Concept Paper

Expanding Red Clover (*Trifolium pratense*) Usage in the Corn–Soy–Wheat Rotation

Sara L. Wyngaarden [1], Amélie C.M. Gaudin [2], William Deen [1] and Ralph C. Martin [1,*

[1] Department of Plant Agriculture, University of Guelph, 50 Stone Road East, Guelph, ON N1G 2W1, Canada; E-Mails: wyngaars@mail.uoguelph.ca (S.L.W.); bdeen@uoguelph.ca (W.D.)

[2] Department of Plant Sciences, University of California, One Shields Avenue, Davis, CA 956 16-8571, USA; E-Mail: agaudin@ucdavis.edu

* Author to whom correspondence should be addressed; E-Mail: rcmartin@uoguelph.ca; Tel.: +1-519-824-4120 (ext. 52460); Fax: +1-519-763-8933.

Abstract: A common agronomic recommendation is under-seeding red clover to wheat in the corn–soy–wheat rotation. As a leguminous cover crop, red clover boosts agro-ecological resilience and productivity through nitrogen fixation, as well as non-nitrogen-related contributions, such as soil temperature and moisture regulation; reduction of erosion, runoff, and leaching; weed suppression; and interruption of pest and disease cycles. The objective of this paper is to propose a system that extends red clover usage into the corn phase of the corn–soy–wheat rotation as a living mulch. The system incorporates strip-tillage, strip-mowing, as well as banded herbicide and fertilizer application in order to maximize productivity and minimize competition. We analyzed the feasibility of this proposal by examining red clover's adequacy for the proposed system in comparison with other broadleaf, leguminous cover crops, and assessed potential agro-ecological benefits. We considered logistical components of the proposition, including the use of strip-tillage, the application of precision technology, as well as the opportunity for further technological developments. We found that the proposed system has potential to increase agro-ecological sustainability, resilience, and the overall productivity of this three-year rotation. Thus, this easily-implemented practice should be formally studied.

1. Introduction

In the face of global climate change, depleted resources, and environmental degradation, crop producers in Southern Ontario must seek to improve agro-ecosystem sustainability and resilience while maintaining productivity. To this end, a recommended practice is under-seeding red clover (*Trifolium pratense*) to wheat (*Triticum* spp.) in the corn–soy–wheat rotation. The benefits of this practice have been well-documented [1–8]; however, they could be further enhanced if red clover was maintained as a living mulch between corn rows, rather than being terminated prior to corn (*Zea Mays* L.) planting.

Living mulches provide a range of benefits to an agro-ecosystem, including diversification; soil temperature and moisture regulation; weed suppression (and herbicide reduction); nitrogen fixation (and fertilizer reduction); erosion control; and organic matter contribution [9]. Paine and Harrison emphasized the value of living mulches for vegetable production and other small-scale, intensively-managed cropping systems [10]. Benefits were clear when the system was optimized; however, they noted difficulties in balancing living mulches with main crop growth (also see [9,11]). Furthermore, cooler, wetter soils facilitated by the presence of the mulch can delay planting date, hinder emergence, and increase the risk of frost [12,13], as well as damage from slugs [14].

Addressing these concerns is feasible, however, and living mulches can contribute to viable systems. Donald *et al.* tested the combination of mowing weeds (albeit not a normal living mulch) between corn and soybean rows while also banding herbicides at a 50% rate within the rows [15]. Contrasted with broadcasting 100% herbicide, the crop yields increased and weeds were as well controlled under the mow/band system. Eberlein *et al.* partially suppressed an alfalfa living mulch to achieve similar corn yields to full suppression, but only under adequate crop moisture [16]. Similarly, weeds were controlled and corn yields maintained with Chewings fescue and ladino clover under adequate, but not under low moisture conditions [17]. Grubinger and Minotti suppressed a white clover mulch by roto-tilling (thus releasing N), resulting in similar or higher corn yields than in clean cultivated corn, mowed mulch, or unsuppressed mulch [18]. Kura clover was a successful living mulch, in that corn yield declines were minimal, weeds were controlled and the mulch fully recovered within a year [19].

We propose to extend red clover as living mulch into the corn phase of the corn–soy–wheat rotation. In this "proposed system", red clover is frost-seeded into the wheat stand and maintained after wheat harvest. Rather than terminating the whole red clover stand prior to corn planting, fall strip-tillage is applied in 30 cm-wide strips at 76-cm spacing. This tillage method leaves an undisturbed inter-row space of 46 cm, allowing the clover therein to over-winter and regrow in the spring. At spring planting, corn is seeded into the tilled strips, in which a fertilizer band and on which a herbicide strip is applied. The clover is mowed until corn canopy closure to ensure sufficient corn establishment. These strips provide inter-row soil coverage, acting as a living mulch throughout the season. Prior to the soybean phase of rotation, they are incorporated (see Figures 1 and 2). It should be noted that, although this

paper assumes a perspective of conventional agriculture, the proposition can be adapted for organic production systems by applying organic fertilizers and substituting herbicide application for practices, such as precision tillage or flame weeding.
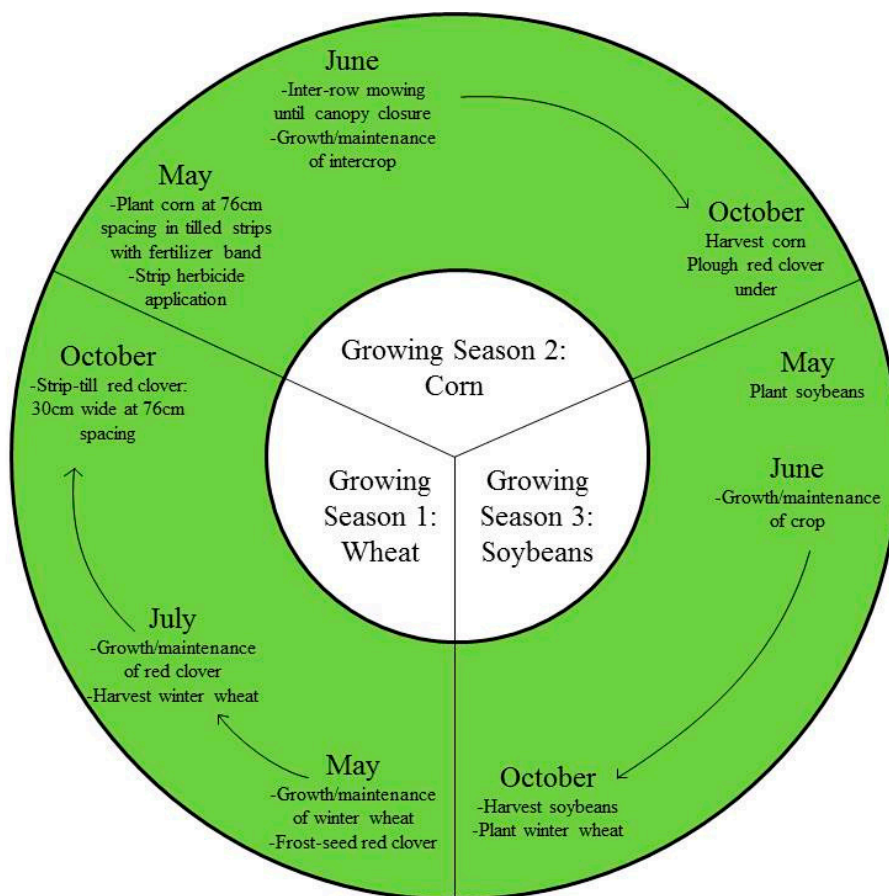

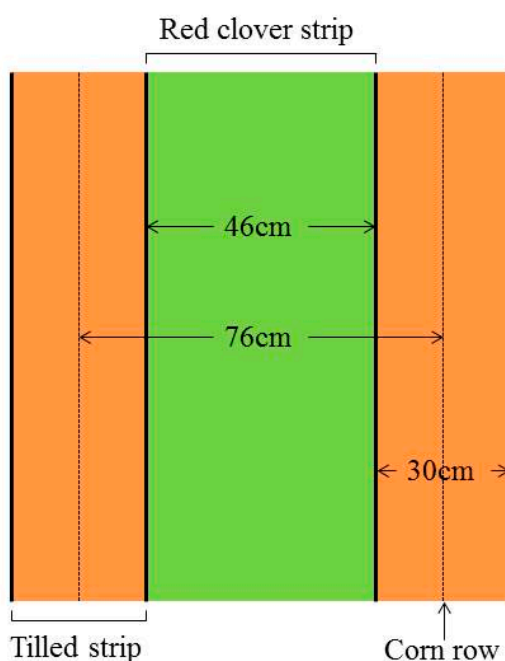
Figure 1. Diagram of the proposed system.

Figure 2. Dimensions of strip-tilled corn rows with inter-row red clover.

Much research has been performed on the corn-soy-wheat rotation, on cover crops, and on strip-tillage independently. Researchers have noted the impact of red clover incorporation on corn productivity, several with specific focus on this rotation [1,2,4–7,20–22]. Studies have examined the use of strip-tillage for corn [2,17–20], and others have looked at the viability of integrating living mulch in corn [9,12,13,23]. Few researchers, however, have endeavoured to incorporate these factors together.

A study that did address these factors was performed in Nova Scotia from 1995–1996 [12]. Martin *et al.* examined the viability of growing corn in a living sod mulch of white clover (*Trifolium repens*) and mixed grasses. They tested various mulch management practices, including mowing, tillage, and herbicides, in order to minimize main crop competition. Treatment plots using a single mulch-suppression technique had yield reductions ranging from 39% to 72%. However, the treatment that combined inter-row mowing with 30 cm-wide strip-tillage and banded herbicide within this strip had yields comparable to the conventionally-managed treatment (8006 kg DM/ha and 10,362 kg DM/ha in 1995, respectively) [12]. The yield difference of 23%, though not found to be statistically significant, was of commercial consequence; however, the authors cite a previous study which applied the same treatments with a yield difference of less than 4% (11, 573 kg DM/ha and 11, 947 kg DM/ha, respectively) [24].

2. Adequacy of Red Clover for the Proposed System

The corn–soy–wheat rotation benefits agro-ecologically from the under-seeding of a broadleaf, leguminous plant to the wheat-phase of rotation. Nitrogen fixation offers nutrient input after wheat, a medium-feeding crop, and before corn, a high-feeding crop. Furthermore, the presence of a dicotelydon between these two monocotelydons provides a break in pest and disease cycles. Although Southern Ontario is host to numerous broadleaf, leguminous plants, red clover is most commonly selected for this rotation. In this section, comparison will be made between red clover and other broadleaf, leguminous cover crops, particularly alfalfa (*Medicago sativa*) due to its prevalence as a cover crop choice, but also including birdsfoot trefoil (*Lotus corniculatus*), white clover (*Trifolium repens*), sweet clover (*Melilotus* spp.), alsike clover (*Trifolium hybridum*), kura clover (*Trifolium ambiguum*), and cicer milkvetch (*Astragalus cicer*). A summary of these comparisons is shown in Table 1. Annuals will not be considered as they would not suit the proposed system.

Table 1. Comparing broadleaf, leguminous cover crops.

Condition	Red Clover	Alfalfa	Birdsfoot Trefoil	White Clover	Sweet Clover	Alsike Clover	Kura Clover	Cicer Milkvetch
Preferred climate conditions	Cool and moist [25]	Moderate moisture [26]	Poor winter hardiness [27]	Mild, temperate, cool and moist [28]	Poor winter hardiness [27]	Good winter hardiness [27]	Prefers cool climates [29]	Good winter hardiness [27]
Ideal pH range	6.0–7.0 [25]	6.5–7.5 [27]	>5.5 [27]	>5.5 [28]	6.5–7.5 [30]	>6.0 [27]	5.0–6.0 [29]	>6.0 [27]
Optimal temp. for growth (°C)	18 to 25 [31]	25 [32]	20–30 [33]	20–25 [28]	-	-	-	-
Establishment	Ease, moderately vigorous [27]	Ease, equal to RC [34]	Slow to establish, weak seedlings [27]	Less competitive than RC [35]	Vigorous, easy to establish [27]	Easy to establish [27]	Slow to establish, but persistent [29]	Years to establish, then competitive [27]
Lifespan/persistence	Short-lived perennial, 2–4 years [31]	3–20 years [27]	10+ years [36]	Perennial [28]	Biennial [27]	1–5 years [27]	Perennial [29]	5–20 years [27]
Regrowth	From crown, high recovery rate [37]	From crown [27]	From crown [27]	Stolons and self-seeding [28]	From crown [27]	From crown [27]	Rhizomes, slow recovery [29]	Stolons, slow recovery [27]
Competitive capacity	High [27]	High [27]	Moderate [27]	-	Moderate [27]	Moderate [27]	Persistent and hardy [29]	Moderate [27]
Drought tolerance	Moderate [31]	High [27]	Moderate [27]	Low [36]	High [27]	Prefers cool, wet conditions [27]	Moderate, goes dormant [29]	Moderate, goes dormant in drought [27]
Shade tolerance	High [25]	Moderate [26]	Low [33]	Moderate [28]	-	-	-	-
Seed prices	$4.50 US/kg [38]	$6.50–$8.50/kg [38]	-	-	-	-	-	-

2.1. Light, Moisture, and Temperature

Red clover germinates in temperatures as low as 5 °C [39] and continues to grow at temperatures above 32 °C, though growth is slowed [40]. It thrives where conditions are shady, cool, and moist [3]. Red clover has a light compensation point of 6% (the light intensity at which photosynthesis rates balance respiration rates). In contrast, the light compensation point for alfalfa is 13% [41]. Blaser *et al.* suggest that this factor explains the observed difference in dry matter production between red clover and alfalfa [34]. The impact of this factor is further demonstrated in a study by Gist and Mott [40]. Under a light intensity of 200 foot-candles (double what is typical for an overcast day, one fifth the intensity of full daylight, and one fiftieth that of direct sunlight), red clover produced 50% more above-ground biomass than alfalfa and both cover crops produced significantly more than birdsfoot trefoil.

These findings suggest the superiority of red clover under shaded conditions, as in the proposed system. Corn canopy closure occurs before summertime, when day length is longest and temperatures are highest in Ontario. Ground-level light intensity corresponds negatively with corn growth, leading to an increasingly shady and cool sub-canopy environment. Furthermore, Wang and Liu demonstrate that soil evaporation decreases exponentially in relation to leaf area index until hitting zero, at a sub-canopy radiation level of 230.57 watts per m^2 [42].

2.2. Establishment, Regrowth, and Termination

Emerging just seven days after seeding [39], red clover's establishment rate is superior to other cover crops, particularly birdsfoot trefoil [43], cicer milkvetch [27], kura clover [36], and white clover [35]. It is equivalent [34] or even superior [44] to alfalfa.

Red clover typically persists well for two years in Ontario [6,44], an ideal lifespan for the proposed system. Though a biennial or short-lived perennial lifespan is common among clovers, the method and success of re-growth differs. For example, white clover propagates by way of stolons [36], which introduces a challenge for the proposed system, where tilled strips must remain clear for corn growth. Red clover and sweet clover both regrow from the established crown; however, in its second year sweet clover produces a long, thick stem, putting less energy into weed-suppressing foliage [36]. Alsike clover thins rapidly, thus also becoming insufficient for weed suppression [36]. Established kura clover is the hardiest of clover species but, growing from rhizomes, it is unfeasible for the short-term rotation of the proposed system [36].

Termination of red clover can be challenging while plants are actively growing, however, once temperatures fall below 15 °C growth rates decline [39]. In the proposed system, partial stand termination occurs in the first year, while termination of the remaining stand occurs after corn and before soybeans, either in the late fall or early spring. Both procedures can be performed in temperatures below 15 °C.

2.3. Main Crop Competition

During the growing season, the competitive nature of red clover raises concerns about hindrance of the main crop. Studies examining the impact of germinating red clover in an established crop, such as

red clover under-seeded to winter wheat [34] or red clover inter-seeded with corn [9], have shown no significant negative impact on grain yields. However, in the proposed system, red clover's spring re-growth occurs alongside corn germination. To the knowledge of the authors, however, no studies have investigated the competitive impact of the proposed intercrop.

In a literature review, Zumwinkle highlights the concern of over-competition, particularly with water and nitrogen resources [11]; however, he suggests that a balance can be attained through effective living mulch stand management. To attain the balance that Zumwinkle suggests, we recommend the combination of strip-tillage, in-row banded herbicide, and mowing of the inter-row clover stand. Using this three-tiered management approach, Martin *et al.* successfully controlled inter-row sod strips until corn canopy closure, when competition with the main crop was no longer a concern [12]. They ensured that the stand never surpassed 12 cm, which required two mowing treatments in total. While red clover may have greater height vigour, and, thus, require more frequent mowing than the mixed sod used by these researchers, it should be noted that forages grow more slowly in Ontario's climate than in the Atlantic Canadian climate where this study was performed.

One way to evaluate potential competition *versus* niche complementarity is to examine the physical distribution of root systems: insofar as plants occupy different spatial niches, resource competition is minimized. Corn has fibrous roots, which grow to a depth of 1.5–2 meters and a width of one meter (see Figure 3A, B) [45,46]. Red clover has both fibrous lateral roots and a taproot (see Figure 4). The majority of red clover root activity takes place amongst the lateral roots, in the top 12 cm of soil [3].

In the proposed system, there is potential for root overlap as the width of the corn root system extends beyond the 30-cm tilled strip. The greatest risk of root zone interference would occur in earlier stages of corn growth, when roots remain in the top 30 cm of soil and can extend 75 cm in any direction [46]. Later in the season, the roots turn downward and the bulk of the corn root system lies deeper than red clover's.

The potential for early-season competition based on root system overlap between established clover and germinating corn requires formal research. Overall, however, some insight may be drawn from a study of root system interactions and nutrient-foraging behaviours of the traditional "three sister" cropping system (corn, beans, and squash) [47]. Based on growth patterns and yields, the results of this study suggest that the divergent nutrient-foraging strategies of these crops, particularly corn and beans, spatially complemented each other, rather than interfering with one another.

(A)

Figure 3. *Cont.*

(B)
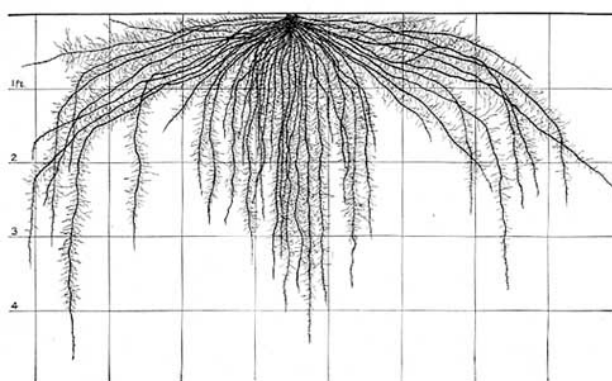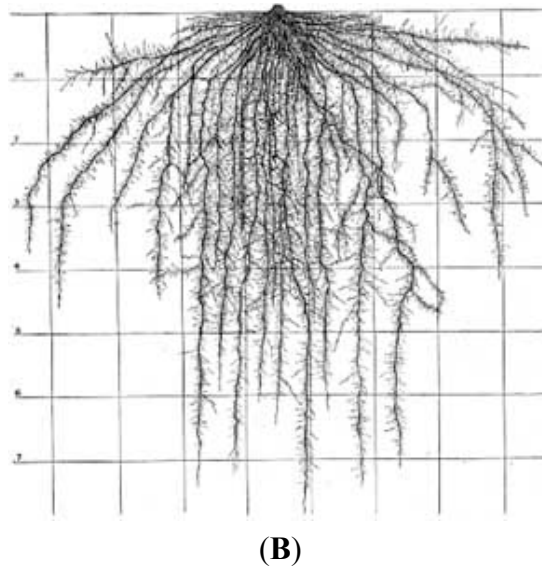
Figure 3. (**A**) Corn root system, 8 weeks [46]; (**B**) Corn root system, mature [46].

Figure 4. Red clover root system, mature [46].

Red clover has one of the highest below-ground biomass measurements among clover species [48]. Its lateral roots have primary access to moisture and nutrient inputs, but are also vulnerable to the immediate impacts of drought and nutrient-deficient conditions. The taproot, on the other hand, allows access to deeper resource deposits, taking up moisture and nutrients from the subsoil [3], which are

less prone to fluctuation than surface deposits [49,50]. Tap roots increase plant resilience, reducing dehydration under drought conditions [51]. Red clover's taproot typically grows to a depth of one meter but can reach up to three meters in light, well-drained soils [52].

2.4. Drought Tolerance

Though considered drought-tolerant [3], Peterson *et al.* found that red clover did not perform as well under drought stress as birdsfoot trefoil, cicer milkvetch, or alfalfa, each of which has a thick taproot [53]. Alfalfa, in particular, maintained more than twice the above-ground biomass as red clover in this study. However, preliminary research indicates that despite a substantial decline in biomass under drought stress, red clover quickly recovers once drought conditions subside [37]. This area requires more formal research; however, perhaps a parallel can be drawn with red clover's growth pattern when under-seeded to winter wheat. Although red clover germinates and sprouts, competition for moisture and nutrients delays flourishing until after the wheat is harvested. Forty days after cereal harvest, Blaser *et al.* measured a two-fold to thirty-fold increase in red clover root dry matter, a 64% increase in root length, and an average shoot: root ratio rising from 8.5 to 11.2 [54]; red clover dry matter production was essentially constant, regardless of winter cereal seeding density [55]; and red clover dry matter production was found to be 42% higher than alfalfa [34].

2.5. Stand Evenness

Red clover exhibits problems with stand evenness. Queen *et al.* observe a correlation with soil moisture [56], while Muñoz *et al.* demonstrate an association with topography, with higher red clover biomass on low-lying areas than on slopes [57]. There are a variety of issues associated with an uneven cover crop stand. Bare patches do not receive the benefits of increased organic matter and nutrients. Additionally, lack of coverage makes soil vulnerable to degradation through erosion and runoff [50], as well as losses through evaporation [58] and volatilization [49]. Furthermore, without the competition of the cover crop, the area becomes susceptible to weeds [23]. To address this issue in the short-term, Williams found that spot seeding with red clover is effective [59]; however, a system resolution requires further research.

2.6. Seed Costs

Compared to alfalfa, red clover seed is inexpensive, priced at approximately $4.50 US/kg [38]. The Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) recommends a seeding rate of 11 kg/ha for red clover [3], resulting in an overall cost of $49.50/ha. In contrast, 13 kg/ha of alfalfa seed [3], priced at $6.50–$8.50/kg [38], costs $84.50–$110.50.

3. Contributions to Agro-Ecosystem Sustainability and Resilience

3.1. Nitrogen Use Efficiency

As a legume, red clover fixes nitrogen from the atmosphere through symbiotic interactions between its underground nodules and surrounding rhizobial bacteria [60]. This feature is beneficial to the agro-ecosystem two-fold; first through nodule transfer, and second through biomass decomposition.

Thilakarathna *et al.* measured a transfer of 4.2% to 15.2% nitrogen from red clover nodules to surrounding bluegrass [61]. In Southern Ontario, nitrogen fertilizer application rates for corn range from 150–180 kg N/ha. Based on these requirements, the upper value (15.2%) would correspond with a nitrogen transfer of approximately 22.8–27.36 kg·N/ha, while the lower value would parallel a study by Martin *et al.* where nitrogen transfer in soybeans contributed an estimated 5–10 kg·N/ha to corn [62]. Though present, this transfer is small and would be further diminished in the proposed system, where the use of strip-tillage causes a degree of separation between red clover roots and corn roots.

More significant is the nitrogen credit from the decomposition of root and shoot biomass. Dapaah and Vyn found that corn grown after red clover consistently gave 10% to 40% higher yields than corn grown after oilseed radish or ryegrass [1]. They attributed this yield boost to the slow release of mineralized nitrogen from red clover. Although Bruulsema and Christie observed a greater nitrogen mineralization aptitude in alfalfa than red clover, resulting in a 7% higher N-concentration in subsequent corn plants, this was not correlated with consistently higher corn yields [20]. In this regard, Stute and Posner found that red clover releases approximately 50% of its nitrogen in the first four weeks after mortality, with nitrogen release continuing for approximately ten weeks in total [63]. In corn crops, nitrogen intake peaks between the sixth and eighth collar and is low after silking [64]. With the hindrance of decomposition over winter in Ontario, as well as the time needed for corn germination and emergence, the timing of red clover's nitrogen release seems to correspond aptly with corn development needs [65].

In the proposed system, nitrogen credit to corn in the untilled strips, representing approximately two-thirds of the field, would be based on winterkill and decomposition of the above-ground biomass and the root system, excluding the crown and tap root. Researchers at Penn State University note that the nitrogen contribution from incorporation is comparable to the contribution from red clover left as a mulch [66]. For the purposes of this paper, therefore, the assumption will be made that the nitrogen credit from red clover is equal between the tilled and untilled strips, with recognition that this assumption warrants testing.

Nitrogen contribution from a red clover stand varies based on the accumulated biomass, as well as weather conditions, soil type, and other dependent variables. Measurements in the literature include 87–184 kg·N/ha [67], 102–108 kg·N/ha [21], 90–125 kg·N/ha [20], and an average of 96.7 kg·N/ha, based on a literature review by Gaudin *et al.* [6]. For this paper, an estimation of 90 kg N/ha will be employed.

Although a nitrogen credit of 90 kg·N/ha is not sufficient to support this high-feeding crop, it does allow for a reduction in the fertilizer rate to 60–90 kg·N/ha. In a meta-analysis, Miguez and Bollero found that a rate of 0–99 kg·N/ha yielded 34% higher in corn plots following a legume than in those with no cover crop. From 100–199 kg·N/ha the productivity was boosted by 17%, and at 200 kg·N/ha

or higher there was no significant impact [4]. Thilakarathna *et al.* support this finding with their study comparing legume and non-legume cover crops [65]. Furthermore, in a corn-soybean intercrop, Martin *et al.* found that a moderate fertilizer application rate (60 kg/ha, rather than 0 kg/ha or 120 kg/ha) maximized corn yield without suppressing nodulation in soybeans [62]. In other words, a reduced fertilizer application rate maximizes systemic nitrogen use efficiency in a corn-legume intercrop, such as the proposed system.

In the proposed system, nitrogen use efficiency could be further facilitated by applying fertilizer in bands adjacent to the corn rows. Banding would simultaneously minimize interference between the fertilizer and red clover nodules while maximizing nitrogen uptake efficiency for the corn. Tarkalson and Byorneberg found that banded fertilizer in a strip-till system boosted corn yields by 12.5%–25.9% compared to broadcast in a conventionally-tilled system [68]. Additionally, Nash *et al.* found that corn yields were approximately 3 Mg/ha higher with fertilizer injected in a band, rather than broadcasted [69].

It is noteworthy that the inter-row red clover strips in the proposed system would also provide a nitrogen credit into the soybean phase of rotation. After a high-feeding crop such as corn, soil nutrients are depleted and need to be replenished. Although soybeans fix nitrogen to supply their own needs, they do not provide a significant soil nitrogen credit. Bruulsema and Christie, however, measured a 25% boost in nitrogen credit from red clover that was cut once [20]. Thus, it is possible that the nitrogen content of the inter-row red clover would be boosted by the mowing management practices proposed in this system.

The complexities of balancing nitrogen sources in the proposed system demand due consideration; however, the benefits of a red clover cover crop extend beyond nitrogen contributions. Henry *et al.* found significantly higher corn yields in treatments with red clover than those without, despite being unable to correlate this with a nitrogen contribution in three out of four years of study [5]. These results suggest that the non-nitrogen related benefits of using red clover are also beneficial to productivity.

3.2. Regulating Soil Conditions

In Ontario, dry, uncovered soils—as found between corn rows prior to canopy closure—can reach temperatures greater than 40 degrees on sunny days [50]. Such temperatures are detrimental to soil micro-organisms, which thrive at a range of 20–30 degrees and which stimulate soil processes such as the nitrogen cycle [50]. Excessive heat can cause further inefficiencies, such as nitrogen losses through volatilization [49] and moisture loss through evaporation. Cover crops help moderate soil temperatures by protecting the soil from direct sunlight [58]. Cover crops also moderate soil moisture conditions by interrupting the soil surface, preventing direct soil-raindrop impact, and thus preventing crusting and sealing and improving water infiltration and retention [70]. Although cover crops contribute to systemic water loss through transpiration, Wang and Liu note that transpiration contributes to total agroecosystem productivity, whereas soil evaporation is lost from the system [42]. Thus, in the proposed system, red clover offers agro-ecological benefits that bare soil cannot.

These moderation effects are not always beneficial, however. When temperatures are cool around the corn seed bed, germination and emergence are hindered, leading to late maturation and reduced yields [71]. This effect is particularly evident in no-till systems on medium- to fine-textured soils. Although studies performed in coarse soil showed an average of 0.9% higher yields under no-till, the

no-till plots in medium and fine soils showed 5.6% and 6.5% lower yields than conventional tillage, respectively [72]. Furthermore, low temperatures and high moisture can cause frost. Red clover is frost-tolerant, but corn is sensitive to frost. Measuring a 40% reduction in yields in one year of study, Martin *et al.* attributed 27% of this yield drop to an unusually late frost, and the rest to the subsequent delay in corn establishment and development. To address the concerns associated with no-till, as well as the cover crop moderation effect, the proposed system implements fall strip tillage.

3.3. Mitigating Soil Degradation

Researchers from OMAFRA recommend maintaining a minimum of 30% soil coverage year-round, which has been shown to effectively lower erosion by 60% [50]. This is supported by Gaudin *et al.* [6], as well as Martin *et al.* [12]. The structure of red clover makes it conducive to providing soil coverage, reducing degradation, and retaining moisture and nutrients within the root zone [49]. Its fibrous lateral root system improves structural stability by holding surface soil in place. Additionally, the tap root helps disrupt subsoil. Temesgen *et al.* measured a difference of 25 mm/season in runoff between control plots and treatments where the subsoil was interrupted (43 mm/season and 18 mm/season respectively) [73]. Though this sub-soiling was performed mechanically, the principles of this study can be applied to tap roots as well, albeit on a smaller scale.

Soil quality is not only improved by living clover, but also by its contribution to soil organic matter. Reaching a height between 15 and 60 cm [3], red clover has ample above-ground vegetative growth. Along with its root structure, it attains significant biomass which, due to a low C:N ratio (between 13.6 and 16.7 [20]), is readily decomposed into soil organic matter [44]. This rich material enhances the structural stability of soil, reducing erosion, runoff, and leaching while increasing water infiltration. Additionally, Dapaah and Vyn demonstrate that the incorporation of red clover results in continual improvement of wet aggregate stability throughout the season [1], which improves water- and nutrient-retention and reduces soil crusting and sealing [3]. A study by Bergström and Kirchmann, found that a leaching rate of approximately 575 mm in uncovered soil was reduced to 400 mm in soil with red clover incorporation due to the improvement in soil water-holding capacity [74].

As it decomposes, red clover facilitates the decomposition of surrounding crop residue. Drury *et al.* noted an average of 38% less crop residue in strip-tilled plots with red clover than those without [2]. In the proposed system, this process would facilitate the conversion of winter wheat residue into soil organic matter in the tilled strips, as well as the un-tilled strips, where the winterkilled clover would offer an added benefit of acting as a mulch.

3.4. Weed Management

According to Blaser *et al.* [34], the presence of red clover after wheat can reduce weed density by approximately 65% within a single season. The continuation of red clover into the corn phase of rotation, as in the proposed system, would serve to maintain and enhance this weed density reduction.

A benefit of using living mulch for weed suppression is that the plant material continually competes with weeds for light, moisture, and nutrient resources [67]. The complexity when intercropping, however, is achieving a balance between weed competition and main crop competition.

After overwintering, red clover regrows quickly from its pre-established crown and is immediately competitive with emerging weeds [37]. Ross *et al.* found that clover was most effective at suppressing weeds in lower-fertility soils [75], which may include post-wheat harvest soils. In their study of seven different clover species, they found that the presence of clover reduced mustard weed biomass by 57% in low-fertility soils and by 29% in high-fertility soils. In high-fertility soils, necessary for successful corn production, competition for light is the biggest factor determining plant success, if water is not limiting. Although red clover's height range would make it an effective competitor for light [3], in the proposed system, competition based on height would be problematic for the establishing corn. Shoots would block sunlight from young corn plants and deplete moisture and nutrient resources for the corn seedlings.

Bosnic and Swanton show that the timing of weed emergence has a greater impact on corn yield potential than weed stand density [76]. Their study of barnyardgrass (*Echinochloa crus*-galli) showed that the presence of 200 weeds/m^2 during the development of corn's first leaves reduced final yields by 26%–35%. On the other hand, after corn's fourth leaf emerged, the same weed incidence only caused a 6% decline in yields. Researchers at OMAFRA relate this to a biological function called "shade avoidance" [77], which refers to the tendency for plants, when sensing the presence of a potential competitor, to put more energy into shoot growth than root development in order to gain height and avoid shading. In this regard, they conclude that weed management in corn is most vital while corn plants have between one and five collars [77].

Some researchers raise concerns that mowing young weeds can improve their competitive ability by stimulating lateral budding [23,78]. However, among clover species studied by Ross *et al.*, including red clover, weed densities were better reduced in cover crop treatments with mowing than those without [75]. On average, mowed clover regrew four times faster than the mustard weed under study. Furthermore, clover regrowth is directed into foliage production [3], which improves its ability to compete with weeds.

The proposed system has the potential to greatly reduce herbicide inputs and, subsequently, input costs. Martin *et al.* found that their 46 cm inter-row cover crop, in combination with a 30 cm-wide banded herbicide application on the row, reduced herbicide application by 60% [12].

Allelopathy

Research suggests that clover has an allelopathic effect on surrounding plants. Den Hollander *et al.* drew this conclusion after observing that weeds out-competed the cover crop for light, but still experienced competitive pressure from the clover [79]. Dapaah and Vyn observed an initial stunting effect in corn plants grown following red clover ploughdown [1]. Six weeks after planting, however, these plants caught up and eventually their productivity surpassed that of corn grown after oilseed radish, as well as ryegrass. Similarly, Ohno *et al.* measured a 20% reduction in wild mustard and bean growth in red clover ploughdown treatments eight days after clover incorporation; however, by day 21 these plants caught up with the control treatments [80]. These researchers were able to correlate their findings with phenolic compounds released by red clover into the soil.

This allelopathic quality accentuates the potential of red clover as a weed suppressant in the proposed system. Its initial phytotoxic effect on emerging weeds could eliminate them entirely or

hinder their growth and allow the red clover to strengthen its competitive advantage. Although there may be a preliminary impact on the main crop, these studies show that the agro-ecological benefits of red clover soon overtake the allelopathic hindrance.

3.5. Pest and Disease Management

In the corn–soy–wheat rotation, red clover acts as a break crop between winter wheat and corn [81]. Two notorious pests that impact crops in the three-year rotation include corn rootworm and soybean cyst nematode. Calvin suggests that the incorporation of any legume into rotation with corn can deter corn rootworm [82]. Supporting this statement, Bruulsema and Christie observed severe damage from corn rootworm in plots without a cover crop, while plots preceded by either alfalfa or red clover showed no rootworm damage [20].

The hatching of soybean cyst nematode is triggered by an exudate from soybean roots [83]. This stimulant is released by other legumes, but after triggering larval hatching they act as a poor host or a non-host [3]. Chen *et al.* measured up to a 40% decline in the soybean cyst nematode population in a soybean-red clover inter-crop. Although their results were inconsistent [84], other studies have supported this finding. Aiba found that some red clover varieties decreased the presence of soybean cyst nematode by 57%–64%, as compared with plots left fallow [83]. Warnke *et al.* found that red clover residue reduced hatching and nematode mortality at a rate equivalent to fresh plant material [85]. Kushida *et al.* found that none of the nematodes that hatched in red clover roots developed into full adults [86]. Overall, in the proposed system, the extension of red clover into the corn phase of rotation could continue to protect corn from rootworm infestations while also further reducing soybean cyst nematodes prior to the soybean phase of rotation.

Red clover has been found to encourage beneficial insects. Bottenberg *et al.* found a significantly higher population of lady beetles as well as damsel bugs in rye plots inter-seeded with red clover than those without [87]. The researchers also found, however, that plots with red clover experienced the most leaf damage.

Red clover is also susceptible to damage from pests and disease. Known pests include the clover seed chalcid, bud weevil, root curculio, root borer, and the Meadow Spittlebug, all of which can overwinter [88]. In the proposed system, Meadow Spittlebug could be particularly problematic, as it overwinters on crop residue, which would be prevalent in the un-tilled strips [66]. Furthermore, when weakened, clover is susceptible to disease, particularly prone to damage by Northern Anthracnose and powdery mildew [3]. To our knowledge, however, there are no recommended management strategies for the pests or diseases which affect red clover, nor is there research on the potential impact of intercropping on these pests and diseases. This area is in need of further investigation.

3.6. Greenhouse Gas Emission Reduction

In the proposed system, red clover would help reduce greenhouse gas emissions in two ways. First, through the reduction of synthetic fertilizer, which is energy-intensive to manufacture. Ahlgren *et al.* calculated energy requirements of 35 MJ/kg N for fertilizer production through natural gas, the most common fuel for ammonia production [89]. Overall, world production of nitrogen fertilizer comprises 1.2% of primary energy use [89]. Second, red clover increases carbon sequestration. When growing,

plants take carbon dioxide from the atmosphere and transform it into organic matter. Upon decomposition, this organic carbon is transferred into the soil's organic carbon reserves [49].

Meyer-Aurich *et al.* performed a cost-benefit analysis of seven crop rotations and two tillage types in terms of Greenhouse Gas emission reductions [8]. Accounting for cost trade-offs, they found that benefits were maximized in the corn-corn-soy-wheat rotation with red clover. Compared to continuous corn, this rotation had 1300 kg CO_2 eq/ha lower emissions and overall financial returns $100/ha higher.

4. Logistical Management of the Proposed System

4.1. Tillage Timing and Method

According to OMAFRA, it takes 75–80 Crop Heat Units for each corn leaf to develop [77]. In Southern Ontario, where the growing season is shortened by winter, producers strive to plant early in order to maximize on harvestable heat units. For early planting to be successful, however, producers must facilitate soil drying and warming, as corn requires a minimum soil temperature of 10 °C in order to germinate [90]. For this reason, red clover in the corn-soy-wheat rotation is typically incorporated in the fall using conventional tillage to ensure that the soil receives direct sunlight in the spring.

Conventional tillage promotes good establishment, quick emergence, and steady development, all of which foster high corn yields [90]. This practice, however, has been reproached for degrading soil quality. Tillage disrupts beneficial soil organisms and breaks up soil aggregates, disturbing structural stability and making the soil vulnerable to compaction, runoff, erosion, and leaching [49]. In Southern Ontario, vulnerability peaks in the winter-spring thaw period. Wall *et al.* found a 10:1 ratio between seasonal and annual erodibility of Southern Ontario soils, where seasonal erodibility was defined as the winter-spring thaw period [91].

In contrast, no-till systems allow for the build-up and maintenance of quality soil structure by preserving soil aggregates and retaining soil structure [49]. However, in Ontario no-till systems typically produce lower corn yields than conventionally-tilled systems [2], particularly in poorly-drained soils [69].

4.2. Strip-Tillage

Strip-tillage has been proposed as an intermediary between conventional and no-till systems, purportedly capturing the benefits of both extremes [2,71,92]. The undisturbed inter-row space offers the benefits associated with no-till. By applying tillage directly to the row, and thus the root zone, the crop experiences development advantages associated with conventional tillage [69]. For example, Licht and Al-Kaisi found that soil temperatures under strip-tillage were essentially equivalent to those under chisel-plough, while 1.2–1.4 °C warmer than that under no-till [71]. Drury *et al.*, in a four-year study of the effects of tillage and red clover on corn yields, found that the average yield from strip-tilled plots with red clover was only 1% lower than conventional tillage and 4% lower than conventional tillage with red clover [2]. Although the presence of red clover increased yields under all tillage types, the yields under strip-tillage experienced the greatest boost: 40% higher than without red clover in 1998. No-till experienced 37% higher yields with red clover and conventional tillage experienced 4%

higher yields. Overall, their findings suggest that when environmental conditions lead to yields that are distinguishable by tillage type, strip-tillage, particularly paired with red clover, outperforms no-till and rivals conventional tillage [2].

One of the concerns associated with strip-tillage is the challenge of weed management. Strip-tillage creates two distinct zones within a field; tilled and un-tilled. The zones differ in their biotic and abiotic characteristics, making them prone to different weeds and therefore responsive to different weed management strategies [92]. Their adjacency can complicate weed management. We believe this issue is addressed with the use of mowing and in-row herbicide in the proposed system. For producers striving to reduce or avoid herbicide application, Brainard *et al.* performed a comprehensive review and synthesis of literature to identify viable implementation options [92]. They emphasize an integrated-management approach including cover crops, precision cultivation, and flame-weeding, among other management options.

4.3. An Opportunity for Precision Agriculture

As noted by Brainard *et al.*, the development of precision agriculture technologies, such as GPS and RTK systems, has made related management practices much more feasible [92]. The proposed system could be further refined and improved by the use of such technologies. For example, these implements would ensure accurate alignment of the strip-seeder in the tilled strips. Additionally, they could be used to properly align the strip-mower in the inter-row space. Between years and throughout the rotation, such technologies would enable a producer to consistently use the same track routes, thus minimizing soil compaction. Farm machinery traffic is identified as one of the key contributors to soil compaction, leading to degraded soil quality and reduced yields [93].

4.4. Strip-Mowing Technology

In order for the proposed system to be viable on a substantial scale, equipment designed for strip-mowing would need to be developed. Although strip-tillage equipment is available, to our knowledge a strip-mower has not yet been developed. To develop this technology, row-width mowing units, equivalent to the number of rows of the corn planter used on the farm, could be attached to a tractor-mounted tool bar.

5. Summary and Conclusions

Based on the literature review presented above, we believe that the proposed system has potential to introduce significant benefits to the agro-ecosystem as well as the producer, and thus is worth formal study. Red clover offers a nitrogen credit to corn, a high-feeding crop. Furthermore, the structure of red clover introduces stability to the soil surface, offers depth within the soil profile, and provides soil coverage, thus reducing erosion, runoff, and nutrient leaching. It competes effectively with weeds and prompts the premature hatching of pests which plague corn and soybean crops, reducing their population and limiting their detrimental impact. Through soil moderation, red clover stimulates beneficial microbial activity. Moreover, its contribution to soil organic matter upon decomposition reduces greenhouse gases and improves overall system resilience through stable soil aggregation.

In comparison with other broadleaf, leguminous plants, red clover's ecological needs and agro-ecological contributions complement those of a corn crop, suggesting their aptitude as an intercropping pair.

Financially, this system offers benefits to producers through input reduction opportunities. Herbicide application can be decreased to 40% of its original level, and nitrogen fertilizer application may be cut by approximately half. Furthermore, conservation tillage reduces the fuel and labour needed to plough. The trade-off is the cost of clover seed, as well as the fuel and labour required for system management. Additionally, although the use of precision agriculture technologies, as well as the development of a strip-mower, would make this system viable on a scale suitable to farms in Southern Ontario, producers may require new equipment specific to strip-system management (tillage and mowing).

There are agronomic concerns and unknowns within the proposed system. Questions as to the true drought tolerant properties of red clover remain, as do concerns surrounding stand irregularity. More specific to the proposition, there is the matter of frost risk, the potential for over-competition between red clover and the main crop, as well as ambiguity surrounding the projected incidence and control of pests and disease.

Further research, in addition to that required for agronomic concerns above, includes clover-corn root system overlap, rate of clover recovery and addressing non-uniform clover cover in a given field.

Though there are risks with this system, there are viable options for addressing them. Fundamentally, this proposition is a step forward for the agricultural industry. As the industry faces challenges associated with global climate change in conjunction with existing environmental contamination and diminishing resources, the creative development of sustainable, resilient, and productive agricultural systems is essential. The proposed system makes use of modern technology to maximize efficiency and capitalize on proper agronomic techniques. Additionally, it instigates new, but feasible, engineering initiatives. We recommend implementing the proposed system in a long-term trial. Although the literature displays many short-term benefits associated with the integration of these crops (particularly in the relationship between red clover plough-down and corn yield), the proposed system is fundamentally designed to work towards long-term sustainability and resilience within agro-ecosystems.

Acknowledgments

Author Contributions

Ralph C. Martin developed the research proposal and provided supervision; Sara Wyngaarden performed the literature review; all authors collaborated to prepare and approve the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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