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Report based on literature and models for the selected underutilized crops

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Contents

1 Introduction

This report is issued as part of the EU funded project CROPDIVA.

At the core of the CROPDIVA project is the ambition to increase the awareness, practical knowledge, productivity and quality of a range of underutilized crops, which all has the potential to diversify both human food intake and European cropping system.

This report contains a presentation of six underutilized crops selected for further studies in the CROPDIVA project as well as a review of the literature on intercropping systems, where these crops are included. Furthermore, the report presents a brief and general introduction to the concept of intercropping and its potential environmental effects.

The structure of the report is as follows: First the six underutilized crops are briefly presented with emphasis on their history, geographical distribution, productivity and nutritional properties. Secondly, the concept of intercropping is explained in practical and agronomic terms. Then follows a review of intercropping studies with each of the six underutilized crops. Finally, the potential environmental effects of intercropping is reviewed and discussed more broadly.

2 Underutilized crops in the CROPDIVA project

2.1 Buckwheat (*Fagopyrum esculentum*)

Buckwheat is a dicotyledonous annual crop, which originate from Central or South Asia and belong to the knotweed family (Polygonaceae) (Baumgärtner et al., 1998; Singh et al., 2020). It is grown for its edible seeds and is referred to as a pseudo-cereal, because its grains are used in similar ways as cereals, but the species is not closely related to actual cereals, which all comes from the family of grasses (poaceae).

Buckwheat is praised for its nutritional value, which is partly due to its content of various flavonoids, a group of bioactive compounds, which have both nutritional and medicinal functions (Christa and Soral-Śmietana, 2008; Panche et al., 2016; Singh et al., 2020).

It is a short-season crop, which can be grown both as a main crop, but is commonly also grown as a secondary crop after another short-season crop (Bavec et al., 2002). In 2020, Russia (44%) and China (34%) accounted for most of the worldwide area cultivated with buckwheat, which is roughly 1.9 Mha (FAOSTAT; https://www.fao.org/faostat/en/#data/QCL).

Buckwheat yields typically range between 1.2-3.0 t ha^{-1} (Schulte Auf'm Erley et al., 2005) or a little less when grown as a secondary crop (Bavec et al., 2002). Due to its rather open canopy structure, weed control is a common problem in buckwheat (Wall and Smith, 1999). Buckwheat can grow in a wide range of climatic conditions, is adapted to soils of relatively low fertility and is known for its efficient phosphorus (P) acquisition which is achieved by exudation of organic acids in the rhizosphere (Baumgärtner et al., 1998; Singh et al., 2020). Schulte Auf'm Erley et al. (2005) found no significant yield effects of nitrogen (N) fertilizer application of up to 60 kg N ha^{-1}. Unfertilized treatment yielded the same as fertilized treatments (roughly 1.4-1.5 t ha^{-1}), but the highest N rate of 60 kg N ha^{-1} increased lodging and reduced the harvest index. Thus, buckwheat is a rather undemanding and not too competitive crop, which could work well in low-input intercropping systems with a suitable companion crop.

2.2 Lupin (*Lupinus* spp.)

The lupin genus (*Lupinus*) contains a few hundred species of plants in the legume family (Fabaceae), but only a few species are commonly used for agricultural purposes, namely narrow-leafed or blue lupin (*L angustifolius* L.), white lupin (*L albus* L.), yellow lupin (*L luteus* L.), which all have their origin in the Mediterranean area, and pearl lupin or tarwi (*L mutabilis* L.), which originate from South America (Abraham et al., 2019; Boukid and Pasqualone, 2021; Mazumder et al., 2021). While wild lupins are toxic and bitter tasting due to their content of quinolizidine alkaloids, breeding efforts on mainly white lupin and narrow leafed lupin have resulted in 'sweet' cultivars with low alkaloid contents in the lupin grain (Huyghe, 1997; Mazumder et al., 2021). Still, the alkaloid content vary depending on the cultivar and growing conditions, and therefore a post-harvest alkaloid removal is practiced in order to ensure the safety for human consumption (Boukid and Pasqualone, 2021). Aside from the alkaloid content, lupin grains have desirable nutritional properties, mainly due to the amino acid composition of its protein, its fiber content and its content of vitamins B and E (El-Adawy et al., 2001; Mazumder et al., 2021; Wandersleben et al., 2018). Lupin grains are gluten free (Boukid and Pasqualone, 2021). This makes oat, which is also gluten free, a suitable intercropping companion crop for production of gluten free food products.

Lupin cultivars have been adapted to many climatic zones, and can grow in most of Europe, either as an autumn sown crop in colder areas (typically narrow leafed lupin cultivars) or a spring sown crop in warmer areas (typically white lupin cultivars) (Abraham et al., 2019; Huyghe, 1997). Its origin in areas with low pH soils makes it well adapted to growth in soils with low to moderate pH, and both white lupin and narrow leafed lupin show improper root growth in limed or calcareous soils with high pH (Kerley and Huyghe, 2002; Tang et al., 1993). It is efficient in increasing the availability and in utilizing P in soils of low fertility, and it does so by exuding organic acids in the rhizosphere (del Pozo and Mera, 2021). Its indeterminate growth can cause problems during harvest, perhaps especially in intercropping systems, where the harvest time is less flexible. However, determinate genotypes have been identified, and such cultivars are expected to reduce yield variability even though the yield potential may be lower compared to indeterminate cultivars (del Pozo and Mera, 2021; Huyghe, 1997).

Australia is the main producer of lupin worldwide - 55% of the world's total lupin cultivated area is found here, while the figure is 29% for Europe. The lupin production decreased drastically in Europe during the second half of the 20th century, probably due to low lupin prices, introduction of higher yielding crops and favorable policies for the import of soy bean to replace locally produced protein crops (Abraham et al., 2019; Preissel et al., 2015). Lupins in the EU are mainly grown for forage and for grains as a protein supplement to animals (Abraham et al., 2019; Ferreira et al., 2021). As a protein source, lupin grains are comparable to soy beans, with a protein content between 30-50%, depending on species, cultivar and environmental conditions (Mazumder et al., 2021). Furthermore, lupin protein has a good amino acid profile, the grains contain high levels of non-digestible fibers and low levels of anti-nutritional alkaloids (van de Noort, 2016). Lupin grain production in the EU therefore represents a great potential to reduce the reliance on imported soy bean based protein (Wilkins and Jones, 2000).

Lupin yields are quite variable, but high yielding autumn sown cultivars produce 2.5-4 t ha^{-1}, which is only a little less than soy bean (Abraham et al., 2019), but yields between 1-2 t ha^{-1} are more common (del Pozo and Mera, 2021). Yield variability is mainly due to weeds, pests and diseases, and while much of the previous breeding efforts have focused on reducing alkaloid content, future breeding programs also focus on yield and yield variability (Abraham et al., 2019; Lucas et al., 2015). Some of the causes for the large yield variability of lupins may also be ameliorated by intercropping. For instance, intercropping of lupin with a cereal can improve weed suppression (Carton et al., 2020) and reduce the common disease ‘brown spot’ (Hauggaard-Nielsen et al., 2008)

2.3 Oats (*Avena sativa* L.)

Oat is a cereal best adapted to cool, moist climates with moderate summer temperatures, and it is sensitive to drought and heat during the generative growth stages. For a cereal, it is versatile with regard to soil conditions, but a higher yield can be expected on a soil with moderate or good water holding capacity. Oats is the sixth most produced cereal in the world, but the area cultivated with oats has decreased steadily since the 1960s. (Ma et al., 2021). The worldwide area cultivated with oats in 2020 was just below 10 Mha and mainly found in Europe incl. Russia (57%) and North America (17%) (FAOSTAT; https://www.fao.org/faostat/en/#data/QCL). The global yield level of oats is around 2.5 t ha^{-1}, but yield levels in several European countries (e.g., Denmark, Germany, the Netherlands, Belgium, UK) typically range between 4.5-5.5 t ha^{-1}.

Among the cereals, oats have a good N use efficiency, and the optimal N fertilizer level is lower than most other cereals, except rye. Depending on soil N availability, the optimal N fertilizer rates often range between 75-110 kg N ha^{-1}, while high N application rates increase the risk of lodging without increasing yields. (Ma et al., 2021). Partly due to the ability of oats to be competitive and produce an acceptable yield of a good quality with a modest N availability, it is considered an appropriate companion crop in low-input cereal-legume intercropping systems (e.g. Helenius & Jokinen, 1994; Kontturi et al., 2011; Lauk & Lauk, 2008; Neumann et al., 2007).

Compared to other cereals, oats has a high content of dietary fibers, while the protein content often ranges between 15-20% of the grain weight (Ma et al., 2021). Some of the oat fibers are of the β-glucan type, which has been linked to several health benefits, including lowering and stabilizing of blood sugar levels and a reduced risk of coronary heart disease, which is one the most common causes of death globally (Mathews et al., 2021; Schmidt, 2020). Oat containing products with an estimated daily intake of at least 3g of β-glucans, has received a health claim by both the ‘American Agency for Food and Drug Administration’ (FDA) and the ‘European Food Safety Authority’ (EFSA) (Schmidt, 2020). Despite the health benefits by human consumption of oats, most of the global oat’s production is used for feeding animals.

2.4 Faba bean (*Vicia faba*)

The legume faba bean has been cultivated since ancient times, and more than 10.000 year old remains of faba-like beans has been found in the near-east (Zohary et al., 2012). From this region, various varieties and cultivars has spread to most of the world, although faba bean has never been a widely cultivated crop in the Americas (Mínguez and Rubiales, 2021). Today, roughly 2.7 Mha are cultivated with faba bean, and this area is less than half of the worldwide area with faba bean in the 1960s. The decline in faba bean production area could be due to reduced N fertilizer prices, which makes cereal production less reliant on N-fixating crops in the rotation, and the introduction of soybean, which in the same period increased the production area more than five-fold and which today is produced on nearly 50 times as large an area as faba bean. In Europe, the soybean production area is approximately 8-10 times larger the faba bean production area. The main sites of production are China with roughly one third, Europe with one fourth and Ethiopia with one fifth of the total global faba bean production area. (Mínguez & Rubiales, 2021; FAOSTAT; https://www.fao.org/faostat/en/#data/QCL)

Global faba bean yields average around 2 t ha^{-1}, but there are large local variations. For instance, yield levels of 3.5-4.5 t ha^{-1} are common in countries such as Belgium, Denmark and Germany, whereas yields as low as 0.7-1.4 t ha^{-1} are common in Southern European countries such as Spain and Portugal (FAOSTAT; https://www.fao.org/faostat/en/#data/QCL).

Various faba bean cultivars are acclimatized to a wide range of climatic conditions, ranging from a semi-arid Mediterranean (often autumn sown to reduce spring drought) over subtropical warm climates where it is grown at high altitude to cold and moist climates such as in Northern Europe (both autumn and spring sown) (Mínguez and Rubiales, 2021). Therefore, the influence of the weather on yield levels depends greatly on location and cultivar. In high latitude areas, frost hardiness is an important trait, while drought resistance or short season adaptation is a key trait in Mediterranean climates.

Nutritionally, faba bean, is a source of protein with good digestibility for humans, other monogastric animals and ruminants. The protein content of the grains typically range between 24-30%, which is similar to that of field pea (Mínguez and Rubiales, 2021). Faba bean contain anti-nutritional tannins in the integuments and vicine and convicine in the grain itself. Although cultivars with reduced content of each of these types of compounds exist, they are not the most commonly grown cultivars in Europe. Since the tannins is located in the integuments, most of the content can be removed by dehulling and this process increase the digestibility. The content of vicine and convicine can be reduced by cooking. (Crépon et al., 2010).

Faba bean can be intercropped with cereals such as barley, wheat or oats. The benefits of intercropping faba bean include improved weed suppression and reduced disease and pest attack compared to sole cropping of faba bean (Jensen et al., 2010).

2.5 Triticale (*x Triticosecale*)

The cereal triticale is a synthetic cross between wheat and rye, and its history is therefore much shorter than more well-known cereals. The wheat-rye crossing was first reported in the late 19th century, and in 1888 Wilhelm Rimpau produced the first fertile amphidiploid[1] triticale seeds (Franke and Meinel, 1990). The ambition with triticale was to combine the yield level and good baking properties of wheat with the robustness and relatively high content of the amino acid lysine in rye, but it was not until the mid to late 20th century that cultivars were developed, which achieved this ambition sufficiently well for farmers to adopt the crop on a broader scale (Lorenz, 2003).

Today, triticale is grown on roughly 3.6-3.8 Mha, most of which is placed in Europe (FAOSTAT; https://www.fao.org/faostat/en/#data/QCL). It is not only cultivated for grain for livestock feed, but also as a forage either as monocropping or in various mixtures (e.g. Dordas & Lithourgidis, 2011; Lithourgidis et al., 2006; M. Lorenz et al., 2008; Maxin et al., 2017; Vasilakoglou et al., 2008). Triticale has not achieved a breakthrough as an ingredient in human food products, although the nutritional and biochemical properties of at least

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[1] Amphidiploid means that the seed contain a diploid set of chromosomes from each parent (wheat and rye)

some cultivars makes them applicable for baking, making pastas or as breakfast cereals (Oettler, 2005).

Under optimal growing conditions, triticale can achieve nearly the same grain yield as winter wheat, however it is its ability to produce an acceptable grain yield under less optimal conditions, which makes triticale an interesting crop choice for soils of low fertility or semi-arid climates (Estrada-Campuzano et al., 2012; Lorenz, 2003; Oettler, 2005). When lower average yields are reported for winter triticale compared with other winter cereals, an explanation could therefore be that the more fertile soils are reserved for wheat and barley production, while triticale and to some extent rye is cultivated on less fertile soils, where wheat and barley would probably produce even lower grain yields.

Previously, triticale was characterized by a better disease resistance than other winter cereals, however as the area cultivated with triticale has increased, the disease resistance has decreased and today triticale is affected by the same array of diseases as other winter cereals and is only considered slightly more resistant against them (Oettler, 2005).

In intercropping with legumes, the rigorous growth of triticale can be utilized to suppress weeds in the legume, however it is considered a strong competitor, and therefore risk outcompeting the legume if managed improperly, i.e. sown too densely or fertilized too much (Carton et al., 2020; Dordas et al., 2012; Sobkowicz, 2006; Sobkowicz and Śniady, 2004).

2.6 Naked Barley (*Hordeum vulgare* L. var. *nudum Hook*. f.)

Barley was one of the first crops domesticated more than 10.000 years ago somewhere in the Near East. Compared to wheat, barley is less demanding with regard to soil conditions and can tolerate harsher climates – it is even considered the most widely distributed crop in the world. (Ullrich, 2014; Zohary et al., 2012). As a food source, wheat has always been preferred over barley, partly due to barleys lack of gluten protein (meaning that it is not possible to make leavened bread based on barley) and because barley has a hull, which stays on the grain during threshing and can only be removed by further processing (de-hulling and pearling) (Baik and Ullrich, 2008; Šimić et al., 2021). As alternative food sources, such as wheat, maize and rice has become more available during the 20th century, barley has lost its role as an important food source and is now primarily used as animal feed and for beer and whisky production, while only 2-4% of the total production is used for human consumption (Baik and Ullrich, 2008; Ullrich, 2014). However, a hull-less ('naked') type of barley exists, which is more easily applicable for human consumption, because less post-harvest processing is required.

The interest in barley as a food source is increasing in certain countries due to the awareness on the nutritional value of including whole grain in the diet. For barley in particular, a high content of soluble β-glucan fibers are of interest, due to their ability to lower blood cholesterol and the glycemic index of foods, which in turn reduce the risk of heart disease and type II diabetes (Baik and Ullrich, 2008). Especially waxy[2] hull-less barley has been shown to contain high levels of β-glucans (Fastnaught et al., 1996). Fibers, both soluble and insoluble, also improve digestion (Šimić et al., 2021). For its effect on blood cholesterol, the 'American Agency for Food and Drug Administration' (FDA), has approved a health claim for barley food products.

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[2] Waxy: barley cultivars, where the starch consist solely of amylopectin

Barley is arguably the most utilized cereal in intercropping systems. While hulled barley is considered a suitable companion crop to legumes, such as pea or faba bean (e.g. Chapagain & Riseman, 2014; Corre-Hellou et al., 2011; H. Hauggaard-Nielsen et al., 2001a; Knudsen et al., 2004), naked barley has received very little attention in such studies.

3 Intercropping

3.1 Intercropping history and terminology

Intercropping is a cultivation technique, where more than one crop species is grown in the same area at the same time. It is an old concept, which was famously utilized in parts of the pre-Columbian Americas with the ‘three sisters’ cropping systems, which consisted of maize, bean and squash (Brooker et al., 2015; Martin-Guay et al., 2018; Mt.Pleasant and Burt, 2010). Today, it remains a widely used cropping technique in many parts of the world (Brooker et al., 2015; Hauggaard-Nielsen et al., 2008; Li et al., 2020; Myaka et al., 2006; Sobkowicz and Śniady, 2004). In most European farming systems, however, intensification of modern agriculture during the last roughly 70 years has led to a decrease or disappearance of intercropping (Hauggaard-Nielsen et al., 2001a).

3.2 Types of intercropping

Intercropping is a broad concept which can be implemented and managed in different ways. Andrews & Kassam (1976) subdivided intercropping into the following four categories.

Mixed intercropping

Two or more species are grown simultaneously either in rows or broad spread, but in no distinct pattern. The species thereby grow in close contact, and interspecies competition and potential complementarity is high (see section 3.2.1). With mixed intercropping, there is no practical option to harvest the crops separately, so it is critical that both crops reach maturity at nearly the same time.

Row intercropping

Two or more crops are grown simultaneously in rows of a distinct pattern (alternating, 2:1 or similar designs). Otherwise, row intercropping resembles mixed intercropping.

Strip intercropping

Two or more crops are grown in strips of multiple rows, which are wide enough to allow independent management but narrow enough to allow interspecies interaction, although not as intense as in mixed or row intercropping.

Relay intercropping

Any of the above types of intercropping, but where the crops are sown and/or harvested at different times and only overlap for part of the growing season. Relay intercropping is most systematically carried out in conjunction with strip intercropping, but in principle relay intercropping is also possible in mixed or row intercropping systems by offsetting the sowing of each crop.

3.3 General mechanisms for beneficial effects of intercropping

The beneficial effects of intercropping compared to sole cropping, such as higher yield, improved resource utilization and increased yield stability can be explained by a few general mechanisms, which are explained in the following sections.

3.4 Complementarity and facilitation

Improved crop growth and yield when intercropping is typically attributed to niche complementarity. It means that each species in the composite crop complement each other with respect to resource acquisition, i.e., their ecological niches are not identical. The complementarity can be with respect to either the way they obtain a resource (e.g. N_2-fixation vs. uptake of N from the soil), the space where the resource is obtained from (e.g. deep root system vs. shallow root system) or the temporal differentiation in resource acquisition (e.g. early vs. late season growth) (Stomph et al., 2020). Facilitation is another mechanism for synergistic crop growth in intercropping systems. It is a broad term from the discipline of ecology covering many types of interactions and it is considered on both long (i.e. natural succession of ecosystems) and short time scales (i.e. co-growth) (Brooker et al., 2008). It means that at least one of the crop species improve the potential resource acquisition of another species. Examples include increased availability of micronutrients in the soil due to root exudes or mycorrhiza activity or the attraction of beneficial insects by one of the intercropped crop species which benefit the other intercropped species (Brooker et al., 2015; Stomph et al., 2020).

3.5 Light acquisition and conversion

A part of the complementary resource utilization of intercropping systems relate to interception of solar radiation (Keating and Carberry, 1993; Wang et al., 2015; Yang et al., 2017). The increased light interception can occur due to complementarity between the canopy architectures of intercropped species, simply meaning that more of the radiation is intercepted in the composite canopy than the average of the respective sole cropped canopies. When two or more crop species grow together, it is not simply a matter of combining their respective canopy architectures to obtain a composite canopy, however, since each crop adapt to the competition of the other crop(s) and may modify its own canopy architecture by the mechanism called phenotypic plasticity (Zhu et al., 2015).

In relay intercropping systems, light acquisition can also increase by having a longer period of ground cover (and less bare soil) relative to the sole cropped systems (Stomph et al., 2020; Zhu et al., 2015). In practice, the first crop can function as a nurse crop for the second (later sown) crop, and as the first crop matures more light becomes available to the second crop which matures later.

Not only light acquisition, but also light conversion may be improved in intercropping systems. This is mainly observed in temperate zones, where it is common to intercrop a C4 species (e.g., maize or sorghum) with a C3 species (e.g., wheat or soybean). The mechanism is, that a tall C4 species overgrows a shorter C3 species, and while the light conversion efficiency (which is higher in C4 than in C3 species) of the C4 crop is not affected much by the intercropping compared to the sole cropping, the partly shadowed C3 crop has a higher conversion efficiency of the light that reach it compared to the sole cropped control (Awal et al., 2006; Stomph et al., 2020). The combined effect is that the intercepted light is used more efficiently in the composite canopy, and the mechanism can be thought of as a functional complementarity between the intercropped species.

3.6 Nutrient and water acquisition.

The concept of complementarity in intercropping systems also apply to nutrient and water acquisition, and as with light acquisition, the complementarity can also be divided into a spatial, a temporal and a functional component – only below ground. The spatial and temporal components of complementarity stem from the different root architectures and root growth dynamics of the intercropped species (Esnarriaga et al., 2020; Hauggaard-Nielsen et al., 2001b). It means that different crops may utilize resources from different parts of the soil and that the composite demand is spread over a larger soil volume and/or a longer part of the growing season compared to sole cropping scenarios.

By far the most of the reported experiments with intercropping involve a cereal or maize in combination with a legume (Li et al., 2020; Stomph et al., 2020; Yu et al., 2015). In those situations, the functional aspect of complementarity is important with regard to N acquisition due to the N-fixating property of legumes. When cereals and legumes are mixed, the cereal is typically more efficient in utilizing the available soil N (compared to the legume), thus forcing the legume to rely on N-fixation to meet its N demand (Hauggaard-Nielsen et al., 2008). Therefore legumes grown in intercropping systems typically contain a larger proportion of N derived from the air (%Ndfa) than sole cropped legumes, where the competition for available soil N is less (Corre-Hellou et al., 2006; Jensen et al., 2020). In effect, the soil available N is disproportionally taken up by the cereal, thereby improving the overall N utilization and reducing the N fertilizer requirement of the intercrop system compared to the respective sole cropped systems.

In addition to complementarity in resource acquisition, intercropping may also increase productivity due to facilitation (Brooker et al., 2015; Stomph et al., 2020). This is mainly reported with regard to P or micronutrient acquisition, where soil acidification by one crop increase the resource availability for both crops, and these effects are primarily seen in low fertility soils, where such resources are limiting for crop growth and yield (Esnarriaga et al., 2020; Li et al., 2007; Myaka et al., 2006).

3.7 Weed suppression

Improved weed suppression is a commonly mentioned trait of intercropping systems (Biszczak et al., 2020; Brooker et al., 2015; Corre-Hellou et al., 2011; Hauggaard-Nielsen et al., 2001a; Stomph et al., 2020). The effect is typically obtained by combining a legume crop with an open canopy architecture (e.g., pea, faba bean, lupin) and a cereal with a rapid growth and dense canopy (e.g., barley, oats, wheat). While the sole cropped legume has poor competitive ability against weeds and typically require some sort of weed management, the weed suppression in the composite canopy is improved compared to the sole cropped legume. While the cereal in effect act as a weed from the point of view of the intercropped legume, the overall effect is that more of the available resources (light, water or nutrients) end up in a harvestable crop (legume or cereal) rather than in weed biomass (Hauggaard-Nielsen et al., 2001a).

3.8 Other effects

Other beneficial effects of intercropping include reduced risks of disease (Fernández-Aparicio et al., 2011) and pests (Ratnadass et al., 2012).

4 Productivity

4.1 Yield stability

Yield stability express the yield variation at a site across years or across several sites with similar treatments in the same season. In a meta-analysis, Raseduzzaman & Jensen (2017) concluded that intercropping systems show significantly higher yield stability compared to sole cropping in both temperate and tropical regions. The yield stability was higher for cereal-legume based intercropping systems than for non-cereal-legume system (such as maize-wheat).

The increased yield stability is a result of the complementarity between the intercropped species and the potential for compensational growth by one crop in case the crop fails due to disease, pests, drought or for other reasons. Increased yield stability is not necessarily the same as higher yields, but a high yield stability increase food security, which is critical especially in many tropical regions (Raseduzzaman and Jensen, 2017).

4.2 LER, RLO and absolute yield difference

The effects of intercropping on productivity are commonly reported using the metric LER (Land Equivalent Ratio), which express the sole-cropping area required to produce the yield obtained in an intercropping system. The partial LER is calculated for each of the intercropped species and the overall LER is simply the sum of the partial LERs. Thus, LER always relate to a reference sole crop grown as a part of the experimental setup to test intercropping effects. A LER value of 1 implies that the yield of an intercropping system could have been obtained on the same area by sole cropping, while a LER above 1 implies that it would require more land of sole cropping to achieve the yield of the intercropped system. The LER does not discriminate or inform about the relative performance of each of the intercropped species, but an analysis of the partial LERs allow to compare the performance and competition between the crop species in the intercropped system (Bedoussac et al., 2015).

While LER is the common metric for intercropping performance, (Martin-Guay et al., 2018) suggest it is also relevant to evaluate the performance with an RLO-index (Relative Land Output), which weighs the respective yields of the intercropped species by e.g. energy content, nutritional or monetary value. The RLO may be especially important when working with crops of very different properties with respect to the use case, for instance nutritional value. In addition, (Li et al., 2020) argue, that LER is insufficient as measure of the ability of intercropping to substantially improve food productivity and security and that the absolute yield effect (the net effect, NE) should also be considered. The reason is that the same LER can cover both large and small intercropping effects in actual yields depending on the yield levels of the compared intercropping and reference sole cropping systems.

There does not seem to be any convention regarding N fertilization strategies in intercropping studies. In a meta-analysis of cereal-legume intercropping experiments, Yu et al. (2016) divided data from hundreds of studies into four N strategies: one where all treatments received the same N rates, one where the intercropped plots received somewhere in between the sole cropped plots, one where the intercropped plots received the same as the lowest rate in the sole cropped plots and one where the intercropped plots received the same as the highest rate in the sole cropped plots. Sometimes no N fertilizer is applied at all, even in the reference sole cropped cereals (e.g. Chapagain & Riseman, 2014; H. Hauggaard-Nielsen et al., 2003; Lauk & Lauk, 2008; Neumann et al., 2007). The choice of N fertilizer strategy (both timing and rate) does affect the competition, growth and relative yield between the intercropped species, since N application favors cereal growth on behalf of the legume (Bedoussac et al., 2015; Naudin et al., 2010). The choice of N application to the sole cropped cereal should affect LER, since this is the baseline, which the intercropping system is evaluated against. Nevertheless, Martin-Guay et al. (2018) found no effects of N fertilizer on LER with their analytic method, while both Li et al. (2020) and Yu et al. (2016) reported effects of N fertilizer rate on LER in their meta-analyses.

The dynamic between N availability and inter-species competition has often lead to the conclusion that intercropping works best in low-input systems, in order to avoid the out-competition of the legume by the cereal (Bedoussac et al., 2015; Brooker et al., 2015). However, it should be noted that intercropping is implemented differently in different parts of the world, and mainly in China, intensive high-input intercropping of maize, soy-bean and wheat is a common intercropping method (Li et al., 2020). These production systems rely on strip intercropping, and very often relay strip intercropping in order to utilize the growing season efficiently. The result is a high-input high-output system, where the inter-species competition is reduced both due to strip design and due to the offset of sowing time between the crops (Yu et al., 2016), but where some of the complementary benefits of intercropping are still utilized.

Reported LER values from intercropping studies are most often above 1 and commonly range between 1.1 and 1.4 for cereal-legume systems (Bedoussac et al., 2015; Hauggaard-Nielsen et al., 2009; Li et al., 2020; Martin-Guay et al., 2018; Yu et al., 2016, 2015).

In a meta-study, C. Li et al. (2020) found that LER was on average 1.29 in intensive maize-soy bean intercropping systems and 1.16 in extensive (low-input) small cereal-legume based intercropping systems. In terms of absolute yield differences, the intensive maize-containing intercropping systems increased average yields by 2.1 Mg ha^{-1}, while the intercropping systems without maize (i.e., small grain-legume based systems) resulted in average yield increases of 0.5 Mg ha^{-1}. In other words, while the LER value for the two approaches to intercropping were similar, the absolute yield effect was four times larger in the high-input high-output intercropping systems.

4.3 Challenges with intercropping

In mixed or row intercropping designs, both crops must be harvested simultaneously. Therefore, a challenge with intercropping is to identify species and cultivars, which mature at nearly the same time and which can be easily separated during or after harvest if separation is needed for further processing of the harvested grains (Bedoussac et al., 2015). If the harvested mixture cannot be separated or if it is costly to do so, the main option for the farmer is to use the mixture for animal feed (Bedoussac et al., 2015; Hauggaard-Nielsen et al., 2008).

A challenge when mixing crop species is a reduced tolerance for the combined crop against herbicides (Vasilakoglou et al., 2008). This is especially the case when intercropping monocots (e.g., cereals or maize) and dicots (e.g., legumes), but this is also by far the most common intercropping strategy. It should be possible to apply selective herbicides using special equipment with a strip intercropping arrangement. With relay intercropping, it is an option to establish the first crop and perform a chemical weed control before establishing the second crop. Otherwise, the obvious alternative is mechanical weed control in-between rows or simply to rely on the improved weed suppression properties of the intercropped arrangement compared to sole cropping (e.g. Corre-Hellou et al., 2011).

Perhaps the biggest challenge facing a farmer who considers implementing intercropping is the lack of concrete hands-on experience during planning, in-season management, harvesting and utilizing or trading the produce. Although the agroecosystem is always complex, monocropping is the simplest possible version of agriculture. As soon as a second crop species is introduced, interactions appear making decisions more complex. As an example, if a sole cropped cereal requires more N-fertilizer, the farmer can simply add more fertilizer, and this will likely increase growth and grain yield or grain quality. The desired rate then depends on the price of grain and fertilizer. In an intercropped system adding N-fertilizer is also likely to favor the cereal growth and yield, but often at the expense of the grain legume yield (Ghaley et al., 2005; Jensen et al., 2020; Naudin et al., 2010). In turn, it might be more economically favorable not to fertilize at all in an intercropping scenario, but the decision requires more consideration and experience than in a monocropping scenario. Experience is also necessary for choosing suitable crop and cultivar combinations and for obtaining a good crop establishment each year. In some fields and years, it may be favorable to sow one crop before the other due to considerations regarding the weather, the soil conditions, the previous crop or weed pressure – in other fields and years maybe not. As systems (and decisions) increase in complexity, it also becomes more difficult to generalize observations and develop 'rules of thumb' in the decision making. To develop the skills and competences to make prudent decisions requires experiences of both successes and failures and it may therefore be a hurdle for some farmers to replace the well-known monoculture system by something less familiar.

5 Review of underutilized crops in intercropping

5.1 Buckwheat (Fagopyrum esculentum)

The published literature on intercropping with buckwheat is sparse, and often focus on the other crop in the system. For instance, Biszczak et al. (2020) (Poland) found, that intercropping soy-bean with buckwheat significantly increased the yield of soy bean if one row of buckwheat was added in between the soy bean rows, but decreased the soy bean yield if two rows of buckwheat were added. The sole cropped soybean yields were low (0.3 to 0.6 t ha^{-1} depending on cultivar) due to weed infestation, and the increased yield by co-growth with buckwheat was attributed to increased weed suppression. Buckwheat yields were not reported. Cheriere et al. (2020) (France), on the contrary found that intercropping soybean with buckwheat reduced soybean yields significantly, especially in 2018, where yields were reduced from 3.12 t ha^{-1} in sole cropping to 0.26 or 0.9 t ha^{-1} depending on intercropping design (mixed and alternating rows, respectively) because the buckwheat outcompeted the soybean.

Razze et al. (2016) (Florida, US) intercropped zucchini squash and buckwheat, and also in this combination, buckwheat was considered as an accompanying crop to the main squash crop. The purpose was to deter pests, attract natural enemies and reduce disease. Several intercropping designs were tested and the presence of buckweed did reduce aphid density and insect transmitted plant viruses in the squash crop. Some designs reduced squash yield, while others had no significant impact on the squash yield.

Salehi et al. (2017, 2018) (Iran) studied an intercropping system with buckwheat and the legume fenugreek (*Trigonella foenum-graecum* L.) in various row designs and fertilizer application strategies. Across all treatments, the presence of a companion crop affected the crop yield of each crop negatively compared to sole cropping, but the combined seed yields were higher in intercropping scenarios. In the highest yielding intercropping design (alternating 2 rows of fenugreek and 1 row of buckwheat), the total seed yield increased by around 30% depending on fertilizer strategy in both 2014 and 2015. Furthermore, the 2:1 intercropping design also improved N and P utilization compared to sole cropping in both scenarios with inorganic and organic fertilizers.

In summary, reported experiences with intercropping buckwheat is rather limited, especially in a European context. Trials with various companion crops and management strategies are necessary to identify robust intercropping designs including buckwheat.

5.2 Lupin (*Lupinus* spp.)

Lupin is mainly intercropped for forage production (e.g. Carruthers et al., 2000; Jannasch & Martin, 1999; Mikić et al., 2013) but also for seed production.

Carton et al. (2020) (France) intercropped lupin with triticale in an additive design, i.e., intercropped lupin was sown at the same density as sole cropped lupin and triticale was added at 30% of the recommended density for sole cropping. The experiment was carried out on six sites in 2015 and five sites in 2016 with either no or low fertilizer input rates, but the intercropping system was only compared to lupin sole cropping. Therefore, a LER could not be calculated. The addition of triticale reduced weed biomass compared to the sole cropped lupin, but also reduced lupin seed yield by 34% (from an average of 2.96 t ha^{-1} in sole cropping). The total grain yield by intercropping increased by 37% on average compared to sole cropping of lupin. Overall, this means that the potential protein production per area is higher in sole cropped lupin (due to the high protein content in lupin), but the introduction of triticale improved yield security, and the authors suggested that this may convince farmers to grow lupin more widely, thereby increasing the gross protein production.

Knudsen et al. (2004) (Denmark) studied mixed intercropping of barley with pea, faba bean and lupin, respectively, on two soil types (sandy loam and sandy soil). In general, intercropping with lupin was less favorable compared to pea and faba bean intercropping with LER values just below 1 on both soil types. Barley dominated lupin on both the sandy and loamy soil, but the yield proportion of lupin (29-44%) in intercropping was more stable than observed in pea and especially faba bean, which was nearly absent in the sandy soil. The total lupin-barley grain yield varied between 2.2-3.4 t ha^{-1} for the two soil types. The authors assumed that choice of lupin cultivar with limited branching and the deep rooting system (compared to pea and faba bean) made the lupin yield more consistent across soil types. Intercropping with lupin did not affect the barley grain protein concentration, whereas intercropping with both pea and faba bean increased the barley grain protein on the loamy soil, but not the sandy.

Danso et al. (1993) (Iceland) intercropped lupin and oats. The intercropped yield (4.69 t ha^{-1}) was slightly lower than sole cropped lupin (4.95 t ha^{-1}) but higher than sole cropped oats fertilized with 80 kg N ha^{-1} (3.81 t ha^{-1}). The intercropped grain yield consisted of nearly 51% lupin and 49% oats.

In summary, intercropping with lupin has shown some promising results in low-input systems, but intercropping tends to reduce the lupin yield per cropped area, as is the common for intercropped legumes. Across the reviewed articles, the lupin yields decreased by around one third in intercropping compared to sole cropping. An increase in the gross production of lupin (and protein) in Europe via intercropping therefore requires a significant expansion of the area cropped with such systems, at least if they are to replace sole cropped lupin. To this end, much work remains to identify which of the numerous lupin species and cultivars perform best in intercropping systems depending on companion crop, soil type and climate.

5.3 Oats (*Avena sativa* L.)

Oats is mostly intercropped with various legumes for forage production (e.g. Caballero et al., 1995; Carr et al., 1998; Dhima et al., 2014; Dordas & Lithourgidis, 2011; Lithourgidis et al., 2006). When oats are intercropped for grain production, pea is the most used companion crop.

Kontturi et al. (2011) (Finland) intercropped pea and oats, mainly to reduce lodging in sole cropped pea at three sites and across three years. The proportion of oats in the replacement intercrop design was therefore quite low at either 7.5 or 15%. The inclusion of oats did decrease lodging, but it also reduced pea yield. The LER values were generally close to one, meaning that the oat yield compensated the pea yield reduction in terms of dry matter. LER values were highest when sole cropped pea yields were low, underlining the effect of compensatory yield when intercropping. The optimal proportion of oats in mixtures varied depending on pea cultivar, site and year and the authors were not able to generalize across the scenarios. In all scenarios, the intercropped oats protein concentration increased by around 0.5-1.5%-points compared to sole cropped oats, even though the intercropped treatments only received 30 kg N ha^{-1}, while the sole cropped oats received 90 kg N ha^{-1}.

Lauk & Lauk (2008) (Estonia) examined intercropping effects of pea with wheat, barley and oats, respectively, in a three-year study. The setup was an additive design, where cereal seeding rates were held constant at 100% of the recommended rate and pea seeding rates varied from 0-120 seeds m^{-2}. Since there was no sole cropped pea treatment, LER could not be calculated, but in all cases the increasing pea seeding rates reduced the cereal yield while increasing the overall yield. Oats were the cereal least (negatively) affected by the co-growth with pea compared to wheat and barley. The intercrop yields were only compared to unfertilized cereal sole cropping scenarios. The sole cropped oats yielded 3.16 t ha^{-1}, while the highest obtained intercrop yield was only 233 kg ha^{-1} higher (60 peas m^{-2}, resulting in an oat yield of 2.29 t ha^{-1}). The authors suggested that intercropping cereals with pea is a good solution in low-input systems and that oats are more competitive against pea than barley or wheat in an unfertilized scenario.

Neumann et al. (2007) (Germany) studied effects of seeding density in row intercropping systems of oats and pea during two seasons. The study contained five seeding densities of both crops in sole cropping plus all combinations of densities in intercropping. No N fertilizers were applied in any scenarios. In all cases, intercropping reduced yields of each crop compared to sole cropping at the same density. However, the total yields of pea and oats were always higher in the intercropping scenarios. In the first year, the high-density combination resulted in the largest benefits of intercropping (70 pea plants m^{-2} x 300 oat plants m^{-2}), but in the second year, the biggest advantage of intercropping was found at a combination of low densities (40 pea plants m^{-2} x 75 oat plants m^{-2}). This finding exemplifies the effect of growing conditions (weather, water, soil nutrients) on optimal sowing density, which makes it difficult to generalize an optimal management strategy across fields and seasons, even for the same crop combination.

In summary, oats intercropping has mainly been reported with pea as the companion crop and such systems seems to perform reliably, although yield benefits are small. Some of the reviewed studies compared unfertilized treatments in both intercropping and sole cropping scenarios. This approach may overestimate the yield benefit of intercropping since sole cropped oats would rarely be unfertilized. On the other hand, the study by Kontturi et al. (2011), showed that oats may well play the role as a secondary, weed suppressing crop in an intercropping design focused on legume production (here pea) and at the same time function as a yield insurance in the situation where the main legume crop fails. As a bonus, the grain quality (protein content) of intercropped oats increased, which makes it more valuable both as a human food source or as livestock feed.

5.4 Faba bean (*Vicia faba*)

Faba bean is a frequently used crop in intercropping studies, and it is applied in quite different types of systems ranging from forage production systems (e.g. Lithourgidis & Dordas, 2010; Strydhorst et al., 2008), high-input systems in combination with maize or wheat (e.g. Fan et al., 2006; Xiao et al., 2018), low input systems in Mediterranean or semi-arid climates in combination with maize, wheat or other companion crops (e.g. Abbes et al., 2019; Agegnehu et al., 2008; Rezaei-Chianeh et al., 2011) to low-input systems in the temperate zone (Jensen et al., 2010).

Knudsen et al. (2004) (Denmark) presented an intercropping experiment where barley was intercropped with faba bean, pea, and lupin (see also section 4.2). In a loamy soil, the faba bean dominated the unfertilized barley and 63% of the intercropping grain yield (3.9 t ha^{-1}) consisted of faba beans. In a sandy soil, however, the faba bean was nearly absent and grew poorly as a sole crop. Due to compensation by the barley crop, the combined intercropping yield (2.1 t ha^{-1}) was therefore higher than the average of the sole cropping treatments.

Hauggaard-Nielsen et al. (2008) studied a similar system (barley + pea/faba bean/lupin) and found that while faba bean and lupin yielded similarly in sole cropping on both a loamy and a sandy soil (roughly 2.7-3.4 t ha^{-1}), faba bean intercropping resulted in a much better LER (1.35-1.51 for faba bean+barley vs. 0.98-1.24 for lupin+barley) in intercropping indicating a better complementarity with the barley intercrop. The LER values were relative to an unfertilized barley sole crop.

Faba bean has also been intercropped for the purpose of reducing the prevalence of the fungal disease ‘chocolate spot’ (*Botrytis fabae* Sard.), which can reduce yields significantly. Fernández-Aparicio et al. (2011) studied the effects of intercropping faba bean with various cereals and legumes for this purpose. They found that intercropping faba bean with a cereal (barley, oats, triticale or wheat) reduced the area under disease attack and increased plant height and weight significantly, while intercropping with another legume (pea or common vetch) had no effect on the area under disease. Yields were not reported in this study, but since chocolate spot is known to reduce yields, yield effects of reducing the prevalence is likely.

In summary, faba bean is one of the more commonly intercropped species and exists in numerous varieties adapted to different climatic conditions. Experiences and decision support may therefore be found locally in farming communities. Apart from agronomic features, an attractive property of faba bean is that the large grains are easy to separate from the grains of a cereal companion crop.

5.5 Triticale (x Triticosecale)

Intercropping studies with triticale mostly focus on forage production (Dhima et al., 2014; Dordas and Lithourgidis, 2011; Lithourgidis et al., 2006; Maxin et al., 2017), however a few intercropping studies with triticale for grain production has been published.

Carton et al. (2020) (France) studied intercropping of winter lupin and triticale (see section 4.2 for further details). The main purpose of triticale in this system was to reduce weed in the lupin crop. The addition of triticale reduced weed biomass but also lupin yield by 34%.

However, the total grain yield increased by 37% and the total protein yield (in lupin and triticale) was maintained.

Sobkowicz (2006) (Poland) intercropped triticale and field bean (*Vicia faba* var. *minor* L.) in different densities and compared the crop growth and yield to sole cropping. Triticale was sown in densities of 200 and 400 plant m^{-2}, field bean was sown in densities of 50 and 100 plants m^{-2} and all four combinations were tested in intercropping. In all intercropping systems, triticale dominated the bean and reduced its yield, but the overall yield was significantly higher in all intercropping scenarios except the 200-100 combination. LER (reported as Relative Yield Total, RYT, which is essentially the same metric) ranged from 1.10 to 1.36. In most scenarios the effect of intercropping on triticale grain yield was little (4-7% in three of four scenarios) and the total protein yield increased significantly in all intercropping scenarios (protein LER or RYT varied from 1.17 to 1.43).

Monti et al. (2016) (Italy) intercropped pea with four cereals, including triticale, in both replacement and additive designs. All cereals dominated the pea crop and reduced the pea yield, also in replacement designs, where the seeding rates of the cereals were 50% of the sole cropping seeding densities. Triticale yielded 4.1-4.8 t ha^{-1} over two seasons in the sole cropping scenarios. For triticale (and most other cereals in this study), the most favorable scenario was the replacement design, while the additive design generally imposed a too strong competition against the pea crop with very low pea yields as a result. In the replacement design, the triticale crop compensated by increased tillering and the yield only decreased by 6% in one year and 33% in the following year compared to the sole cropping scenario sown at 100% density. Total grain N yield in the triticale intercropping scenarios was not much improved, mainly due to low pea yields, but the triticale N concentration increased significantly from 1.99% to 2.25% in the replacement design.

In summary, the reported experiences with triticale-legume intercropping show quite favorable results. A general comment is that triticale imposes a tough competition on a legume crop, and a reduced seeding density of triticale improves the balance between the crops. Like other cereals, intercropping is found to improve the protein content of triticale, making it more valuable as a feed source.

5.6 Naked Barley (*Hordeum vulgare* L. var. *nudum Hook*. f.)

Little is published on intercropping with naked barley. A combined search on these terms on "web of science" returns only one published study: Schmidtke et al. (2004) (Germany) studied the N utilization in an intercropping system with lentils and naked barley (cv. Taiga). Sole crops were sown with densities of 150 and 300 plants m^{-2} for lentils and barley, respectively, and the relative seeding rates in the intercropping design were 0.8 for lentils and 0.2 for barley. In the first year, the lentil yield was 2.2 t ha^{-1}, the (unfertilized) barley yield was 2.4 t ha^{-1} and the combined intercropping yield was 3.1 t ha^{-1}. In the second year, the yields were: Lentil 2.7 t ha^{-1}, barley 4.3 t ha^{-1} and intercropping 3.7 t ha^{-1}. In the first year, the relative yield of each crop was roughly equal, but in the second year, barley dominated with 81% of the total intercropped grain yield, even though its relative seeding rate was lower than that of lentils. The study showed that the advantage of intercropping in terms of crop growth mainly occurs when the soil-N is limited. In that situation, the cereal grows rapidly early in the season and nearly depletes the soil of available N, after which most of the growth is accounted for by the legume, which can fixate N from the atmosphere (here: lentils). When the available soil N is higher (as the second year of this study), the cereal tends to outcompete the legume too far into the growing season, and the ability of the legume to continue the composite growth rate of the crop is reduced at the time when the cereal growth ceases due to low N availability.

While naked barley cultivars remain largely uninvestigated for intercropping purposes, the review of the other underutilized crops reveal that common (hulled) barley is a frequently selected intercropping partner, and experiences from such studies may be informative of the performance of naked barley in intercropping designs. If so, naked barley could be intercropped with several legumes' species, including pea, faba bean and lupin. Since naked barley cultivars are well suited for human consumption, it would make sense to intercrop it with legume cultivars intended for the same purpose.

6 Environmental effects of intercropping

Intercropping is sometimes presented as a sustainable intensification of agriculture (Martin-Guay et al., 2018), and the reason is that this cultivation method potentially result in higher yields and simultaneously reduce adverse environmental effects of agriculture. The effects mainly concern fertilizer use, weed control, land use, and soil fertility.

6.1 N fertilizer use

An opportunity for cereal-legume based intercropping systems is to rely on the N fixating properties of the legume to produce a higher grain yield per kg of N fertilizer compared to sole cropping. Legumes are often found to contain larger proportions of N derived from the atmosphere (%Ndfa) when intercropped, mainly because the companion crop depletes the soil on available N more efficiently, thus forcing the legume to fixate N (e.g. Corre-Hellou et al., 2011; Ghaley et al., 2005; H. Hauggaard-Nielsen et al., 2003, 2006). On an area-basis, however, a sole cropped legume fixate more N, so in order for intercropping to replace inorganic N fertilizer via this mechanism, intercropping systems needs to be implemented more widely.

Another reason why intercropping can increase grain yield per kg N fertilizer is because the environmental loss of N from the soil-system is less. In other words, the N utilization is higher and the leaching potential is less (Manevski et al., 2015; Mariotti et al., 2015; Salehi et al., 2018). This is mainly due to the complementary N acquisition strategies by the intercropped species. The complementarity and high utilization is most pronounced in low-input systems, otherwise the cereal tend to outcompete the legume and the total N-yield decrease. It should be considered, however, that a higher N utilization could imply less available N to the following crop depending on how the crop residues are managed. Therefore, it would make sense to evaluate and compare N utilization over time for various cropping systems (intercropping based vs. sole cropping-based rotations) and not just calculate the N utilization for a single season.

The replacement of inorganic N fertilizer due to increased fixation (if intercropping is implemented more widely and not only replace sole cropped legumes) and better N utilization has direct environmental benefits, because the production of N fertilizer require large amounts of energy, which often comes from fossil fuels (Fowler et al., 2013; Galloway and Cowling, 2002). The improved N utilization during the growing season reduce the risk of N leaching, especially in systems without catch crops.

Jensen et al. (2020) estimate that the improved N efficiency of intercropping systems could reduce the inorganic fertilizer requirement by 26% on a global scale.

6.2 Weed control

The environmental effects of improved weed suppression in intercropping systems (see 3.2.4) is difficult to quantify, since it depends on local conditions, weed pressure, crop rotation, soil tillage and on the reference weeding strategies in the corresponding sole cropping systems they replace. Low-input cereal-legume intercropping is often studied in the context of organic cropping systems, in which case intercropping will not replace the use of herbicides by improved weed suppression, but it could reduce the labor and energy required to do mechanical weeding. In other farming systems, intercropping could reduce the dependence on herbicides for weed control, which would benefit the environment. Similar remarks apply to pest and disease control, where intercropping could reduce the reliance on fungicides and pesticides, but only if it replaces systems where these are used.

6.3 Land use

LER values above one is often reported in intercropping studies, which implies that intercropping can produce more grain per area compared to sole cropping of the intercropped species. With improved N utilization and lower relative yield, it is often also found that an intercropped cereal is of a better quality (more protein), while an intercropped legume typically contains the same concentration of protein as a sole cropped legume (Bedoussac et al., 2015; Stomph et al., 2020).

If the same amount of food can be produced on less land, it could imply more space for other types of land use, such as nature or at least something that resembles natural systems more than an agricultural field.

6.4 Soil fertility and carbon storage

Soil fertility is an important topic, both with regard to sustainability of production systems and with regard to climate change, since soils constitute a large pool of carbon (C) and is important in the global C cycle (Schmidt et al., 2011). While soil fertility is an ancient concept with many local connotations (Brevik and Hartemink, 2010), today it is common to consider soil organic matter (SOM) or soil organic carbon (SOC) as a simplified proxy for soil fertility (Manlay et al., 2007), because SOM controls or affect a large number of soil functions.

Intercropping can produce a larger crop biomass compared to sole cropping (Carton et al., 2020; Hauggaard-Nielsen et al., 2003; Keating and Carberry, 1993), although a larger crop biomass is not always the result of intercropping (Dhima et al., 2014; Lithourgidis and Dordas, 2010). Intercropping can also affect the quality of crop residues by lowering the C:N ratio of the cereal straw while roughly maintaining the legume straw N concentration (Monti et al., 2016), and this could affect the decomposition rate of the residue (Kumar and Goh, 2000). Furthermore, the general picture of cereal-legume intercropping systems is, that intercropping leaves less available soil N after harvest especially compared to a sole cropped legume, but in some cases also compared to a sole cropped cereal (Hauggaard-Nielsen et al., 2003; Mariotti et al., 2015). The combined effect of a larger input of more labile crop residues to a soil with lower N availability on the short- or long-term soil fertility and SOC development is difficult to assess, because these effects draw in different directions with respect to soil C accumulation. Effects of management strategies may take decades to evolve into significant and certain measurements and much longer to reach a new equilibrium, because the soil system develops slowly and because the annual fluxes of C are small relative both to the C pool in the soil system and to the natural spatial variation of soil properties (Powlson et al., 2011; Schmidt et al., 2011). Few intercropping studies run for more than a couple of years on the same land and few studies focus on effects of intercropping on SOC.

Sun et al. (2021) found no development in soil C stocks in the top 40cm of soil after intercropping maize and soybean for four years. There were no significant differences between cropping of continuous maize, continuous soybean or maize-soy bean rotation and intercropping of maize and soybean either. The authors suggest that longer running experiments are needed to document potential effects of intercropping on soil C stocks.

Cong et al. (2015) conducted a seven-year trial in China, where strip intercropping of maize/wheat, maize/faba bean and wheat/faba bean was compared to sole cropping of the same crop combinations in rotations. The difference in topsoil (0-20cm) concentration of C was about 4% (+/-1%) after the seven years with higher C concentration in the intercropping systems compared to the monocultures (12.5 vs 12.1 g/kg). Both systems sequestered C compared to the start of the experiment, but the intercropping systems did so at a higher rate. They estimated an additional C sequestration of 184 +/- 86 kg C ha^{-1} y^{-1} in the intercropping systems compared to the sequential monoculture systems. Below 40cm, there was no significant difference in SOC. The difference in soil N concentration was about twice as large as the difference in soil C and extended to deeper soil layers. In the top 20cm, there was 8% higher soil N concentration after seven years of intercropping (1.47 vs. 1.36 g/kg). The differences in soil N were also found in non-legume treatments (i.e., wheat/maize). The assumed reason was a reduced N leaching in intercropping due to root complementarity about both depth, abundance, and timing of N uptake. A similar conclusion was reached by Cong et al. (2014) where non-legume mixtures lead to higher soil N compared to monocultures of non-fertilized grassland species. This is an interesting mechanism – species richness led to more soil C and more soil N, higher mineralization rates and higher N yields but still soil N was higher than in monocultures (all unfertilized). The only possible explanation is that less N was lost from the soils where mixtures grew via either leaching or to the atmosphere via denitrification. Fu et al. (2017) also reported that more diverse cropping systems resulted in higher SOC stocks in the topsoil (30cm) compared to monoculture or simple rotations. While the study covered 30 years, it did not include intercropping treatments. The effects on SOC and soil fertility of increased crop diversity is therefore not only a matter of simultaneous complementarity of multiple crops in intercropping, but also a matter of complementarity between seasons of crops with different root architectures, growth potentials and nutrient requirements.

X. F. Li et al. (2021) compared four long-term intercropping trials (10-16 years) from three sites with varying soil fertility. The treatments included various combinations of wheat, maize, soybean, chickpea, and oilseed rape. They found that the yield advantages of intercropping increased over time and attributed this finding to soil fertility improvements caused by intercropping. This relation was supported by the measurement of topsoil macro-aggregates (>2 mm) as a measure of soil structure, which influence several soil functions including water infiltration, aeration, and erosion. At most sites and soils, the abundances of macro-aggregates in intercropped soils were 10-20% higher than in monocropped soils. In the least fertile soil, intercropping also resulted in significantly more SOM (roughly 10-12%) and total soil N (TN) (roughly 9%) compared to monocropping, while SOM and TN were not affected significantly in the more fertile soils.

Overall, intercropping seems to have beneficial effects on soil fertility and perhaps on soil C storage, although the evidence in not yet clear. However, the reported studies on long-term effects of intercropping on soil C and fertility, we have found relate to strip intercropping systems, which are typically fertilized. The mechanisms proposed to explain beneficial effects of intercropping on soils should also apply to low-input mixed intercropping or row intercropping systems, but evidence of such effects is not documented.

6.5 Other effects

Intercropping systems are sometimes shown to improve above- and/or belowground biodiversity of mainly invertebrates (Brooker et al., 2015; Letourneau et al., 2015; Ratnadass et al., 2012).

7 Discussion

When intercropping is presented as a mean to achieve a "sustainable intensification" of agriculture, it mainly comes down to a more efficient use of resources (radiation, nutrient and water). As pointed out by C. Li et al. (2020), when it comes to productivity and food security, not only the relative yield effects (LER), but also the absolute yield differences are of relevance. Their point relates to the comparison of low-input low-output systems vs. high-input high-output systems, where they found that even though LER values are generally reported in the same range, the absolute yield benefit of intercropping is four times larger in the high-input high-output systems. Another important consideration in this regard is whether it is still reasonable to consider intercropping as a mean to a sustainable intensification is if low-input intercropping systems replace high-yielding sole cropping systems. The sole cropping yield reference in most studies are systems, which resemble the intercropping system to a large degree in terms of management, and this makes sense for the purpose of scientifically comparing the treatments with as few variables as possible. It is often stated that intercropping systems have the largest advantages in low-input systems (e.g. Bedoussac et al., 2015), but it is important to note that this statement not only refer to the intercropping system itself, but also to the alternative monocropping systems. This may be one of the reasons why intercropping is a more common practice in low-income countries in the tropics (e.g. Brooker et al., 2015; Henrik Hauggaard-Nielsen et al., 2008; Myaka et al., 2006; P. Sobkowicz & Śniady, 2004), where the reference by necessity is a low-input system and often on a soil with low fertility or limited water holding capacity. In modern agricultural systems in the EU most farmers can afford fertilizers and the low input agricultural systems are less common. For instance, organic agriculture constitutes only 8.5% of the agricultural area in EU (Eurostat: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Organic_farming_statistics) of which vegetable production is overrepresented (19%) and cereals underrepresented (7%) and these systems are not necessarily low-input systems compared to many intercropping reference sole cropping scenarios, where the cereal often receive no or only little N fertilizer (Yu et al., 2016). Cereals yield an average of roughly 6 t ha^{-1} across the EU (most of which consist of wheat, barley and maize; Eurostat: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agricultural_production_-_crops#Cereals), while winter cereals typically yield a bit more on average in many Western European countries (e.g. 7.6 t ha^{-1} for winter wheat in Denmark between 2011-2020; Statistics Denmark). For comparison, according to a meta-analysis by C. Li et al. (2020) low-input intercropping systems yielded on average 3.4 t ha^{-1} (324 records of non-maize containing intercropping yields, of which 44% came from Europe), while Bedoussac et al. (2015) in a review of intercropping experiments in South France and Denmark reported intercropping yields between 0.6 and 5.7 t ha^{-1} where most observations were in the range 2.5-4.5 t ha^{-1}.

The high yielding, often maize based intercropping systems, which are common in China (Li et al., 2020), mainly succeed in achieving a higher production level by cropping in strips, where the cereal (maize or wheat) can be fertilized independently of the legume (often soy bean) and by off-setting the sowing of each crop to reduce competition. While this system arguably succeeds with the intensification part of "sustainable intensification", the sustainability aspect can be debated, since it still relies on a high input of fertilizer to match the productivity of sole cropped, fertilized maize. Increasing the N fertilizer rates in mixed or row intercropping systems comes with the risk of outcompeting the legume, thereby decreasing the complementary benefits of intercropping (Hauggaard-Nielsen et al., 2001a; Monti et al., 2016; Naudin et al., 2010). Relay sowing is also more complicated in mixed or row intercropping, while differentiated harvest of each crop is not possible for most crop combinations. The bottom line is, that while sustainable intensification is a desirable goal, the choice of reference frame means that there probably is a trade-off between these two objectives in most European farming systems.

Many intercropping studies focus on crop productivity with a unified t ha^{-1} metric for the combined yield. For instance, it is necessary for the calculation of the LER metric, which is often presented as the main effect of intercropping. However, some studies also present and discuss the product quality and Martin-Guay et al. (2018) even suggest the metric RLO (Relative Land Output) to express how each intercropped species represents a different value as a product and that the quality of each crop may also be affected by intercropping. For example, cereal protein concentration typically increase when intercropped with a legume (e.g. Chapagain & Riseman, 2014; Lauk & Lauk, 2008; Naudin et al., 2010) and if the protein reach a certain threshold, the grain could be sold at a premium price for making bread or semolina rather than as animal feed (Bedoussac et al., 2015; Ghaley et al., 2005; Hauggaard-Nielsen et al., 2008; Monti et al., 2016). This point adds a different perspective to the trade-off between sustainability and productivity. If produce of a sufficient quality for direct human consumption is the result of intercropping, then bypassing the livestock in the food supply chain far outweighs a yield loss of a few t ha^{-1} by replacing a high yielding cereal for animal feed with a low-input cereal-legume intercrop for human consumption in terms of both energy- and protein utilization per area of production land (Ferreira et al., 2021; Shepon et al., 2016).

Such perspectives are lost when productivity is only evaluated in terms of dry matter production. The details of intercropping productivity thereby provide a good opportunity to evaluate and consider the European food supply system on a larger scale.

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