Rijksdienst voor Ondernemend Nederland

Ecosystem benefits of perennial grain crop intermediate wheatgrass (Kernza) and its potential use in the Dutch dairy farming sector

In opdracht van het ministerie van van Landbouw, Natuur en Voedselkwaliteit

>> *Duurzaam, Agrarisch, Innovatief en Internationaal Ondernemen*

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Voorwoord

De gezamenlijke ambitie van de ondertekenaars van het Klimaatakkoord is in 2030 een extra vastlegging van 0,5 Mton CO_2-eq per jaar te realiseren op basis van de huidige circa 1,85 miljoen hectare landbouwgrond in Nederland. Dit realiseren partijen door een toename van het organische stofgehalte en een verminderde vorming van lachgas in deze bodems. Hiervoor is een integrale aanpak ('duurzaam bodembeheer') vereist, omdat zaken als organische stofgehalte, bodemleven en bodemverdichting onlosmakelijk aan elkaar verbonden zijn.

Op het melkveebedrijf is behoefte aan voldoende zetmeelvoorziening. Dit wordt meestal voorzien door mais. Continue maisteelt heeft vaak een netto CO_2-emissie door het éénjarig karakter met een lage aanvoer van organische stof en de jaarlijkse grondbewerking die de afbraak van organische stof versneld. Daarnaast blijft waterkwaliteit en verlies van bodemkwaliteit en biodiversiteit een probleem. Het levert dus nadelen op voor maatschappelijke diensten.

Meerjarige teelten, vooral blijvend grasland, leveren veel ecosysteemvoordelen. Door de voortgaande organische stofopbouw onder meerjarige teelten, wordt een bijdrage geleverd aan:

- Klimaatmitigatie (vastleggen C uit CO_2)
- Klimaatadaptie door een goede waterregulatie van de bodem (sponswerking bij droogte en afvoer bij piekbuien).

Blijvend grasland biedt t.o.v. andere teelten een grotere biodiversiteit ondergronds (soorten en volume) en ook bovengronds. Blijvend grasland staat onder druk in de melkveehouderij door een hoge aan een zetmeelproducerend gewas op het melkveebedrijf wat nu met name wordt ingevuld door mais. Een combinatie van blijvend grasland met een meerjarig gewas dat ook zetmeel produceert, zou een oplossing zijn. Meerjarig graan zou deze oplossing kunnen bieden.

Om de mogelijkheden van meerjarige graan als onderdeel van een innovatief teeltsysteem te verkennen heeft RVO het Louis Bolk Instituut opdracht gegeven tot een (veld)oriëntatie. Daarbij wordt meerjarig graan (Kernza) vergeleken met een éénjarig gewas (triticale) en een meerjarig gewas (grasklaver). Daarnaast is onderdeel van het project onderliggend Engelstalig literatuuroverzicht van de potentiële bijdrage van meerjarig graan aan de verschillende ecosysteemdiensten: (i) productiviteit, (ii) nutriëntengebruik, verlies en waterkwaliteit, (iii) beperking van en aanpassing aan klimaatverandering en (iv) biodiversiteit en landschap.

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Samenvatting

De vraag naar éénjarige granen en voedergewassen neemt toe door bevolkingsgroei, veranderingen in dieet en intensivering van landbouwproductie. Deze verschuiving heeft gevolgen voor de ecosysteemdiensten waaraan landbouwsystemen- en bodems kunnen bijdragen. Meerjarige graangewassen zoals intermediair tarwegras die het graan genaamd Kernza produceert, zouden echter een duurzaam alternatief kunnen zijn, aangezien ze de productie van zetmeel kunnen combineren met de ecologische voordelen van een meerjarig teeltsysteem. De veredeling van intermediair tarwegras voor een verhoogde graanopbrengst begon in de late jaren 80 en in 2019 werd de eerste *"food-grade"* cultivar van Kernza intermediair tarwegras gelanceerd.

De graanopbrengst van de meest recente cultivars is echter nog tussen de 600-1000 kg graan per jaar en een enkele studie vermeldt een opbrengst van ruim 1,6 ton graan per hectare. Deze maximale opbrengsten worden echter vaak behaald in het eerste en tweede oogstjaar, aangezien de graanopbrengst in jaar 3 of 4 sterk daalt. Veredeling voor graanopbrengst, die pas eind jaren tachtig gestart is, zorgt echter consistent voor toenames en door verfijning van veredelingstechnieken kan dit proces verder versneld worden. Hoewel de graanopbrengst dus nog verhoogd zou moeten worden om competitief te zijn met éénjarige graangewassen, is de biomassa productie van het gewas hoog (tot 10-17t ha^{-1}), waardoor het als dubbeldoel gewas (voor graan en voeder) of hele plant silage ingezet zou kunnen worden. De vegetatieve biomassa kan drie keer per jaar geoogst worden (voor stengel elongatie in het voorjaar, stro ten tijde van graanoogst, en hergroei in het najaar). Deze drie snedes leveren materiaal op met een verschillende voederkwaliteit, waarvan die in het voorjaar en najaar hoog is, en de stro fractie de laagste kwaliteit heeft, maar hoger dan tarwestro. Daarnaast kan het gewas toegepast worden op marginale gronden die minder geschikt zijn voor éénjarige gewassen en in gewasrotaties of polyculturen om zo bij te dragen aan de productiviteit en duurzaamheid van een teeltsysteem in het geheel.

Intermediair tarwegras heeft een wortel biomassa die 3 tot 12 keer hoger is dan die van tarwe, laat staan die van mais. Hierdoor is het in staat om meer stikstof in de wortelbiomassa vast te houden en daarmee uitspoeling van nitraat tot verwaarloosbare waardes te verminderen in het tweede groeiseizoen; het is in staat meer stikstof op te nemen dan toegepast wordt in de vorm van (kunst)mest. Intermediair tarwegras zou op deze manier ook uiterst geschikt zijn als buffergewas om de uitspoeling van nitraat naar grond- en oppervlaktewateren te verminderen.

Door het uitgebreide wortelstelsel, kan intermediair tarwegras ook bijdragen aan het vastleggen- en houden van koolstof in de bodem. Wortelmassa- en exudatie zijn de belangrijkste bijdragers aan organische stof in de bodem. Intermediair tarwegras kan in zijn wortelmassa tot wel 15 keer zoveel koolstof vastleggen als tarwe en zijn diepe wortels kunnen koolstof vastleggen in diepere bodemlagen waar het beter beschermd is tegen

mineralisatie. Hoewel het meerdere jaren kan duren voordat er meetbare verschillen in organische stof optreden tussen intermediair tarwegras en éénjarige granen zoals tarwe, laten bepaalde koolstof fracties die gevoeliger zijn en daarom als indicator van koolstofvastlegging op de langere termijn kunnen dienen al eerder significante verschillen zien. Er is berekend dat het omzetten van bouwland met éénjarige gewassen naar meerjarige graangewassen kan leiden tot een toename van tussen 0,13 en 1,70 t C ha^{-1} $year^{-1}$.

Door deze toename in organische stof kan intermediair tarwegras ook bijdragen aan klimaat adaptatie aangezien organische stof een hoge capaciteit heeft om water in de bodem vast te houden en de waterhuishouding te verbeteren. Ook kunnen de diepe wortels bijdragen aan wateropname, met name in tijden van droogte. Echter kan het verhoogd waterverbruik van meerjarige granen (net als gebruikelijke grassen) ten opzichte van eenjarige granen ook tot versnelde uitdroging van de bovenste bodemlagen leiden. Tenzij dit hogere verbruik uitgebalanceerd kan worden door een verhoogde interceptie van water, opname uit diepte of wanneer er genoeg regenval is, zal intermediair tarwegras niet geschikt zijn om op een locatie te telen.

Het is vastgesteld dat intermediair tarwegras de complexiteit van de nematode gemeenschap met 55% en ook de bacteriële diversiteit kan verhogen in vergelijking met tarwe na vier jaar. Dit komt waarschijnlijk door een hogere investering in het wortelstelsel en wortelexudatie, maar ook door de afwezigheid van ploegen en het feit dat de grond het hele jaar door bedekt is wanneer er meerjarige gewassen geteeld worden. Over de invloed van intermediair tarwegras op macrobiota en bovengrondse fauna is weinig bekend, maar aanwijzingen uit andere meerjarige landbouwsystemen wijzen op verhoogde diversiteit van deze groepen. Doordat het gebruik van herbicides en fungicides potentieel verlaagd zou kunnen worden, zou het telen van intermediair tarwegras ook op deze manier de druk op de biodiversiteit kunnen verminderen.

Intermediair tarwegras zou als dubbeldoel gewas of als hele plant silage geschikt kunnen zijn voor de Nederlandse veehouderij, vooral als het in rotaties toegepast wordt waar extra waarde gehaald kan worden uit het beschermende en herstellende vermogen van de plant op de bodem. Door de gunstige invloed van intermediair tarwegras op verschillende ecosysteemdiensten, zou dit meerjarige graan in Nederland in positieve zin bij kunnen dragen aan de vraagstukken omtrent kringlooplandbouw, de stikstofcrisis, droogteresistentie en klimaatadaptatie- en mitigatie.

1 Introduction

Annual crops cover the vast majority of global agricultural land (Monfreda et al., 2008). Annual grain crops represent about 50% of global human caloric intake (Kearney, 2010) and are important sources of fodder for the livestock industry. The demand for these crops is expected to increase significantly over the next few decades due to population growth and dietary shifts (Tilman et al., 2002). The increase in farmland needed to supply the increasing world population with food has led to the conversion of natural ecosystems and at the same time the intensification of agriculture (Bommarco et al., 2013).

These factors, plus inherent management demands by annual crops have led them to have a profound negative impact on the environment due to soil loss, nutrient pollution of ground and surface waters, and loss of biodiversity (Tilman, 1999). Harvested perennial grasslands, on the other hand, have been shown to be able to maintain ecosystem functioning and restore it after being lost due to annual agricultural management (van Eekeren et al., 2008, 2010; Glover 2010a; Pimentel et al., 2012; Beniston et al., 2014; Crews and Rumsey, 2017). Even compared to no-till annual agriculture, perennial crops are able to perform more ecosystem services, since perennial systems foster a greater and continual investment in the below-ground (DuPont et al., 2010, 2014).

Therefore, in an effort to combine the benefits of perennial grasslands with the production of grains, a number of authors have advocated for grain agriculture to move toward perennial systems (Jackson., 1980; Cox et al., 2006; Glover et al., 2010a, b; Asbjornsen et al., 2014; Crews et al., 2016). This has prompted the generation, through breeding, of perennial grain crops with the ultimate goals of using them in perennial grain polycultures (Reimann-Phillip, 1986; Wagoner and Schaeffer, 1990; Sacks et al., 2006; Cox et al., 2010, 2018; Van Tassel et al., 2017; Crews et al., 2018; Schlautman et al., 2018).

Breeding of intermediate wheatgrass, which is a common grassland species and forage crop for grazing livestock on throughout its native habitat in Central Eurasia, for improved grain yields started in the late eighties (Wagoner and Schaeffer, 1990) and led to the creation of the perennial grain Kernza; the first of its kind to be released commercially by The Land Institute during the 2010's (DeHaan and Ismael, 2017). Kernza is the trade name of the grain belonging to the plant intermediate wheatgrass (IWG).

In recent years perennial grain research has been gathering momentum and in Europe the possibility of the incorporation of IWG and perennial grain crops alike into national agricultural lexicons are being investigated in France (Duchene et al., 2019; Wayman et al., 2019) and Sweden (Marquardt et al., 2016) and interest is brewing in other countries as well, such as Ukraine and Russia (Karpenko et al., 2019; Morgounov et al., 2019). Commercially, it is still only grown in The United States where farmers experiences have been collected as well (Adebiyi et al., 2016; Lanker et al., 2019).

In this review the ecosystem services and challenges of intermediate will be detailed in four categories: 1) productivity, 2) nutrient use, losses and water quality, 3) climate change mitigation and adaptation and 4) biodiversity and landscape. After that we will detail the current knowledge and knowledge gaps on the optimal agronomic practices regarding this crop bring forth some of the potential avenues for incorporating IWG into the Dutch agricultural context.

2 Ecosystem Services

2.1 Productivity

Although perennial systems in general and IWG in particular have been shown to bring about a number of environmental benefits, Kernza grain yields still lack greatly behind its annual cereal cousins. IWG shows peak grain production at the second or third harvest, but then rapidly declines, also with high fertilization rates (Jungers et al., 2019). Increases in yield may come from breeding improved genotypes and from developing and improving management practices. Perennial grain crops such as IWG have longer growing seasons, start photosynthesizing earlier in the season and maintain green tissue for longer, have a re-usable root system which is fully functioning when annual roots have not yet developed or have already senesced, and regrow, thus continuing to photosynthesize after harvest. Perennial grain crops could pay for their additional costs of longevity with these additional resources that are unavailable to the annual crop besides producing comparable grain yields with the resources captured during the period of the annual growth season (Cox et al., 2010; DeHaan et al., 2005; Van Tassel et al., 2010).

However the high investment in aboveground vegetative biomass and belowground biomass and the relative low investment in seed production, have resulted in a low harvest index, which is the main point that needs improvement (DeHaan et al., 2005; Culman et al., 2013; see Box 1) and has been increased through selection for grain yield (Cattani and Asselin, 2018). Wild perennials are very competitive, but in agro-ecosystems where less vegetative growth is needed to compete and survive, a perennial grain crop could invest more in seed instead. Indeed much of the yield increase of annual crops over the last century

Box 1. Trade-off between yield and perennialism

Concerns about the possibility to improve the trade-off between perennial grain yields and maintaining root biomass and longevity have been raised (Smaje, 2015; González-Paleo et al., 2016; Vico et al., 2016). In a similar vein, the feasibility of reaching high yields with perennial grain crops through breeding has been questioned. However, perennialism and high grain yield are not necessarily mutually exclusive (Van Tassel et al., 2010; DeHaan and Van Tassel, 2014; Vico et al., 2016). Grain yield, for example, may be sink limited. Increasing the sink size, meaning improving the seed set, may induce an increased production of photosynthate without taking resources away from the perennating structures (Cox et al., 2010; Van Tassel et al., 2010).

Moreover, other negatively correlated traits such as grain yield and quality have been improved simultaneously (Cox et al., 2010). That trade-offs may not be as dichotomous as thought and an increased fitness may result in the resolution of negative correlating of traits is also shown in the study by Pugliese et al. (2019) in which an increase in root biomass in one year did not decrease, but in fact increased the next years forage yield in IWG. DeHaan et al. (2018) describes that perennial characteristics such as the spread by rhizomes or post-harvest regrowth had no correlation with seed yield per head. Selection for higher grain yield may thus have no impact on longevity and vice versa.

has been due to a reduction in intraspecific competition, an increase in crowding stress tolerance, a reduction in height or by increasing the harvest index; modern grain crops have a narrow profile both above and below ground and are shorter than their ancestral varieties, which has reduced investments in competition and in unnecessary vegetative growth (DeHaan et al., 2005; Van Tassel et al., 2010). The same can be done for perennial grain crops. In fact, some degree of reduction in excessive root growth, tillering, asexual reproduction and extreme longevity is acceptable and desirable (Van Tassel et al., 2010).

Low yields may just be the result of the fact that perennial grain breeding has received only a fraction of the attention and resources compared to annuals. The first breeding programs for a perennial cereal only started in the 1987 (Wagoner and Schaeffer, 1990) and were initially only performed by The Rodale Institute and later exclusively by The Land Institute with limited resources compared to conventional breeding companies. The first reliable, food grade Kernza variety has only been released in 2019 (Bajgain et al., 2020). The domestication of annual cereals on the other hand goes back some 8000-10000 years with big investments in breeding being made over the last century. Breeding of perennial grain will not take as long, as perennial species can be hybridized with related annuals to incorporate domestication traits more quickly and genetic marker techniques are available to modern breeders which are extremely helpful to perennial crop breeders (Cox et al., 2016; DeHaan et al., 2016). First year yields have been found to be poor predictors of yield magnitude in the subsequent years, so the third year has been found to be necessary in identifying the individual plants with a high productivity in the third year (Cattani et al., 2016); genetic markers can be used to already detect important alleles in young plants for yield maintenance in later years (Zhang et al., 2016).

As it happens, Kernza yields have in fact been increased by breeding. The first food grade Kernza cultivar (MN-Clearwater) has a yield of 696 kg ha^{-1} averaged over the first two growing years, compared to a seed yield of 352 kg ha^{-1} for an IWG forage cultivar (Rush) with no history of selection for grain yield (Bajgain et al., 2020). However grain yield of the Clearwater cultivar in the third year was reduced to 163kg ha^{-1} (Bajgain et al., 2020). The maximum second year yield found in the literature is 1662 kg ha^{-1} (1390 kg ha^{-1} for an organic treatment; Culman et al., 2013) although more typical second year yields are between 600-1000 kg ha^{-1} (eg. Jungers et al., 2017, 2018, 2019; Tautges et al., 2018, Pugliese et al., 2019).

Furthermore, in the study by Culman et al. (2013), the first year yield, averaged across one organic and two inorganic treatments, was 4.5% compared to annual wheat but in the second year rose to 33% of the annual wheat yield, while also producing more than three times as much (141 ton ha^{-1}) vegetative biomass in the second year.

Reaching competitive and reliable yield levels may still take multiple decades and may be first reached when annual and perennial grain crops are compared growing under marginal conditions where annual crops are underyielding (Cox et al., 2010). However, based on estimations, Pimentel et al. (2012) conclude perennial grains may be a viable alternative to annual grains despite lower yield, because of reductions in fertilizer, pesticide, seed and labor costs. Bell et al. (2008) performed a whole-farm economic analysis which underpins these findings. Furthermore, perennial polycultures may outperform monocultures due to complementarity of growth characteristics and resource use (Picasso et al., 2011).

2.1.1 Multifunctional management

Although Kernza yields are projected to increase through breeding efforts in the coming decades, grain yields remain low in the present relative to annual grains. In order to counterbalance low grain yields, which are still too low to be profitable in and of itself, IWG should be deployed as a multifunctional crop. That is, a crop that besides providing grains is also used to provide other sources of income and (ecosystem) services (Ryan et al., 2018). In future high grain yielding scenarios, multifunctionality will likely remain a key benefit of IWG.

Forage production

Contrary to grain yields, overall biomass yields of IWG are high and more stable, reaching up to 17 ton/ha depending on the rate of fertilization and environmental variables (Culman et al., 2013; Jungers et al., 2019; Tautges et al., 2018), which has led to the idea of using IWG as a dual-purpose crop, meaning that IWG could be harvested for both grain and forage (straw and hay; Ryan et al., 2018). The yield outcomes of the two studies who compared IWG performance to other crops (maize, wheat and switchgrass) have been summarized in table 1. These studies report only the vegetative biomass at harvest.

Table 1. Grain and biomass yield from comparison studies

Crop	Grain yield (kg ha^{-1})	Vegetative biomass yield (kg ha^{-1})	Yield averaged over	N fertilization	Reference
Wheat	3597	4029	2 years	90 kg N ha^{-1} y^{-1}	Culman et al., 2013
Maize	8769	8436	3 years	160 kg N ha^{-1} y^{-1}	Jungers et al., 2019
Switchgrass	-	13920	3 years	120 kg N ha^{-1} y^{-1}	Jungers et al., 2019
IWG (Kernza)	887	17131	2 years	90 kg N ha^{-1} y^{-1}	Culman et al., 2013
	439	10752	3 years	120 kg N ha^{-1} y^{-1}	Jungers et al., 2019

However, the perennial growth habits of IWG give rise to three windows of opportunity each year for harvesting or grazing of the vegetative biomass. The early season growth before the phase of culm elongation and the late season post-harvest regrowth can be grazed by livestock or harvested as grass forage. Thirdly, the crop residue after summer harvest, as noted in Table 1, can be used as fodder and the remaining stubble could potentially be grazed on as well (Ryan et al., 2018).

Although harvesting IWG biomass more frequently does not necessarily increase total yield, it does increase the average nutritive value (Favre et al., 2019). Favre et al. (2019) calculated for these three stages the relative forage quality (RFQ), which is an umbrella index dependent on fiber content and digestibility and protein, fatty acid and ash content and is calculated in relation to a standard nutritive value of full bloom alfalfa (RFQ = 100). In both spring and fall the nutritive value of IWG was shown to be higher than that of full bloom alfalfa with RFQ values of 175 and 116, respectively (Favre et al., 2019). Crop residue is by far the highest contributor to the yearly biomass yield, between 70-80%, but it has the lowest nutritive value with a RFQ value of 65. These values are similar or greater to forage IWG and other common cool-season forage grasses in the Upper Midwestern United States (Jungers et al., 2017; Favre et al., 2019). One advantage of IWG straw is that at the time when the grains are ready for harvest, the stems remain green for the greatest part, which gives the straw a relatively high N content. This adds nutritional value to the straw and gives it a nutritional advantage over annual grain straw; IWG crop residue has been shown to have a crude protein content which is 30% higher than wheat straw (Favre et al., 2019). The spring vegetation harvest is therefore suitable for lactating dairy cows, the post-harvest regrowth is suitable for lactating beef cows and dairy heifers and the crop residue from summer harvest could potentially sustain non-lactating beef cattle with the necessary addition of supplementation (Newell and Hayes, 2018; Favre et al., 2019). Intercropping IWG with a perennial leguminous forage species could improve forage quality of the crop residue and late season forage fraction (Newell and Hayes, 2018; Favre et al., 2019). Furthermore grazing the post-harvest stubble has been shown to reduce weed incursion (Favre et al., 2019).

Cutting or grazing early and late season forage besides cutting for grain harvest has been shown to increase root biomass, root turnover and mineralizable carbon, which is a proxy for nutrient cycling, in comparison to harvesting for grain only, thereby increasing forage and grain yields (Pugliese et al., 2019). They hypothesize that harvesting for forage drives increased root exudation and turnover which increases decomposition rates to free up nutrients for above-ground regrowth. Hunter et al. (2019, 2020) describe grain yield benefits as a consequence of mowing in the second year but grain and forage yield penalties in later years. Dick et al. (2018) also reports increased grain yield and harvest index as a consequence of sheep grazing.

Bell (2013) reported that profits derived from IWG may be 38% higher when grazing is applied alongside grain harvest, relative to harvesting grains only. Hunter et al. (2020) calculated that the potential value of IWG straw due to the large quantity and superior quality was enough to offset the production costs of both straw and grain, thereby greatly reducing the financial risk in Kernza grain production.

Using IWG as whole plant silage (HPS), instead of separating grain from forage would be another option. Compared to annual grain forage IWG would have higher biomass yield with a greater protein content. Compared to grass, IWG would have the benefit of starch from the grains, while potentially still providing the same ecosystem benefits.

Crop rotations

IWG could also be used in crop rotation to restore soil quality and health in rotation with annual crops (see Figure 1). Culman et al. (2013) studied how and how fast IWG could improve ecosystem services compared to an annual wheat crop. This two-year study therefore serves as an indicator of how useful IWG could be in improving (per unit input) productivity of a crop rotation, which points to another facet of the multifunctionality of this perennial crop.

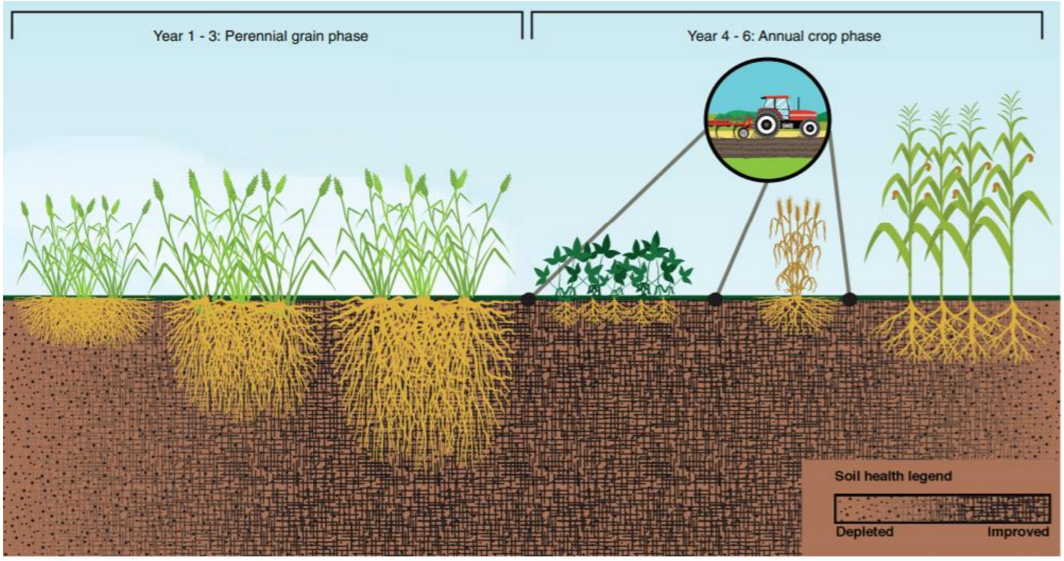

Figure 1. Perennial grain crops can be used to regenerate soil health and quality and reduce pest and weed problems in between sets of annuals in a crop rotation (from Ryan et al., 2018).

To demonstrate how quickly IWG can improve some ecosystem functioning, Culman et al. (2013) compared IWG to annual wheat on a soil conditioned by annual agriculture. In the first year, NO_3 leaching was not influenced by crop type, but in the second year IWG showed low to almost negligible concentrations of NO_3 below the rooting zone. At the same depth below wheat significantly higher nitrate levels were detected in comparison to the perennial IWG and in comparison to the previous year below wheat (Culman et al., 2013). IWG thus reduces leaching in the second year, whereas leaching was increased under wheat in the second year. Similar results were found by Jungers et al. (2019) when IWG was compared to maize.

The higher C mineralization rates in soils under IWG furthermore suggest that over a two-year period more biologically active carbon is present under IWG relative to annual wheat (Culman et al., 2013), although more stable forms of carbon will take multiple year to build up to significant levels under IWG (Sprunger et al., 2018b).

A possible challenge IWG could pose in crop rotations is depletion of soil water relative to annual grains (Culman et al., 2013; Sprunger et al., 2018a). It is well-known that perennials with large root systems have higher transpiration rates and lower water use efficiencies than congeneric annuals (Oliveira et al., 2019). Although there are also indicators that IWG has a relatively high water use efficiency and may be able to reduce drainage of precipitation and reach deeper soil water compared to annual grains (Culman et al. 2013; Oliveira et al., 2019). The benefit of deep roots will depend on many environmental factors such as the height of the water table, the aridity index and soil type.

Using perennial grasses in rotation has been shown to restore soil biological functioning to a great extent. In a 36 year old ley-arable cropping experiment where maize and perennial ryegrass were grown in 3 year rotations besides permanent grass and permanent maize, the temporary perennial grass cropping was found to have the ability to restore soil biological quality after a three year cropping of maize (van Eekeren et al., 2008). Soil microbial and faunal abundance and biomass were low in the permanent maize cropping, but in the three-year grass ley, the abundance of earthworms and nematodes returned to the level of permanent grassland within two years and the earthworm biomass in three years. However, in the first year of arable cropping these figures declined steeply again. Bacterial growth rate and rate of biodegradation recovered in the second year of the grass rotation, but the structure of the bacterial community in the rotation remained altered when compared to the permanent grassland. Services provided by the soil microbiome, such as nitrogen cycling as well as soil organic matter, did not reach levels of the permanent grassland in the three years of grass due to the loss of certain essential species, but were improved compared to the continuous arable land (van Eekeren et al., 2008). These findings are translatable to IWG, as shown in the study by Sprunger et al. (2019) who found that IWG improved the trophic complexity of the soil nematode community by 55% and increased bacterial diversity compared to annual wheat after four years. This restorative power is likely driven by a higher investment in root systems and root exudation, the absence of tillage and year-round ground cover during the years of perennial cropping (Sprunger et al., 2019).

Intermediate wheatgrass would thus be a suitable crop to improve annual crop rotation and could also be used in rotation with perennial forages. If other high yielding perennial grains will be bred, crop rotations could possibly rotate from perennial grain crop to perennial grain crop or could be used to establish perennial grain polycultures (Ryan et al., 2018). Figure 2 shows some additional application which IWG's multifunctionality lends itself to.

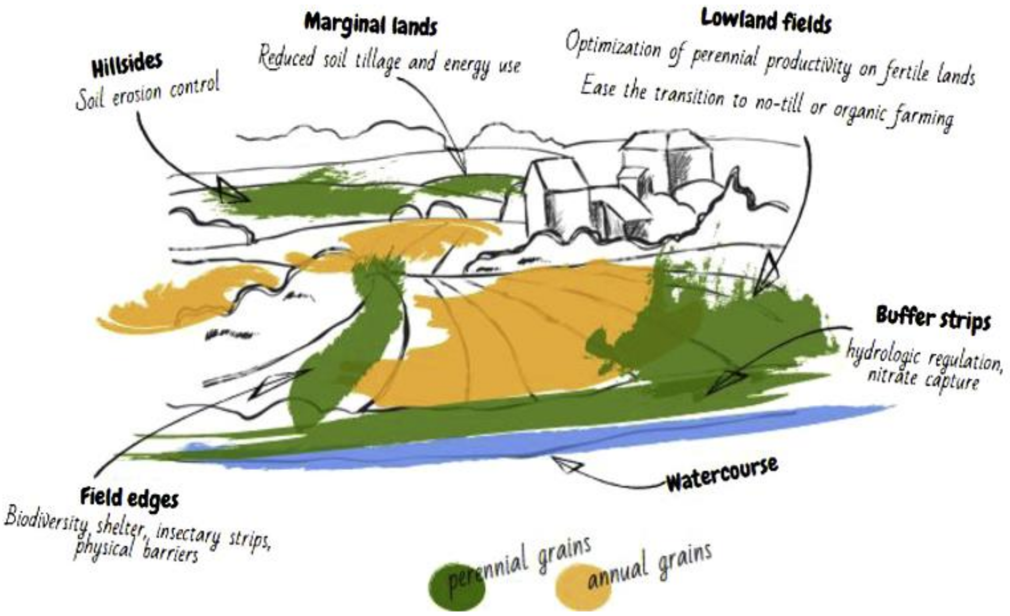

Figure 2. A graphic summary of some farm zones where IWG could be productive and deliver specific ecosystem services for from Duchenne et al. (2019).

2.2 Nutrient use, losses and water quality

Perennials often sustain a higher root biomass than annuals and do so throughout the year. Furthermore, due to the absence of tillage and a higher investment in belowground structures and processes perennials are able to reduce nutrient losses and increase nitrogen retention and capture, thereby improving nutrient use efficiencies (NUE). Perennial root systems may also be able to increase the capacity to rely on endogenous nutrients present in the soil through increased investment in below-ground processes, stimulating the soil microbiome and increasing synchrony between nutrient demand and supply, thereby minimizing their reliance on external inputs (Crews, 2005).

2.2.1 Enhanced nutrient retention

Sprunger et al. (2018a) found IWG to have between 3 and 12 times greater coarse and fine root biomass than wheat and annually allocated between 23 and 50% of its total biomass to roots as compared with wheat, which allocated ~10% to roots. Consequently, the total N content of IWG roots was higher than that in wheat. Furthermore, wheat root biomass did not respond to nitrogen fertilization whereas IWG root biomass responded positively to higher fertilization rates over a 3-year growing period (Sprunger et al., 2018a). Total crop NUE (thus including not only harvestable parts, but also roots) was higher in IWG compared to wheat, ranging from 0.8 to 1.5 in IWG and from 0.56 to 0.86 in wheat (Sprunger et al., 2018a). The high root biomass and N content of IWG roots were the likely driver of this high NUE. NUE was also found to increase over the years in IWG and more strongly under high fertilization (Sprunger et al., 2018a). NUE values >1 as reported in this study indicate that IWG is able to recover more N from the soil than was applied with fertilizer, likely through the stimulation of soil life and the subsequent mineralization and uptake of soil N. IWG thus has a superior ability to conserve nitrogen by its large root system and respond better, in terms of nitrogen retention, to fertilization which leads to a higher total crop NUE compared to wheat. The higher retention of fertilizer N and the greater ability to stimulate the supply of endogenous N could contribute to a lower reliance on nitrogen fertilization.

2.2.2 Reduced leaching

As a result of the large capacity to take up and retain nitrogen, losses by way of leaching under IWG are reportedly minimal (see Table 2). In a study by Culman et al. (2013), in situ lysimeter measurements show almost undetectable nitrate concentrations 1m below IWG and showed no increase with increasing nitrogen fertilization (60-90kg N ha^{1}). In the same study, modelled nitrate losses under IWG were 86 to 99% less compared to winter wheat in the second year of production, while being similar in the first year. In the second year, the magnitude of the effect of plant type (annual or perennial) was found to be 4.5 times larger than the effect of nitrogen management on N leaching (Culman et al., 2013).

Table 2.

Crop	Fertilization rate (kg N ha^{-1})	Cumulative NO_3 leached (kg NO_3-N ha^{-1})	Period	References
Wheat	90 120	53.8 148.3	April 2010-October 2011	Culman et al., 2013
Maize	160	21.86	Average annual leaching over 3 years	Jungers et al., 2019
Switchgrass	120	3.65	Average annual leaching over 3 years	Jungers et al., 2019
IWG (Kernza)	90 120 120	15 32 0.17	April 2010-October 2011 Average annual leaching over 3 years	Culman et al., 2013 Jungers et al., 2019

Jungers et al. (2019) compared nitrate leaching in IWG with maize and switchgrass with no application of N fertilizer up to a high fertilizer treatment of 160 kg N ha^{-1} which was reduced to 120 kg N ha^{-1} in the second and third year for IWG and switchgrass to reduce stem lodging. They found that annual average nitrate leaching was not significantly influenced by fertilization treatment in IWG, which showed a small but insignificant decrease from 0.24 kg N ha^{-1} when no fertilizer was applied to 0.17 kg N ha^{-1} when high fertilization was applied for IWG, whereas for maize the leachate contained significantly higher levels of nitrate at 5.76 kg N L^{-1} and 21.68 kg N ha^{-1} for the no N fertilization and high N fertilization treatment, respectively. The perennial biomass crop switchgrass consistently showed intermediate levels of nitrate leaching (Jungers et al., 2019).

Thus, nitrate leaching is consistently lower under IWG compared to the two most important annual grain crops and shows no increase in leaching with increasing levels of fertilization.

2.2.3 Phosphorus

Besides problems related to nitrate losses, perennial crops have the potential to optimize the uptake of phosphorus (P). One of the greatest challenges to efficient phosphorus uptake is the fact that phosphate binds strongly to the solid phase of soils, which limits uptake even when fertilized. Crews and Brookes (2014) compared the changes in phosphorus forms between two >100 years old Rothamsted experiments of continuous wheat and annually hayed grassland with similar annual exports of P. They found that the harvested perennial grassland maintained greater pools of active organic P (Po) over time and lower recalcitrant inorganic P (Pi) pools relative to the continuous wheat cropping. These findings are supported by Daroub at al. (2001) and Tiessen et al. (1992) who found more available Po under native vegetation and perennial fallow periods respectively, compared to soil under annual cropping. Tillage induces the mineralization of P which is then removed from P cycling by fixation to metal oxides (Tiessen et al., 1992). Also, the higher levels of SOM, including organic acids, under perennial vegetation may block the absorption of phosphate to metal oxides by competing for binding sites (Crews and Brookes, 2004).

Furthermore, perennial grain cropping systems may benefit from increased solubilization and uptake of phosphate due to beneficial symbiosis with arbuscular mycorrhiza (AMF) and associated bacteria, which have been found to have the highest abundance in low input perennial grasslands (Rasche et al, 2017). Indeed, fungal community structure under IWG and beneath native prairie vegetation have been found to be similar and AMF richness greatest under IWG (McKenna et al., 2020). Perennial grain crops could therefore have improved access to phosphorus, compared to annual counterparts.

2.2.4 Intercropping and perennial polycultures

The supply of nutrients and independence from chemical fertilizers could be improved further by incorporating IWG into intercropping or polyculture systems which could supply nitrogen through nitrogen fixation and improve the synchrony between nutrient supply and demand (Crews and Peoples, 2005). IWG may provide benefits to neighboring crops and conversely neighboring crops may provide benefits to IWG. Multiple combinations of intercrops have been tested, the performance of which is summarized in Box 2. Declining yields as stands age may be related to nutrient depletion but N fertilization may reduce sustainability of perennial grain production, thus intercropping may be a useful way to improve nutrient availability in aging IWG stands (Tautges et al., 2018). Intercropping could increase N-input through biological fixation, increase P-solubilization and stimulate microbial activity and soil organic matter mineralization thereby increasing the availability of nutrients (Tautges et al., 2018). Hayes et al. (2017) showed that subterranean clover could compensate in terms of N-fixation for the annual removal of 1.5-2.0 tons of grain per hectare. However, access to nitrogen fixed by the legume intercrop could be limited when intercropped in strips (Hayes et al., 2017). It may take time for nitrogen to build up in a soil through nitrogen fixation and legume biomass decomposition; effects on soil nitrogen by a legume intercrop were shown to be initially absent but cumulative over the years (Li et al., 2019). An interesting management strategy that should be investigated would be to sow IWG in two or three year old alfalfa stands, where N has had the time to accumulate through organic matter (Li et al., 2019).

Box 2. Performance of perennial legumes intercropped with Kernza

The yield decline common in aging IWG is one of the biggest problems faced by perennial grain crops, and one of the main reasons for including legume intercrops. Intercropping could potentially reduce the yield losses in observed in aging, pure stands of IWG (Weik et al., 2002). Intercropping may increase investment in sexual reproduction by increasing below-ground competition, thereby increasing grain yield (Tautges et al., 2018).

However, reported effects of intercropping on IWG yields and yield maintenance show contrasting outcomes, depending greatly on the choice of intercrop species, success of establishment and persistence of IWG or the intercropped legume, experimental design (eg. seeding density, mixed or row cropping) and site and climatic conditions (Hayes et al., 2017; Dick et al., 2018; Tautges et al., 2018).

White clover mixed cropping could increase the yield in the second year of the study, possibly through N-fixation, whereas in pure IWG stands steep declines in grain yield were observed (Weik et al., 2002). Subterranean clover row intercropping resulted in yield loss per area of Kernza grain, but total biomass yields were improved (Hayes et al., 2017). This study could not conclude on long term yield maintenance because of limited time span of 2 years of the study. Dick et al. (2018) intercropped IWG with sweet clover, white clover and alfalfa. They found both grain and biomass yield to not be affected by legume intercropping. Sweet clover was found to not be competitive enough and alfalfa to be too competitive, leading to domination, while white clover performed the best.

Tautges et al. (2018) found that from year 3 to 4 yields were kept relatively stable in bi-cultures whereas they showed stronger declines in both unfertilized and fertilized monocultures. Yields at 3 out of 5 test locations was comparable between fertilized monocultures and bi-cultures and higher than unfertilized monocultures in year 3 and 4, although significantly lower than in year two when yields were optimal. Alfalfa biomass was found to be positively correlated with grain yield, nutrient uptake and harvest index (HI) of IWG in the fourth year of the study. The positive influence of alfalfa intercropping on the IWG HI means that the investment in seed relative to vegetative biomass may be improved by intercropping. This study, in contrast to Hayes et al. (2017), suggests that N fertilization may be needed anyway in later years to supply adequate amounts of N.

Alfalfa can be quite competitive in terms of soil nutrient and water uptake, and may cause problems to IWG stand maintenance over the years (Dick et al., 2018; Tautges et al., 2018). Li et al. (2019) therefore advises moderate fertilizer application to reduce competitive advantage of the nitrogen fixer alfalfa to keep it from dominating IWG. However, Jungers et al. (2019) reports that alfalfa did not persist when an IWG-alfalfa intercrop was fertilized with 40kg N ha^{-1} and states other legume intercrops should still be considered and researched. This points to variability in suitability of forage legume species possibly caused by differences in soil types and climatic factors.

Weik et al. (2002) performed an early study into intercropping perennial grain species, but found asynchronous seed maturation and subsequent seed shattering to be too problematic. For the time being therefore, forage legume crops may be better suited for growing in mixed stands or intercropping with IWG (Weik et al., 2002). However, potential perennial grain legumes have been inventoried and will be bred for improved seed yield (Schlautman et al., 2018).

2.3 Climate change mitigation and adaptation

2.3.1 Mitigation

Higher SOM levels in (native) grasslands compared to annual cropland and the loss of SOM following the land use change to annual cropping have been well documented (Beniston et al., 2014; Crews and Rumsey, 2017). Turnover of fine roots in perennial systems may account for 50–80% of net productivity (Caldwell, 1979). Therefore root turnover in perennial systems has been found to supply between 30 and 80% of organic C inputs to soils (Kalyn and Van Rees, 2006). And roots have been shown to be the biggest contributor to SOM (Rasse et al., 2005).

IWG root biomass increased by 51% from the second to fourth year (Sprunger et al., 2018b). In the fourth year, IWG had 1.9 times more straw C and up to 15 times more root C relative to wheat (Sprunger et al., 2018a). IWG also consistently had greater coarse root C:N ratios compared to wheat (Sprunger et al., 2019). Greater C:N ratios of organic matter are often associated with recalcitrance and thus longer mean residence times which could increase the capacity of IWG roots to contribute to soil carbon storage and thereby climate change mitigation (Sprunger et al., 2019). Moreover, deep roots, a key characteristic of IWG, have the potential to sequester carbon in deeper layers were it is less prone to mineralization (Lorenz and Lal., 2005).

Although IWG had greater above and belowground biomass (to 70 cm) and greater coarse root C:N ratios, labile particulate organic matter (POM-C) fractions in soils under IWG and wheat were similar (Sprunger et al., 2018a). However, several measures such as permanganate-oxidizable carbon (POXC) and mineralizable C have been used as indicators for SOC accrual or loss (Culman et al., 2013; Sprunger et al., 2019). IWG had significantly greater POXC values relative to annual wheat after four years, but no difference in mineralizable C was detected (Sprunger et al., 2019). Culman et al. (2013) found greater C mineralization in the IWG plots compared to annual wheat, but no differences in POXC after 1.5 years. A posthoc power analysis showed that on a sandy soil with low cation exchange capacity, it will take >4 years for Kernza to accumulate a significant increase in POM-C fractions (Sprunger et al., 2018a). Kernza has been shown to be a carbon sink on the long term (Oliveira et al., 2019).

Crews and Rumsey (2017) calculated the potential soil C accumulation if annual cropland would be brought into perennial grain production based on a range of assumptions. The maximum C accumulation was estimated at 54 Pg of carbon and in line with soil sink estimates of annual cropland. SOC accumulation rates per hectare were also estimated to be between 0.13 and 1.70 t ha^{-1} $year^{-1}$, which was in line with empirical results from perennial grassland and bioenergy crop studies (Crews and Rumsey, 2017).

2.3.2 Adaptation

SOM is known to be an important factor in the retention of water in a soil. Hudson (1994) showed that, depending on soil texture, a 1% increase in organic matter can result in an increase of between 2.2 and 3.7% of plant available water capacity.

Furthermore, deep roots may reach moist deep soil layers and groundwater in times of drought and therefore may prove beneficial in climate change adaptation. At maturity, significant amounts of residual water can still be found in the subsoil under many crops experiencing even severe drought conditions (Passioura, 1983). Deep roots can extend and access deeper reserves of water, thereby improving drought tolerance. Indeed, drought resistant cereal varieties often have deeper roots than their drought susceptible counterparts (Christopher et al., 2008; Manschadi et al., 2006; Manschadi et al., 2013).

In the period between anthesis and harvest, modelled root water uptake showed IWG to rely for almost 50% on deep roots (>1m) for its water demand, which may contribute to yield stability during summer droughts (Clément et al, 2021; not yet published). Clément et al. (2021) reports rooting of IWG up to 2m depth and other authors have mentioned rooting depths of up to 3m (DeHaan and Ismail, 2017). However, IWG displayed similar root biomass at 1m depth to wheat in a study by Sprunger et al. (2018a), but a higher root biomass in the topsoil, which, combined with higher rates of transpiration in perennials can lead to lower soil moisture contents in the topsoil. This could actually result is a higher susceptibility to drought (Sprunger et al., 2018a).

Nonetheless, IWG has a higher water use efficiency (defined as the ratio of carbon assimilation or productivity over water loss) than reported from annual crops such as soybean and maize (Oliveira et al., 2019). A contributing factor to this is the fact that during the onset of the growing season Kernza can make use of water which was retained in the soil after past rainy events during the dormant season (Oliveira et al., 2019). IWG maintains a relatively high water use efficiency throughout the growing season, even when the top soil dries up due to evaporative forces, which can be explained by the reliance on deep roots for supplying the crop with adequate amounts of water (Oliveira et al., 2019; Clément et al., 2021). This could be an advantage in comparison with annual crops in the face of climate change (Vico and Brunsell, 2018). The higher depletion of topsoil water by IWG reported by Sprunger et al. (2018a) could thus partly or completely be offset by its water retaining and deep rooting characteristics, although this will depend on soil and climatic factors to some extent (Oliveira et al., 2019).

2.4 Biodiversity and landscape

2.4.1 Biodiversity

As stated above perennial grain crops, such a IWG, are able to stimulate soil life and increase its abundance and diversity. Little is known about aboveground biodiversity. However, other perennial grain crops are in the process of being bred to be integrated into perennial polycultures resembling a native grassland (Cox et al., 2002). Perennial grain systems, could support higher diversities of macrofauna than annual systems especially in polycultures by providing year round habitat and abstaining from tillage (see Figure 3). This has been found to hold true in the case of insects, including pollinators and detritivores which help recycle nutrients (Glover et al, 2010a). But also bird population could benefit from these factors in perennial grain systems as has been shown to be the case for perennial versus annual bio-fuel systems (Bellamy et al., 2009; Meehan et al., 2010). These benefits will be highest in organically managed systems and polycultures and will be influenced by grazing/forage harvesting intensity (McLaughlin and Mineau, 1995; Hole et al., 2005).

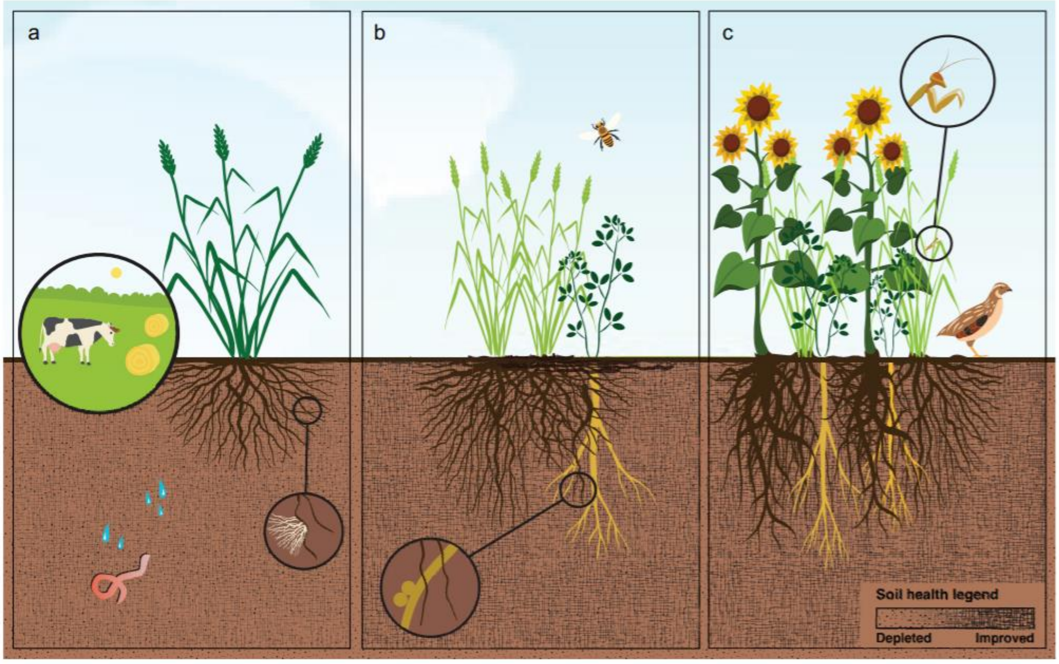

Figure 3 Perennial crops can improve soil health, reduce inputs and increase biodiversity (including worms, pollinators, birds and natural pest predators) by providing year-round habitat and food sources and provide high quality forage in an increasing trend from monoculture (a) to legume bi-culture (b) to a perennial polyculture with in this example a perennial oil seed crop (c) from (Ryan et al., 2018).

2.4.2 Weed, pest and disease control

A potential reduction in pest, disease and weed occurrence could lower the need for pesticides in conventional systems and thereby promote biodiversity and landscape and human health.

Pests and diseases

Perennials pose a certain set of challenges when it comes to disease and pest control that are different from annual grain crops and are therefore less well understood. Due to the longer growing season and perennial presence of below and aboveground crop biomass, diseases and pests may have a larger window of opportunity to infect and affect crop performance (Cox et al., 2005). Therefore in perennial grain systems it may prove to be important to use host diversity, which is the growing of different genotypes of the same crop in mixtures, to increase resilience against pests and diseases (Cox et al., 2005).

However, since IWG hosts a more diverse and active soil microbiome than annual grains, pathogenic organisms may become relatively less abundant due to an increase in predation and competition, leading to natural pest and disease suppression in perennial grain systems. Moreover, Intermediate wheatgrass exhibits innate genetic pest and disease resistance due to the natural selection pressure perennials experience due to their sedentary growth habits (Glover et al., 2010b; Pimentel et al., 2012). Genes from IWG have been used to confer disease and pest resistance to annual wheat and crosses of IWG and wheat are often more resistant to diseases that wheat is sensitive to; IWG has been found to be highly resistant against tan spot, stripe rust, leaf rust, barley yellow dwarf and wheat streak mosaic diseases and fusarium head blight (Cox et al., 2005; Bajgain et al., 2019). Growing perennial grains in rotation or polycultures will also reduce pest and disease problems (Cox et al., 2006; Picasso et al., 2008).

Weeds

Weed control in a IWG crop will also pose unique challenges. IWG is slow to emerge and provide full soil cover compared to annual grains (Jungers et al., 2018). Weed control during this period using either herbicides or strip cultivators will be necessary. Alternatively intercrops could provide soil cover while IWG is in its establishing phase. Moreover, when IWG has established itself, it may be competitive enough for light due to its permanent ground cover and nutrients through its dense root system to outcompete any weeds (Dick et al., 2018).

Furthermore, Zimbric at al. (2020) found that even though IWG displaced annual weed species in favor of perennial weed species, overall weed biomass was reduced by 88% over a 3-year growing period. In rotations with annuals this may prove beneficial to the following annual crop as IWG will have suppressed annual weed presence, but also since the perennial weed species that have become dominant cannot cope with the soil disturbance caused by cultivation in an annual-perennial crop rotation. Furthermore, intercropping of forage legumes with IWG has been found to reduce weed incursion as well (Weik et al., 2002; Hayes et al., 2017).

2.4.3 Eutrophication of water bodies and nitrogen deposition

Since IWG prevents leaching of nitrate, even at high fertilization rates, it can be expected that the water quality in rivers and lakes adjacent to perennial grain field and on a larger scale the watershed, will improve. Besides, compared to annuals, perennials like IWG can reduce erosion, which will also prevent eutrophication of surface waters (see Figure 4). An increased proportion of annual cropland over perennial grassland in the study by Glover et al. (2010a) significantly increased watershed nitrate concentrations. This may result in drinking water of superior quality but also improvement of the landscape quality due to the absence of the eutrophication of water bodies, which is a common phenomenon caused by excessive levels of nitrate.

Furthermore, since the whole plant nitrogen use efficiency of IWG was shown to be higher (Sprunger et al, 2018a), fertilizer use could be limited on perennial grain systems which leads to reductions in carbon emission during fertilizer production and in nitrogen volatilization after fertilizer application. Perennial forage legumes could supply nitrogen to perennial grain crops which further reduces the need for fertilization and thus reduces volatilization.

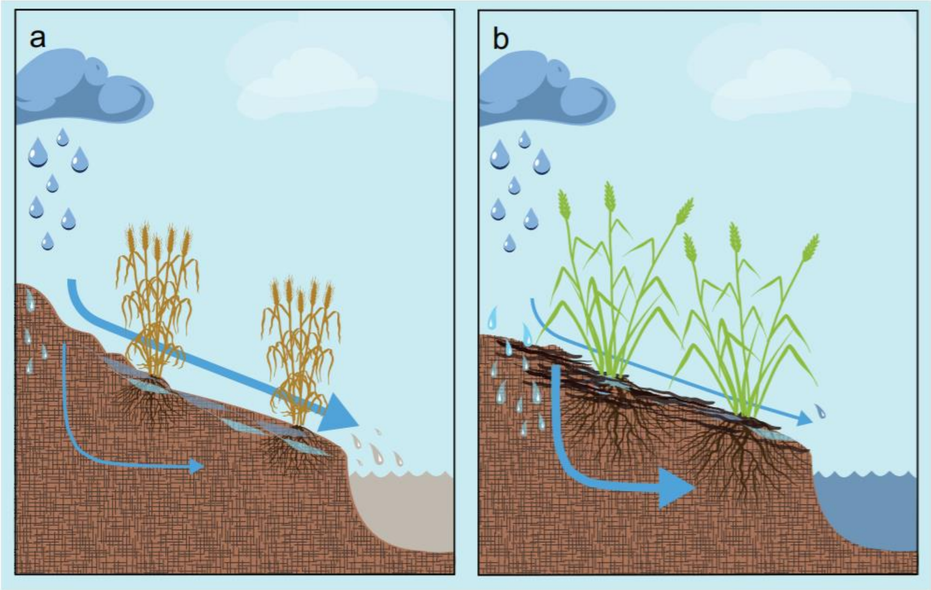

Figure 4. Perennial grain crops (b) compared to annual grain crops (a) can reduce erosion and improve water quality, especially when grown on a slope (from Ryan et al., 2018).

3 Management

The following chapter is a summary of the document "Approaches to Managing Intermediate Wheatgrass for Dual-Use Forage and Kernza Perennial Grain Production" (last updated in March 2019). This document was developed in cooperation with farmers in the US and contains early management recommendations which have not been set in stone and may differ between geographical region. We have provided some additional information from recent literature throughout this chapter.

3.1 Planting

IWG should be sowed in late summer. It needs vernalization by a period of cold to produce seed the next summer. It is recommended to plant IWG after a leguminous crop for optimal nitrogen availability. Planting after a spring cereal is possible but could bring about problems with carryover of diseases and/or pests. For this reason planting after a winter cereal is "strongly discouraged".

Seeds can be sown in a field after plowing with a "Brillion-type seeder", but also in a no-till field with an adequate seed drill. Seeds should not be place lower than 1.25 cm below the surface of the seed bed. Seed will likely germinate approximately 5 days after the first soaking rain after sowing.

Seeding density should be between 11.2 and 16.8 kg ha^{-1} with the aim of 13.5kg ha^{-1} of pure live seed. A row spacing of 30cm was shown to maximize both grain and forage yield over a 3 year growing period (Hunter et al., 2019, 2020). Between 8-20 seedlings per 30cm in a row will be required for optimal yields in the first year, but rows with only one seedling per 30cm increase their yield over time due to rhizomatic spreading.

3.2 Fertilization and mitigating lodging risk

Phosphorus levels of 10-20 ppm should be sufficient to sustain IWG yields without additional P fertilization. On highly productive soils, first year yields have been successful without any added fertilizer at all.

IWG tillers can reach heights of up to two meters and is therefore sensitive to lodging, which is a risk factor for yield losses. Optimal nitrogen fertilization rates for grain production are therefore those which do not lead to lodging but are enough to produce high amounts of biomass as well. Optimal nitrogen fertilization rates have been established by Jungers et al. (2017) and were found to be between 60 and 100 kg N ha^{-1}. In the same study first year grain yield in the absence of fertilization was about as high as the second year grain yield with an optimal fertilization rate of 61 kg N ha^{-1}, proving that, depending on the fertility of the soil, first-year grain yield may be successful without the need for fertilization.

Split application of nitrogen fertilizer in spring and fall minimize the risk of lodging and leaching. Split application is also recommended when the aim is to make use of the post-harvest regrowth for hay production. Moreover, when the nitrogen status of the soil is too low in spring when the crop starts to grow, seed head growth will not be initiated and grain yield will be reduced. The ideal soil-N concentrations are still being researched.

Plant growth regulators are also often deployed to reduce lodging in grain crops. Frahm et al. (2018) found the plant growth regulator trinexapac-ethyl to reduce plant height by 10 to 20%, thereby reducing lodging by up to 20% and increasing yield by 65 to 100% in a year with a high lodging risk.

Furthermore, Jungers et al. (2018) provide the first description of growth and development of intermediate wheatgrass, so that farmers and researchers can make informed decisions for the optimal timing of agronomic management practices.

3.3 Grazing/mowing

Direct grazing or mechanical cutting of spring vegetation should occur before the phase of stem elongation. If done after this phase has been initiated, the reproductive tillers will be destroyed and grain harvest will be ruined. The mowing height has to be high enough so that the first nodes of the stem are safe from being cut off. Post-harvest regrowth vegetation in fall can also be grazed upon or cut.

Rotational grazing is advised over continuous grazing, especially in spring as overgrazing by livestock that graze too low can lead to the destruction of the initiated seed head and stand loss. Overgrazing in fall can lead to stand loss as well and reduced winter hardiness. A residual height of 15cm is recommended.

3.4 Pest, disease and weed management

With the exception of scientific research, as of March 2019, no agricultural chemicals have been approved for production of Kernza (in the USA), this includes the above-mentioned plant growth regulators. In order to make weed control easier, the choice can be made to grow Kernza in wider, supra-optimal rows compared to the row-spacing mentioned above which allows for inter-row cultivation but may result in sub-optimal yields.

3.5 Harvest

The optimal timing of harvest of Kernza grain is still up for research. IWG is still relatively wild and selection for domestication traits such as reduced seed shattering and synchronized seed maturation is still ongoing. Waiting for all seeds to mature could therefore lead to a loss of grain yield; harvesting too early can result in problems during storage due to a seed moisture content that is too high. Special care therefore has to be taken to check seeds from the lower and higher end of the seed head and from several places in the field for their maturation stage. When enough seeds are brown and able to resist squeezing and pinching with fingernails without showing dents, it is time for harvest. More precisely, harvest can be initiated when seed moisture levels reach 35% or less. Contrary to wheat, IWG stems will likely still be mostly green when the grain is ready to be harvested.

Kernza grain can be harvested by direct combining when the weather is hot and dry and fields are relatively weed free. Following combining, grain should be aerated immediately until seed moisture levels reach 13% or less and the grain is dry enough for storage. Since the stems at harvest will still be green and moist, which could cause spoilage, the combine head should be set high as to only harvest the seed heads. The rest of the crop can then be swathed and baled.

Alternatively the whole crop could be swathed with a draper windrower when seed moisture levels are as much as 50% (but have already turned from green to yellow or brown), which can reduce seed shattering and dry the green biomass for improved combining. Swaths should be cut at 15-20cm to keep the crop off the ground and facilitate drying, which may take 3 to 5 days depending on the weather.

The grain should be stored in such a way that their moisture content can be kept below 13%.

3.6 Stand termination

The optimal procedure and consequences of stand determination after grain yield have declined below a profitable limit, which currently is after 3 to 4 years, although biomass production for forage will maintain its levels, likely for many years after that. Termination of the crop stand by tillage is most effective when the crop has regrown some 5 centimeters after harvest in fall or after growth has started in early spring. Tillage however would probably nullify many of the build-up benefits from growing a perennial grain crop like IWG. Research is being conducted into how to use close grazing and mowing as a herbicide free way to terminate the crop.

4 Kernza in the Netherlands

There are multiple opportunities for Kernza IWG in the Netherlands but also multiple challenges, which will be shortly summarized here.

4.1 Dairy and mixed farming systems

The second window of opportunity is that of increasing the value of production of grasslands for dairy and provide mixed farms with a new, sustainable multipurpose crop. IWG has been shown to produce high levels of forage biomass, possible of being harvested at three points in time every growing season (Favre et al., 2019; Pugliese et al., 2019). The spring and fall harvest have high nutritive value. The straw residue is of lower quality, although higher than wheat straw, but can be supplemented with legume or grass/legume hay to provide adequate nutrition for (lactating) cattle. It should be investigated how this forage relates to perennial ryegrass forage and maize silage in terms of yield and nutritive value, what additional mineral or leguminous supplementation would be required for the health of the cows consuming it and how this could be taken care of by intercropping.

Furthermore, in addition to forage production, IWG yields grain. The production of grain is presently not yet on competitive levels with annuals grains, but it could increase the value of grassland which normally does not produce grain at all. The Kernza grain is of superior nutritive quality compared to annual grains, with a higher fiber, carotenoid and protein content (Becker et al., 1991; Tyl and Ismail, 2019) and could there profit from premium pricing when marketed as a health product besides an ecologically sound product. However Kernza grain shows a high degree of compositional variability between genotypes, which also influence options for end-use such as bread baking (Zhang et al., 2015). Due to the higher production of forage it could also potentially compete with annual grains in terms of value production. Farmers would need a thresher or combine harvested and potentially a seed de-huller, as Kernza grains tend to hold on to their hull (Personal experience).

Thus, land which is currently only used for forage production for cattle could be used for the combination of forage production and grain production for human consumption. This would reduce the amount of land necessary for the production of energy and protein for human consumption, if the forage is capable of maintaining similar levels of animal product production as perennial ryegrass. However, whether IWG could be grown on farms in the low-laying parts of the Netherlands on dense clay soils or shallow organic soils with high ground water tables is questionable and should be investigated.

4.2 Circular and low input farming

The Netherlands recently woke up to the so-called nitrogen crisis. The protected nature areas with their already fragmented and vulnerable flora and fauna in this densely populated country, is suffering from nitrogen deposition and leaching, leading to increasing losses of biodiversity. Agriculture is the main culprit, but not the only, traffic, including air travel and other industries amongst which the building industry are also significant contributors (RIVM, 2019). The origin of the nitrogen emissions from agriculture are mainly found in (over)fertilization with both chemical and some organic fertilizers of which slurry manure is the most used and most problematic. IWG first of all, does not need the amount of fertilizer a ryegrass or corn field conventionally receives to produce adequate forage biomass and the maximum amount of grain it is currently capable of producing (Jungers et al., 2017,2019). By building SOM and stimulating soil life, IWG could furthermore stimulate its own nitrogen supply (Crews, 2005, Sprunger et al., 2018a). Intercropping with perennial forage legumes has been shown to be able to supply large parts of IWG's nitrogen demand as well (Hayes et al., 2017). The reduction in use of fertilizers will inevitably lead to reductions in nitrogen emissions and therefore deposition in nature areas.

Furthermore, as explained above, IWG is capable of reducing leaching to almost undetectable levels, through retention in living biomass, even under relatively high fertilization regimes (Culman et al., 2013; Sprunger et al., 2018a; Jungers et al., 2019). This will reduce washing out of nitrogen into the groundwater and ultimately into surface water bodies and drinking water (Glover et al., 2010a). Atmospheric nitrogen emissions from a IWG crop are currently being researched.

The nitrogen emission reducing qualities of IWG are of general benefit but also lead us to more specific, opportunities; buffer cropping (Ryan et al., 2018). IWG could be established as a border crop around fields which are prone to leaching and prevent nutrients from washing out into the greater watershed. But IWG could also be planted as a buffer around nature areas, where it can produce agricultural products, while also serving as a biological barrier regarding nitrogen emissions, deposition and leaching.

Moreover, presently a number of organizations concerned with nature conservation in the Netherlands have been designating agricultural fields in and around protected areas for nature conservation efforts. These specific fields are not allowed to receive full fertilization or in other cases no fertilization at all, thereby effectively marginalizing them. On these fields, productivity of annual crops is therefore lacking behind. IWG, however has shown to be capable of greatly maintaining its current capacity of productivity even under low or no fertilization (Jungers et al., 2019). In the study by Jungers et al. (2019) IWG had a higher second year yield when no fertilizer was applied compared to 40 and 160kg N ha^{-1} and higher or similar second year biomass yields. IWG has therefore been proposed as a potential crop to re-invigorate and produce on marginal soils (Glover et al., 2010b).

Fertilizer restrictions will become harsher in the future and organic fertilizers such as manure will likely become more scarce and costly in the future when livestock numbers are reduced. Crops with high nitrogen efficiencies and low nitrogen fertilization requirement will therefore become more important in the future circular farming models.

4.3 Climate adaptive agriculture

The Netherlands is increasingly experiencing summer-droughts over the last couple of years. Maize, with its shallow roots, and being one of the most abundant crops in the Netherlands, visibly struggled with these droughts and withered in great areas, especially on sandy soils. Perennial ryegrass fields also turned brown on a large scale. During these droughts an estimated 20 to 30 percent of ryegrass production and 35% of maize silage was lost in the Netherlands in 2018 (Prins et al., 2018). Spring barley and winter wheat suffered less yield losses, estimates at 2%, due to harvest before the drought peak in the summer of 2018 (Prins et al., 2018).

Besides providing higher levels of SOM and year-round ground cover, increasing the water holding capacity of the soil and reducing evaporative losses, IWG has been shown to have a high water use efficiency throughout the growing season, even when evaporative forces caused the topsoil to dry up (Oliveira et al., 2019). This can partly be attributed to IWG's deep roots capable of reaching receding water tables and in part to its ability, as a perennial, to draw upon past rain events in the beginning of the growing season (Oliveira et al., 2019; Clément et al., 2021). However, deep/groundwater depletion could be a risk factor with a deep rooting crop with a high evaporation relative to annual grains. The potential of IWG to mitigate water stress during summer droughts should be investigated further. This should be done on sandy soils that are most prone to droughts, but also on soils where the water table is high where the benefit of IWG's deep roots could be absent.

5 Knowledge gaps

The main knowledge gap is why the Kernza grain yields diminish so steeply after the second or third harvest. Initially the yield decline was attributed to nutrient depletion, but this has been refuted, since fertilization has not been able to overcome it. The problem is now attributed to the increase in plant and root density over the year, leading to increased competition and decreased investment in reproductive tiller and grain production (Pugliese et al., 2019, Bajgain et al., 2020, Hunter et al., 2020). Initial experiments with strip tillage resulted in an increase in fertile tillers and grain yield, although this increase was only from about 175 to 240 kg ha^{-1} for the fourth year harvest (Law et al., 2020). The mechanisms responsible for the steep yield decline should be further unraveled so that breeders can select for the rights traits and agronomists can develop suitable management practices.

Another knowledge gap is how the crops performs with organic fertilization. IWG is promoted as a sustainable alternative crop, but most scientific publications have used artificial fertilizers in their experiments. Culman et al., (2013) also used chicken manure as a treatment, but N in chicken manure is also very readily available in its inorganic form. The use of cattle or pig manure, whether it be slurry or solid, has not been put to the test although the use of IWG in mixed farming systems has been promoted for several years now. Using these types of organic manure may need different equipment and/or timing of fertilization and may lead to different environmental consequences compared to artificial fertilizers.

A major knowledge gap for the Dutch case is how whole plant silage yield and quality compare to that of annual grain crops and perennial grasses. Whereas the yield and quality of grain and vegetative biomass have been investigated separately, no study up to this point has investigated the feed quality of IWG whole plant silage.

Moreover the water use dynamics across differing geographical and climatic regions and soils have to be investigated to provide insight into in which regions and soil types IWG can thrive and use the available water sustainably and not deplete it. Also relevant for the Netherlands is the functioning of IWG on shallow soils with high ground water tables.

A fifth problem that has to be solved is the termination of the perennial crop and the influence of this management choice on the previously accumulated ecosystem benefits. Options for stand termination could be herbicides, tillage, intensive/over grazing, burning. These options may affect soil health and quality in different ways and have differential effectiveness. In a similar vein the extent of continuation or extinction of the build-up ecosystem services in subsequent annual or perennial crops should be researched.

Lastly, the potential of IWG in mono- or polycultures to improve soil structure, host a more abundant and diverse earthworm community and provide shelter and breeding ground for meadow birds and the impact of for example the (forage) harvesting regime on insect and bird populations has not yet been investigated.

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