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Replacing Glyphosate Shifts Environmental Burdens: Trade-Offs Between Ecotoxicity and Climate Impact in Chemical and Non-Chemical Strategies

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Abstract

The potential withdrawal of glyphosate necessitates a comprehensive evaluation of alternative weed control strategies that balances human health safety with environmental concerns. This study applied a decision-support grid to compare the impacts of glyphosate-based reference strategies against chemical and non-chemical alternatives across four Belgian case studies: pome fruit orchards, grassland renewal, arable weed patches, and railways. The assessment integrated twelve risk indicators including human, environmental and biodiversity risk, and life cycle assessment for global warming potential (GWP) into a Final Scenario Score (FSS). The results indicated that only one alternative strategy, the chemical alternative in local weed patch control, achieved the FSS threshold (<0.75) required to justify substitution (FSS = 0.70). Chemical alternatives in other case studies frequently shifted burdens; for instance, bio-herbicides in railways increased risks to residents and aquatic organisms compared to the reference. Conversely, mechanical and thermal alternatives eliminated chemical toxicity but resulted in GWP increases up to 32 times higher than glyphosate-based practices. These findings demonstrate that chemical substitutes often maintain toxicity risks while non-chemical strategies trade them for increased climate impacts. Consequently, a ban on glyphosate is currently unsupported by the environmental performance of available alternatives in these temperate high-intensity systems. Sustainable progress requires a transition period where optimized conventional strategies remain available within integrated weed management, while innovations in electrification and precision technology are accelerated to resolve current trade-offs.

Keywords: glyphosate; risk indicator; herbicides; pome fruit; arable land; mechanical weeding; thermal weeding; decision-support grid

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1. Introduction

Effective weed control is crucial for agricultural production and infrastructure safety. Weeds are widely recognized as the most significant biotic factor affecting crop production,

with average potential crop losses estimated at 34% [1]. For decades, the non-selective, systemic herbicide glyphosate has been a cornerstone of weed management globally. Its widespread adoption is driven by its unique agronomic benefits. It offers high efficacy against a broad spectrum of annual and perennial weeds, kills the entire plant through systemic translocation to the roots, remains highly cost-effective compared to alternative chemical or mechanical methods, and has a unique mode of action (targeting 5-enolpyruvyl-shikimate-3-phosphate synthase) [2].

However, increasing environmental and human health concerns, highlighted by its 2015 IARC classification as probably carcinogenic to humans, have placed glyphosate under regulatory pressure [3]. Conversely, the European Food Safety Authority (EFSA), also in 2015, concluded that glyphosate is "unlikely to pose a carcinogenic hazard to humans", citing differences in data interpretation regarding animal studies and genotoxicity [4]. This position has been supported by more recent regulatory evaluations, including the U.S. Environmental Protection Agency (EPA) in 2020, which reaffirmed that glyphosate is not likely to be carcinogenic to humans [5]. Despite this regulatory divergence, concerns persist regarding broader human health impacts. Recent studies have demonstrated that glyphosate exposure can induce neurotoxicity via NLRP3-mediated microglial pyroptosis [6] and synaptic impairment [7]. Furthermore, causal links have been established linking glyphosate exposure to metabolic disruption through catalase inhibition [8], oxidative stress [9], and gut dysbiosis, specifically via the upregulation of pro-inflammatory Th17 immunity [10]. Furthermore, recent data link high lifetime occupational use to genomic instability markers associated with hematologic malignancies [11].

Glyphosate-based herbicides may further effect non-target organisms across terrestrial and aquatic ecosystems. In aquatic systems, exposure can drive compositional shifts in microphytobenthic communities [12] and induce phytotoxicity in green algae [13]. Furthermore, examples of negative effects of glyphosate-based herbicides on aquatic fauna include physiological risks such as oxidative stress and biomarker alterations in bivalves [14], while fish species can exhibit developmental delays [15,16], histopathological damage [17] and behavioral impairments [18].

Soil health may also be destabilized by glyphosate residues, which can alter trace element mobility, potentially increasing arsenic leaching [19] and by imposing selection pressures that enrich soil bacterial communities with antibiotic resistance genes [20]. Broader evidence indicates disruptions to soil microbial community structures and enzymatic activities [21]. Formulations have been shown to impair springtail (Collembola) reproduction months after application [22] and induce sublethal effects in earthworms [23]. In pollinators, sublethal exposure has been linked to critical functional impairments like spatial memory and learning in bumblebees [24] and alters developmental trajectories in honeybees [25].

The public and regulatory debate regarding glyphosate is happening within the context of the European Union's high-level objectives, such as the European Green Deal and its associated Farm to Fork strategy, which originally aimed to significantly reduce overall use and risk of chemical pesticides. This policy is driving a mandatory shift toward integrated weed management (IWM), forcing a search for viable alternatives to glyphosate [26–28].

Two primary pathways dominate the search for alternatives, each with limitations. The first is a reliance on other chemical herbicides. This strategy can accelerate herbicide resistance, particularly when a unique mode of action like glyphosate's is lost. Moreover, these alternative chemicals may introduce their own different health or environmental risks [29]. The second is a shift to non-chemical methods, such as mechanical or thermal weeding.

While avoiding synthetic chemicals, these methods face significant practical limitations, including slower operation speeds and lower efficacy per treatment. Furthermore, they often result in a heavier environmental footprint due to increased fuel consumption

and labor requirements. For example, a recent evaluation of weed control in sugar beet found that conventional mechanical methods (specifically tractor-mounted hoeing) were associated with 100–150% higher greenhouse gas (GHG) emissions compared to conventional herbicide application [30].

To address this complex trade-off, this study applies a novel decision-support grid [31], a quantitative tool that integrates ecotoxicological risks and life cycle assessment (LCA)-based global warming potential (GWP) into a unified "Final Scenario Score" (FSS). This framework enables a transparent comparison of complete, season-long weed management strategies against a glyphosate-based reference. The season-long aspect is important, as the withdrawal of a high-risk product often necessitates multiple replacement interventions (alternative pesticide applications or repeated mechanical passes) to maintain efficacy. The objective of this study is to evaluate the relative human health, environmental and climate impacts of feasible glyphosate alternatives using this integrated risk assessment tool. We hypothesize that non-chemical alternatives may reduce certain ecotoxicological pressures but will generally exhibit higher carbon footprints, and that chemical substitutes may shift risk rather than eliminate it. The grid was applied to four key Belgian glyphosate use-cases:

1. Weed control in intensively managed low-stem pome fruit orchards: Management of the weed-free strip is highly reliant on glyphosate.
2. Localized grassland renewal: Glyphosate is a standard tool for chemical pasture renewal, used to destroy the old grass cover before establishing a new pasture.
3. Targeted control of weed patches in arable land: Glyphosate is used for post-harvest burndown of perennial weed patches during the stubble of fallow period.
4. Railways: Glyphosate is used for site-specific weed control on and alongside the tracks.

2. Materials and Methods

2.1. Selection and Description of Case Studies

To evaluate the environmental trade-offs of replacing glyphosate, four case studies were selected to represent distinct agronomic bottlenecks and high-risk scenarios relevant to Belgium:

1. Pome Fruit Orchards: Following the withdrawal of alternative herbicides (e.g., glufosinate, diquat, amitrole), glyphosate has become the primary chemical control option for maintaining weed-free tree strips in Belgian orchards (approx. 15,500 ha).
2. Arable Weed Patches: This case targets hard-to-control perennial weeds (e.g., *Cirsium arvense*, *Elymus repens*). These species were selected because they are becoming increasingly problematic under reduced tillage practices and climate-change-driven conditions that favor deep-rooted species with extensive root or rhizome systems, making them difficult to control without systemic herbicides.
3. Localized Grassland Renewal: This case represents a scenario requiring complete vegetation destruction, posing a unique challenge for mechanical alternatives which typically require intensive soil disturbance that contradicts soil conservation goals.
4. Railway Infrastructure: This case is selected to represent critical infrastructure where vegetation control is dictated by safety standards (braking traction and signal visibility) and technical functionality (electrical isolation and drainage). This case involves unique environmental risks due to the high permeability and low organic matter of ballast beds.

2.2. Development of Strategies

Weed control strategies were developed for four case studies in Flanders, Belgium, in consultation with a panel of experts from various research institutes (e.g., pcfruit, Inagro,

Infrabel) and based on literature desktop studies. These strategies were designed to achieve comparable seasonal efficacy where possible. Instances where equivalent efficacy could not be guaranteed or validated (e.g., due to the weather-dependence of mechanical strategies or the lack of operational data for railway alternatives) are explicitly noted in the respective case study descriptions.

While comprehensive decision-making ideally integrates public health, environmental, and economic aspects, this project restricts its scope to the first two. Economic factors were excluded due to their strong susceptibility to fluctuating market conditions and the fact that the final selection among legally authorized methods is ultimately determined by individual economic actors. Furthermore, the selection of alternative strategies prioritized commercially available technologies and chemical formulations currently authorized in Belgium. However, to ensure a comprehensive assessment, specific exceptions were made for use-cases where no authorized chemical alternative currently exists, such as localized grassland renewal and couch grass control on fallow land. Additionally, for railway infrastructure, the analysis accounted for complex commercial and regulatory barriers. While lower-concentration products (e.g., Ultima Pro) are authorized, the operationally preferred high-concentration formulations (e.g., Katoun Gold) often rely on temporary emergency authorizations and synergistic combinations with sulfonylureas are currently restricted by patent rights.

For each case study, strategies were categorized:

1. Reference Strategy: The reference is based on standard practice involving glyphosate.
2. Chemical Alternative Strategy: Glyphosate is replaced with other approved (or, where noted, non-approved) herbicides.
3. Mixed Chemical and Mechanical Strategy: Where possible, a combination of alternative herbicides and mechanical methods is considered.
4. Non-Chemical Alternative Strategy: Glyphosate is replaced with mechanical (e.g., tillage, mowing, brushing) or thermal (e.g., hot water) methods.

Strategies were designed to achieve comparable seasonal efficacy where possible. For case studies where weed pressure dictates the management strategy (e.g., localized grassland renewal/destruction), best-case (low weed pressure) and worst-case (high/perennial weed pressure) strategies were defined. For other cases, such as pome fruit orchards, strategies focused on comparing different technical configurations (e.g., different mechanical implements) under standard conditions.

2.2.1. Weed Control in Low-Stem Pome Fruit Orchards

Weed control across all strategies was primarily focused on managing vegetation in the tree strip (intra-row area). This area represents approximately 30% of the orchard floor. Management of this zone is critical to eliminate competition for water and nutrients between weeds and fruit trees, particularly during the moisture-sensitive periods of flowering and fruit set. The vegetation in these strips is often characterized as a persistent and diverse flora, frequently dominated by difficult-to-control perennial species such as horsetails (*Equisetum* spp.) and other deep-rooting weeds that are resilient to standard control measures. Weed control across all strategies was primarily focused on managing vegetation in the tree strip (intra-row area). This area represents approximately 30% of the orchard floor. Specifically, the study assumed a standard orchard layout with a row spacing of 3.5 m. Based on this, the managed tree strip had a width of 1.05 m, leaving a grassed alleyway of 2.45 m. Consequently, the exact treated surface area was 0.30 ha per hectare of orchard. All herbicide applications are continuous band sprays along the entire length of the tree row, rather than sensor-based patch spraying.

Six distinct weed control strategies were defined for low-stem pome fruit orchards, including a conventional reference based on the key herbicide glyphosate, an alternative chemical strategy, a chemical + mechanical integrated strategy, and three mechanical strategies. All products, application periods, and dosage rates for the chemical treatments (herbicides) and the frequency of mechanical passes are comprehensively detailed in Table 1. In the alternative chemical strategies, the broad-spectrum, non-selective application of glyphosate was substituted with a combination of selective systemic herbicides to maintain control over the diverse weed flora. Specifically, glyphosate was replaced by a mix of synthetic auxins (MCPA, dichlorprop-P, and mecoprop-P) to target difficult broad-leaved perennials, supplemented with propaquizafop to control grass species. This substitution strategy aims to replicate the broad efficacy of glyphosate by combining active substances with additive ranges of activity, thus shifting from a single non-selective compound to a mixture of selective agents targeting specific weed groups.

Table 1. Detailed parameters for six weed control strategies in pome fruit orchards, including a reference strategy, a chemical strategy, an integrated chemical and mechanical strategy, and three fully mechanical alternative strategies. Data includes application period, product, number of mechanical treatments, active substance (a.s.), and the applied herbicide dose.

Strategy	BBCH	Commercial Product	Dose (L or kg Product per ha)	Active Substance (a.s.)	Concentration (a.s. g/kg or L Product)	Dose (a.s. g/ha)
Reference	00	AZ 500 [1]	0.30	Isoxaben	500	150.0
		KERB 400 SC [2]	0.93	Propyzamide	400	372.0
	51–59	Roundup ++ [3]	1.20	Glyphosate	360	432.0
	>69	Roundup Force [3]	1.20	Glyphosate	360	432.0
		Diflanil 500 SC [4]	0.18	Diflufenican	500	90.0
		MCPA 750 [2]	1.20	MCPA	750	900.0
		Fusilade Max [4]	0.90	Fluazifop-P-butyl	125	112.5
Chemical	00	AZ 500	0.30	Isoxaben	500	150.0
		KERB 400 SC	0.93	Propyzamide	400	372.0
	>69	Diflanil 500 SC	0.18	Diflufenican	500	90.0
		MCPA 750	1.20	MCPA	750	900.0
		Fusilade Max	0.90	Fluazifop-P-butyl	125	112.5
	>73	Gramix super [4]	0.78	MCPA	160	124.8
				Dichlorprop-P	310	241.8
				Mecoprop-P	130	101.4
		Agil	0.45	Propaquizafop	100	45.0
Mixed Chemical + Mechanical	00	AZ 500	0.30	Isoxaben	500	150.0
		KERB 400 SC	0.93	Propyzamide	400	372.0
	81–87	Fusilade Max	0.90	Fluazifop-P-butyl	125	112.5
		Gramix super	0.78	MCPA	160	124.8
				Dichlorprop-P	310	241.8
			Number of Treatments	**Mechanical Method**		
Mechanical 1	>69		3×	Line/swivel mower		
	01–74		5×	Rotary cultivator		
	75–87		3×	Line/swivel mower		
Mechanical 2	01–74		8×	Roll hoe + finger weeder		
	75–87		3×	Line/swivel mower		
Mechanical 3	01–74		3×	Rotary cultivator		
			5×	Roll hoe + finger weeder		
	75–87		3×	Line/swivel mower		

[1] Corteva Agriscience Netherlands B.V., Bergen op Zoom, Netherlands; [2] PHYBELCO, Namur, Belgium; [3] Bayer Cropscience, Machelen, Belgium; [4] Q-CHEM, Sint-Truiden, Belgium; [4] NUFARM, Capelle aan den Ijsel, Netherlands.

The mixed chemical + mechanical strategy utilizes a hybrid approach to reduce herbicide dependence while maintaining operational efficiency. In this strategy, chemical control is restricted to the dormant and pre-harvest periods. Residual soil herbicides (isoxaben

and propyzamide) are applied in winter to suppress germination and a foliar treatment (synthetic auxins and graminicides) is applied pre-harvest to clean the strip. During the active growing season (post-flowering to summer), chemical applications are replaced by three mechanical passes using a line or swiveling rotary mower. This allows for vegetation management at relatively high working speeds (approx. 7 km/h) without soil disturbance during the critical phases of fruit development.

The three mechanical strategies were selected to represent different approaches to organic weed management, distinguishing between intensive soil disturbance and high-speed maintenance. Mechanical strategy 1 relies on a horizontally rotating retracting miller (e.g., Ladurner), characterized by a low working speed (approx. 3 km/h) but intensive soil disturbance, effective against established weeds. The focus in mechanical strategy 2 is on operational efficiency using passive implements like a roll hoe combined with a finger weeder. This strategy allows for significantly higher working speeds (6–12 km/h) but typically requires a higher frequency of passes to maintain control. Mechanical strategy 3 combines the two previous methods, utilizing the intensive rotary tiller in spring to clean up overwintered vegetation, followed by the faster roll hoe for summer maintenance.

Mechanical weed control was performed using specialized under-tree implements: a line or swiveling rotary mower for vegetation trimming, and a roll hoe and finger weeder for uprooting, undercutting, and/or smothering weeds alongside (roll hoe) and on (finger weeder) the tree line. The mechanical strategies involved timely passes during the growing season to control weeds without herbicide use.

2.2.2. Localized Grassland Renewal

The reference strategy, as well as the chemical and mechanical alternatives can be found in Table 2. All strategies are treated as targeted applications treating 40% of the total field area. The case study assumes grassland re-establishment in autumn following termination in the summer. The reference strategy assumes a single, localized application of glyphosate on degraded grassland, targeting only problematic perennial weeds, all of which are sensitive to a dose of 1.44 kg glyphosate per ha. This dosage reflects the 2022 European maximum standard for targeted perennial weed control (max. 40% of the area), ensuring reduced environmental and human risk. Following the herbicide application, the protocol proceeds to grassland re-establishment in autumn, following the termination of the sward in summer.

Table 2. Detailed parameters for different strategies for localized grassland renewal (40% of total field area), including a reference strategy, a chemical strategy and a best-case and worst-case mechanical approach. Data includes application period, product, number of mechanical treatments, active substance (a.s.), and the final dose of active substance applied (a.s. g/ha) of total field area.

Strategy	Commercial Product	Dose (L or kg Product per ha)	Active Substance (a.s.)	Concentration (a.s. g/kg or L Product)	Dose (a.s. g/ha)
Reference	Roundup ++	4.00	Glyphosate	360	1440
Chemical	Focus plus [1]	5.00	Cycloxydim	100	500
	MCPA 750	2.70	MCPA	100	2025
		Number of Treatments		**Mechanical Method**	
Mechanical Best-Case		1×		Bio-mulch rotary tiller	
		1×		Cultivator	
		1×		Bio-mulch rotary tiller	
Mechanical Worst-Case		5×		Cultivator	

[1] *BASF Belgium, Antwerpen, Belgium.*

Currently, there are no authorized effective chemical alternatives for grassland renewal in Belgium. Consequently, a theoretical, unauthorized scheme was modeled based on the application of an ACCase inhibitor (cycloxydim: 500 g a.s./ha), which acts systemically and is effective against a broad spectrum of grasses. To control broad-leaved species, a synthetic auxin herbicide (MCPA: 2025 g a.s./ha) was included in the treatment schedule, targeting a broad range of susceptible species. These alternative herbicides exhibit weak soil activity, which allows for rapid re-establishment of grassland after treatment.

The best-case mechanical strategy assumes the absence of difficult-to-control perennial weeds with creeping underground stems (rhizomes) or roots. The selected control strategy involves a sequence of three treatments: an initial pass with a bio-mulch rotary tiller (working depth 4 cm), followed by a single pass with a tine cultivator (working depth of 15 cm), and a final pass with a bio-mulch rotary tiller. The efficacy of this sequence is weather-dependent, relying on a dry period to ensure not only the desiccation of the uprooted weeds and grasses but also the depletion of root reserves through fragmentation and the suppression of regrowth.

The specified bio-mulch rotary tiller (e.g., KUHN EL 162-300 BIOMULCH, KUHN S.A.S., Saverne, France) is equipped with six L-shaped or slightly curved blades per flange and four gauge wheels to ensure uniform, intensive, and shallow soil disturbance (6 cm depth; driving speed 5 km/h; maximum PTO speed 1000 min^{-1}).

The worst-case mechanical strategy addresses grassland containing patches of couch grass (*Elymus repens* L.), a perennial rhizomatous grass weed. While multiple control methods exist [27], this strategy utilizes five consecutive passes with a tine cultivator (working depth of 15 cm). This intensive strategy was selected to implement a depletion approach: through repeated fragmentation and lifting, the rhizomes are forced to expend their energy reserves on regrowth, which is then destroyed by the subsequent pass. As with the best-case strategy, these treatments must be conducted during a dry period to ensure effective desiccation of the weakened rhizomes.

2.2.3. Control of Couch Grass Patches in Temporarily Uncultivated Arable Areas

The detailed parameters for all strategies including product selection, application frequency, active substances and final dosage rates are summarized in Table 3. Consistent with the scope of localized renewal, all strategies are treated as targeted applications treating 40% of the total field area as an infection zone. The reference strategy is based exclusively on a single, localized application of glyphosate. In this conventional strategy, a dosage of 1.44 kg active substance (a.s.) per hectare is applied. This dose is considered sufficient for the localized control of couch grass (*Elymus repens*) patches on arable land. This species was selected as the primary target because it is the most prevalent and difficult-to-control perennial weed in temperate arable systems, serving as a model organism for rhizomatous weeds that typically demands glyphosate use in inter-cropping periods.

Table 3. Detailed treatment parameters for local weed patch control strategies on arable land. Data includes the specific product, application frequency, active substance (a.s.), and the final applied dose of active substance (g a.s./ha) for 40% of total field area.

Strategy	Commercial Product	Dose (L or kg Product)	Active Substance (a.s.)	Concentration (a.s. g/kg or L Product)	Dose (a.s. g/ha)
Reference	Roundup ++	4.00	Glyphosate	360	1440
Chemical	Agil [1]	1.50	Propaquizafop	100	150
		Number of Treatments	**Mechanical Method**		
Mechanical		2×	Bio-mulch rotary tiller		
Non-inversion		2×	Cultivator		

Table 3. *Cont.*

Strategy	Commercial Product	Dose (L or kg Product)	Active Substance (a.s.)	Concentration (a.s. g/kg or L Product)	Dose (a.s. g/ha)
Mechanical		2×		Bio-mulch rotary tiller	
Inversion tillage		2×		Ploughing	

[1] *ADAMA REGISTRATIONS B.V., Leusden, Netherlands.*

Similar to the previous case study, there is no authorized chemical alternative for this specific application. For the purpose of this case study, the active substance propaquizafop (Agil) was selected. Although propaquizafop is authorized for in-crop applications, it is technically not registered for use on fallow land in Belgium. We chose not to test in cropped environments, as selectively killing creeping perennials in sensitive crops is difficult to achieve, particular when shoots grow in the crop row. Propaquizafop demonstrates significant efficacy against *Elymus repens* [32] and is applied in this strategy at a dose of 150 g a.s./ha.

The mechanical alternatives are categorized by tillage type. The first mechanical strategy utilizes non-inversion tillage based on a desiccation strategy. The protocol involves treating the *Elymus repens* patches during a dry period with a total of four passes: two passes with a bio-mulch rotary tiller (working depth 4–6 cm) to fragment rhizomes and two passes with a tine cultivator or rotary harrow (working depth 10–15 cm) to lift them to the surface. This frequency of four passes is supported by the carbohydrate depletion strategy described by Ringselle et al. (2020) [27], where repeated disturbance is required to first fragment rhizomes (breaking apical dominance) and then successively destroy the energy-draining regrowth, thereby exhausting the plant's underground reserves.

The second mechanical strategy employs inversion tillage. The strategy involves treatments during two dry periods, consisting of passes with a bio-mulch rotary tiller followed by ploughing (working depth 15 cm) (soil inversion) to deeply bury the fragmented and weakened rhizomes. Consequently, a total of four mechanical treatments are required.

2.2.4. Railways

Effective weed control is essential for railway safety because it prevents track instability, maintains the required clearing distance, ensures clear signal visibility, reduces fire hazards, and supports safe braking distances by reducing vegetation-induced contamination that can impair wheel–rail adhesion.

This case study focuses on weed control strategies applied to the main tracks of the Belgian railway network. The specific treated zones include the ballast bed and the adjacent safety paths. Management of these zones is critical for maintaining braking distances, signal visibility, fire safety, and the functional integrity of the ballast (electrical isolation and drainage). This study utilizes data from two spraying campaigns conducted in 2022, covering three railway lines with a total network length of 175 km.

The reference strategy represents the current standard practice employed by the railway infrastructure manager. Weed control is primarily chemical and site-specific, utilizing a high-tech precision spray train equipped with weed detection cameras and adjustable nozzles. This technology allows for variable dosing and targeted application, significantly reducing herbicide use compared to the maximum authorized limits. Applications are performed at high speeds (50–60 km/h) to minimize disruption to train traffic. The spray train can perform vegetation control on 13 to 195 km of railway tracks, dependent on the area that needs to be treated. On average the spray train treats approximately 29.5 ha/day, taking 21 days for a full campaign to treat 619 ha of the ballast and path.

The current conventional strategy relies on systemic broad-spectrum foliar herbicides to manage the specific vegetation of the railway environment. The flora in these zones

is typically characterized by a mix of fast-growing annual pioneer species in the ballast bed (which compromise drainage) and robust perennial or woody species (such as *Rubus* or woody saplings) encroaching from the safety paths. To effectively control this diverse spectrum, the reference strategy includes a spring application of glyphosate, combined with the soil-acting herbicide flazasulfuron to prevent germination and, according to the detected weed species composition, synthetic auxins (2,4-D and triclopyr) to target perennial or woody species. This is followed by a targeted glyphosate-only application in late summer to manage regrowth and new germination. All active substances in this reference strategy are currently authorized in Belgium for professional use on railway infrastructure. Treatments occur one to two times per year.

While a general ban on pesticide use in public domains has been in effect in Flanders since 2015, the railway manager retains an exception due to the current lack of fully equivalent, operationally viable alternatives that can match the speed end efficacy of the chemical reference. However, herbicide usage has decreased by 84% between 2010 and 2020 [33]. This drastic reduction is primarily driven by the transition to camera-guided precision weed control (replacing full-width spraying) and the continued phase-out of residual soil herbicides (such as diuron and triazines) that were previously standard.

Alternative strategies were chosen to provide equivalent control efficacy on a per-year basis to the glyphosate-based reference. The alternative railway strategies presented here have not yet been validated for operational performance equivalent to the reference strategy under Belgian railway conditions. The percentage of treated surface area for alternatives was assumed to be identical to the vegetation coverage detected in the 2022 reference campaigns. However, it is important to note that this assumption likely underestimates the true treated area for the alternative strategies as the lower per-treatment efficacy of contact herbicides would realistically lead to faster regrowth and expanding weed patches over time. The conventional (reference) strategy and chemical alternative strategies can be found in Table 4.

Table 4. Detailed treatment parameters for weed control in railway environments. Data includes the specific product, application frequency, active substance (a.s.), the final applied dose of active substance (g a.s./ha) and the net treated area.

Strategy	Campaign	Commercial Product	Max Dose (L or kg Product)	Active Substance (a.s.)	Concentration (a.s. g/kg or L Product)	Applied Dose a.s. (g/ha)	Net Treated Area (%)
Reference	1	Stern 360 [1]	4.00	Glyphosate	360	271.0	18.8
	1	Genoxone [3]	4.63	2,4-D	93	81.0	18.8
				Triclopyr	104	90.2	18.8
	1	Chikara [3]	0.20	Flazasulfuron	250	9.4	18.8
	2	Taifun 360 [4]	4.00	Glyphosate	360	403.0	28.0
Chemical 1 (PA)	1	Genoxone	4.63	2,4-D	93	81.0	18.8
				Triclopyr	104	90.2	18.8
	1	Chikara	0.20	Flazasulfuron	250	9.4	18.8
	1	Katoun Gold [5]	22.50	Pelargonic acid	500	2876.0	18.8
	2	Hinoki [3]	0.20	Flazasulfuron	250	14.0	28.0
	2	Katoun Gold	22.50	Pelargonic acid	500	3150.0	28.0
Chemical 2 (PA + MH)	1	Genoxone	4.63	2,4-D	93	81.0	18.8
				Triclopyr	104	90.2	18.8
	1	Chikara	0.20	Flazasulfuron	250	9.4	18.8
	1	Ultima Pro [6]	166.00	Pelargonic acid	187	5827.0	18.8
				Maleic hydrazide	30	936.0	18.8

Table 4. *Cont.*

Strategy	Campaign	Commercial Product	Max Dose (L or kg Product)	Active Substance (a.s.)	Concentration (a.s. g/kg or L Product)	Applied Dose a.s. (g/ha)	Net Treated Area (%)
	2	Hinoki	0.20	Flazasulfuron	250	14.0	28.0
	2	Ultima Pro	166.00	Pelargonic acid	187	8672.0	28.0
				Maleic hydrazide	30	1394.0	28.0

Note: Applied dose a.s. (g/ha) is calculated as follows $AppliedDose = MaxDose \times Concentration \times \frac{Net\ Treated\ Area\ \%}{100}$. Calculations were performed using exact parameter values (e.g., 103.6 g/L triclopyr, 18.82% treated area); values displayed in the table are rounded for clarity. [1] *Bayer Cropscience, Machelen, Belgium;* [3] *ISK Biosciences Europe, Machelen, Belgium;* [4] *Adama Registrations B.V., Leusden, Netherlands;* [5] *Certis Belchim B.V., Utrecht, Netherlands;* [6] *W. Neudorff GmbH KG, Emmerthal, Germany*.

Two alternative chemical strategies were designed for this study. These do not have established efficacy profiles on railway environments. The first strategy, Chemical Alternative (PA), relied exclusively on the application of pelargonic acid, which functions as a contact herbicide. The second strategy, Chemical Alternative (PA + MH), utilized a formulation combining pelargonic acid with the growth regulator maleic hydrazide (only the commercial product Ultima pro is currently authorized in Belgium for use on railways). Maleic hydrazide was added to compensate for the lack of systemic activity in pelargonic acid. While pelargonic acid burns down foliage, maleic hydrazide is translocated to the roots where it inhibits cell division, thereby suppressing the regrowth of perennial vegetation. It is important to note that the lower-concentration products of pelargonic acid (i.e., Ultima Pro) are authorized; however, the operationally preferred high-concentration formulations (e.g., Katoun Gold) often rely on temporary emergency authorizations and synergistic combinations with sulfonylureas are currently restricted by patent rights.

Due to the high intensity of railway traffic and the international logistical commitments of the spray train, a maximum of two applications per year was set as a feasibility constraint for the railway manager. The alternatives were applied based on the highest vegetation coverage recorded. This approach was chosen to ensure a direct comparison of environmental impact normalized to the same functional unit of vegetation pressure. Furthermore, for the risk assessment, the highest recorded coverage (28%) was used to define the worst-case exposure strategy.

A thermal control strategy using a "hot water train" was chosen as a non-chemical alternative, using water heated to 90 °C to thermally control weeds. Currently, only experimental prototypes are available with lower working speeds (driving speed of 20 km/h). However, to be practically useful, a working speed of 50–60 km/h is desirable. Unlike the chemical spray train, this method requires a significantly heavier logistical setup and is supplemented by mechanical mowing on the path. The strategy assumes the use of a fully operational hot water train with sufficient autonomy (20 km range). The operational train is estimated at 640 tonnes (comprising two locomotives, wagons for fuel/generators and multiple water cisterns), compared to approximately 350 tonnes for the standard chemical spray train. The energy required to heat the water was estimated at 3.75×10^5 MJ per campaign (based on a light fuel oil boiler at 100 kW). The thermal treatment is combined with rotary mowing (1.1 m width) on the side of the track.

Specific adjustments were made to the chemical risk indicator calculations to reflect the unique application method on railways. The operator indicator was excluded from the analysis. The precision spray train utilizes a direct injection system where active substances are mixed with water immediately before the nozzle, eliminating operator exposure during tank mixing. Furthermore, the operator is stationed in a sealed cabin during application. Therefore, the standard model calculations would overestimate the risk. For strategies involving pelargonic acid, the worker risk could not be calculated, as no

Acceptable Operator Exposure Level (AOEL) or Acute Acceptable Operator Exposure Level (AAOEL) has been defined by EFSA for this substance. As this study concerns non-crop railway infrastructure, the consumer indicator was not calculated. Lastly, the bird risk indicator was also excluded, as the POCER model considers railway infrastructure to be a negligible risk environment for birds due to a lack of attractants [34].

The LCA compares the environmental impact of a single campaign over a 20 km track segment. The analysis includes fuel consumption (diesel consumption for both the chemical spray train (350 tonnes) and the hot water train (640 tonnes)), light fuel oil consumption for heating water in the thermal strategy and water use (the volume of water required for thermal application vs. chemical application).

2.3. Risk Indicators

2.3.1. Human Health

Human health risks for the operator, worker, bystander, and resident were calculated using calculations based on the OPEX calculator [35]. Consumer health risk was based on the POCER risk indicator. Data was sourced from the Pesticides Properties Database (PPDB) [36] and Fytoweb (www.fytoweb.be, accessed on 20 August 2025). Personal Protective Equipment was chosen as instructed on the commercial product label.

2.3.2. Biodiversity

Biodiversity risk indicators were taken from the POCER model (for aquatic organisms, birds, and earthworms) [34] and the revised EFSA bee guidance (for honeybees, bumblebees, and solitary bees) [37].

The EVA indicator for beneficial arthropods was not applied here, as it has not yet been developed for herbicide impacts. This is treated as a limitation in the biodiversity assessment.

2.3.3. Environmental Risk

Environmental risks for Soil Persistence and Groundwater (via PESTLA model) were taken from POCER [34]. Global warming potential (GWP) was calculated using life cycle assessment (LCA) methodology with the open-source OpenLCA software (version 1.11) and the Agribalyse database [38]. This included GWP estimations for pesticide application (e.g., fuel combustion during the spraying operation, transport to the field, transport of the train) and non-chemical methods (e.g., mowing with a rotary mower, ploughing, transport to the field and the estimated energy consumption for the hot water train). GWP values for non-chemical methods were estimates derived from standardized agricultural inventories in the Agribalyse database [38] (Tables A1–A4). The analysis focused on direct operational emissions. Therefore, the full manufacturing life cycle of the machinery and secondary effects, such as tillage-induced CO_2 emissions from soil mineralization, were not quantified. Consequently, the GWP values presented for mechanical strategies likely represent conservative estimates, as soil disturbance typically exacerbates carbon loss relative to the no-till reference.

2.4. Final Scenario Score (FSS) Calculation

A maximum of twelve risk indicators were used (operator, worker, resident, bystander, consumer, soil persistence, ground water, GWP, aquatic organisms, birds, earthworms, and bees).

The FSS was calculated by summing the weighted, normalized scores for each indicator relative to the reference strategy, using the formula from the parallel study [31]. To account for the trade-off between local ecotoxicity and global climate impact, GWP was weighted at 10%. The remaining 90% was distributed equally among the 11 toxicological and ecotoxicological indicators. This equal distribution was chosen to treat human health

(e.g., operator, resident) and ecosystem quality (e.g., bees, groundwater) as equal, avoiding subjective prioritization of specific protection goals in the absence of a standardized valuation hierarchy.

An FSS below 0.75, representing a 25% overall risk improvement, was the threshold to justify replacing the glyphosate reference strategy. It must be emphasized that this selected threshold (FSS < 0.75) represents an operational benchmark adopted for comparative interpretation rather than a scientifically derived or ecologically validated cutoff. This threshold was introduced as a pragmatic decision criterion to facilitate scenario comparison and to identify cases showing a substantial relative improvement (i.e., >25%) over the reference strategy within the applied framework. Consequently, this value does not correspond to a biological, regulatory, or environmental tipping point, nor does it imply a universally applicable standard for substitution decisions.

Furthermore, it is important to clarify the distinction between the underlying metrics and the aggregated FSS. While the individual risk indicators are derived from validated absolute risk models (e.g., Toxicity Exposure Ratios, POCER quantifications, and GWP in kg CO_2 eq), the Final Scenario Score (FSS) functions as a comparative decision-support indicator rather than an absolute measure of risk. The aggregation of these heterogeneous indicators into a single composite score reflects specific methodological choices regarding normalization and weighting. Therefore, the FSS does not imply a direct physical equivalence between fundamentally different impact categories. Instead, it serves as a tool designed to facilitate structured comparison of management scenarios relative to the reference, specifically intended to highlight trade-offs.

3. Results

3.1. Low-Stem Pome Fruit Orchards

The environmental and human health impacts of the weed control strategies were evaluated, by calculating the total and individual risk indicator scores for the active substances used in the reference, chemical alternative, and the combined chemical + mechanical alternative strategies. Detailed scores for eleven endpoints are presented in Table 5. Analysis of the aggregated total risk (ALL) showed a substantial reduction in environmental risk in the combined chemical + mechanical alternative strategy. This strategy achieved the lowest total risk score across most categories compared with both the chemical alternative and the conventional reference strategies. The improvement was primarily due to the substitution and reduction of higher-risk active substances with mechanical weed control. However, human exposure risks increased, mainly due to the continued use of diflufenican and the addition of dichlorprop-P and mecoprop in the chemical component of the strategy.

Table 5. Total and individual risk indicator scores for active substances of different strategies for weed control in low-stem pome fruit orchards.

Strategy	Active Substance	Operator	Worker	Resident	Bystander	Consumer	Soil Persistence	Ground Water	Aquatic Organisms	Bees	Earth Worms	Birds
Reference	ALL	0.18	6.61	2.13×10^{6}	1.42×10^{2}	1.80×10^{-7}	3.62×10^{-2}	2.30×10^{-4}	1.54	1.08×10^{2}	6.44×10^{-4}	2.81×10^{-3}
	isoxaben	7.97×10^{-3}	1.00	1.77×10^{5}	3.05×10^{1}	1.18×10^{-8}	2.15×10^{-2}	6.67×10^{-5}	9.18×10^{-2}	2.77×10^{-4}	3.34×10^{-5}	6.98×10^{-5}
	propyzamide	0.11	1.00	1.13×10^{6}	7.85×10^{1}	2.36×10^{-8}	1.33×10^{-3}	2.13×10^{-5}	7.08×10^{-2}	2.59×10^{-3}	2.40×10^{-4}	5.26×10^{-5}
	glyphosate (1)	3.75×10^{-3}	1.00	7.73×10^{4}	4.62	1.18×10^{-8}	2.28×10^{-4}	1.75×10^{-7}	2.30×10^{-2}	4.24×10^{1}	8.60×10^{-6}	2.01×10^{-4}
	glyphosate (2)	3.93×10^{-3}	1.00	7.73×10^{4}	4.62	1.18×10^{-8}	2.28×10^{-4}	1.75×10^{-7}	2.30×10^{-2}	4.24×10^{1}	8.60×10^{-6}	2.01×10^{-4}
	diflufenican	8.84×10^{-4}	0.61	2.42×10^{3}	0.69	2.95×10^{-9}	1.26×10^{-2}	5.95×10^{-10}	1.00	2.05×10^{-5}	2.01×10^{-5}	3.89×10^{-5}
	MCPA	3.70×10^{-2}	1.00	6.45×10^{5}	1.85×10^{1}	5.90×10^{-8}	1.85×10^{-4}	1.41×10^{-4}	6.48×10^{-4}	2.38×10^{1}	3.09×10^{-4}	2.22×10^{-3}
	fluazifop-P-butyl	1.66×10^{-2}	1.00	2.02×10^{4}	4.62	5.90×10^{-8}	1.05×10^{-4}	0.00	0.33	1.37×10^{-4}	2.51×10^{-5}	2.64×10^{-5}
Chemical	ALL	0.41	8.61	3.34×10^{6}	3.35×10^{2}	5.30×10^{-7}	3.64×10^{-2}	7.60×10^{-4}	1.61	9.51×10^{1}	7.45×10^{-4}	3.82×10^{-3}
	isoxaben	7.97×10^{-3}	1.00	1.77×10^{5}	3.05×10^{1}	1.18×10^{-8}	2.15×10^{-2}	6.67×10^{-5}	9.18×10^{-2}	2.77×10^{-4}	3.34×10^{-5}	6.98×10^{-5}
	propyzamide	0.11	1.00	1.13×10^{6}	7.85×10^{1}	2.36×10^{-8}	1.33×10^{-3}	2.13×10^{-5}	7.08×10^{-2}	2.59×10^{-3}	2.40×10^{-4}	5.26×10^{-5}
	MCPA	3.70×10^{-2}	1.00	6.45×10^{5}	1.85×10^{1}	5.90×10^{-8}	1.85×10^{-4}	1.41×10^{-4}	6.48×10^{-4}	2.38×10^{1}	3.09×10^{-4}	2.22×10^{-3}
	fluazifop-P-butyl	1.66×10^{-2}	0.61	2.02×10^{4}	4.62	5.90×10^{-8}	1.05×10^{-4}	0.00	0.33	1.37×10^{-4}	2.51×10^{-5}	2.64×10^{-5}
	diflufenican	8.84×10^{-4}	1.00	2.42×10^{3}	0.69	2.95×10^{-9}	1.26×10^{-2}	5.95×10^{-10}	1.00	2.05×10^{-5}	2.01×10^{-5}	3.89×10^{-5}
	MCPA	2.92×10^{-2}	1.00	8.95×10^{4}	1.85×10^{1}	5.90×10^{-8}	1.85×10^{-4}	1.41×10^{-4}	8.99×10^{-5}	2.38×10^{1}	4.28×10^{-5}	3.08×10^{-4}
	dichlorprop-P	1.66×10^{-2}	1.00	8.23×10^{5}	8.77×10^{1}	1.97×10^{-8}	1.85×10^{-4}	3.16×10^{-4}	2.07×10^{-4}	6.38×10^{-2}	5.39×10^{-5}	8.99×10^{-4}
	mecoprop	0.14	1.00	3.64×10^{5}	9.23×10^{1}	2.95×10^{-7}	1.52×10^{-4}	7.28×10^{-5}	2.91×10^{-5}	4.75×10^{1}	1.14×10^{-5}	1.89×10^{-4}
Chemical + mechanical	ALL	0.32	6.61	2.61×10^{6}	3.12×10^{2}	4.68×10^{-7}	2.35×10^{-2}	6.18×10^{-4}	0.50	7.13×10^{1}	4.06×10^{-4}	1.54×10^{-3}
	isoxaben	7.97×10^{-3}	1.00	1.77×10^{5}	3.05×10^{1}	1.18×10^{-8}	2.15×10^{-2}	6.67×10^{-5}	9.18×10^{-2}	2.77×10^{-4}	3.34×10^{-5}	6.98×10^{-5}
	propyzamide	0.11	1.00	1.13×10^{6}	7.85×10^{1}	2.36×10^{-8}	1.33×10^{-3}	2.13×10^{-5}	7.08×10^{-2}	2.59×10^{-3}	2.40×10^{-4}	5.26×10^{-5}
	fluazifop-P-butyl	1.66×10^{-2}	0.61	2.02×10^{4}	4.62	5.90×10^{-8}	1.05×10^{-4}	0.00	0.33	1.37×10^{-4}	2.51×10^{-5}	2.64×10^{-5}
	MCPA	2.92×10^{-2}	1.00	8.95×10^{4}	1.85×10^{1}	5.90×10^{-8}	1.85×10^{-4}	1.41×10^{-4}	8.99×10^{-5}	2.38×10^{1}	4.28×10^{-5}	3.08×10^{-4}
	dichlorprop-P	1.66×10^{-2}	1.00	8.23×10^{5}	8.77×10^{1}	1.97×10^{-8}	1.85×10^{-4}	3.16×10^{-4}	2.07×10^{-4}	6.38×10^{-2}	5.39×10^{-5}	8.99×10^{-4}

Note: glyphosate (1) and glyphosate (2) are two separate applications.

In contrast, the chemical alternative strategy showed increased risks in most categories. This outcome was driven by the combined toxicity profiles of the substitute herbicides (MCPA, dichlorprop-P, and mecoprop). Only the risk indicator for bees showed an improvement compared with the reference strategy.

The FSS and the GWP for all weed control strategies in pome fruit cultivation are presented in Table 6. None of the alternative strategies reached the justification threshold of FSS < 0.75. The combined chemical + mechanical strategy achieved the lowest score among them (FSS = 0.81). While this indicates a measurable reduction in some risk indicators (soil persistence, earthworms and birds) compared to the reference, it does not meet the threshold required for a fully justifiable substitution. Its performance was strongly influenced by the trade-off between reduced chemical exposure and increased carbon footprint. The GWP for this integrated approach (1212 kg CO_2 eq) was considerably higher than the reference strategy (844 kg CO_2 eq), mainly due to the increased fuel consumption required for the mechanical passes. The chemical alternative strategy resulted in an FSS of 0.96, offering negligible improvement over the reference. Although it presented the lowest carbon footprint of all strategies (GWP = 633 kg CO_2 eq.), the substitution of glyphosate with dichlorprop-P and mecoprop-P maintained high risk scores across all risk indicators.

Table 6. Global warming potential (GWP) (in kg CO_2 equivalents per hectare of tree strip) and the Final Scenario Scores (FSS) for all strategies for weed control in low-stem pome fruit orchards. Values for mechanical strategies are presented as the calculated score (minimum–maximum). The range represents a sensitivity analysis based on operational variability, specifically the potential need for additional mechanical passes under adverse weather conditions or weed pressure (best case vs. worst case). Chemical strategies follow fixed Good Agricultural Practices and are treated as deterministic.

Strategy	GWP (kg CO_2 Equivalents)	Contribution of GWP to FSS (%)	FSS
Reference	844	10	1.00
Chemical	633	10	0.96
Chemical + mechanical	1212 (1212–1479) [a]	10	0.81
Mechanical 1	5897 (3749–7690) [b]	100	1.00
Mechanical 2	2899 (2115–3469) [c]	100	1.00
Mechanical 3	5063 (4787–5328) [d]	100	1.00

[a] The range represents 3–4 passes with a line/swivel mower, with 3 passes as the standard. [b] The range represents 3–7 passes with a rotary cultivator, with 5 passes as the standard. [c] The range represents 5–10 passes with a roll hoe + finger weeder, with 8 passes as the standard. [d] The range represents 3–4 passes with a line/swivel mower with 3 passes as the standard.

The three purely mechanical alternatives (mechanical 1, 2, and 3) all resulted in an FSS of 1.00. Because these strategies involved no chemical applications, the biodiversity and human health risk indicators were effectively zero. Consequently, the FSS depended on the GWP component of the decision-support grid. The GWP for these strategies ranged from 2899 to 5897 kg CO_2 eq., approximately 7 times higher than the reference strategy (844 kg CO_2 eq.). This single dominating factor prevented these pesticide-free alternatives from achieving a justifiable FSS (<0.75).

3.2. Localized Grassland Renewal

In this case study, the consumer risk indicator is not considered, as the treated vegetation is destroyed during the renovation process and not harvested for consumption. This results in a total of 11 risk indicators being considered. An analysis of the individual risk indicators in Table 7 reveals that although the chemical alternative reduced the risk to aquatic organisms (from 7.67×10^{-2} to 5.22×10^{-3}), this benefit was counterbalanced by increases in nearly all other categories. In particular, the risk to residents increased from 8.10×10^{3} to 4.77×10^{4}, and the risk to earthworms rose substantially from 2.06×10^{-5} to 5.78×10^{-4}. Higher risks were also observed for operators, workers, bystanders, bees and

birds in the chemical alternative compared to the reference strategy. Furthermore, the GWP of the chemical alternative remained unchanged relative to the reference strategy (Table 8), offering no compensatory advantage in greenhouse gas emissions. Conversely, both mechanical alternatives (best case and worst case) required substantially higher energy inputs. This resulted in GWP values approximately 5 to 15 times higher than the reference strategy.

Table 7. Total and individual risk indicator scores for active substances of different strategies for localized grassland renewal.

Strategy	Active Substance	Operator	Worker	Resident	Bystander	Soil Persistence	Ground Water	Aquatic Organisms	Bees	Earth Worms	Birds
Reference	ALL	3.86×10^{-3}	1.00	8.10×10^{3}	0.39	2.28×10^{-4}	1.75×10^{-7}	7.67×10^{-2}	5.47×10^{1}	2.06×10^{-5}	6.70×10^{-4}
	glyphosate	3.86×10^{-3}	1.00	8.10×10^{3}	0.39	2.28×10^{-4}	1.75×10^{-7}	7.67×10^{-2}	5.47×10^{1}	2.06×10^{-5}	6.70×10^{-4}
Chemical	ALL	4.31×10^{-2}	2.00	4.77×10^{4}	1.83	2.89×10^{-4}	1.41×10^{-4}	5.22×10^{-3}	6.10×10^{1}	5.78×10^{-4}	5.23×10^{-3}
	cycloxydim	3.52×10^{-3}	1.00	2.11×10^{3}	0.29	1.03×10^{-4}	1.46×10^{-7}	3.76×10^{-3}	1.86×10^{1}	8.00×10^{-5}	2.33×10^{-4}
	MCPA	3.95×10^{-2}	1.00	4.56×10^{4}	1.54	1.85×10^{-4}	1.41×10^{-4}	1.45×10^{-3}	4.24×10^{1}	4.98×10^{-4}	5.00×10^{-3}

Table 8. Global warming potential (GWP) (in kg CO_2 equivalents per hectare) and the Final Scenario Scores for all strategies for localized grassland renewal. Values for mechanical strategies are presented as the calculated score (minimum–maximum). The range represents a sensitivity analysis based on operational variability, specifically the potential need for additional mechanical passes under adverse weather conditions or weed pressure (best case vs. worst case). Chemical strategies follow fixed Good Agricultural Practices and are treated as deterministic.

Strategy	GWP (kg CO_2 Equivalents)	Contribution of GWP to FSS (%)	Final Score
Reference	210	10	1.00
Chemical	210	10	0.92
Mechanical best-case (non-inversion tillage)	1107 (1107–1347) [a]	100	1.00
Mechanical worst-case (inversion tillage)	3130 (2504–3130) [b]	100	1.00

[a] The range represents 3–4 passes with a bio-mulch rotary tiller, with 3 passes as the standard; [b] The range represents 4–5 passes with a cultivator, with 5 passes as the standard.

The FSS for localized grassland renewal are detailed in Table 8. The chemical alternative (cycloxydim + MCPA) yielded an FSS of 0.92. As this value does not meet the required threshold (FSS < 0.75), the chemical alternative strategy does not provide a sufficient overall risk reduction to justify substituting the glyphosate-based reference strategy. Without chemical inputs, the evaluation relied solely on their carbon footprint. Due to their high GWP values, both the best-case and worst-case strategy resulted in an FSS of 1.00, preventing these alternative strategies from achieving a justifiable score.

3.3. Local Weed Patch Control

The individual risk indicator scores in Table 9 illustrate the trade-offs associated with substituting glyphosate with propaquizafop. The chemical alternative shows clear improvements in certain ecotoxicological parameters. Notably, the risk to bees decreased markedly from 5.47×10^{1} (reference) to 2.79 and the risk to birds dropped from 6.70×10^{-4} to 6.98×10^{-5}. Moreover, the risk to groundwater was reduced to zero. However, these benefits were counterbalanced by increased risks in other categories. The risk to aquatic organisms increased from 7.67×10^{-2} to 3.87×10^{-1}, while the risk to operators rose from 3.86×10^{-3} to 7.07×10^{-2}. The GWP for the chemical alternative remained unchanged to the reference strategy at 210 kg CO_2 eq (Table 10). Conversely, the mechanical strategies resulted in significantly higher greenhouse gas emissions. The non-inversion tillage strategy produced the lowest emissions of the two, with a GWP of 1732 kg CO_2 eq (approximately three times higher than the reference). The inversion tillage strategy, which

required fewer total passes than the non-inversion strategy, resulted in a higher GWP of 1972 kg CO2 eq, around nine times higher than the reference.

Table 9. Risk indicator scores for active substances of different strategies for *E. repens* patch control in arable land.

Strategy	Active Substance	Operator	Worker	Resident	Bystander	Soil Persistence	Ground Water	Aquatic Organisms	Bees	Earth Worms	Birds
Reference	glyphosate	3.86×10^{-3}	1.00	8.10×10^{3}	0.39	2.28×10^{-4}	1.75×10^{-7}	7.67×10^{-2}	5.47×10^{1}	2.06×10^{-5}	6.70×10^{-4}
Chemical	propaquizafop	7.07×10^{-2}	1.00	8.44×10^{3}	3.85	1.11×10^{-4}	0.00	0.39	2.79	2.40×10^{-5}	6.98×10^{-5}

Table 10. Global warming potential (GWP) (in kg CO_2 equivalents) and the Final Scenario Scores for all strategies for local weed control. Values for mechanical strategies are presented as the calculated score (minimum–maximum). The range represents a sensitivity analysis based on operational variability. Chemical strategies follow fixed Good Agricultural Practices and are treated as deterministic.

Strategy	GWP (kg CO_2 Equivalents)	Contribution of GWP to FSS (%)	Final Score
Reference	210	10	1.00
Chemical	210	10	0.70
Mechanical non-inversion tillage	1732 (1107–2358) [a]	100	1.00
Mechanical inversion tillage	1972 (1732–2213) [b]	100	1.00

[a] The range represents 1–3 passes with a cultivator, with 2 passes as the standard; [b] The range represents 1–3 passes with a bio-mulch rotary tiller, with 2 passes as the standard.

The FSS for the control of *E. repens* patches on arable land are presented in Table 10. The chemical alternative (propaquizafop) achieved an FSS of 0.70, which represents a notable reduction in risk compared to the reference strategy (FSS = 1.00) and succeeds in meeting the justification threshold of <0.75. Both mechanical alternatives resulted in an FSS of 1.00. In the absence of chemical inputs, the scores were determined exclusively by the GWP. These elevated emission levels prevented the mechanical strategies from achieving a score low enough within the decision-support grid, to justify replacing the reference strategy.

3.4. Railways

The individual risk indicators in Table 11 provide insight into the drivers of the high risk scores observed in this case study. Unlike the previous case studies where trade-offs between categories were mixed, the railway alternatives showed increased risks across almost all indicators.

Table 11. Total and individual risk indicator scores for active substances of different strategies for weed control in railway environment.

Strategy	Active Substance	Worker	Resident	Resident	Soil Persistence	Ground Water	Aquatic Organisms	Earth Worms	Bees
Reference	**ALL**	**4.57**	**9.44×10^{3}**	**9.44×10^{3}**	**1.67×10^{-3}**	**1.06×10^{-2}**	**0.11**	**8.97×10^{-5}**	**4.85×10^{1}**
	glyphosate	1.00	1.52×10^{3}	1.52×10^{3}	2.28×10^{-4}	1.75×10^{-7}	1.44×10^{-2}	3.87×10^{-6}	0.18
	2,4-D	0.57	4.56×10^{1}	4.56×10	1.25×10^{-4}	5.32×10^{-6}	1.92×10^{-4}	1.85×10^{-5}	4.00
	triclopyr	1.00	5.07×10^{3}	5.07×10^{3}	2.62×10^{-4}	2.53×10^{-3}	6.47×10^{-5}	1.38×10^{-5}	3.66
	flazasulfuron	1.00	5.29×10^{2}	5.29×10^{2}	8.23×10^{-4}	8.10×10^{-3}	7.49×10^{2}	4.77×10^{-5}	0.83
	glyphosate	1.00	2.27×10^{3}	2.27×10^{3}	2.28×10^{-4}	1.75×10^{-7}	2.15×10^{-2}	5.76×10^{-6}	2.21×10^{1}
Chemical 1 (PA)	**ALL**	**3.57**	**4.43×10^{8}**	**4.43×10^{8}**	**2.25×10^{-3}**	**1.87×10^{-2}**	**1.80**	**1.00**	**6.48×10^{4}**
	2,4-D	0.57	4.56×10^{1}	4.56×10	1.25×10^{-4}	5.32×10^{-6}	1.92×10^{-4}	1.85×10^{-5}	4.00
	triclopyr	1.00	5.07×10^{3}	5.07×10^{3}	2.62×10^{-4}	2.53×10^{-3}	6.47×10^{-5}	1.38×10^{-5}	3.66
	flazasulfuron	1.00	5.29×10^{2}	5.29×10^{2}	8.23×10^{-4}	8.10×10^{-3}	7.49×10^{-2}	4.77×10^{-5}	0.83
	pelargonic acid	0.00	4.04×10^{5}	4.04×10^{5}	1.07×10^{-4}	0.00	0.19	2.19×10^{-3}	5.92×10
	flazasulfuron	1.00	7.89×10^{2}	7.89×10^{2}	8.23×10^{-4}	8.10×10^{-3}	0.53	7.11×10^{-5}	1.01
	pelargonic acid	0.00	4.43×10^{8}	4.43×10^{8}	1.07×10^{-4}	0.00	7.00	1.00	6.47×10^{4}
Chemical 2 (PA + MH)	**ALL**	**5.57**	**3.04×10^{6}**	**2.12×10^{6}**	**2.46×10^{-3}**	**1.87×10^{-2}**	**1.41**	**8.60×10^{-3}**	**1.04×10^{3}**
	2,4-D	0.57	4.56×10^{1}	4.56×10	1.25×10^{-4}	5.32×10^{-6}	1.92×10^{-4}	1.85×10^{-5}	4.00
	triclopyr	1.00	5.07×10^{3}	5.07×10^{3}	2.62×10^{-4}	2.53×10^{-3}	6.47×10^{-5}	1.38×10^{-5}	3.66
	flazasulfuron	1.00	5.29×10^{2}	5.29×10^{2}	8.23×10^{-4}	8.10×10^{-3}	7.49×10^{-2}	4.77×10^{-5}	0.83
	pelargonic acid	0.00	1.22×10^{6}	2.97×10^{5}	1.07×10^{-4}	0.00	0.14	1.61×10^{-3}	4.36×10^{1}
	maleic hydrazide	1.00	2.98×10^{5}	2.98×10^{5}	1.04×10^{-4}	1.46×10^{-7}	3.98×10^{-2}	1.12×10^{-4}	4.06×10^{2}
	flazasulfuron	1.00	7.89×10^{2}	7.89×10^{2}	8.23×10^{-4}	8.10×10^{-3}	0.53	7.11×10^{-5}	1.01
	pelargonic acid	0.00	1.22×10^{6}	1.22×10^{6}	1.07×10^{-4}	0.00	0.58	6.61×10^{-3}	1.78×10^{2}
	maleic hydrazide	1.00	2.98×10^{5}	2.98×10^{5}	1.04×10^{-4}	1.46×10^{-7}	3.98×10^{-2}	1.11×10^{-4}	4.06×10^{2}

Resident risk score escalated sharply from 9.44×10^{3} (reference) to 4.43×10^{8} in the Chemical 1 (PA) strategy and 2.12×10^{6}, largely due to the high application rates of pelargonic acid required for efficacy, resulting from two annual applications. The only indicator to show improvement was worker risk in the Chemical 1 (PA) alternative strategy, which decreased from 4.57 (Reference) to 3.57, likely reflecting the toxicological characteristics of pelargonic acid relative to glyphosate which it replaced. However, in the Chemical 2 (PA + MH) strategy, worker risk increased to 5.57 due to the high contribution of maleic hydrazide.

All environmental indicators scored worse under the alternative strategies. Aquatic organisms risk increased from 0.11 (reference) to 1.80 (Chemical 1 (PA)) and 1.41 (Chemical 2 (PA + MH)). Earthworm risk rose from 8.97×10^{-5} (reference) to 1.00 (PA) and 8.60×10^{-3} (PA + MH). Similarly, bee risk escalated from 48,5 (reference) to 6.48×10^{4} in the Chemical 1 (PA) and to 1.04×10^{3} in the Chemical 2 (PA + MH) strategies. The doubling of flazasulfuron applications in both alternative strategies further increased risks to soil persistence and groundwater.

The FSS for the thermal alternative (hot water train) was determined exclusively by the GWP, which reached 12,568 kg CO_2 eq, approximately 32 times higher than the chemical strategies (393 kg CO_2 eq).

The FSS values for weed control on railway tracks are presented in Table 12. The chemical alternative based solely on pelargonic acid achieved an FSS of 0.97, while the combination of pelargonic acid and maleic hydrazide (PA + MH) resulted in an FSS of 1.00. Both values exceed the justification threshold of 0.75, indicating that neither alternative offers a meaningful reduction in overall risk compared to the reference strategy (FSS = 1.00). The thermal alternative resulted in an FSS of 1.00, due to the extreme carbon footprint described above.

Table 12. Global warming potential (GWP) (in kg CO_2 equivalents for 20 km of vegetation control) and the Final Scenario Scores for all strategies for weed control in railway environments. Values for mechanical strategies are presented as the calculated score (minimum–maximum). The range represents a sensitivity analysis based on operational variability. Chemical strategies follow fixed Good Agricultural Practices and are treated as deterministic.

Strategy	GWP (kg CO_2 Equivalents)	Contribution of GWP to FSS (%)	Final Score
Reference	393	10	1.00
Chemical alternative 1 (PA)	393	10	0.97
Chemical alternative 2 (PA + MH)	393	10	1.00
Thermal alternative	12,568 (12,568–25,686) [a]	100	1.00

[a] The range represents 2–4 passes, with 2 passes being the standard due to operational constraints. However, 4 passes is a better approximation for the same efficiency.

4. Discussion

4.1. Weed Control in Pome Fruit Orchards

The evaluation of weed control strategies in pome fruit orchards shows that none of the evaluated alternative strategies achieved an FSS below the justification threshold of 0.75. This indicates that, within the boundaries of the decision-support grid applied here and how weighting factors were assigned, substituting the conventional glyphosate-based reference strategy cannot be justified on the basis of overall risk reduction.

The chemical alternative (FSS = 0.96) did not offer a meaningful improvement relative to the reference strategy. Although phasing out glyphosate could address regulatory and societal concerns, its substitution with a mixture of selective herbicides (MCPA, dichlorprop-P and mecoprop-P) resulted primarily in a redistribution of risk rather than a true reduction. Most risk indicators showed an increase in risk, with only the bee risk indicator showing a decline. The need to deploy multiple active substances, to replace a single broad-spectrum herbicide effectively increases the toxicological load on the environment, counteracting the potential benefit of removing glyphosate.

The combined chemical + mechanical alternative came closest to the threshold (FSS = 0.81). This strategy reduced several environmental health risks, particularly those related to aquatic organisms, bees and earthworms. However, the chemical component of the strategy maintained elevated human exposure risk, preventing a substantial improvement in the overall risk profile. Moreover, the gain in reduced toxicity was partly offset by the higher GWP, which nearly doubled compared with the reference (Table 3), predominantly due increased fuel consumption associated with mechanical passes.

The mechanical alternative strategies (FSS = 1.00) illustrate a key limitation in organic weed management, namely the trade-off between toxicity and emissions. Although these strategies achieved a zero score for all chemical risk indicators, the high frequency of mechanical interventions (8 to 11 times per season) resulted in GWP values up to 7 times higher than the reference strategy. With GWP acting as the decisive indicator in these cases, no improvement in the FSS was observed.

From a practical perspective, relying solely on mechanical methods also introduces agronomic challenges not captured by the risk grid. Repeated passes with heavy machinery, such as the roll hoe-finger weeder combination, increase the risk of soil compaction and may potentially damage tree trunks and shallow roots [39,40]. Furthermore, intensive soil disturbance can lead to increased soil carbon emissions through enhanced mineralization of organic matter [41].

While chemical efficacy is also influenced by meteorological conditions, mechanical methods face stricter limitations regarding soil trafficability. Wet soil conditions can prevent timely interventions, allowing weeds to compete with trees for water and nutrients during critical growth stages. Other non-chemical alternatives such as mulch [39,42] or

thermal/physical methods (e.g., hot air, hot foam or electroweeding) [43] were not considered here. These strategies were excluded because they are not currently applied as standard commercial practice in Belgian pome fruit production and were therefore outside the scope of this study, which prioritized readily available operational technologies.

Ultimately, this analysis underscores that a direct substitution of glyphosate is difficult from the perspective of the grid. The current chemical alternatives, relying on higher loads of auxin-mimics and additional graminicides, maintain high indicator risk scores for the operator, bystander and consumer, while fully mechanical solutions currently impose an unacceptable carbon burden.

A robust integrated weed management (IWM) strategy for the future may require a more balanced approach. The mixed chemical + mechanical strategy represents a step in the right direction, offering reduced environmental exposure while avoiding the increased emissions associated with mechanical-only strategies.

In conclusion, the previous case study highlights that replacing a broad-spectrum herbicide with a suite of selective herbicides does not ensure lower ecotoxicological or human health risks. Moreover, a complete shift to mechanical strategies does not guarantee sustainability, as it often trades local ecotoxicity for global carbon burdens.

4.2. Localized Grassland Renewal

Although the chemical alternative did not meet the justification threshold (FSS = 0.92), it is worth noting that this strategy currently lacks legal authorization in Belgium for use on fallow arable land. Agronomically, rapid reseeding following termination is not always feasible with this approach due to the potential residual soil activity of the alternative herbicides (cycloxydim and MCPA) that can delay the establishment of the new sward.

The practical implementation of mechanical alternatives for grassland renewal faces even greater agronomic challenges. These strategies are highly weather-dependent, specifically the desiccation strategy which requires sufficiently dry conditions to be effective. If weather forces farmers to distribute treatments over two years, at least one silage cut or grazing rotation is likely to be lost. Additionally, if the new sward cannot be established before winter due to the prolonged mechanical treatment period, a high-yielding spring cut may be compromised. These production risks, combined with the high GWP identified in the results, suggest that mechanical renewal is currently a difficult strategy to implement sustainably, without substantial improvements in low-emission machinery or more efficient mechanical termination systems.

4.3. E. repens Control in Temporarily Uncultivated Arable Land

The evaluation of strategies for controlling local patches of *Elymus repens* (couch grass) on arable land highlights the difficulty of finding alternatives that simultaneously meet ecotoxicological and climate targets. The chemical alternative achieved an FSS of 0.70, making it the only strategy in this study to meet the justification threshold (<0.75). This favorable outcome is driven by the substitution of the broad-spectrum glyphosate with the selective graminicide propaquizafop, which delivered meaningful reductions in risks to terrestrial fauna, specifically bees and birds, where risk scores decreased substantially compared to the reference strategy. However, sensitivity analysis reveals that this success is conditional on the specific prioritization of ecotoxicity over climate impact. The strategy's passing score relies on the significant weighting of toxicity reductions (90%). Because the alternative offers no carbon benefit (emissions are effectively equal to the reference at 210 kg CO_2 eq/ha), increasing the weight of the GWP indicator serves to dilute the relative value of the toxicity reduction. Consequently, our analysis indicates a tipping point: If the weight assigned to GWP exceeds 25%, the FSS rises above 0.75, causing the strategy to fail

the justification threshold. Thus, propaquizafop represents a sustainable alternative only within a decision framework that maintains a strong priority on local ecotoxicity reduction.

Beyond the modeled risk profile, regulatory reality constraints further limit the viability of this alternative. Propaquizafop lacks legal authorization for use on fallow land in Belgium, meaning that even a passing FSS cannot translate into a practical replacement. From a regulatory perspective, however, the passing score (FSS = 0.70) suggests that a regulatory review is scientifically warranted. While the strategy introduces a trade-off by increasing aquatic and operator risks relative to the reference, the absolute values for these indicators remain well below the risk quotient threshold of 1.0 (e.g., operator risk 0.07; aquatic risk 0.39). This conclusion is supported by recent regulatory evaluations. For instance, EFSA [44] established safety limits for propaquizafop use on sensitive edible crops such as lettuces and salad plants, confirming that consumer exposure risks are acceptable even in high-intake scenarios. Consequently, a regulatory reform to authorize propaquizafop for fallow land (stubble cleaning) appears scientifically justified. The substantial reductions in risk to pollinators and birds outweigh the manageable increases in aquatic toxicity, which could be further mitigated through standard drift-reducing nozzles or buffer zones. Extending the registration of this graminicide to fallow periods would provide farmers with a critical tool for managing rhizomatous grasses without resorting to carbon-intensive tillage. Without regulatory adjustments, the current authorized chemical toolbox for controlling *E. repens* during the arable fallow period is insufficient to allow the replacement of glyphosate.

The mechanical alternatives both reach an FSS of 1.00. Both the non-inversion and inversion tillage strategies eliminated chemical risk entirely but showed an increase in GWP. The inversion tillage strategy (ploughing) proved to be the most carbon-intensive method in this study, generating nearly nine times more emissions than the reference strategy. Even the non-inversion tillage strategy, relying on a desiccation approach with a bio-mulch rotary tiller, while lower in emissions than the non-inversion approach, was still approximately three times more carbon-intensive than the chemical standard.

From an agronomic perspective, mechanical removal of a rhizome-forming weeds like *E. repens* is complicated with challenges not captured by the decision-support grid. The non-inversion desiccation strategy relies heavily on depletion by fragmentation and drying of surface-exposed rhizomes. If this is performed during a wet summer window or if the soil does not dry out sufficiently between the required passes, weed control efficiency may be negatively affected. This corresponds with the established biology of *Elymus repens*, where rhizome fragmentation without sufficient desiccation can stimulate bud dormancy breaking, potentially exacerbating infestations [27,45]. Conversely, while the inversion strategy is less weather-dependent for immediate efficacy, it, like the intensive non-inversion strategy, contradicts modern soil conservation principles by disrupting soil structure and increasing erosion risks. Moreover, these intensive tillage strategies should be combined with a catch crop or winter crop to mitigate nitrate leaching caused by increased mineralization [46].

In summary, while the chemical alternative provides a scientifically justifiable replacement (FSS = 0.70) under the current decision framework, its lack of authorization prevents its implementation. Meanwhile the mechanical alternatives, despite their lack of direct chemical toxicity (they still pose physical risks to soil-dwelling organisms), are difficult to justify as sustainable replacements due to their high carbon footprint and poor performance consistency across variable weather conditions.

4.4. Railways

Application of the decision-support grid to railway weed control leads to a clear conclusion, none of the evaluated alternatives currently justify replacing the standard glyphosate-based strategy. With FSS values of 0.97 and 1.00, the chemical alternatives offer virtually no improvement in the aggregated risk profile and, in some cases, shift the burden significantly toward acute ecotoxicity and resident exposure.

The classification of pelargonic acid as a natural substance does not intrinsically ensure a superior overall safety profile, as risk is fundamentally a function of the dose required for efficacy rather than origin. To match the performance of low-dose systemic herbicides, pelargonic acid-based strategies require significantly higher active substance rates. Specifically, while the reference strategy typically utilizes less than 2 kg of glyphosate per treated hectare, the alternative strategies require up to 31 kg of pelargonic acid per hectare to achieve effective burn-down. While this resulted in a slight reduction in worker risk for the pure pelargonic acid strategy (decreasing from 4.57 to 3.57), this local benefit is effectively negated by the consequences of the high chemical load on the broader environment. This high chemical load is directly responsible for the exponential increase in risks to residents ($10^3 \rightarrow 10^8$) and bees ($10^1 \rightarrow 10^4$). The vast quantity of active substance introduces a new tier of acute exposure risks that outweighs the chronic toxicity concerns associated with glyphosate.

Because pelargonic acid lacks systemic action and has a narrower weed spectrum (performing poorly on established grasses), the alternative strategies require a higher frequency of the complementary residual herbicide, flazasulfuron (two applications per year vs. one). This compensatory measure worsens groundwater and soil persistence indicators. This illustrates a key challenge when replacing systemic synthetic herbicides with non-synthetic contact herbicides: the loss of systemic, long-lasting efficacy often requires more frequent treatments or increased reliance on residual soil-active herbicides, which can offset the anticipated environmental benefits.

While bio-herbicides are often perceived as low-risk, our results corroborate the findings of Smith & Perfetti (2020) [47], who noted that the high application rates and higher frequency required for contact bio-herbicides can result in ecotoxicological loads exceeding those of synthetic systemic herbicides. This is further supported by the recent regulatory review of pelargonic acid by EFSA [48], which confirms that the high active substance loading (up to 30 kg/ha) necessitates strict mitigation measures, such as vegetated buffer strips (up to 20 m) and significant drift or run-off reduction, to address critical risks to aquatic organisms and non-target arthropods.

The thermal alternative (hot water train) is likewise uncompetitive. Although not scoreable on all the chemical indicators, its energy demand increases substantially, multiplying the GWP 32-fold. For thermal control to become a viable component of a sustainable strategy, the technology would need a fundamental redesign based on electrification and renewable energy. This dependency on fossil fuels extends to the supplementary mechanical operations required on the safety paths. Our finding that these mechanical interventions significantly increases GWP aligns with recent LCAs in row crop systems [30], which identified fuel consumption as a major driver of greenhouse gas emissions in non-chemical weed management.

It is critical to note that the environmental burdens presented here likely represent conservative minimum estimates for the alternative strategies. The study assumes a functional unit of comparable efficacy between glyphosate and alternatives. However alternatives often require higher treatment frequencies or slower application speeds to effectively control persistent perennial weeds on ballast. If these real-world efficacy gaps were fully quantified, the required number of applications could be higher, further elevating

the already prohibitive GWP of thermal strategies and the ecotoxicity load of organic acids. Consequently, the conclusion that these alternatives do not currently offer a sustainable substitution is robust, as lower efficacy would only exacerbate the identified trade-offs.

Operational constraints remain another major barrier. Railway networks operate with limited maintenance windows and the chemical alternatives require larger spray volumes, reducing the autonomy of the spray train and increasing the frequency of refilling stops, thereby disrupting commercial traffic. Furthermore, the combination of pelargonic acid and sulfonylureas (like flazasulfuron) is subject to patent restrictions [49], complicating its operational adoption.

In this context, where zero vegetation-tolerance is often mandatory for safety, the reference strategy relying on glyphosate remains the most optimized solution. It balances efficacy, operational feasibility, and environmental risk more effectively than any of the current alternatives.

4.5. Limitations of the Proposed Framework

The evaluation of these diverse case studies using the decision-support tool highlighted several limitations. The GWP estimate for non-chemical methods (e.g., tine cultivators, hot water trains) rely on available database proxies and do not include the full manufacturing life cycle or secondary effects like soil carbon release. Second, the EVA indicator for beneficial arthropods is not developed for herbicides, leaving an important gap in the biodiversity assessment. Conversely, for non-chemical methods, current indicators fail to quantify the direct physical impacts on fauna. This includes the mechanical disturbance of soil-nesting beneficial organisms (e.g., earwigs, ground-nesting bees) by cultivators, as well as the acute risks posed by thermal treatments. Specifically, the application of hot water trains presents a direct hazard to thermophilic species, such as lizards sunbathing on the railway ballast and other soil-dwelling insects along the tracks. Third, the FSS only evaluates risk, not agronomic performance. Crucially, the strategies in this study were not validated for agronomic efficacy. If non-chemical methods fail to provide season-long control, this may necessitate increased treatment frequency in the long run, thereby reducing environmental benefits.

While this study provides a comprehensive assessment of weed management strategies, the FSS must be interpreted within the constraints of the analytical framework. Although the individual components represent quantitative risk metrics, their aggregation into an FSS is designed to facilitate structured comparison of specific management scenarios within a defined regional context, rather than to establish a universal ranking of environmental sustainability. Similarly, the justification threshold (FSS < 0.75) serves as a pragmatic operational benchmark for identifying relative improvement, rather than an objective scientific boundary or regulatory safety limit. The aggregation of results is inherently dependent on the specific weighting factors used (currently 10% GWP, 90% aggregated ecotoxicity). A sensitivity analysis (varying GWP weight from 0% to 100%) revealed distinct behavioral trends across the strategies.

In mechanical and thermal strategies, a monotonic worsening of scores is observed when increasing the GWP. Since their carbon footprints are 1.3 to 32 times higher than the reference, they only approach a favorable ranking if climate impacts are disregarded (0% GWP weight). Conversely, the chemical strategy in pome fruit has a lower GWP than the reference, thus showing an improved score as GWP weight increased. However, it always failed to reach the threshold of 0.75. The successful chemical strategy (FSS 0.70) displayed a tipping point in local weed patch control. Because its success relies on toxicity reduction (while GWP remains equal to the reference), increasing the GWP weight dilutes

this benefit. The strategy ceases to be a justifiable alternative (FSS > 0.75) if the GWP weight exceeds 25%.

This confirms that while the grid is robust in rejecting high-carbon mechanical alternatives, the acceptance of chemical alternatives can be sensitive to the specific balance struck between global climate goals and local ecotoxicology.

Finally, while this study focused on environmental parameters, practical adoption remains a challenge. The economic viability of increasing tractor passes is a critical barrier, as is the technical feasibility of integrating these new strategies into existing cropping systems (e.g., logistical timing and machinery compatibility).

5. Conclusions

This study applied a multi-criteria decision-support grid to assess the environmental and human health impacts of replacing glyphosate-based weed control in pome fruit orchards, grassland renewal, temporarily non-cultivated arable land and railway infrastructure. Withing the Belgian high-intensity systems analyzed and under the assumptions embedded in the applied risk and life cycle assessment framework, the evaluated alternative strategies did not demonstrate a consistently improved environmental performance relative to the reference strategy. Rather, the decision involves navigating complex trade-offs among toxicity, efficacy and climate impacts.

Only one of the proposed strategies achieved the FSS threshold of <0.75 necessary to clearly support substitution, namely the use of the selective graminicide propaquizafop in local weed patch control (FSS = 0.70). However, this success is currently theoretical, as the product lacks regulatory authorization for this specific use. In the remaining case studies, chemical alternatives often shifted rather than reduced the risk. For instance, in railway maintenance, the high application rates required for contact bio-herbicides (e.g., pelargonic acid) generated acute ecotoxicity risks to aquatic organisms and pollinators that exceeded those of the reference strategy. Likewise, substituting glyphosate with selective herbicide mixtures in orchards maintained high risks to residents and groundwater.

Non-chemical alternatives exhibited a pronounced conflict between toxicity reduction and climate goals. While mechanical and thermal strategies eliminated chemical exposure, they consistently increased GWP. In the most extreme case, thermal weed control on railways, carbon emissions were approximately 32 times higher than the reference. This demonstrates that for this strategy, the elimination of chemical risk is accompanied by a sharply increased carbon footprint under current technological conditions.

These findings hold important implications for the European Green Deal's target of reducing pesticide use. The case studies suggest that removing glyphosate without viable low-risk, high-efficacy alternatives may shift the environmental burden toward elevated greenhouse gas emissions or acute ecotoxicity, rather than achieving a holistic reduction in human and environmental harm.

In conclusion, within the empirical scope of this analysis, the results suggest that improving the sustainability of weed management cannot rely solely on prohibiting specific active substances, particularly if the environmental and human health impacts of alternatives are not considered, or if viable sustainable alternatives are lacking. Consequently, future strategies must prioritize a site-specific integrated weed management (IWM) approach. This entails combining conventional methods with innovative non-chemical techniques to minimize trade-offs, rather than relying on a single dominant strategy. Promising strategies include precision patch spraying to reduce active substance inputs [50] and the use of laser-based technologies, which have recently been shown in vegetable systems to provide weed control comparable to chemical herbicides without soil disturbance. [51]. Furthermore, electrification of precision weeding is required to decouple non-chemical control

from high carbon emissions. Life cycle assessments suggest that, under low-carbon electricity scenarios, replacing conventional diesel tractors with autonomous battery-electric platforms can reduce total global warming potential by up to 74%. [52], thereby resolving the primary trade-off identified in this study.

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Appendix A

Table A1. Overview of field operations for the pome fruit weed control strategies and their corresponding life cycle assessment (LCA) proxies.

Strategy	Field Operation	LCA Proxy
Reference	Chemical weeding Transport	Plant protection, chemical weeding, with atomizer 400 L/FR U Transporting to farm, with trailer (<15 T) heavy tractor, processing/RoW U
Chemical	Chemical weeding Transport	Plant protection, chemical weeding, with atomizer 400 L/FR U Transporting to farm, with trailer (<15 T) heavy tractor, processing/RoW U
Mixed Chemical + Mechanical	Chemical weeding Line/swivel mower Transport	Plant protection, chemical weeding, with atomizer 400 L/FR U Mowing, with rotary mower 3 m/FR U Transporting to farm, with trailer (<15 T) heavy tractor, processing/RoW U
Mechanical 1	Rotary cultivator Line/swivel mower Transport	Hoeing, with rotary hoe 3 m/FR U Mowing, with rotary mower 3 m/FR U Transporting to farm, with trailer (<15 T) heavy tractor, processing/RoW U
Mechanical 2	Roll hoe + finger weeder Line/swivel mower Transport	Plant protection, weeding, with vibrating tine/FR U Mowing, with rotary mower 3 m/FR U Transporting to farm, with trailer (<15 T) heavy tractor, processing/RoW U
Mechanical 3	Roll hoe + finger weeder Rotary cultivator Line/swivel mower Transport	Plant protection, weeding, with vibrating tine/FR U Hoeing, with rotary hoe/FR U Mowing, with rotary mower 3 m/FR U Transporting to farm, with trailer (<15 T) heavy tractor, processing/RoW U

Table A2. Overview of field operations for the localized grassland renewal strategies and their corresponding life cycle assessment (LCA) proxies.

Strategy	Field Operation	LCA Proxy
Reference	Chemical weeding Transport	Plant protection, chemical weeding, with atomizer 400 L/FR U Transporting to farm, with trailer (<15 T) heavy tractor/FR U
Chemical	Chemical weeding Transport	Plant protection, chemical weeding, with atomizer 400 L/FR U Transporting to farm, with trailer (<15 T) heavy tractor/FR U
Mechanical Best-Case	Bio-mulch rotary tiller Cultivator Transport	Soil preparation, with rotary tiller/FR U Harrowing, with vibrating tine cultivator (standard equipment) 5 m/FR U Transporting to farm, with trailer (<15 T) heavy tractor/FR U
Mechanical Worst-Case	Cultivator Transport	Harrowing, with vibrating tine cultivator (standard equipment) 5 m/FR U Transporting to farm, with trailer (<15 T) heavy tractor/FR U

Table A3. Overview of field operations for the local weed patch control strategies and their corresponding LCA proxies.

Strategy	Field Operation	LCA Proxy
Reference	Chemical weeding Transport	Plant protection, chemical weeding, with atomizer 400 L/FR U Transporting to farm, with trailer (<15 T) heavy tractor/FR U
Chemical	Chemical weeding Transport	Plant protection, chemical weeding, with atomizer 400 L/FR U Transporting to farm, with trailer (<15 T) heavy tractor/FR U
Mechanical Non-inversion	Bio-mulch rotary tiller Cultivator Transport	Soil preparation, with rotary tiller/FR U Harrowing, with vibrating tine cultivator (standard equipment) 5 m/FR U Transporting to farm, with trailer (<15 T) heavy tractor/FR U
Mechanical Inversion	Bio-mulch rotary tiller Ploughing Transport	Soil preparation, with rotary tiller/FR U Ploughing, with 5 or 6 soc plough/FR U Transporting to farm, with trailer (<15 T) heavy tractor/FR U

Table A4. Overview of field operations for the railway weed control strategies and their corresponding LCA proxies.

Strategy	Field Operation	LCA Proxy
Reference	Spray train	Transport, freight train {Europe without Switzerland} | diesel | Cut-off, S
Chemical 1 (PA)	Spray train	Transport, freight train {Europe without Switzerland} | diesel | Cut-off, S
Chemical 2 (PA + MH)	Spray train	Transport, freight train {Europe without Switzerland} | diesel | Cut-off, S
Thermal control	Transport Heating of water Mowing	Transport, freight train {Europe without Switzerland} | diesel | Cut-off, S Heat, central or small-scale, other than natural gas {CH} | heat production, light fuel oil, at boiler 100 kW, non-modulating | Cut-off, S Mowing, with rotary mower 3 m/FR U

References

1. Oerke, E.C. Crop losses to pests. *J. Agric. Sci.* **2006**, *144*, 31–43. [CrossRef]
2. Duke, S.O.; Powles, S.B. Glyphosate: A once-in-a-century herbicide. *Pest Manag. Sci.* **2008**, *64*, 319–325. [CrossRef]
3. IARC, IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. Some Organophosphate Insecticides and Herbicides. Lyon (FR): International Agency for Research on Cancer. 2017. (IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, No. 112.). Available online: https://www.ncbi.nlm.nih.gov/books/NBK436774/ (accessed on 1 December 2025).
4. EFSA (European Food Safety Authority). Conclusion on the Peer Review of the Pesticide Risk Assessment of the Active Substance Glyphosate. *EFSA J.* **2015**, *13*, 4302. [CrossRef]
5. US Environmental Protection Agency. Glyphosate Interim Registration Review Decision: Case Number 0178, Washington, DC, 2020. Available online: www.regulations.gov (accessed on 30 January 2026).
6. Shu, S.; Chen, X.; Ren, J.; Yu, X.; Zhang, H.; Yu, Y. Glyphosate Induces Anxiety-Like Behaviors in Mice via Activating NLRP3-Mediated Hippocampal Microglia Pyroptosis. *J. Appl. Toxicol.* **2025**, *45*, 1572–1582. [CrossRef]
7. Chiantia, G.; Comai, D.; Hidisoglu, E.; Gurgone, A.; Franchino, C.; Carabelli, V.; Marcantoni, A.; Giustetto, M. Glyphosate impairs both structure and function of GABAergic synapses in hippocampal neurons. *Neuropharmacology* **2025**, *262*, 110183. [CrossRef]
8. Rani, N.; Alam, M.M.; Parvez, S. Toxicity of glyphosate accelerates neurodegeneration in *Caenorhabditis elegans* model of Alzheimer's disease. *Front. Toxicol.* **2025**, *7*, 1578230. [CrossRef]
9. Kaur, G.; Farooq, S.; Malik, Y.S.; Sodhi, S.S.; Sethi, R.S. Assessment of Lung Damage via Mitochondrial ROS Production Upon Chronic Exposure to Fipronil and Imidacloprid. *Agric. Res.* **2024**, *13*, 755–762. [CrossRef]
10. Lehman, P.C.; Cady, N.; Ghimire, S.; Shahi, S.K.; Shrode, R.L.; Lehmler, H.-J.; Mangalam, A.K. Low-dose glyphosate exposure alters gut microbiota composition and modulates gut homeostasis. *Environ. Toxicol. Pharmacol.* **2023**, *100*, 104149. [CrossRef]
11. Chang, V.C.; Zhou, W.; Berndt, S.I.; Andreotti, G.; Yeager, M.; Parks, C.G.; Sandler, D.P.; Rothman, N.; Freeman, L.E.B.; Machiela, M.J.; et al. Glyphosate use and mosaic loss of chromosome y among male farmers in the agricultural health study. *Environ. Health Perspect.* **2023**, *131*, 127006. [CrossRef]
12. Sylwestrzak, Z.; Zgrundo, A. Are Toxic Substances Always Toxic? Case Studies of Different Organismal Responses Based on Brackish-Water Microphytobenthic Communities from the Baltic Sea. *Appl. Sci.* **2023**, *13*, 12238. [CrossRef]
13. Klátyik, S.; Simon, G.; Oláh, M.; Takács, E.; Mesnage, R.; Antoniou, M.N.; Zaller, J.G.; Székács, A. Aquatic ecotoxicity of glyphosate, its formulations, and co-formulants: Evidence from 2010 to 2023. *Environ. Sci. Eur.* **2024**, *36*, 22. [CrossRef]
14. Lozano, V.; Paolucci, E.; Sabatini, S.; Abad, T.N.; Muñoz, C.; Liquin, F.; Hollert, H.; Sylvester, F. Assessing the impact of imidacloprid, glyphosate, and their mixtures on multiple biomarkers in *Corbicula largillierti*. *Sci. Total Environ.* **2024**, *942*, 173685. [CrossRef]

15. Stevens, D.; Kramer, A.T.; Coogan, M.A.; Sayes, C.M. Developmental effects of zebrafish (*Danio rerio*) embryos after exposure to glyphosate and lead mixtures. *Ecotoxicol. Environ. Saf.* **2024**, *271*, 115886. [CrossRef]
16. Panda, S.S.; Das, I.I.; Biswas, G.; Sundaray, J.K.; Kumar, R.; Sahoo, L. Effects of Sublethal Concentrations of the Herbicide, Glyphosate, on Embryonic Development of the Indian Major Carp, *Labeo rohita*. *J. Appl. Ichthyol.* **2023**, *2023*, 5512805. [CrossRef]
17. Azadikhah, D.; Varcheh, M.; Yalsuyi, A.M.; Vajargah, M.F.; Chorehi, M.M.; Faggio, C. Hematological and Histopathological Changes of Juvenile Grass Carp (*Ctenopharyngodon idella*) Exposed to Lethal and Sublethal Concentrations of Roundup (Glyphosate 41% SL). *Aquac. Res.* **2023**, *2023*, 4351307. [CrossRef]
18. Spulber, S.; Reis, L.; Alexe, P.; Ceccatelli, S. Decreased activity in zebrafish larvae exposed to glyphosate-based herbicides during development—Potential mediation by glucocorticoid receptor. *Front. Toxicol.* **2024**, *6*, 1397477. [CrossRef]
19. Bemelmans, N.; Arbalestrie, B.; Dailly, H.; Bodart, E.; Agnan, Y. Influence of glyphosate and aminomethylphosphonic acid on the mobility of trace elements in uncontaminated and contaminated agricultural soils. *Environ. Sci. Pollut. Res.* **2023**, *30*, 103983–103995. [CrossRef]
20. Bearson, B.L.; Douglass, C.H.; Duke, S.O.; Moorman, T.B.; Tranel, P.J. Effects of glyphosate on antibiotic resistance in soil bacteria and its potential significance: A review. *J. Environ. Qual.* **2025**, *54*, 160–180. [CrossRef]
21. Wei, X.; Pan, Y.; Zhang, Z.; Cui, J.; Yin, R.; Li, H.; Qin, J.; Li, A.J.; Qiu, R. Biomonitoring of glyphosate and aminomethylphosphonic acid: Current insights and future perspectives. *J. Hazard. Mater.* **2024**, *463*, 132814. [CrossRef]
22. Altmanninger, A.; Brandmaier, V.; Spangl, B.; Gruber, E.; Takács, E.; Mörtl, M.; Klátyik, S.; Székács, A.; Zaller, J.G. Glyphosate-Based Herbicide Formulations and Their Relevant Active Ingredients Affect Soil Springtails Even Five Months after Application. *Agriculture* **2023**, *13*, 2260. [CrossRef]
23. de Lima e Silva, C.; Pelosi, C. Effects of glyphosate on earthworms: From fears to facts. *Integr. Environ. Assess. Manag.* **2024**, *20*, 1330–1336. [CrossRef]
24. Kaakinen, K.; Ramula, S.; Loukola, O.J.; Helander, M. Effects of glyphosate and glyphosate-based herbicide on learning and memory of the buff-tailed bumblebee (*Bombus terrestris*). *Entomol. Exp. Appl.* **2024**, *172*, 324–333. [CrossRef]
25. Vázquez, D.E.; Verellen, F.; Farina, W.M. Early exposure to glyphosate during larval development induces late behavioural effects on adult honey bees. *Environ. Pollut.* **2024**, *360*, 124674. [CrossRef]
26. Beckie, H.J.; Flower, K.C.; Ashworth, M.B. Farming without glyphosate? *Plants* **2020**, *9*, 96. [CrossRef]
27. Ringselle, B.; de Cauwer, B.; Salonen, J.; Soukup, J. A review of non-chemical management of couch grass (*Elymus repens*). *Agronomy* **2020**, *10*, 1178. [CrossRef]
28. Klauk, B.; Petersen, J. The potential of glyphosate-alternatives like electrophysicaweeding in the stale seedbed method for *Alopecurus myosuroides* (Huds.) control. *Plant Soil Environ.* **2023**, *69*, 522–531. [CrossRef]
29. Gensch, L.; Jantke, K.; Rasche, L.; Schneider, U.A. Pesticide risk assessment in European agriculture: Distribution patterns, ban-substitution effects and regulatory implications. *Environ. Pollut.* **2024**, *348*, 123836. [CrossRef]
30. Fishkis, O.; Weller, J.; Lehmhus, J.; Pöllinger, F.; Strassemeyer, J.; Koch, H.J. Ecological and economic evaluation of conventional and new weed control techniques in row crops. *Agric. Ecosyst. Environ.* **2024**, *360*, 108786. [CrossRef]
31. Raimondi, M.; López, E.D.; Peeters, L.; Reybroeck, W.; Belien, T.; Bylemans, D.; Buysse, J.; De Cauwer, B.; Spanoghe, P. A Decision-Support Grid for Evaluating Neonicotinoid Alternatives Based on Environmental and Human Health Impact. *Agronomy* **2025**, *15*, 2392. [CrossRef]
32. Clay, D.V.; Dixon, F.L.; Willoughby, I. Efficacy of graminicides on grass weed species of forestry. *Crop. Prot.* **2006**, *25*, 1039–1050. [CrossRef]
33. Vlaamse Milieumaatschappij. Duurzaam Gebruik van Pesticiden—2020. 2021. Available online: www.vmm.vlaanderen.be (accessed on 29 February 2024).
34. Vercruysse, F.; Steurbaut, W. POCER, the pesticide occupational and environmental risk indicator. *Crop. Prot.* **2002**, *21*, 307–315. [CrossRef]
35. Charistou, A.; Coja, T.; Craig, P.; Hamey, P.; Martin, S.; Sanvido, O.; Chiusolo, A.; Colas, M.; Istace, F. Guidance on the assessment of exposure of operators, workers, residents and bystanders in risk assessment of plant protection products. *EFSA J.* **2022**, *20*, e07032. [CrossRef]
36. Lewis, K.A.; Tzilivakis, J.; Warner, D.J.; Green, A. An international database for pesticide risk assessments and management. *Hum. Ecol. Risk Assess.* **2016**, *22*, 1050–1064. [CrossRef]
37. Adriaanse, P.; Arce, A.; Focks, A.; Ingels, B.; Jölli, D.; Lambin, S.; Rundlöf, M.; Süßenbach, D.; Del Aguila, M.; Ercolano, V.; et al. Revised guidance on the risk assessment of plant protection products on bees (*Apis mellifera*, *Bombus* spp. and solitary bees). *EFSA J.* **2023**, *21*, e07989. [CrossRef]
38. Colomb, V.; Amar, S.A.; Mens, C.B.; Gac, A.; Gaillard, G.; Koch, P.; Mousset, J.; Salou, T.; Tailleur, A.; van der Werf, H.M. AGRIBALYSE®, the French LCI Database for agricultural products: High quality data for producers and environmental labelling. *OCL—Oilseeds Fats* **2015**, *22*, D104. [CrossRef]

39. Granatstein, D.; Wiman, M.; Kirby, E.; Mullinix, K. Sustainability Trade-Offs in Organic Orchard Floor Management. *Acta Hortic.* **2010**, *873*, 115–122. [CrossRef]
40. Merwin, I.A. Orchard-floor management systems. In *Apples: Botany, Production and Uses*; Ferree, D.C., Ed.; Ohio State University: Warrington, UK; HortResearch: Auckland, New Zealand, 2003; pp. 303–319.
41. Reicosky, D.C. Tillage-induced CO_2 emission from soil. *Nutr. Cycl. Agroecosyst.* **1997**, *49*, 273–285. [CrossRef]
42. Paušič, A.; Tojnko, S.; Lešnik, M. Permanent, undisturbed, in-row living mulch: A realistic option to replace glyphosate-dominated chemical weed control in intensive pear orchards. *Agric. Ecosyst. Environ.* **2021**, *318*, 107502. [CrossRef]
43. Antonopoulos, N.; Kousta, A.; Gazoulis, I.; Kontogeorgou, V.; Danaskos, M.; Kanatas, P.; Petraki, D.; Travlos, I. Optimization of hot foam applications for thermal weed control in perennial crops and open-field vegetables. *Open Agric.* **2025**, *10*, 20250438. [CrossRef]
44. Anastassiadou, M.; Brancato, A.; Carrasco Cabrera, L.; Ferreira, L.; Greco, L.; Jarrah, S.; Kazocina, A.; Leuschner, R.; Magrans, J.O.; Miron, I.; et al. Modification of the existing maximum residue levels for quizalofop (resulting from the use of propaquizafop) in lettuces and salad plants. *EFSA J.* **2019**, *17*, e05747. [CrossRef]
45. Ringselle, B.; Bertholtz, E.; Magnuski, E.; Brandsæter, L.O.; Mangerud, K.; Bergkvist, G. Rhizome fragmentation by vertical disks reduces *Elymus repens* growth and benefits italian ryegrass-white clover crops. *Front. Plant Sci.* **2018**, *8*, 2243. [CrossRef]
46. Askegaard, M.; Olesen, J.E.; Rasmussen, I.A.; Kristensen, K. Nitrate leaching from organic arable crop rotations is mostly determined by autumn field management. *Agric. Ecosyst. Environ.* **2011**, *142*, 149–160. [CrossRef]
47. Smith, C.J.; Perfetti, T.A. A comparison of the persistence, toxicity, and exposure to high-volume natural plant-derived and synthetic pesticides. *Toxicol. Res. Appl.* **2020**, *4*, 2397847320940561. [CrossRef]
48. Álvarez, F.; Arena, M.; Auteri, D.; Leite, S.B.; Binaglia, M.; Castoldi, A.F.; Chiusolo, A.; Colagiorgi, A.; Colas, M.; Crivellente, F.; et al. Updated peer review of the pesticide risk assessment of the active substance pelargonic acid (nonanoic acid). *EFSA J.* **2025**, *23*, e9408. [CrossRef]
49. Michael, K.; Marienhagen, C. Herbicide Combination Containing Pelargonic Acid and Defined ALS Inhibitors. U.S. Patent No. US009999221B2, 19 June 2018.
50. Li, H.; Travlos, I.; Qi, L.; Kanatas, P.; Wang, P. Optimization of herbicide use: Study on spreading and evaporation characteristics of glyphosate-organic silicone mixture droplets on weed leaves. *Agronomy* **2019**, *9*, 547. [CrossRef]
51. Sosnoskie, L.M.; Bill, K.; Butler-Jones, A.; Bouchelle, W.M.; Besançon, T.E. Deep learning-based laser weed control compared to conventional herbicide application across three vegetable production systems. *Pest Manag. Sci.* **2025**, *81*, 4922–4936. [CrossRef]
52. Lagnelöv, O.; Larsson, G.; Larsolle, A.; Hansson, P.A. Life cycle assessment of autonomous electric field tractors in Swedish agriculture. *Sustainability* **2021**, *13*, 11285. [CrossRef]

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