaranth has a strong tendency to evolve resistance due to its high genetic variability (RANGANI et al., 2023). This plant has already been ranked several times as the most troublesome cotton weed in nine southern American states and the second most troublesome weed in soybean by the end of the 2010s decade (JHALA et al., 2015). Given the importance of this weed and its distribution, the resistance to the most used herbicide in the world (glyphosate) is a huge challenge for the productivity and profitability of Roundup Ready® crops (DAYAN, 2019).

Glyphosate-resistant Palmer amaranth was first found in Georgia in 2005 (CULPEPPER et al., 2006), forcing cotton producers to abandon their fields. In 2011, the first multiple-resistant Palmer amaranth, tolerant to glyphosate and ALS inhibitors, was also discovered in Georgia (SOSNOSKIE et al., 2014; SOSNOSKIE et al., 2011). The higher prevalence of herbicide-tolerant weeds has forced producers to seek alternatives to chemical control. Palmer amaranth has reported resistance to several other herbicide modes of action, in addition to inhibitors of acetolactate synthase (ALS) and enolpyruvyl shikimate3-phosphate synthase (EPSPS) already mentioned; the weed has resistance reported to photosystem II (PSII), protoporphyrinogen oxidase (PPO), hydroxyphenyl pyruvate dioxygenase (HPPD), very long-chain fatty acid synthesis, microtubule inhibitors, synthetic hormones, and glufosinate in the United States until 2023 (RANGANI et al., 2023).

3.5. Herbicide options to control glyphosate-resistant Palmer amaranth in alfalfa

The presence of glyphosate-resistant (GR) Palmer amaranth does not discard glyphosate as a tool to manage weeds in the hayfield. The systemic herbicide still controls several weeds, such as morning glory (*Ipomoea* L.), warm-season grasses, and winter annuals, but it requires an additional molecule to control GR Palmer amaranth and other resistant weeds. Before the release of Roundup Ready® alfalfa, ALS inhibitors such as imazethapyr were widely used to control weeds; however, ALS-resistant Palmer amaranth has been present since 1994 and multi-resistant (ALS and glyphosate) since 2009 (STECKEL, 2009). Still, 90% of alfalfa growers are satisfied with the Roundup Ready® technology in alfalfa (DUKE, 2018; ORLOFF et al., 2011). Nonetheless, the increasing prevalence of herbicide-resistant biotypes, particularly Palmer amaranth, highlights the need for alternative and complementary chemical options beyond glyphosate.

In this context, PPO inhibitors, labeled for alfalfa for both pre- and post-emergence use, remain effective tools for controlling Palmer amaranth and several other broadleaf weeds across much of the United States. When the PPO enzyme is inhibited, protogen leaks out of the chloroplast and is converted to protox in the cytosol. This is the physiological basis for the very rapid, light-dependent activity of PPO-inhibiting herbicides. Singlet oxygen generation leads to a chain reaction of reactive oxygen species production and lipid peroxides that destroy cell membranes (BARKER et al., 2023; DAYAN et al., 2010). When leaves are exposed to the herbicide, browning and necrosis occur in a few hours. When a seedling is exposed to the chemical in the soil, yellowing, burning, stunting, and, potentially, hypocotyl girdling can result in plant death (AL-KHATIB, 2025).

PPO herbicides have been on the market since the 1960s, and resistance to this mode of action has evolved slowly, unlike ALS herbicides (TRANEL et al., 2002). It took 40 years since its release, and to date, it has only been confirmed in seven weed species. Advantageous characteristics of PPO inhibitors include a broad herbicidal spectrum, low effective rates, rapid onset of action, long residual activity on some herbicides in this group, and low toxicity to mammals (RANGANI et al., 2023; SALAS et al., 2016).

One option from the PPO mode of action is flumioxazin, which, when applied at 140 g ha^{-1} when alfalfa was dormant, followed by one between-cutting application at a rate of 70 g ha^{-1}, provided a range of 85 to 95% of Palmer amaranth control in late summer due to flumioxazin residual effects (PUTMAN, 2013). Another PPO herbicide labeled for alfalfa is saflufenacil. The herbicide causes initial injury when applied in the summer slump for the first two weeks after being treated, but becomes visually insignificant and does not affect forage mass harvested four weeks after treatment (DEVKOTA et al., 2021). Saflufenacil was also capable of controlling Palmer amaranth up to 90 days after application at levels above 80%, demonstrating its pre-emergence potential in the field (KAUR et al., 2024). In addition, when applied post-emergence, it provided 87% and 76% control of glufosinate-resistant Palmer amaranth 1 and 2 weeks after treatment, which is considered satisfactory (CARVALHO-MOORE et al., 2025).

Paraquat is another option for controlling glyphosate- and multiple-resistant Palmer amaranth, providing up to 91% control two weeks after treatment. However, as a contact, non-systemic herbicide with no residual activity, it does not provide control of subsequent weed regrowth (CROW et al., 2015). In addition, the herbicide also controlled glufosinate-resistant Palmer amaranth up to 97% two weeks after treatment (CARVALHO-MOORE et al., 2025). Although the herbicide's efficacy in controlling Palmer amaranth is proven, its use on alfalfa is limited to applications between cuttings and during the dormant season (SYNGENTA, 2019). Furthermore, alternatives to paraquat for controlling resistant weeds should be investigated, given that its use has been banned in 67 countries since 2024. Major agricultural producers in the Western world and other developed nations are on the list, such as the United Kingdom (where it was created), the European Union, South Korea, Taiwan, and Brazil, which brings the concern that the herbicide ban in the United States may be considered by the Environmental Protection Agency (ALBRECHT et al., 2022; HUNZIKER, 2024; KIM et al., 2017; KIM et al., 2020; STUART et al., 2023).

3.6. Combining tools to improve weed control

Weed management cannot rely solely on herbicides. Integrated weed management combines cultural, genetic, mechanical, biological, and chemical control methods (SHAW, 1982; WALKER et al., 1982). Control methods applied alone rarely deliver long-term weed suppression. For example, herbicide use in an unfertilized, poorly managed hayfield may briefly control weeds, but they re-establish because the forage lacks competitive vigor. In contrast, when cultural practices (fertility and adequate stubble height), proper cultivars for the system, and herbicide use are aligned, the result is a more competitive, resilient hayfield and more effective weed suppression (SWANTON et al., 1991; THILL et al., 1991; YOUNG, 2018).

The concept of integrating soil fertility and herbicide strategies to investigate weed control aims to achieve the crop's nutritional requirements, resulting in faster regrowth (BUHLER, 2002). These strategies accelerate ground coverage faster than weeds, enhance resilience to adversities such as drought, and increase forage production (STORKEY et al., 2021). The reduction in weed competition leads not only to a higher forage quality but also to a more marketable product (GETTS, 2022).

Depending on how it interacts with other variables, soil fertility affects forage production and weed presence. In certain scenarios, the lack of response is due to other resource limitations. Bringing the concept of "Leibig's law of the minimum, defined as growth is determined by the scarcest resource rather than the total amount of resources available (TANG et al., 2021; THOMAS, 1929). Crop-weed competition can vary with fertility levels, influenced by environmental and management factors. Research suggests that when used in conjunction with fertility management, weed control techniques can improve crop development. The efficacy of herbicides at the plant level can vary with the amount of fertilizer applied. Fertility affects crop growth and weed control at the field level. Studies found that when associated with chemical weed control, higher fertilizer levels increased crop competitiveness over weeds (LITTLE et al., 2021).

4. CONCLUSIONS

Alfalfa's agronomic potential depends heavily on fertility management and weed control. In this literature review, we learned that while boron fertilization, soil pH, and adequate macronutrient supply are critical for proper forage accumulation and stand persistence, isolated practices cannot suppress highly competitive weeds such as Palmer amaranth.

When soil fertility is optimized to increase crop vigor and paired with proper weed-control methods, such as herbicide management, weed control improves, and the system is more likely to succeed. Although technologies such as glyphosate-resistant alfalfa have expanded weed management flexibility, the rapid development of glyphosate-resistant weeds and multiple resistance has limited reliance on any single herbicide mode of action.

Alternatives to manage glyphosate-resistant weeds, such as PPO inhibitors and paraquat, need to be considered to provide meaningful control, but they remain constrained by practical, regulatory, or biological limitations. Collectively, there is a clear need for integrated weed management strategies that blend soil fertility management with a diversified set of herbicide modes of action to improve crop competitiveness, reduce selection pressure, and sustain long-term productivity. Ultimately, effective weed suppression in alfalfa requires a systems-based approach that strengthens the crop as much as it targets weeds (CANEVARI et al., 2017).

5. REFERENCES

AL-KHATIB, K. **Protoporphyrinogen Oxidase (PPO) Inhibitors**. Herbicide Symptoms, University of California Division of Agriculture and Natural Resources, 2025. Available online: https://herbicidesymptoms.ipm.ucanr.edu/MOA/PPO_inhibitors/. Accessed on: Feb. 21. 2025.

ALBRECHT, A. J. P.; ALBRECHT, L. P.; SILVA, A. F. M. Agronomic implications of paraquat ban in Brazil. **Advances in Weed Science**, v. 40, Spec. 1, e20220040, 2022. https://doi.org/10.51694/AdvWeedSci/2022;40:seventy-five009

BALL, D. M.; HOVELAND, C. S.; LACEFIELD, G. D. **Southern Forages: Modern Concepts for Forage Crop Management**. Roma: FAO / Potash & Phosphate Institute and the Foundation for Agronomic Research / International Plant Nutrition Institute, 2014. 366p.

BARKER, A. L.; PAWLAK, J.; DUKE, S. O.; BEFFA, R.; TRANEL, P. J.; WERFFEL, J.; YOUNG, B.; PORRI, A.; LIEBL, R.; APONTE, R.; BETZ, M.; LERCHL, J.; CULPEPPER, S.; BRADLEY, K.; DAYAN, F. E. Discovery, mode of action, resistance mechanisms, and plan of action for sustainable use of Group 14 herbicides. **Weed Science**, v. 71, n. 3, p. 173-188, 2023. https://doi.org/10.1017/wsc.2023.15

BASINGER, N. T.; JENNINGS, K. M.; MONKS, D. W.; JORDAN, D. L.; EVERMAN, W. J.; HESTIR, E. L.; BERTUCCI, M. B.; BROWNIE, C. Large crabgrass (*Digitaria sanguinalis*) and Palmer amaranth (*Amaranthus palmeri*) intraspecific and interspecific interference in soybean. **Weed Science**, v. 6, n. 6, p. 649-656, 2019. https://doi.org/10.1017/wsc.2019.43

BEEGLE, D. **Soil fertility management for forage crops: Maintenance**. Available online: https://extension.psu.edu/soil-fertility-management-for-forage-crops-maintenance. Accessed on: 19 Aug. 2025.

BOURGEOIS, B.; MUNOZ, F.; FRIED, G.; MAHAUT, L.; ARMENGOT, L.; DENELLE, P.; STORKEY, J.; GABA, S.; VIOLLE, C. What makes a weed a weed? A large-scale evaluation of arable weeds through a functional lens. **American Journal of Botany**, v. 106, n. 1, p. 90-100, 2019. https://doi.org/10.1002/ajb2.1213

BROWN, B.; KING, A. Soil conditions under which alfalfa responded to boron. **Soil Science Society Proceedings**, p. 310-313, 1940.

BROWN, B. A.; MUNSELL, R. I.; KING, A. V. Potassium and Boron fertilization of alfalfa on a few Connecticut soils. **Soil Science Society of America Journal**, v. 10, p. 134-140, 1946. https://doi.org/10.2136/sssaj1946.03615995001000C00022x

BUHLER, D. D. 50th Anniversary - Invited Article: Challenges and opportunities for integrated weed management. **Weed Science**, v. 50, n. 3, p. 273-280, 2002. https://doi.org/10.1614/0043-1745(2002)050[0273:AIAAOF]2.0.CO;2

BURROWS, G. E.; TYRL, R. J. **Toxic plants of North America**. John Wiley & Sons, 2012. 1392p.

CANEVARI, M.; VARGAS, R. N.; ORLOFF, S. B. Weed **Management in Alfalfa**. Davis: University of California, 2017. 19p. Available online: https://alfalfa.ucdavis.edu/sites/g/files/dgvnsk12586/files/media/documents/UCAlfalfa8294Weeds_free.pdf

CAPSTAFF, N. M.; MILLER, A. J. Improving the yield and nutritional quality of forage crops. **Frontiers in Plant Science**, v. 9, e535, 2018. https://doi.org/10.3389/fpls.2018.00535

CARVALHO-MOORE, P.; NORSWORTHY, J. K.; SOUZA, M. C. C. R.; BARBER, L. T.; PIVETA, L. B.; MEINERS, I.; PORRI, A. Resistance profile of glufosinate-resistant palmer amaranth accessions and herbicide options. **Weed Technology**, v. 39, e31, 2025. https://doi.org/10.1017/wet.2025.8

CHANDLER, R., JR; PEECH, M.; BRADFIELD, R. A study of techniques for predicting the potassium and boron requirements of alfalfa: 1. The influence of muriate of potash and borax on yield deficiency symptoms, and potassium content of plant and soil. **Journal of the American Society of Agronomy**, v. 38, n. 4, p. 299-307, 1946. https://doi.org/0.2136/sssaj1946.03615995001000c00023x

CLODE, S.; HOOSON, J.; GRANT, D.; BUTLER, W. Long-term toxicity study of amaranth in rats using animals exposed in utero. **Food and Chemical Toxicology**, v. 25, n. 12, p. 937-946, 1987. https://doi.org/10.1016/0278-6915(87)90287-0

COMBS, D.; HARTNELL, G. Alfalfa containing the glyphosate-tolerant trait has no effect on feed intake, milk composition, or milk production of dairy cattle. **Journal of Dairy Science**, v. 91, n. 2, p. 673-678, 2008. https://doi.org/10.3168/jds.2007-0611

CROW, W. D.; STECKEL, L. E.; HAYES, R. M.; MUELLER, T. C. Evaluation of POST-Harvest Herbicide applications for seed prevention of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). **Weed Technology**, v. 29, n. 3, p. 405-411, 2015. https://doi.org/10.1614/WT-D-14-00146.1

CULPEPPER, A. S.; GREY, T. L.; VENCILL, W. K.; KICHLER, J. M.; WEBSTER, T. M.; BROWN, S. M.; YORK, A. C.; DAVIS, J. W.; HANNA, W. W. Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. **Weed Science**, v. 54, N. 4, p. 620-626, 2006. https://doi.org/10.1614/WS-06-001R.1

DAVIS, J. G.; BERRADA, A.; MEYER, R. F. Alfalfa response to boron fertilization. In: BRUMMER, J. E.; PEARSON, C. H.; JOHNSON, J. J (Eds). **Colorado Forage Research 1999: alfalfa, irrigated pastures, and mountain meadows**. Colorado: Colorado State University, 1999. p. 41-45. (Technical Report, TROO-6). Available online: https://webdoc.agsci.colostate.edu/AES/aes/pubs/pdf/tr00-6.pdf

DAYAN, F.; DUKE, S. Protoporphyrinogen oxidase-inhibiting herbicides, in Hayes' Handbook of Pesticide Toxicology. In: **Hayes Handbook of Pesticide Toxicology**. 3 ed. San Diego, CA: Elsevier Inc., 2010. v. 2, p. 1733-1751. https://doi.org/10.1016/B978-0-12-374367-1.00081-1

DAYAN, F. E. Current Status and future prospects in herbicide discovery. **Plants**, v. 8, n. 9, e341, 2019. https://doi.org/10.3390/plants8090341

DE MAZANCOURT, C.; SCHWARTZ, M. W. Starve a competitor: evolution of luxury consumption as a competitive strategy. **Theoretical Ecology**, v. 5, p. 37-49, 2012. https://doi.org/10.1007/s12080-010-0094-9

DEVKOTA, P.; BACHIE, O. G. Evaluation of the summer slump application of saflufenacil on nondormant conventional alfalfa. **Crop, Forage & Turfgrass Management**, v. 7, n. 1, e20095, 2021. https://doi.org/10.1002/cft2.20095

DREGNE, H.; POWERS, W. Boron fertilization of alfalfa and other legumes in Oregon. Agronomy Journal, v. 34, n. 10, p. 902-912, 1942. https://doi.org/10.2134/agronj1942.00021962003400100005x

DUKE, S. O. The history and current status of glyphosate. **Pest Management Science**, v. 74, n. 5, p. 1027-1034, 2018. https://doi.org/10.1002/ps.4652

DUKE, S. O.; POWLES, S. B. Glyphosate: a once-in-a-century herbicide. **Pest Management Science: formerly Pesticide Science**, v. 64, n. 4, p. 319-325, 2008. https://doi.org/10.1002/ps.1518

EDDE, P. Arthropod pests of alfalfa (*Medicago sativa* L.). In: **Field crop arthropod pests of economic importance**, Academic Press, 2022. p. 684-750.

FEINBERG, A.; STENKE, A.; PETER, T.; HINCKLEY, E.-L. S.; DRICSCOLL, C. T.; WINKEL, L. H. E. Reductions in the deposition of sulfur and selenium to agricultural soils pose risk of future nutrient deficiencies. **Communications Earth & Environment**, v. 2, e101, 2021. https://doi.org/10.1038/s43247-021-00172-0

FERGUSON, B. J.; LIN, M. H.; GRESSHOFF, P. M. Regulation of legume nodulation by acidic growth conditions. **Plant Signaling & Behavior**, v. 8, n. 3, e23426, 2013. https://doi.org/10.4161/psb.23426

GETTS, T. Strategies to control weeds in established alfalfa. In: WORLD ALFALFA CONGRESS, **Proceedings…** San Diego, CA: UC Davis, 2022. 6p. Available online: https://alfalfa.ucdavis.edu/sites/g/files/dgvnsk12586/files/inlinefiles/STRATEGIES%20TO%20CONTROL%20WEEDS%20IN%20ESTABLISHED%20ALFALFA%20-%20Tom%20Getts.pdf

GILLESPIE, J. Feed rations fed by US dairy producers. **Journal of Dairy Science**, v. 106, n. 11, p. 8152-8168, 2023. https://doi.org/10.3168/jds.2023-23363

GREEN, J. M. Evolution of glyphosate-resistant crop technology. **Weed Science**, v. 57, n. 1, p. 108-117, 2009. https://doi.org/10.1614/WS-08-030.1

GROSSMANN, K. Auxin herbicides: current status of mechanism and mode of action. **Pest Management Science: formerly Pesticide Science**, v. 66, n. 2, p. 113-120, 2010. https://doi.org/10.1002/ps.1860

GURETZKY, J. A.; MOORE, K. J.; KNAPP, A. D.; BRUMMER, E. C. Emergence and survival of legumes seeded into pastures varying in landscape position. **Crop Science**, v. 44, n. 1, p. 227-233, 2004. https://doi.org/10.2135/cropsci2004.2270

HALL, M. H.; HEBROCK, N. S.; DIEDRICK, K. A.; DILLON, J. M. Delayed glyphosate application doesn't reduce plant density of glyphosate-tolerant alfalfa. **Forage & Grazinglands**, v. 6, n. 1, p. 1-5, 2008. https://doi.org/10.1094/FG-2008-0711-01-RS

HEAP, I. Global perspective of herbicide-resistant weeds. **Pest management science**, v. 70, n. 9, p. 1306-1315, 2014. https://doi.org/10.1002/ps.3696

HEDGE, R. S.; MILLER, D. Allelopathy and autotoxicity in alfalfa: characterization and effects of preceding crops and residue incorporation. **Crop Science**, v. 30, n. 6, p. 1255-1259, 1990. https://doi.org/10.2135/cropsci1990.0011183X003000060020x

HUNZIKER, R. 67 Countries Banned This Toxic Product-But the EPA Says: Go for it!". **CounterPunch**, 2024.

HUSSAIN, M. Z.; HAMILTON, S. K.; ROBERTSON, G. P.; BASSO, B. Phosphorus availability and leaching losses in annual and perennial cropping systems in an upper US Midwest landscape. **Scientific Reports**, v. 11, e20367, 2021. https://doi.org/10.1038/s41598-021-99877-7

JHALA, A. J.; CHAHAL, P. S.; JUGULAM, M. Herbicide-Resistant Palmer amaranth (*Amaranthus palmeri* S. Wats.) in the United States - mechanisms of resistance, impact, and management. In: PRICE, A.; KELTON, J.; SARUNAITE, L. (Eds.). **Herbicides - Agronomic Crops and Weed Biology**. Rijeka: IntechOpen, 2015. https://doi.org/10.5772/61512

JUNGERS, J. M.; KAISER, D. E.; LAMB, J. F. S.; LAMB, J. A.; NOLAND, R. L.; SAMAC, D. A.; WELLS, M. S.; SHEAFFER, C. C. Potassium Fertilization affects alfalfa forage yield, nutritive value, root traits, and persistence. **Agronomy Journal**, v. 111, n. 6, p. 2843-2852, 2019. https://doi.org/10.2134/agronj2019.01.0011

KAUR, R.; CHAHAL, P. S.; SHI, Y.; LAWRENCE, N. C.; KNEZEVIC, S. Z.; JHALA, A. J. Comparison of residual activity of pre-emergence herbicides for control and seed production of multiple herbicide-resistant Palmer amaranth in food-grade white corn. **Agrosystems, Geosciences & Environment**, v. 7, n. 1, e20483, 2024. https://doi.org/10.1002/agg2.20483

KIM, J.; SHIN, S. D.; JEONG, S.; SUH, G. J.; KWAK, Y. H. Effect of prohibiting the use of Paraquat on pesticide-associated mortality. **BMC Public Health**, v. 17, e858, 2017. https://doi.org/10.1186/s12889-017-4832-4

KIM, J.-W.; KIM, D.-S. Paraquat: toxicology and impacts of its ban on human health and agriculture. **Weed Science**, v. 68, n. 3, p. 208-213, 2020. https://doi.org/10.1017/wsc.2019.70

LITTLE, N. G.; DITOMMASO, A.; WESTBROOK, A. S.; KETTERINGS, Q. M.; MOHLER, C. L. Effects of fertility amendments on weed growth and weed–crop competition: a review. **Weed Science**, v. 69, n. 2, p. 132-146, 2021. https:/ Chemistry and biology of boron/doi.org/10.1017/wsc.2021.1

LOOMIS, W. D.; DURST, R. W. Chemistry and biology of boron. **Biofactors**, v. 3, n. 4, p. 229-239, 1992.

MAHLER, R.; MCDOLE, R. **Essential Plant Micronutrients**. Boron in Idaho. Idaho: University of Idaho Library, 2009. 6p. Available online: https://objects.lib.uidaho.edu/uiext/uiext31289.pdf

MALHI, S. Relative response of forage and seed yield of alfalfa to sulfur, phosphorus, and potassium fertilization. **Journal of Plant Nutrition**, v. 34, n. 6, p. 888-908, 2011. https://doi.org/10.1080/01904167.2011.544357

MATTIELLO, E. M.; RUIZ, H. A.; SILVA, I. R. D.; BARROS, N. F. D.; NEVES, J. C. L.; BEHLING, M. Transport of boron in soil and its uptake by eucalypt. **Revista Brasileira de Ciencia do Solo**, v. 33, n. 5, p. 1281-1290, 2009. https://doi.org/10.1590/S0100-06832009000500021

MATZRAFI, M.; SCARABEL, L.; MILANI, A.; IAMONICO, D.; TORRA, J.; RECASENS, J.; MONTUL, J. M.; LLENES, J. M.; GAZOULIS, I.; TATARIDAS, A.; RUBIN, B.; PARDO, G.; CIRUJEDA, A.; MARÍ, A. I.; MENNAN, H.; KANATAS, P.; DOGAN, M. N.; BEFFA, R.; TRAVLOS, I. *Amaranthus palmeri* S. Watson: A new threat to agriculture in Europe and the Mediterranean region. **Weed Research**, v. 65, n. 1, e12596, 2025. https://doi.org/10.1111/wre.12596

MILLER, D. A.; SMITH, R. K. Influence of boron on other chemical elements in alfalfa. **Communications in Soil Science and Plant Analysis**, v. 8, n. 6, p. 465-478, 1977. https://doi.org/10.1080/00103627709366739

O'HARA, P.; FRASER, A. Nitrate poisoning in cattle grazing crops. **New Zealand Veterinary Journal**, v. 23, n. 4, p. 45-53, 1975. https://doi.org/10.1080/00480169.1975.34192

ORLOFF, S.; PUTNAM, D. **Roundup Ready® alfalfa - what have we learned to date?** San Diego, CA: UC Davis, 2011. 15p. Available online: https://alfalfa.ucdavis.edu/sites/g/files/dgvnsk12586/files/media/documents/11WAS-25_Orloff_RRAlfalfa.pdf

PEIRETTI, P. Amaranth in animal nutrition: A review. **Livestock Research for Rural Development**, v. 30, n. 5, p. 1-20, 2018.

POWLES, S. B.; PRESTON, C. Evolved glyphosate resistance in plants: biochemical and genetic basis of resistance. **Weed Technology**, v. 20, n. 2, p. 282-289, 2006. https://doi.org/10.1614/WT-04-142R.1

POWLES, S. B.; YU, Q. Evolution in action: plants resistant to herbicides. **Annual Review of Plant Biology**, v. 61, p. 317-347, 2010. https://doi.org/10.1146/annurev-arplant-042809-112119

PUTMAN, J. A. **Palmer amaranth control in established alfalfa and documentation of glyphosate-resistant Amaranthus species in Kansas**. Kansas State

University, 2013. Available online: https://krex.k-state.edu/bitstreams/f448799d-1a23-4a71-806f-42706edc4ea2/download

PUTNAM, D. H. Factors influencing yield and quality in alfalfa. In: YU, L. X.; KOLE, C. (Eds.). **The alfalfa genome: compendium of plant genomes**. Springer, Cham, 2021. p. 13-27. https://doi.org/10.1007/978-3-030-74466-3_2

RANDELL-SINGLETON, T.; HAND, L. C.; VANCE, J. C.; CULPEPPER, A. S. An integrated approach to delaying herbicide resistance in Palmer amaranth (*Amaranthus palmeri*) by quantifying selection for resistance in a 2,4-D-based cotton production system. **Weed Technology**, v. 38, e55, 2024. https://doi.org/10.1017/wet.2024.65

RANGANI, G.; PORRI, A.; SALAS-PEREZ, R. A.; LERCHL, J.; KARAIKAL, S. K.; VELÁSQUEZ, J. C.; ROMA-BRUGOS, N. Assessment of Efficacy and Mechanism of Resistance to Soil-Applied PPO Inhibitors in *Amaranthus palmeri*. **Agronomy**, v. 13, n. 2, e592, 2023. https://doi.org/10.3390/agronomy13020592

RAZMJOO, K.; HENDERLONG, P. R. Effect of potassium, sulfur, boron, and molybdenum fertilization on alfalfa production and herbage macronutrient contents. **Journal of Plant Nutrition**, v. 20, p. 1681-1696, 1997.

RENGEL, Z.; CAKMAK, I.; WHITE, P. J. **Marschner's mineral nutrition of plants**. Academic Press, 2022. 816p.

ROBERTS, J.; FLORENTINE, S. A review of the biology, distribution patterns and management of the invasive species *Amaranthus palmeri* S. Watson (Palmer amaranth): Current and future management challenges. **Weed Research**, v. 62, n. 2, p. 113-122, 2022. https://doi.org/10.1111/wre.12520

SALAS, R. A.; BURGOS, N. R.; TRANEL, P. J.; SINGH, S.; GLASGOW, L.; SCOTT, R. C.; NICHOLS, R. L. Resistance to PPO-inhibiting herbicide in Palmer amaranth from Arkansas. **Pest Management Science**, v. 72, n. 5, p. 864-869, 2016. https://doi.org/10.1002/ps.4241

SAPKOTA, A.; MECCAGE, E. C.; STOUGAARD, R. N.; TANNER, J. P.; PETERSON, D. M.; TORRION, J. A. Boron fertilization of irrigated alfalfa in Montana. **Crop, Forage & Turfgrass Management**, v. 4, n. 1, p. 1-8, 2018. https://doi.org/10.2134/cftm2017.11.0085

SCHWARTZ-LAZARO, L. M.; NORSWORTHY, J. K.; SCOTT, R. C.; BARBER, L. T. Resistance of two Arkansas Palmer amaranth populations to multiple herbicide sites of action. **Crop Protection**, v. 96, p. 158-163, 2017. https://doi.org/10.1016/j.cropro.2017.02.022

SHAW, W. Integrated weed management systems technology for pest management. **Weed Science**, v. 30, n. 1, p. 2-12, 1982. https://doi.org/10.1017/S0043174500060252

SHI, X.; SEGUIN, P.; SAGUEZ, J.; MARTEL, H.; CLAESSENS, A. Potato leafhoppers in alfalfa: effects of alfalfa–grass mixtures, cultivar resistance status, and insecticides on forage yields. **Canadian Journal of Plant Science**, v. 105, p. 1-10, 2025. https://doi.org/10.1139/cjps-2024-0087

SHORROCKS, V. M. The occurrence and correction of boron deficiency. **Plant and Soil**, v. 193, p. 121-148, 1997. https://doi.org/10.1023/A:1004216126069

SOSNOSKIE, L. M.; CULPEPPER, A. S. Glyphosate-resistant Palmer Amaranth (*Amaranthus palmeri*) increases herbicide use, tillage, and hand-weeding in Georgia cotton. **Weed Science**, v. 62, n. 2, p. 393-402, 2014. https://doi.org/10.1614/WS-D-13-00077.1

SOSNOSKIE, L. M.; KICHLER, J. M.; WALLACE, R. D.; CULPEPPER, A. S. Multiple resistance in Palmer amaranth to glyphosate and pyrithiobac confirmed in Georgia. **Weed Science**, v. 59, n. 3, p. 321-325, 2011. https://doi.org/10.1614/WS-D-10-00132.1

STECKEL, L. **Case: Multiple Resistant Palmer Amaranth**. In: International Herbicide-Resistant Weed Database, 2009. Available online: https://www.weedscience.org/Pages/Case.aspx?ResistID=5571

STECKEL, L. E. The dioecious Amaranthus spp.: here to stay. **Weed Technology**, v. 21, n. 2, p. 567-570, 2007. https://doi.org/10.1614/WT-06-045.1

STECKEL, L. E.; HAYES, R. M.; MONTGOMERY, R. F.; MUELLER, T. C. Evaluating glyphosate treatments on Roundup Ready alfalfa for crop injury and feed quality. **Forage & Grazinglands**, v. 5, n. 1, p. 1-9, 2007. https://doi.org/10.1094/FG-2007-0201-01-RS

STORKEY, J.; HELPS, J.; HULL, R.; MILNE, A. E.; METCALFE, H. Defining integrated weed management: A novel conceptual framework for models. **Agronomy**, v. 11, n. 4, e747, 2021. https://doi.org/10.3390/agronomy11040747

STUART, A. M.; MERFIELD, C. N.; HORGAN, F. G.; WILLIS, S.; WATTS, M. A.; RAMÍREZ-MUÑOZ, F.; SÁNCHEZ U, J.; UTYASHEVA, L.; EDDLESTON, M.; DAVIS, M. L.; NEUMEISTER, L.; SANOU, M. R.; WILLIAMSON, S. Agriculture without paraquat is feasible without loss of productivity - lessons learned from phasing out a highly hazardous herbicide. **Environmental Science and Pollution Research**, v. 30, p. 16984-17008, 2023. https://doi.org/10.1007/s11356-022-24951-0

SWANTON, C. J.; WEISE, S. F. Integrated weed management: the rationale and approach. **Weed Technology**, v. 5, n. 3, p. 657-663, 1991. https://doi.org/10.1017/S0890037X00027512

SYNGENTA. **Gramoxone SL3 Label**. 2019. Product label accepted by Environmental Protection Agency. Available online: https://www.syngenta-us.com/herbicides/gramoxone-sl-3.0

TANG, J.; RILEY, W. J. Finding Liebig's law of the minimum. **Ecological Applications**, v. 31, n. 8, e02458, 2021. https://doi.org/10.1002/eap.2458

THILL, D. C.; LISH, J. M.; CALLIHAN, R. H.; BECHINSKI, E. J. Integrated weed management–a component of integrated pest management: a critical review. **Weed Technology**, v. 5, n. 3, p. 648-656, 1991. https://doi.org/10.1017/S0890037X00027500

THOMAS, W. Balanced fertilizers and Liebig's law of the minimum. **Science**, v. 70, n. 1816, p. 382-384, 1929.

TRANEL, P. J.; WRIGHT, T. R. Resistance of weeds to ALS-inhibiting herbicides: what have we learned? **Weed Science**, v. 50, n. 6, p. 700-712, 2002. https://doi.org/10.1614/0043-1745(2002)050[0700:RROWTA]2.0.CO;2

TUCKER, J. J.; MULLENIX, M. K.; RIOS, E.; BASIGALUP, D.; HOUTON, J. H. Systems management strategies for increasing alfalfa use in warm-humid regions. **Grassland Research**, v. 3, n. 2, p. 187-198, 2024. https://doi.org/10.1002/glr2.12080

UNDERSANDER, D.; COSGROVE, D.; CULLEN, E.; GRAU, C.; RICE, M. E.; RENZ, M.; SHEAFFER, C.; SHEWMAKER, G.; SULC, M. **Alfalfa management guide**. John Wiley & Sons, 2021. 68p. Available online: https://www.agronomy.org/files/publications/alfalfa-management-guide.pdf

UNDERSANDER, D.; MARTIN, N.; HALL, M.; MUELLER, S. Review of Roundup Ready alfalfa. **Forage & Grazinglands**, v. 7, n. 1, p. 1-6, 2009. https://doi.org/10.1094/FG-2009-1019-01-RV

UNDERSANDER, D.; RENZ, M.; SHEAFFER, C.; SHEWMAKER, G.; SULC, M. Alfalfa Nutrient and irrigation management. **Crops & Soils**, v. 49, n. 3, p. 20-25, 2016. https://doi.org/10.2134/cs2016.49.0306

VAN DEYNZE, A.; PUTNAM, D.; ORLOFF, S.; LANINI, T.; CANEVARIA, M.; VARGAS, R.; HEMBREE, K.; MUELLER, S.; TEUBER, L. **Roundup ready alfalfa: an emerging technology**. Montana: University of California - Division of Agriculture and Natural Resources, 2004. 12p. Available online: https://animalrangeextension.montana.edu/forage/documents/roundupready.pdf

VAN SOEST, P. J. **Nutritional ecology of the ruminant**. Cornell University Press, 1994. 122p. Available online: https://www.bibliotecaagptea.org.br/zootecnia/nutricao/livros/NUTRICAO%20DE%20RUMINANTES.pdf

WALKER, R. H.; BUCHANAN, G. A. Crop manipulation in integrated weed management systems. **Weed Science**, v. 30, n. 1, p. 17-24, 1982. https://doi.org/10.1017/S0043174500060276

WARD, S. M.; WEBSTER, T. M.; STECKEL, L. E. Palmer amaranth (*Amaranthus palmeri*): a review. **Weed Technology**, v. 27, n. 1, p. 12-27, 2013. https://doi.org/10.1614/WT-D-12-00113.1

WILSON, R. G. Effect of imazethapyr on legumes and the effect of legumes on weeds. **Weed Technology**, v. 8, n. 3, p. 536-540, 1994. https://doi.org/10.1017/S0890037X00039646

YOUNG, S. L. Beyond precision weed control: A model for true integration. **Weed Technology**, v. 32, n. 1, p. 7-10, 2018. https://doi.org/10.1017/wet.2017.70

Author contributions: R.F.J.: methodology, investigation, writing (original), writing (review & editing); T.M.: conceptualization, acquisition of financing, methodology, validation, writing (review & editing); L.S.: conceptualization, writing (review & editing); R.N.O.: writing (review & editing); B.C.P.: conceptualization, acquisition of financing, methodology, supervision, validation, writing (review & editing). All authors have read and agreed to the published version of the manuscript.

Data availability: Data from this study can be obtained via email upon request to the corresponding author.

Conflict of interest: The authors declare no conflicts of interest.