agronomy

Review

A Review of Non-Chemical Management of Couch Grass (*Elymus repens*)

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Abstract: Couch grass (*Elymus repens*) is a morphologically diverse, rhizomatous, perennial grass that is a problematic weed in a wide range of crops. It is generally controlled by glyphosate or intensive tillage in the intercrop period, or selective herbicides in non-susceptible crops. The aim of this review is to determine the efficacy of non-chemical strategies for *E. repens* control. The review shows that indirect control measures like crop choice, subsidiary crops, and fertilizer regimes influence *E. repens* abundance, but usually cannot control *E. repens*. Defoliation (e.g., mowing) can control *E. repens* growth, but efficacy varies between clones, seasons, and defoliation frequencies. Tillage in the intercrop period is still the main direct non-chemical control method for *E. repens* and its efficacy can be increased, and negative side-effects minimized by an appropriate tillage strategy. Some new tillage implements are on the market (Kvik-up type machines) or under development (root/rhizome cutters). Alternative methods that can kill *E. repens* rhizomes (e.g., steaming, soil solarization, biofumigation, hot water, flooding) often have high costs or time requirements. More studies on the effect of cropping system approaches on *E. repens* and other perennial weeds are needed.

Keywords: *Elytrigia repens*; *Agropyron repens*; quackgrass; tillage; perennial; organic agriculture; mechanical weeding; IPM; steaming; defoliation

1. Introduction

1.1. Aim and Purview

A glyphosate ban, which is currently under serious discussion within the EU, would likely result in a large disruption in the current agricultural system and a shift towards more complex and integrated weed control in which non-chemical control are likely to be an integral component [1]. Creeping perennial weeds with a high tillage tolerance, such as *Elymus repens* (L.) Gould, are one of the weed groups most likely to benefit from a glyphosate ban. The aim of this review is to determine the efficacy of non-chemical strategies for *E. repens* control. Focus is on direct control methods, but some indirect control measures are also discussed. The pros and cons (efficacy, consistency, flexibility, availability, compatibility, costs, dangers, and environmental effects) of each tool and strategy are discussed in varying detail depending on the available information. The main point of comparison is the most common chemical control method, i.e., glyphosate.

1.2. Description and Biology

Latin names: *Elymus repens* (L.) Gould, *Elytrigia repens* (L.) Desv. ex Nevski, *Agropyron repens* (L.) P. Beauv., *Triticum repens* L.

Common names: Couch grass, Common Couch, Quackgrass, Quackgrass Rye.

Elymus repens is a highly competitive, allelopathic, perennial grass that propagates both sexually through seeds and asexually through rhizomes. It is present in most of the temperate regions of the world on all continents except Antarctica [2,3], and has been listed as one of the world's worst weeds [4]. In Northern Europe, *E. repens* is a common and aggressive grass species favored by cereal-dominated crop rotations and nitrogen fertilization [5,6]. However, repeated weed surveys in Northern Europe have shown that the extensive herbicide use in the region, particularly glyphosate, has led to a decline in *E. repens* frequency [7,8].

The biology of *E. repens* has been extensively studied (e.g., [2,9–12]). It can live on a wide range of soils ranging from wet to dry, acid to alkaline, and with a high salt content [3]. Andreasen et al. [13] also found that phosphorus, potassium, and manganese availability did not affect *E. repens* distribution. The life spans of *E. repens* rhizomes and seeds are short compared to many other perennial weeds, usually no longer than a few years, and the seeds lack a long-distance dispersal mechanism. *Elymus repens* seed does not require an after-ripening period and can germinate after shedding provided that there are diurnal temperature fluctuations [2].

Optimal rhizome depth for plant establishment and growth is 2.5–7.5 cm [14], and consequently most rhizomes can be found above 10 cm soil depth, and new rhizomes will develop shallowly in the absence of tillage [15]. *Elymus repens* rhizome buds have no innate dormancy except from apical dormancy [16]. This means the plants can re-sprout and grow throughout the year, unless hindered by environmental factors, such as low temperatures [17], low light [18], or dry conditions [19]. Low light levels especially limit *E. repens* rhizome production, as biomass is allocated towards aboveground biomass under low light conditions [17,20–22]. Low light also delays the development of aerial and rhizome offshoots beyond the 3–4 leaf stage [18,23]. Thus, competition from other plants during the summer can delay real growth until the canopy becomes lighter after harvest [10,24].

Elymus repens is competitive against essentially all annual crops, but the size of the *E. repens* population greatly influences the potential yield loss [25]. In grasslands/leys, *E. repens* is generally unwanted as it can replace the sown species that are more high yielding and more nutritious [26]. It can also open up the sward, enabling other weeds to establish [27]. Moreover, if *E. repens* is not controlled before rotating from a grassland ley to an annual crop, the effect on the annual crop yield is likely to be significant [28]. There is a surprising lack of studies on *E. repens* effect in orchards, even though *E. repens* can be highly problematic in these crops [29]. However, *E. repens* has been shown to cause considerable losses during tree establishment [30].

Elymus repens contains a number of allelopathic chemicals, some of which are released by healthy living shoots and/or rhizomes (examples in [31,32]) and some released by decaying plant parts (examples in [33–36]). Agropyrene (or hexa-2,4-diynylbenzene) constitutes 95% of *E. repens* essential oils and has an antibiotic effect on fungi and bacteria [33]. Other substances have been identified and are listed by Glinwood et al. [37]; of which, DIBIO and ferulic acid have been found to have growth inhibiting effects at high concentrations, especially on dicot species [31].

1.3. Genetic and Morphological Variation

The available literature shows that *E. repens* displays pronounced morphological and physiological variation within and between natural *E. repens* populations, as a result of phenotypic plasticity or genotypic or ontogenetic variation. According to Taylor & Aarssen [38] phenotypic plasticity is most pronounced in older populations of *E. repens* as a consequence of past selection for more plastic genotypes in a variable or unpredictable environment.

In line with its wide cosmopolitan distribution, and wide range of habitats, *E. repens* exhibits extensive morphological differentiation, which is reflected in different taxonomic treatments of intra-specific taxa [39–41] and in many Floras [40,42–46]. Recent classification efforts focus on genome-based taxonomy (see Section 1.3.2).

1.3.1. Morphological Variation

Many pot and field studies aimed at elucidating morphological variability in *E. repens* using clone/population collections indicate huge intraspecific variability in growth habit, plant color, awn length [2,47–49], leaf pubescence, flag leaf width, plant height, and rhizome length [50–53].

Apart from morphological differences, differences in growth and development and more generally physiological differences have also been reported. Biomass production (rhizomes and aerial sprouts) can differ substantially between *E. repens* clones [47–49,53–55] or seedlings [48], as can the ratio of aboveground shoot weight to rhizome weight or inter-shoot dry weight partitioning [48], the volume per cm rhizome [51], and the production of seeds [49,56], spikes [48,51,53], and rhizome buds [53]. Varying ability of clones to utilize nitrogen is an important factor behind differences in biomass production [57]. Interclonal differences in response to mowing [27,58] and growth characteristics [59] have also been reported.

It is likely that land use (or associated crop and land management) or geographic location can pose a selection pressure on clones. Neuteboom [50] found that plants collected from arable fields formed rhizomes that were markedly thicker than those from plants collected from permanent grasslands, whilst plants collected from temporary grasslands/leys had rhizomes of an intermediate diameter. Bulcke et al. [49] reported that intensively run grasslands with high nitrogen dressings seem to select for more aggressive *E. repens* clones. According to Neuteboom [27], *E. repens* clones with a strong ability to tiller may better be able to stand intensive and short defoliation in grassland over the long term. Håkansson & Wallgren [52] found that clones from Northern Sweden emerged earlier in the year and produced a higher dry weight of rhizomes during the year than clones from Central and Southern Sweden. Espeby et al. [60] found a strong covariance between geographic and genetic distance among Swedish clones collected from different habitats.

1.3.2. Genetic Variation

Several reports suggest that *E. repens* and related species have their origin through a combination of two or more differentiated genomes (allopolyploidy) [61]. Results of recent investigations of chloroplast and nuclear DNA support reticulate evolution and the hexaploid origin of the species, involving hybridization and introgression [62,63]. So far, a consensus on the genomic composition and its taxonomic consequences has not yet been reached. The data of Fahleson et al. [64] suggest that the Swedish *E. repens* population is slightly heterogeneous and comprises multiple origins of genome donors; a nuclear genome with contributions from *Pseudoroegneria* (St), *Hordeum* (H), *Thinopyrum* (E), and Y with an unknown donor together with a maternal genome donated from *Pseudoroegneria*.

So far, the taxonomy of *E. repens* and classification in varieties (e.g., var. *repens,* var. *aristatus,* var. *subulatus)* is mainly based on morphological characteristics [39,40,65]. Szczepaniak et al. [66] checked whether these variations are also reflected at the DNA level. The UPGMA dendrogram showed no clear variety-specific subclusters. Hence, only low rank taxonomic categories (varieties) are justified in description of morphological variation in *E. repens*.

Despite the higher importance of vegetative reproduction over sexual reproduction (Werner & Rioux, 1977), gene flow and repeated seedling recruitment may be more frequent than commonly thought. In a study with Polish *E. repens* populations, Szczepaniak et al. [66] found that most genetic diversity between clones resided within populations, indicating that reproduction by seed can be important in a local agricultural setting. The relative importance of asexual versus sexual reproduction clearly differs between populations [66]. Genetic variation in a Swedish *E. repens* collection [64] was clearly less than that found in a Polish *E. repens* collection [67]. An observation that might reflect differences in agronomical practices in the two countries but also various influences of different natural flora and degree of sexual and clonal reproduction. Flowers of *E. repens* are wind pollinated (allagamous species), but very little is known about the distance its pollen can travel and the factors influencing *E. repens* pollen movement.

1.4. History of Elymus repens Control

Traditionally, on arable land, *E. repens* has been controlled through a combination of indirect control measures (crop rotations, competitive crops/varieties, fertilizing regimes etc.) and mechanical control, usually in various forms of tillage. Starving the rhizome network by forcing *E. repens* to reshoot multiple times through a series of repeated non-inversion soil cultivations (e.g., harrowing) followed by deep ploughing at the depth of 20–25 cm used to be a common method against *E. repens* [68]. This depletion strategy is considered effective, but by removing the vegetation cover for an extended period, it has a high risk of nutrient leaching and erosion, particularly during wet autumns [69,70]. Moreover, the time-window for repeated soil cultivation between the crop harvest and ploughing/winter is very narrow in many regions, for example due variable weather conditions in autumn, high latitudes, or regulation requiring catch crops. Thus, the extended tillage strategy is nowadays often replaced with a short fallow period [28,71].

With the discovery of synthetic herbicides in the mid-1900's, weed control was fundamentally changed. From then onward many herbicides have been introduced against *E. repens*, the most common in the scientific literature being glyphosate (HRAC group G), TCA-sodium and dalapon (both HRAC group N). Of these three active ingredients, only glyphosate is currently registered for use in the EU. Since its introduction in 1974, glyphosate has gradually become the most common chemical control method against *E. repens*, particularly prior to establishing cereal and grassland crops. In grasslands, there are essentially no selective herbicides against *E. repens*, so control must be performed prior to sowing. In cereals and maize, a number of selective herbicides were introduced over the years, (1) introduction of sulfonylureas (rimsulfuron, nicosulfuron, foramsulfuron) in maize, (2) introduction of sulfosulfuron and propoxycarbazone Na in wheat and rye, (3) introduction of cycloxydim resistant maize (Duo system). In some dicot crops, selective grass herbicides have been introduced against *E. repens*, e.g., fluazifop-P-butyl, haloxyfop-P-methyl, and quizalofop-P-ethyl. The availability, price, dose, and use of selective herbicides in maize, cereals, and dicot crops vary greatly between countries, however.

Glyphosate use increased dramatically during the 1990's when Monsanto's patent expired and the price for glyphosate went down. At the same time, incentives for farmers were introduced in many countries with the aim to reduce soil cultivation and to preserve soil structure and moisture and prevent erosion. Unfortunately, reduced tillage tends to favor perennial weed species, thus changing the composition of plant populations towards species which are difficult to control and have a high crop yield reduction potential (e.g., [72,73]). Glyphosate made it possible to control *E. repens* and some other perennial weeds as well as overwintering annual species such as *Tripleurospermum inodorum*, *Stellaria media*, and *Poa annua* when reducing tillage [74,75].

In the past, contamination of *E. repens* seeds in crop seed lots was one of the main sources of introduction of *E. repens* into new areas [76]. Improved seed purification techniques and seed purity rules have mainly solved this problem but preventing seed spread should still be taken into consideration. All control measures prior to *E. repens* heading are naturally highly effective in this respect.

2. Non-Chemical Management of *Elymus repens*

Non-chemical weed management consists of two major components: (1) indirect control to keep the weed populations low; (2) direct control measures as needed. Indirect control measures (also known as preventive measures) consist of all aspects of the cropping system that can be tweaked to affect the weed flora: crop rotation, crop/cultivar choices, fertilization regime, subsidiary crops, etc. [77].

2.1. Indirect Control Measures

2.1.1. Main Crops

Crop competition can greatly reduce *E. repens* growth (e.g., [24,78–82]). However, competitive ability varies considerably among different crops and crop varieties. Ringselle et al., [22,83] found that ryegrass was more effective at reducing *E. repens* shoot biomass, while red clover was more effective at reducing rhizome biomass. Cussans [24,84] found that barley and oilseed rape are more competitive against *E. repens* than wheat and field beans, and similar rankings have been made by others (e.g., [79,85–87]). Frankow-Lindberg [88] found that some timothy varieties were more competitive against *E. repens*, and that *E. repens* increased the competitiveness of red clover against timothy.

Cussans [24] argues that how effectively a crop competes with *E. repens* is not primarily dependent on the biomass production of these crops, but rather the ability to establish quickly and have efficient growth in respect to light reception. Since barley establishes early and tillers extensively, this could explain its relative success against *E. repens* [24]. For the same reason a higher seeding rate can help the crop compete against *E. repens* [89].

Some farmers claim that *E. repens* is not a problem in grasslands, while others claim that *E. repens* usually increases in grasslands. This inconsistency may be due to differences in fertilization and mowing management (see Sections 2.1.3 and 2.2.1) and different grassland species composition, but also because some *E. repens* clones are more adapted to grassland management than others [27]. Some farmers are also not aware of the full extent of their *E. repens* infestation as it is a grass among grasses. In permanent grasslands some farmers will not prioritize *E. repens* control since it is harvestable. However, even in competitive ryegrass crops *E. repens* can still produce new rhizomes [27,90].

Some crops have also been shown to exude allelochemicals with a negative effect on *E. repens* germination, development, and/or biomass accumulation, either while alive or by their decaying plant parts. Examples are buckwheat [91–95], timothy [96], oilseed rape [91] and barley, oats and rye [91,97,98]. Of the tested species, buckwheat exhibits the strongest reductive effect on *E. repens* [94], with significant reductions under lab as well as field conditions [92,95]. These effects have not been demonstrated to be strong enough to control *E. repens* on their own. However, the effects are significant enough that allelopathic crops could be an important component of an integrated non-chemical control strategy for *E. repens*.

2.1.2. Subsidiary Crops

A major problem in annual crop production is that a high proportion of *E. repens* growth occurs after the competing crop has set seed and commenced ripening [24,99]. As a result, many recent studies have looked at the possibility of using subsidiary crops to complement the competitive potential of the main crops and/or to extend the competitive period into the autumn. Subsidiary crops are crops that are sown together with the main crop or after the main crop harvest, primarily to provide services other than harvestable yield (e.g., reduced nutrient leaching, improved soil health, nitrogen fixing, weed competition).

Some studies show a significant reduction in *E. repens* rhizome production due to subsidiary crops (e.g., [12,85,100]) or that they increased the crops competitive ability [71], while others show a more limited effect [72,101–103]. The studies that show a large reduction in *E. repens* growth also generally have a large subsidiary crop biomass by late autumn (above 100 g m^{-2} in [12,100]) compared to the studies with more limited effects (cf. 15–60 g m^{-2} in [103]). The subsidiary crop species used also matters. For example, Cussans [12] found that Italian ryegrass was more suppressive than red clover and oilseed rape, which in turn was more suppressive than white mustard. None of the species were able to prevent *E. repens* from developing new rhizomes though.

A major downside of subsidiary crops is that they can end up competing with the main crop [12,85,104], or end up benefitting *E. repens*, e.g., by providing nitrogen [103]. Subsidiary crops can also benefit *E. repens* indirectly by being incompatible with post-harvest tillage operations that would otherwise be used against *E. repens* [105].

2.1.3. Fertilizing Regimes

Many weed species respond even more favorably to added nitrogen than some crops [106]. Numerous controlled studies have shown that the addition of nutrients/nitrogen improves *E. repens* growth (e.g., [11,22,107]). In field trials the results are not as consistent [27], but generally a higher fertilization rate tends to benefit *E. repens* [108]. For example, Käding et al., [109] found that a higher nitrogen fertilization led to a higher proportion of *E. repens* at the expense of forbs in a 40-year grassland trial. Similarly, in a long-term crop rotation experiment, Melander et al. [105] found that manuring was beneficial to *E. repens*. However, clones differ in their ability to utilize nitrogen for biomass production [57]. Moreover, fertilization level can affect control measures. For example, Turner [11] found that shoot cutting drained the carbohydrate content of *E. repens* rhizomes faster at a higher nitrogen level.

2.2. Direct Control Measures

2.2.1. Direct Control of Shoot Biomass

Plants survive defoliation (i.e. destruction of aboveground plant parts) by two main strategies: (1) avoidance and (2) reshoot potential. Bad taste and toxins are effective measures to avoid grazing (e.g., *Ranunculus* spp.) and growing close to the ground helps plants avoid losing all aboveground biomass to mowing/grazing (e.g., *Taraxacum* spp.). Having a growth point below the defoliation point enables plants to reshoot following defoliation. Perennial weeds have the back-up of their storage organs to ensure that they can reshoot even if their growth point is severed or otherwise destroyed. For example, their large taproot enables established *R. obtusifolius* plants to survive weekly selective defoliation, even when it is performed during an entire growth season [110].

Mowing/Cutting/Crushing

Its stemmy growth habit means that *E. repens* often loses a large proportion of its shoot biomass and growth points during mowing and consequently most often has to reshoot from basal stem buds or re-sprout from its rhizomes [27]. Like many grasses, *E. repens* responds to mowing by increased tillering [111], though this response is reduced by competition [82] and lower cutting height [112].

In pot experiments, *E. repens* plants from rhizomes were capable of reshooting even after several months of defoliations as frequent as weekly [113] or every time it reached two leaves [82]. However, defoliation every two weeks seem to be able to prevent new rhizome growth and gradually drains the rhizomes of resources [11,58]. In the field, a higher mowing frequency leads to a lower *E. repens* growth compared to lower mowing frequencies, but *E. repens* can produce new rhizomes even at frequencies as high as every third week [27,90]. Comparatively, Courtney [114] found that a four-week mowing interval was sufficient to prevent rhizome production; Štýbnarová et al. [108] found that three harvests per year kept *E. repens* below 10–15% of the grassland coverage; and Pavlu et al. [115] found *E. repens* populations gradually decreasing already at two grassland harvests per year. Moreover, more recent studies in Sweden found that when cut every time it reached two leaves during summer, *E. repens* rhizome biomass was reduced by >75% compared to no mowing [83,116]. However, there appears to be some influence of season on mowing efficacy, as mowing post-cereal harvest has had a limited effect on *E. repens*, at least in the Nordic countries [102,103,116]. Importantly, Neuteboom [27] found that mowing efficacy differed greatly between different *E. repens* clones, meaning that intensive mowing regimes may select for more resilient clones, and strategies may have to be adapted to the resilience level of the clones in the field.

Alternative Defoliation Strategies

In addition to mowing/cutting/crushing there are other ways to destroy the aboveground biomass without necessarily affecting the belowground parts. Examples are thermal treatments (such as hot water and flaming), bioherbicides (e.g., pelargonic acid), and physical destruction (e.g., air-propelled grit). These methods are not as well-studied as mowing, especially not against *E. repens*. A major drawback is that these methods, unlike mowing, would be very destructive in a grassland crop or cover crop. However, they could be applied selectively or between rows [117] or in the period between crops. Another major drawback is the energy and time requirements.

Hot water has been used with a >80% efficacy against *R. obtusifolius* [118]. A major difference between *R. obtusifolius* and *E. repens* is that *R. obtusifolius* taproot is reasonably concentrated under the plant, while *E. repens* rhizomes are spread out in a network. Thus, unless the hot water is applied to the rhizome network in the soil (see Section on Other Direct Control of Rhizomes) the efficacy against *E. repens* with hot water is likely to be closer to a mowing treatment than to the efficacy against *R. obtusifolius*. The same can be said for bioherbicides, flaming, brush hoeing [119], and air-propelled grit [120]. One reason to believe that they could have a higher efficacy than mowing is that they could potentially destroy the *E. repens* shoots at the soil surface, while mowing generally cannot reach lower than two-three cm height. Håkansson [113] found a higher efficacy of cutting the *E. repens* shoots at the soil surface than at two cm above the soil surface. Another reason the alternative defoliation methods could be more effective than mowing would be if they are more effective against the clones that are especially resilient to mowing.

2.2.2. Direct Control of Rhizomes

Elymus repens belongs to a category of creeping perennials with strongly regenerative rhizomes and high tolerance to tillage [68]. However, directly targeting *E. repens* rhizome network is generally more effective than starving it by destroying the above-ground biomass, especially since most methods that destroy the rhizomes also damage or destroy the above-ground biomass. The most common and direct approach is to use mechanical implements (e.g., ploughs, harrows, hoes, rotary cultivators, rhizome cutters) to cultivate the soil. Alternatives include thermal treatments (steam, hot water, electricity, soil solarization), flooding, and biofumigation.

Tillage has been one of the most important weed control methods since the invention of the hoe, harrow, and plough. Factors that determine the response of plants to tillage include (i) regenerative characteristics of the plant, (ii) type of tillage (depth, injury), and (iii) soil and environmental conditions [68]. The main environmental factors affecting the control efficacy are soil type, temperature, and moisture.

Tillage Strategies with Ploughing

Tillage affects *E. repens* in multiple ways depending on the implement used: it can destroy the above-ground biomass, damage the root system, fragment the rhizomes network and/or displace the rhizome fragments; either by burying them deeper in the soil (e.g., inversion ploughing), pulling them through the soil or pulling them to the soil surface to desiccate or be collected (see Section on Rhizome Removal and Exhaustion with Tillage).

Repeated non-inversion tillage (e.g., harrowing) followed by ploughing either in autumn or early spring has long been a popular treatment of *E. repens* and it is still a common practice in crop rotations of annual crops and in terminating a rotational ley. The aim of the repeated non-inversion tillage is to deplete the rhizome network's resources by (1) fragmenting the rhizomes and thus dividing its resources between many fragments, and (2) forcing them use their resources by reshooting multiple times. Ploughing is used to finish off the weakened rhizome fragments. Many studies discuss the depletion strategy of *E. repens* related to rhizome fragmentation and rhizome length (e.g., [11,78,82,121–124]).

Typically, the rhizomes of *E. repens* grow within shallow depths, reasonably close to the soil surface, where they can easily reshoot [72]. With moldboard ploughing, the pieces of rhizomes are more uniformly distributed throughout the ploughed layer. Consequently, the emergence pattern of new shoots is uneven. The greater the burial depth, the smaller the number of emerged shoots and the more the emergence is delayed [14,52].

Coupled with fragmentation, the smaller the rhizomes and the greater the depth, the harder it is for the shoot to reach the surface [10,14]. Consequently, deeper tillage is generally more effective than shallow tillage [125]. Cussans and Ayres [126] carried out a five-year field experiment in the UK 1969–1973 and reported that the mean shoot number of *E. repens* was five times higher with tine cultivation (12–18 cm) compared to moldboard ploughing at 17–25 cm. Moreover, rhizome biomass was 42% lower in the ploughed treatment.

In Norway, Brandsæter et al., [127] showed that ploughing to 25 cm reduced *E. repens* above-ground dry weight and number of shoots by 50% compared to ploughing to 15 cm. Similarly, in a study over 17 years at 19 different Swedish sites with different soil types, Håkansson et al., [128] found that at sites with perennial weed problems, ploughing to 22 or 28 cm increased the relative crop yield by several percent as compared with ploughing to 15 cm.

Boström and Fogelfors [129] found that stubble cultivation before ploughing reduced biomass of *E. repens* by 90% compared with ploughing alone. Early ploughing reduced the biomass of the species by 50% compared with late ploughing. Consequently, the highest grain yields were obtained with a combination of stubble cultivation after harvest followed by ploughing later in autumn [130]. Håkansson and Wallgren [52] suggested that at mean temperatures of 15–18 °C and good moisture conditions the maximum interval between soil cultivations to control *E. repens* could be 3–4 weeks. Ringselle et al. [131] demonstrated that one early stubble cultivation right after harvest can be as effective as repeated cultivations, but it may depend on the length of the autumn growth period.

Brandsæter et al. [116] studied the timing of ploughing and additional effect of stubble cultivation against *E. repens*. There was no significant difference between ploughing times. On the other hand, ploughing + stubble cultivation reduced both shoot density and shoot dry matter compared to ploughing alone (63% compared to autumn ploughing, 88% compared to spring ploughing, averaged over all three years) and kept the *E. repens* population low throughout the three years.

Midsummer fallow was studied in Denmark [71] with the intent to study the interaction between tillage and catch crops in *E. repens* management. Fallowing that started with 10 cm moldboard ploughing in early July and was followed by weekly tine cultivation from July–August, ending with 20 cm ploughing gave very high and consistent reductions of *E. repens* infestations, leading to 91–99% efficacy compared with the infestation level prior to starting the strategy.

Majek et al. [132] studied the effect of tillage on rhizome growth pattern. The experimental plots were ploughed and disked either in early May, late-June, or mid-August 1978 and 1979. In untreated plots, the plants were tall and produced seed heads in June and shed pollen in early July. In plots ploughed in May the plants were smaller and produced seed heads in July. Those ploughed in June or August did not produce seed heads. Fewest rhizome buds survived after ploughing in May and most after ploughing in August. Many of the new rhizomes survived ploughing, while the old rhizomes did not. This indicates that to reduce a *E. repens* infestation by tillage, new rhizome production must be prevented.

Tillage Strategies without Ploughing

Replacing standard ploughing at the depth of 20–25 cm with so called conservation tillage practices would bring economic benefits and support the common aim of sustainable cropping that preserves soil quality and fertility [133].

Brandsæter et al., [102] studied contrasting stubble treatments after harvest. The field experiment in Norway during 2004–2005 included (1) untreated control; (2) mowing; (3) rotary tillage; or (4) shallow ploughing plus two passes with S-tine harrowing. Treatments gave 23–63%, 56–90%, and 86–90% reduction in above-ground biomass in the following year compared to untreated control. Treatments 2 and 3 also reduced shoot numbers by 58–88% and 86–95%.

Landström [134] reported that continuous cultivation of barley together with annual stubble cultivations heavily reduced the occurrence of *E. repens* (dry weight/ha) (50% less the first year, then more than 75% the following years) compared to no tillage treatment. Even stubble cultivations every other year had a reducing effect. Barley yield was higher after stubble cultivations. In contrast, Pessala [135] obtained only 20–30% reductions of *E. repens* with stubble cultivation after harvest in Finland.

Chandler et al. [136] carried out field experiments in Canada during 1985–1989, through two cycles of soybean-corn rotation. The treatments included autumn or spring shallow tillage (modified chisel plough, with twisted shovels, depth 15 cm), moldboard plough, and no-till. Autumn tillage tended to be more effective than spring tillage, and ploughing was more effective than soil-saver, with no-till being the worst. In the final year of the study, shallow tillage in autumn had reduced the rhizome+shoot dry weight of *E. repens* by 64% and shallow tillage in spring by 31% compared to no-till. In comparison, the efficacy of autumn ploughing was 88% and that of spring ploughing 78%. Rhizomes were found to grow closer to the soil surface in untilled plots.

Bulcke et al. [49] evaluated *E. repens* control obtained after renewal of old grassland (executed at the end of September and reseeded with *Lolium perenne*) on sandy soil by means of soil tillage operations without chemicals. Six months after tillage operations, the number of *E. repens* sprouts became 1.5, 3, 3.5, and 4 times higher after single rotavation at 10 cm depth, two rotavations (a first pass at a depth of 5–10 cm and a second pass at a depth of 10–15 cm), ploughing (30 cm), and overtop rotavating (15 cm) followed by rolling compared to the untreated untilled old sward (47 aerial sprouts per m^2).

Tillage in the autumn may also have unwanted consequences; for instance Aronsson et al. [70] found that harrowing in autumn before ploughing increased N leaching (more when harrowing twice than once) compared to the untreated control, and to mowing or inter-row hoeing together with cover crops (sown in the crop row).

Inter-Row Hoeing

There are not many studies on the effect of inter-row hoeing on *E. repens*, and the few that exist have shown no to modest effects. Aronsson et al. [70] could not find a significant reduction in *E. repens* biomass as a result of inter-row hoeing in combination with cover crops, but the addition of cover crops prevented both the downward flow of nitrogen in the soil profile and the nitrogen leaching that were found in tillage treatments without cover crops. Landström [134] found that one year with hoed *Brassica napus* in the rotation reduced the occurrence of *E. repens*. Brandsæter et al. [137] found that the combination of inter-row hoeing and autumn disk cultivation followed by ploughing resulted in better control of a mixed perennial weed population including *E. repens* than all but one of the other tillage treatments.

Rhizome Removal and Exhaustion with Tillage

Vegetative propagation is the main source of growth and spread of *E. repens*. Bringing rhizomes to the soil surface and letting them be exposed and killed by drying out is called the desiccation strategy. Rhizomes can be expected to die if they are brought as low as 16% water content of total biomass but can survive even at soil moisture as low as 4% [19]. Old rhizomes are more sensitive than younger rhizomes. The Danish Kvik-up cultivator (www.kvikagro.com) and similar Finnish modifications Kvick-Finn (www.bt-agro.fi and www.lyckegard.com) and Tiustech Root Stopper (www.tiustech.com) have been developed for bringing rhizomes to the soil surface. Lifted pieces of rhizomes can even be collected and burned [138].

Melander et al. [71] compared Kvik-up treatment with rotary cultivator and shallow ploughing at 10 cm depth in spring barley stubble two days after harvest. Mechanical disintegration conducted two days after harvest of barley and straw removal (and followed by radish/ryegrass mixture within one week after barley harvest), reduced growth of *E. repens* in a subsequent spring barley crop significantly. The highest growth reduction, 40% less *E. repens* aboveground biomass relative to initial infestation, was achieved with rotary cultivation followed by 'Kvik-up' and classic stubble cultivation. Moldboard ploughing to only 10 cm depth was ineffective.

The concept of uprooting and rhizome removal was further studied in Denmark [72]. Up to four passes with a modified rotary cultivator were carried out and followed by rhizome removal. The reduction in *E. repens* shoot growth, studied as a subsequent effect in spring barley in two growing seasons, was 84% and 97%.

Gilbert et al. [139] reported on Kvik-up efficacy compared to stubble cultivation. Three weeks after mechanical grassland destruction at the beginning of May by a heavy-duty cultivator, the Kvik-up reduced rhizome biomass in the 0–10 cm soil profile by 78% compared to stubble cultivation. Five months after tillage, rhizome biomass was 47% lower in Kvik-up treated plots than in cultivated plots. However, efficacy of the Kvik-up was much lower when performed immediately after grassland destruction.

Jacobsson [140] examined the Kvik-up cultivator in Sweden. Timing and the number of passes were studied in six field trials, half on a light soil and half on a clay soil. Stubble treatments included: Autumn ploughing and spring ploughing as main plots, and (1) disk cultivation twice in autumn, (2) Kvik-up once in autumn, (3) Kvik-up twice in autumn, (4) Kvik-up twice in autumn plus once in spring, and (5) mowing 2–3 times in autumn. On average, Kvik-up once resulted in 71% (variation 57–80%) less *E. repens* shoot biomass in the following year and Kvik-up twice by 81% (variation 72–92%) and Kvik-up in autumn and spring by 84% (variation 70–91%), compared to ploughing only. In comparison, the disk cultivation resulted in 51–74% less shoot biomass; i.e., usually not significantly worse than the Kvik-up, but sometimes there was a tendency towards worse efficacy. Mowing had very poor efficacy (12%) on *E. repens*. They also conducted a survey among 14 farmers about the use of the Kvik-up. Most them were happy with the tool and found that it was effective against *E. repens*; more effective when used more than once and better in light soils than heavy ones.

Lötjönen and Salonen [28] compared Kvick-Finn cultivation with other common tillage practices against *E. repens* in organic soil. A short-period fallow before sowing of spring cereals in May was not effective because of wet weather conditions. On the other hand, late summer fallow after the first ley harvest succeeded very well; after repeated Kvick-Finn treatments on average 5% of *E. repens* remained alive in the barley crop in the autumn of the following year. After use of ordinary cultivators 10% of *E. repens* remained alive, after use of the spade harrow 25%, and after frequent mowing over 50% remained alive. As a result of effective *E. repens* control, barley yield was about 1000 kg ha^{-1} higher than without any fallow. The study concluded that effective control of *E. repens* is achieved with proper machinery and repeated treatments at the optimal time.

Kristensen et al. [141] focused on technological solutions to improve uprooting, exposing, and destroying rhizomes of *E. repens* with high speed and high capacity techniques as alternatives to Kvik-up type cultivators. The new designed spike discs were not capable of uprooting more rhizomes than the standard spring-loaded tine cultivator. However, the rigid tine cultivator with spike discs showed a more uniform distribution of the rhizomes, i.e., no large and lumpy batches of rhizomes was observed after treatment as observed after treatment with the spring-loaded tine cultivator. The rigid tine cultivator with spike discs provided significantly better coverage of leaves of *E. repens* and broad-leaved weeds, indicating potential weed control efficiency in general.

Brandsæter et al. [137] found that one Kvik-up treatment in spring did not significantly reduce a mixed perennial weed stand including *E. repens*, but that one treatment in autumn and another in spring did. It reduced *E. repens* the most out of six tillage strategies including: (1) stubble mowing, (2) vertical root/rhizome cutter in a white clover mulch, (3) inter-row hoeing, (4) inter-row hoeing + autumn disking, (5) Kvik-up in spring, (6) Kvik-up in autumn and spring.

Root/Rhizome Cutters

Rhizome fragmentation has long been considered an important aspect in the starvation strategy used to control *E. repens*. The repeated non-inversion tillage followed by ploughing both destroys the shoot biomass and fragments the rhizomes, forcing them to reshoot, only to be disturbed again.

By fragmenting the rhizomes, each fragment has fewer resources available to them, making them more susceptible to burial by ploughing and competition from crops.

Fragmenting the rhizomes breaks the apical dominance that keeps the rhizome buds from producing shoots [121]. Thus, a major argument against only fragmenting the rhizomes, without destroying the aboveground shoots or burying the rhizome fragments, has been that it can potentially lead to an increase in shoot numbers per unit area compared to the intact rhizome network. Bergkvist et al. [116] tested this hypothesis using flat spades to fragment *E. repens* rhizomes in 20 × 20 or 10 × 10 cm grid. When performed post-cereal harvest the effect on *E. repens* was minimal, but when performed in spring the fragmentation reduced shoot numbers and reduced the rhizome biomass by up to 60%. There was some tendency toward an increased shoot number when using the 20 × 20 cm grid, but the smaller grid-size more consistently led to a reduction in *E. repens* shoot numbers. Kolberg et al. [82] found that rhizome fragmentation from 40 cm pieces down to 20, 10, or 5 cm did not increase total shoot numbers as the increase in main shoots was offset by a reduction in tiller numbers.

Ringselle et al. [83] and Ringselle et al. (Unpublished) tested a prototype from Kverneland with vertical coulter disks that cut through the soil and rhizomes with minimal soil disturbance. Both sets of experiments tested the prototype in spring and/or in summer in a grass and/or clover crop and aimed to use the same 10 × 10 cm grid as in Bergkvist et al. [116]. Ringselle et al. [83] found that *E. repens* shoot numbers decreased by approximately 30% by rhizome fragmentation, and that fragmentation before sowing the crop or in the growing crop both reduced the rhizome biomass by approximately 38% and performing it at both times reduced it by about 63%. The crop responded well to the treatment, particularly when it was performed in the growing crop, with the perennial ryegrass being 200% larger in the late autumn in the treatments with fragmentation compared to no fragmentation. However, no yield was registered in that study, nor was winter effects on the weakened rhizomes registered; though a germination trial on the fragmented rhizomes showed that the reduction in rhizome biomass was not only due to a die-off of rhizomes, but also because the living rhizomes were lighter and consequently had fewer resources left after fragmentation. Ringselle et al. (Unpublished) also found a reduction in rhizome biomass by rhizome fragmentation. However, the treatment years (2017 and 2018) were exceptionally dry years in Sweden and it was almost impossible to conduct the treatments as intended even with tons of additional weight added. In particular, the summer treatment was very difficult to perform in the dry clay soil. In a single three-year experiment, Brandsæter et al. [137] compared the vertical cutter to several other weed control strategies, but similarly to Bergkvist et al. [116], fragmenting the rhizomes post-cereal harvest did not significantly reduce *E. repens* shoot numbers. Contrastingly, while Bergkvist et al. [116] had found a reduction in *E. repens* shoot biomass due to fragmentation post-cereal harvest, this was also not significantly lower in Brandsæter et al. [137].

An additional prototype by Kverneland, but which cuts the soil horizontally rather than vertically, has been tested in Norway and Sweden by Brandsæter et al. (Unpublished). They found that the horizontal root/rhizome cutter reduced *Cirsium arvense* shoot biomass by 80% compared to an untreated control and *E. repens* shoot numbers by 80% compared to the initial *E. repens* shoot numbers over three years when cutting at 25 cm (in spring before sowing spring cereals) and 7 cm (in autumn, as stubble cultivation) depth, respectively. The effect on *E. repens* was not significantly different from using a disk-harrow or stubble cultivator, but was less effective than the rototiller, which almost eradicated the *E. repens* population. The horizontal cutter also did not significantly increase soil leaching or erosion over three years compared to an untreated control (personal communication, Lars Olav Brandsæter, 13 May, 2020).

Soil Disinfestation

Apart from desiccation and depletion approaches for controlling *E. repens*, rhizomes may also be thermally killed by soil steaming, soil solarization, or immediately upon an uprooting operation.

In addition, rhizomes may be biologically or physically controlled using soil biofumigation or flooding, respectively.

Soil steaming (broadcasted, banded, or spot application) has the potential to rapidly and consistently control *E. repens*. According to van Loenen et al., [142] unexposed *E. repens* rhizomes are very sensitive to short duration steaming. Aerated steaming at 50 or 60 °C for 3 min, followed by an 8-min resting period in the steamed soil (loamy sand, sandy loam at field capacity) and immediate removal from the soil thereafter, resulted in 100% kill of *E. repens* rhizome fragments (4–6 node rhizomes) in a laboratory environment. During the resting period, the temperature stayed very close to target temperature (50–60 °C). So far, because of the high energy costs involved, broadcast steam treatment in situ is currently limited to a few high value horticultural and floricultural crops. The results of van Loenen et al. [142] suggest that the duration of steaming and hence costs and negative impact of steaming on chemical, physical, or microbial soil properties could be substantially reduced. For in situ steaming hooded/sheeted or injector steam applicators are commonly used; these devices may require longer exposure times as steam penetration under a hood or sheet cannot be entirely uniform as in the lab steaming method in the experiment by van Loenen et al. [142]. For band steaming under outdoor conditions it should be noticed that the cooling-down period is generally faster than for broadcast steaming; observations made by van Loenen et al. [142] do imply a faster cooling-down period in the bordering zone when only a limited soil volume has been steamed.

Apart from soil steaming, soil solarization can also be a good small-scale way to eliminate an *E. repens* patch. The infested area should be covered with a transparent plastic sheet (well-sealed at the edges) for six weeks during the hottest part of the summer. Afterwards, the area is rototilled and planted with a winter grain or a green manure crop [143]. Birthisel and Gallandt [144] found that solarization in Maine (cloudy climate) did reduce *E. repens* shoot density, at least in the short term. Unfortunately, the authors did not verify the vitality of the rhizomes exposed to solarization. Substantive control of the rhizomes likely requires prolonged solarization duration. A farmer in Maine successfully killed his *E. repens* rhizomes by covering a field with two layers of clear plastic for a whole season (personal communication of Birthisel). Conducting solarization within a greenhouse [145,146] or covering fields with multiple plastic layers [147], particularly when separated by an airspace of at least a couple of inches typically results in higher soil temperatures than single-layer solarization, and can improve pest control efficacy [148–150].

Although solarization is considered a 'mild' (i.e., low temperature) soil treatment in comparison to other disinfestation techniques including steaming [151], it nonetheless affects the soil ecosystem beyond the control of target pests particularly depending on soil temperatures reached during solarization. Solarization often increases dissolved organic matter [152] and plant available nutrients including inorganic nitrogen and can alter microbial community composition during treatment [150,153].

One type of biofumigation is based on the disruption and soil incorporation of glucosinolate-rich cruciferous plant biomass, which releases several substances (in particular, isothiocyanates) able to suppress some soilborne pests, diseases, and weeds [154]. Upon tissue disruption and incorporation in the soil, glucosinolates are released from the plant cells and are converted to volatile isothiocyanates by myrosinase enzymes that hydrolyse glucosinolates in the presence of water. According to De Cauwer et al. [155], a 73% reduction in propagule viability (%) of two-node *E. repens* rhizomes buried at five cm depth was achieved after 14 days when a high dose of fine-chopped *B. juncea* biomass (200 t ha^{-1} or 36 t dry biomass ha^{-1}) was combined with plastic sheeting to reduce volatilization losses. The effective dose will depend on the fineness of *B. juncea* particles (the finer, the lower the dose), pedohydrological conditions (lower doses under warm moist conditions). To cope with expected N mineralization after incorporation of huge amounts of biofumigant biomass, fields should not be left uncropped after being biofumigated. One risk of biofumigation is the potential biocidal effect on beneficial organisms, such as *Rhizobia* bacteria for future legume inoculation, and vesicular–arbuscular mycorrhizal fungi, which aid some crops (but not *Brassicas*) in uptake of phosphorus and other nutrients.

Flooding tolerance of *E. repens* is expected, since it is a highly-adaptive species growing in a wide variety of habitats, including alluvial flooded meadows and periodically flooded habitats [156,157] together with the fact that plants with sufficient rhizome mass are able to survive oxygen deficiency ([158] reported that *E. repens* survived a 50-day flood). However, longer flooding periods and long duration of anoxia in particular may be harmful to *E. repens*. Van Zaayen [159] reported on the effects of inundation of ornamental bulb soils on weeds; flooding a production field for 6 to 10 weeks in summer prior to bulb planting gave good control of *C. arvense*, *Tussilago farfara*, and *E. repens*. Unfortunately, levels of control thus obtained were not quantitatively expressed. Anaerobic conditions are reached quicker (within a few days) in warm (17 °C or higher) sandy soils then in cold heavy-textured soils. Rhizome fragmentation by rototilling the soil prior to flooding may enhance control efficacy of inundation. Major drawbacks of inundation are the higher water requirement and temporary disturbance of the biological equilibrium of the soil. Crops sensitive to *Pythium* spp., *Rhizoctonia solani*, or *Olpidium brassicae* should not be cultivated in the first year after inundation.

Other Direct Control of Rhizomes

Melander et al. [160] proposed a technology that integrates: (i) effective uprooting; (ii) rhizome separation from soil, stones, and other objects; and finally (iii) direct physical destruction of rhizome buds before bringing them back to the soil surface (so far, such technology is not yet available). Hereto, Melander et al. [160] evaluated the potential of physical destruction of sprouting ability of uprooted *E. repens* rhizome buds. Exerting mechanical pressure on uprooted clean rhizome buds of *E. repens* can destroy their sprouting ability. The higher the pressure the more likely it is to destroy the meristematic tissue of the buds, with all buds being killed at 10 N per mm rhizome length (20 kN of pressure), irrespective of rhizome ecotype (or cellulose content of the rhizomes). Moreover, for crushed rhizome fragments that are still viable, crushing rhizome buds and then burying them seem to have an additive effect, although not a synergistic one.

Bud destruction can also be achieved by heating rhizome buds using hot water (deemed to be the least energy demanding method for heating rhizomes according to [160]). The effect of water temperatures <70 °C on bud sprouting ability was inversely related to exposure time (low temperatures required longer duration to reduce the sprouting ability), while 70 °C or more gave a complete bud kill, irrespective of heat exposure time within the range of 5 to 300 s. However, thermal destruction (heating rhizomes with hot water at 70 °C) is far more energy demanding than mechanical destruction (with a compressive force of 10 N mm^{-1}), actually requiring 20 times (58 versus 3 L of diesel oil ha^{-1}) more diesel oil ha^{-1} for the destruction of 1 kg of rhizome biomass m^{-2}. Alternatively, *E. repens* bud destruction could also be achieved by composting (Kristensen and Melander, personal observations). However, the rhizomes should be removed from the field and the compost returned after composting to recycle nutrients in rhizome fragments, which is a very laborious procedure.

Electricity has long been considered a potentially interesting weed control method as it can both kill aboveground biomass and be transferred down into root and rhizome systems [161]. Thus, it is one of the few options for non-chemical control of perennial weeds without disturbing the soil. The potential danger to the operator and the high energy usage have so far kept adoption and development of electrical weed control applications low [162]. Electricity is an interesting option for automated weed control [163], in particular with recent advances in battery technology. However, there are no published studies on the effect of electricity on *E. repens*. Also unclear are the potential effects on non-target organisms.

3. Discussion

This review seeks to answer two main questions. First: can non-chemical measures be used to effectively control *E. repens* in different agricultural contexts (e.g., annual cropping systems, grasslands, orchards)? Secondly: how efficient is the non-chemical control in comparison to glyphosate, the main chemical alternative? Before these questions can be answered it is important to specify what is meant by effective and efficient control. Weed control efficacy is usually defined as the reduction in weed coverage/number/biomass of the treatment compared to an untreated control. This is straight-forward and easy to calculate, but the review shows the way it is used differs between studies.

Firstly, studies usually do not use the same measure and some only measure the aboveground biomass and/or coverage. Obviously, there is a correlation between aboveground and belowground biomass, but it may vary with a various environmental factors, the clone and clone health [136], as well as time of the year [12] and between years [99]. Consequently, a 30% reduction in shoot biomass may not mean the same thing if it is measured in autumn or in spring. For example, Ringselle et al. [103] found that post-harvest mowing and cover crops led to a reduction in autumn shoot biomass, but did not translate into a consistent reduction in rhizome biomass in the following year. Secondly, studies measure the control efficacy at different times, both over the year (spring, summer, autumn) and number of years (only treatment year, subsequent year, and/or over several years). Studies that only measure in the treatment year are less reliable, both because they may overestimate the effect or instead underestimate the effect (e.g., omit winter effects). Third, studies are using different controls as what is meant by 'untreated' differ between crops, cropping systems and countries. The main difference seems to be that some studies have ploughing in all treatments as well as the control (e.g., [131]), while other studies do not (e.g., [102]). Fourth, there is a huge number of different mechanical tools, both in brands, models and types (e.g., disk harrows vs. tine harrows). Tools and associated machinery (e.g., tractors) from the 1970s can also be expected to differ from more modern tools and machinery. In addition, the tools have different settings that can be changed (e.g., angle, distance between disks) or used differently (e.g., different speeds and depths). The customizability of farm equipment enables tremendous flexibility of use, but also means that experience in calibrating the settings to match the field conditions can change the results. This means that even studies that set out to test the same tillage regime may be testing different things. Additionally, the type of soil and soil conditions can severely influence tillage [164]. Soil moisture is especially important [136].

One problem that the review makes abundantly clear is that *E. repens* displays a large interclonal morphological variation that results in, among other things, different control efficacy from the same treatment (e.g., [27]). This clearly makes comparing studies a challenge as even large differences could be the result of sensitive versus resilient clones, emphasizing the need for multi-site/multi-clone studies. This also problematizes the low number of comparative assessments between non-chemical and chemical (glyphosate-based) control strategies for *E. repens*.

One problematic aspect of the control efficacy definition is that it fails to properly capture the actual increase/decrease in the population as a result of the treatment. A large reduction compared to a control treatment may not be sufficient if the *E. repens* population still increased [12,27,90]. Many studies do report the change compared to the initial population, but not all, and most measure the initial population very differently (cf. [12,102,103]). What effect the treatment has on the population dynamics is more in line with integrated pest management (IPM). In IPM, the goal is not exterminating the pests, but rather to keep them below the level where they cause unacceptable yield or quality losses (i.e., the economic threshold), and only use direct control measures when the population is above that level [165]. However, for perennial weeds, which have a huge potential to cause yield losses and proliferate rapidly even from minor populations, the concept of economic thresholds is not very useful. For such weeds, a threshold that predicts the potential problems in the coming crop may be more useful. However, to complicate matters, the same treatment may have different effects depending on the size of the *E. repens* population [131].

Efficiency refers to how much resources are used to achieve the desired effect. Side-effects, positive and negative alike, can also be included in the efficiency calculation. For example, a nuclear weapon is an effective way to kill an anthill, but it is not an efficient use of resources, nor are the negative side-effects acceptable. Resources that can be relatively easily compared are time, energy and costs. Side-effects are more difficult to compare as they often have very different units, e.g., risk of herbicide residues in the food vs. risk of increased soil erosion or compaction. However, even reasonably objective effects can be difficult to compare. For example, Coleman et al., [166] found that many mechanical treatments use less energy than glyphosate per pass because of the energy needed to produce glyphosate. However, they could only estimate glyphosate energy consumption based on one old study since this information is considered a trade secret. Consequently, objective comparisons on the total energy use by chemical vs. non-chemical control becomes difficult.

3.1. Control in the Intercrop Period

Most studies on *E. repens* control focus on the intercrop period, specifically on the stubble of annual crops or when breaking grassland. This is primarily because most non-chemical control methods, and glyphosate, are non-selective and will damage or kill most plants that are affected by them. Thus, in a growing crop they must be used (1) in the areas underneath a crop or without a crop (e.g., inter-row hoeing/spraying/mowing); (2) by targeting the weeds directly without hitting crop plants, i.e., precision weeding; or (3) apply it in such a way or at such a time it does not cause unacceptable damage to the crop (e.g., mowing in grasslands/grass-strips, glyphosate used pre-harvest or pre-emergence).

Based on the review, tillage can be used to effectively control *E. repens* in stubble and when breaking grasslands. The traditional repeated non-inversion tillage followed by ploughing will effectively prevent *E. repens* populations from increasing or reduce them outright (e.g., [68,126,129,131,167]). Deep ploughing (20–30 cm) is more effective than shallow ploughing (10–15 cm) [71,127,128]. Conducting the non-inversion tillage close to harvest appears more important than repeating it [131]. Ploughing timing is less important than for many other creeping perennials [167], but can still matter [129]. A short fallow period with rotary harrow or a Kvik-up type machine also seem to effectively reduce *E. repens* populations [28,71,140]. The horizontal root/rhizome cutter may be an effective tool against creeping perennials as well, but it is not yet commercially available.

In comparison to tillage strategies, glyphosate seems to be generally more resource efficient. Firstly, in many cases glyphosate only needs to be applied once to be effective while most tillage strategies require multiple tillage operations. Secondly, glyphosate generally often has as high or higher efficacy than most tillage strategies [49,136]. This means that after a successful application, glyphosate will often not need to be applied as frequently as the tillage strategies, which may have to be applied annually or biennially. By some estimates, tillage treatments against annual weeds can have a lower overall energy cost than glyphosate [166], but for perennials like *E. repens* this is likely to be offset by the increased number and frequency of operations that are needed for control. One of the major arguments against tillage has been that it increases the risk of nutrient leaching and erosion, especially if conducted during periods of heavy rainfall, which is often the case in autumn. However, recent research has shown that it is not the soil cultivation itself that is the main cause of this, but rather the prolonged periods of bare soil, which is the result of an extended tillage strategy [69]. Thus, a shorter, more intensive fallow may consequently not cause more leaching than using glyphosate (which also results in temporarily bare soil, albeit with retained crop straw and dead plant material), at least if a sufficient vegetation cover can be achieved in a timely manner afterwards [69]. Tillage, in particular ploughing, is not only used for weed control. Ploughing is often performed to prepare the soil for the next crop, bury straw, and/or to reduce plant diseases (e.g., *Fusarium*) and can therefore increase yields or safeguard quality regardless of whether weeds are a problem [168]. However, many papers also describe the overall benefits of reduced-till and no-till systems (e.g., in [133]).

Subsidiary crops and post-harvest mowing can sometimes reduce *E. repens* autumn growth, but not consistently nor effectively enough to replace tillage or chemical control (e.g., [12,72,102,103]). They could, however, be components in set of preventive measures to reduce the frequency of direct control measures, and to provide other ecosystem services (e.g., reduced nutrient leaching, improved soil health). Control efficacy could potentially be improved through further optimization [103].

The review shows that there are several other control methods that can effectively kill *E. repens* rhizomes, for example soil disinfestation techniques and hot water. Major constraints for most of them are labor and energy requirements. In general, they are too costly to be used over large areas and risk killing beneficial soil organisms as well as pests, so their use must be motivated by large economic gains, e.g., disinfecting an area that can be used for high-value crops sensitive to competition or by spot application. However, usually glyphosate would be a more efficient solution for this unless performed to e.g., kill soil borne plant pathogens, nematodes, and belowground reproductive weed propagules.

3.2. Control in Growing Crops

Some crops are clearly better at suppressing *E. repens* than others, e.g., barley vs. field beans. A carefully planned crop rotation in combination with other preventive measures could most likely slow the development of *E. repens* within fields and consequently reduce the need for or frequency of direct control methods. This has not been sufficiently studied, however. The results of the review indicate that crops cannot control *E. repens* on their own. Even the most competitive crops, like barley, cannot reduce *E. repens* post-harvest. Consistency is also a large concern as crop competition varies between years and within fields. Indirect and direct control measures that can increase the *E. repens* control level and consistency in the crop are therefore needed.

There does not seem to be that many effective non-chemical direct control methods for *E. repens* that work in growing crops. In grasslands, it is primarily the mowing frequency that can be manipulated. A high mowing frequency is detrimental to *E. repens* and can potentially be sufficient to manage some *E. repens* clones in grasslands [108,115], but it seems that mowing approximately every two weeks is necessary to prevent *E. repens* from developing new rhizomes. Such a frequency is unfeasible in most circumstances. Using vertical disks seemed to provide an interesting option for restoring grasslands infested with *E. repens* [83], but follow-up studies show that the technology does not work well in hard soil conditions (Ringselle et al., Unpublished). Other defoliation treatments (e.g., thermal, etc.) are not feasible in grasslands as they are likely to cause unacceptable damage to the crop and leave openings in the sward. They may work for the grass strips in orchards or between crop rows in annual crops, but there is a lack of studies on this, particularly in orchards and berry production. Based on the variable success of inter-row hoeing (which can also damage the rhizomes) and mowing, it is likely that the treatment frequency of any defoliation treatment between crop rows would have to be high to control *E. repens*.

Van Evert [110] suggested that one way to make selective cutting an efficient control method of *R. obtusifolius* was to design a robot that would perform weekly cuttings. Such targeted spot-applications are also a way to make other defoliation methods more resource efficient [166] and a way to perform non-selective treatments without damaging or killing the crop. Compared to *R. obtusifolius*, a grass such as *E. repens* is far more difficult to distinguish in grasslands, but targeted applications are likely to be possible in other crops. The main problem is that if defoliation needs to be performed every two weeks to prevent rhizome growth, it would require a large number of robots to cover a large agricultural area. Moreover, it would be more resource efficient to spot-apply glyphosate or to use systemic graminicides in dicot crops, since this would likely result in very high efficacy, while keeping herbicide use levels low [169]. An alternative would be to either develop a non-chemical method that also destroy *E. repens* rhizomes when spot-applied, or to minimize the area that needs to be treated. For example, if *E. repens* is mapped in for example the intercrop period, control efforts could be applied in only the affected areas [170].

3.3. Future of Elymus repens Control

Glyphosate is likely to continue being the main control method for *E. repens* in conventional agriculture. Glyphosate is highly effective against *E. repens,* while only needing one pass to be applied, resulting in high efficacy per work hour. Perhaps most importantly for farmers, glyphosate is also effective in controlling other perennial weeds (e.g., *C. arvense*, *Sonchus arvensis*, *Rumex* spp.) and most annual weeds, meaning that a large proportion of the weed problems in a field can be controlled in a single treatment. Even though there is variation in susceptibility to glyphosate between *E. repens* clones, so far the species has not developed resistance [60]. Automated precision weeding is likely to fundamentally change weed control in the future, but the broad-spectrum efficacy of glyphosate makes it a better candidate for this type of control than any current non-chemical method or other herbicide. However, once their accuracy has become sufficiently high, weed mapping and automated targeting may focus control efforts sufficiently to make many types of targeted non-chemical control sufficiently resource efficient against perennial weeds [170].

The main non-chemical control method for *E. repens* is still tillage as other non-chemical control methods either use too much energy unless spot-applied [166], or they are too ineffective against *E. repens*. Tillage also has a high efficacy against *E. repens*, is effective against many weed species, but requires many passes/treatments to be effective against *E. repens* and other perennial weeds. As a result, glyphosate is most likely a more resource efficient treatment for *E. repens* than tillage, but comparisons are not always straightforward. Just like chemical weed control, mechanical weed control requires experience to be performed so that it is adapted to the field conditions and efficacy is maximized, while costs and negative environmental effects are minimized. The review shows that several new tillage machines have been developed that can shorten the treatment period (e.g., Kvik-up type machine) or cause less soil disturbance (e.g., root/rhizome cutters). It remains to be seen how big an impact these will have on the control of *E. repens* and other perennial weeds.

If glyphosate was banned/restricted, tillage intensity and use is most likely to increase in areas where ploughing is still common (e.g., the Nordic countries), as farmers there are more likely to consider the addition of non-chemical options like the Kvik-up type machine or the horizontal root/rhizome cutter. In areas and farms with a lot of reduced-till and no-till systems (e.g., Central and Eastern Europe), most farmers are likely to adopt alternative chemical control methods before increasing their use of non-chemical measures against *E. repens*. Using more dicot crops in the rotation would, for instance, make it easier to control *E. repens* using selective herbicides. Some major problems with the chemical alternatives is that (1) the selective herbicides may also be banned in the future or have their use restricted, (2) currently allowed doses and uses for the alternatives are already too low in some countries to effectively control *E. repens*, (3) alternatives do not have the same weed control spectrum as glyphosate and may thus lead to an increase in inversion tillage, and (4) alternatives may necessitate longer time intervals between treatment and sowing crop seeds due to higher soil activity and persistence. Thus, even if a glyphosate ban would not necessarily increase the tillage intensity and use to control *E. repens*, specifically, it is not unlikely to increase the need for more weed control measures (both chemical and non-chemical) or more treatments to achieve the same broad-spectrum weed control as glyphosate can. In case of a glyphosate dose reduction, the fact that lower doses of glyphosate combined with tillage can have as high an effect as higher doses of glyphosate is likely to be utilized more [171].

Weed control is a complex process involving many weed species, crops, cropping systems, and environments. No single weed control method can control all weed species, at all times, in all places, especially since a high selection pressure will lead to weed flora shifts (both between and within species). Therefore, a systematic approach with a broad toolbox of control methods will be key to be able to prevent and directly control *E. repens* in the future. Especially as rhizomatous species such as *E. repens* will benefit most from CO_2 enrichment [172,173]. Consequently, it is important to continue developing control methods for *E. repens* and other weed species. Both to give farmers as many tools as possible so that control can be customized to their specific needs, but also because effective and efficient non-chemical control methods would reduce the overreliance of glyphosate and other chemical control methods. A reduction in glyphosate use could also reduce some of the pressure to restrict/ban it, potentially protecting a very important weed control tool.

4. Conclusions

1. There is significant variation in how studies are conducted, how precise the methodology is described, how control is applied (e.g., implements, speed, timing, depth of treatments, soil and weather conditions, energy input), how *E. repens* responds to control measures, how *E. repens*

response to control strategies are measured, and in sample timing and duration. This makes objective comparisons between studies difficult.

2. Despite its considerable reliance on asexual reproduction, *E. repens* displays significant genetic and morphological variation, and vary in its response to control measures. Different control measures are likely to select for different *E. repens* clones.
3. Crop choice, subsidiary crops, and fertilization strategies can affect *E. repens* growth but are generally not sufficient to control *E. repens* without direct control. Such preventive measures often provide other benefits for cropping systems and economic services than weed control but can also be a hindrance to direct control measures. Further optimization of preventive measures is likely possible, but more studies on cropping system approaches to control *E. repens* are needed.
4. Defoliation by mowing or other methods can control *E. repens* growth, but efficacy varies between clones, seasons, and defoliation frequencies. There is room for further optimization of treatments. Spot applications may increase resource use efficiency in crops sufficiently distinct from *E. repens*.
5. Tillage can effectively control *E. repens* in the intercrop period (including breaking grasslands), while inter-row hoeing is not sufficient studied and has shown variable success against *E. repens*. Tillage is still the primary non-chemical control method for *E. repens.*
6. There are new tillage tools that can reduce the treatment period (e.g., Kvik-up type machines) or the soil disturbance (e.g., root/rhizome cutters) of the tillage treatments.
7. Current non-tillage methods that destroy *E. repens* rhizomes (e.g., soil solarization, soil steaming) are generally limited to small treatment areas or high-value cash crops due to high energy requirements. However, these methods are generally performed to achieve a full soil disinfestation, so *E. repens* control is usually a bonus rather than the primary goal.
8. The difficulties in achieving efficient non-chemical control of *E. repens* illustrates how the agricultural system may have to be holistically reviewed and fundamentally modified to manage perennial weeds with no or little chemical control. However, *E. repens* control must also be considered in the context of general weed control, as few farmers are concerned with the control of only one weed species. Being able to control many weed species is what makes glyphosate and tillage useful over large areas and in a wide range of circumstances. However, no one weed control method can control all weed species under all circumstances in a changing world, nor is it recommendable to exclusively lean on one particular method (due to weed flora shifts, antagonistic action, etc.), so a large toolbox of different weed control methods is needed for resource efficient control of *E. repens* and other weeds, now and in the future. To effectively and efficiently apply such a weed control toolbox, a systematic approach is vital.

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