Swedish University of Agricultural Sciences
Faculty of Natural Resources and Agricultural Sciences
Department of Crop Production Ecology

Sofia Lloyd

Perennial wheat

Independent Project in Biology

Agronomprogrammet mark/växt
Uppsala 2015

Swedish University of Agricultural Sciences
Faculty of Natural Resources and Agricultural Sciences
Department of Crop Production Ecology

Author: Sofia Lloyd
Title: Perennial wheat

Supervisor: Göran Bergqvist, Dept. of Crop Production Ecology
Examiner: Martin Weih, Dept. of Crop Production Ecology
Ass. Examiner: Birgitta Båth, Dept. of Crop Production Ecology

Credits: 15 hec
Level: Basic
Course title: Självständigt arbete i biologi
Course code: EX0689
Programme/education: Mark/växtagronom

Place of publication: Uppsala
Year of publication: 2015
Online publication: http://stud.epsilon.slu.se

Keywords: Perennial wheat, *Triticum aestivum* hybrids, *Thrinopyrum sps.*, hybridization, plant breeding, cropping systems, erosion control, reduced inputs

Abstract

Perennial wheat is a new cereal crop being researched at several different institutions worldwide. The main purpose of developing this new crop is to reduce negative impact on the environment from crop production and to maintain production with lesser inputs. This is a bachelor thesis aiming at providing an overview of the current knowledge concerning perennial wheat research through a literature review. This review is limited to research regarding hybrids between wheat and the wild wheat relatives of *Thinopyrum sps,* and their potential as grain crops. Biologically, the hybrids show good potential but yield remains low. The hybrids currently tested are most suitable for marginal lands with high risk of soil erosion, or as a dual purpose crop where the post reproductive-cycle re-growth is utilized as forage. Efforts should be made to create a large gene pool within the new hybrid, from which further breeding may be carried out.

List of Contents

1 Introduction

The main challenge and goal of the agricultural sector has always been to adapt the environment as to provide enough food and other goods for the people. The amount of goods demanded continues to increase as the human population grows and living conditions improve. However, according to Field (2001) humans already occupy a very large portion of available resources on Earth, which raises questions of whether further appropriation of land, water and net primary production is possible without causing great problems for the biosphere balance. Since the area of arable land has remained at approximately 1.39 billion hectare the last 20 years (FAO *FAOSTAT*), area for cultivation is clearly a limiting factor for production. The growing demand therefore has to be met by an increase in yield per acreage.

Yields have increased over time due to improved agricultural techniques and the development of high yielding varieties that have improved pathogen resistance, greater tolerance of stresses and greater yield potential (Reynolds *et al.*, 2009). The main improvements of yield potential have been realized through changes in allocation (dwarf varieties and other adaptations), greater tolerance for nitrogen fertilizers (higher biomass without lodging) and improved crop canopy architecture (optimizing of LAI) resulting in increased harvest index and higher biomass from increased fertilization (Gifford *et al.*, 1984).

Today, researchers are focusing more and more on increasing the total biomass production by enhancing photosynthesis (introduction of C_4-functions into C_3 species or increasing the amount of RUBISCO in photosynthetic tissues) and increasing the time of active photosynthesis (by improved establishment, delayed senescence and increased light stress tolerance under bright conditions) (Parry *et al.*, 2011). The progress is limited and further advances seem primarily to be realized through improved flag leaf placement and increased ear contribution (Maydup *et al.*, 2012).

Improvement of agricultural techniques include the use of an increasing amount of inputs such as fuel, fertilizer and pesticides, as well as technical innovations in land management such as tillage, irrigation and drainage methods. With better utilization of resources, the availiability of those resources becomes limiting. Shortage of water for irrigation has become a major problem in many agricultural regions causing both conflict and low production levels (Merlet, Jamart and L'Orphelin, 2014).

According to Jackson (2002) the possibility to further increase the use of inputs (such as fuel, fertilizer and pesticides) is limited by source availability and negative effects on the environment. These include climate change, loss of biological diversity and water contamination. Increased tillage and irrigation can also have detrimental effects on soil fertility resulting in erosion, salinization or soil degradation with subsequent loss of arable land (Jackson, 2002).

Production of the traditional agricultural products on arable land faces several conflicts of interest. Urbanization and development of industry on fertile land, an increased demand for agricultural bio-fuels, and increasing concerns for nature conservation cause a decrease in acreage available for food production.

The same fields should no longer only produce for a greater number of people, but must be able to do so with less resources. At the same time, the negative impacts from farming on soil fertility, biodiversity and ecosystems must decrease. This will require new sustainable methods in agriculture based on recirculation of nutrients and water and with much greater concern for the environment than has earlier been the case (Rydberg, 2012).

Using perennial varieties of agricultural crops have the potential to mitigate some of these problems through soil and water conservation, decreased need for fuel and fertilizer inputs and improved plant health. In order to realize the idea of perennial crops researchers must find new species or varieties that can compete with conventional annual crops in terms of economy for the farmer and usefulness as food or feed. Many different crops are investigated for the development of perennial varieties; such as wheat, maize, rice, rye, barley, sorghum, sunflower, peanuts, rapeseed and other oilseed; of which some, namely rice, rye and wheat, show promising results and are currently tested in field trials (Zhang *et al*., 2011).

The aim of this literature review is to investigate if perennial wheat has the potential to mitigate some of the problems associated with agriculture today. Challenges concerning the possibility of developing perennial wheat are identified and suggestions to overcome these challenges are presented.

2 Materials and Methods

Current knowledge concerning the development of perennial strains of wheat is summarized through a review of published research. Relevant publications available through the SLU library are considered, as well as statistics from FAO and other supportive sources. The review is focused on the potential of wheat as a perennial crop for grain production and is limited to hybrids between wheat and the wild wheat relatives of *Thinopyrum sps.,* which are currently being investigated by researchers worldwide. The current knowledge is then discussed in relation to the aim of finding a realistic and viable perennial crop available to farmers.

3 Results

Annuality vesus perenniality

Biology

For a herbaceous plant to be perennial in a temperate climate, it must overcome several challenges. It must be able to survive the period of the year when low temperature or drought limit growth, it must retain indeterminate meristems after the initial flowering and it must be able to protect itself from pests and diseases to a greater extent than annuals.

In order to survive periods of limited growth, the plant needs storage organs and adaptations to withstand related stresses. When a plant allocates energy to storage organs, typically less photoassimilate can be used for reproductive purposes (Gifford *et al*., 1984). Annual plants that can focus solemnly on seed production have therefore dominated agriculture (DeWet, 1981).

Thomas, Thomas and Ougham (2000) explain how indeterminate meristems enable the plant to continue to grow after harvest and to produce new shoots and flowers the following season. The longevity of plants is strongly tied to the continuous growth of plant tissues; old, dead tissue either decomposes, creating a creeping behavior of the plant, or is transformed into supporting tissues (for example as the wood of trees). This process is regulated both by genetic and environmental factors and is very important for proper development of plant morphology. The individual will survive as long as the continuous growth exceeds the die-back of old tissues.

Wild, perennial grasses have in many cases evolved protective measures against pest and disease either as physical structures or by secondary metabolites. The thick permanent stand of perennial grasses provides an environment that is less favourable for many pathogens due to increased competition and greater numbers of earthworms. Most of the damaging pathogens common in agriculture does seldom infect perennial relatives (Cox, Garrett and Bockus, 2005).

Many plant families contain a mixture of annual and perennial, closely related species. Examples from the grasses are *Lolium* sps. and *Festuca* sps. which have broad ranges of persistence and have proven to hybridize between annuals and perennials. Thomas, Thomas and Ougham (2000) argue that the many cases of hybridization among grasses and the high variability of longevity between even very closely related species mean that it should not be very difficult to develop new varieties with the desired phenology.

Perennial grasses invest a big portion of assimilated carbon into an extensive root system and the resources required for this could have been used to produce harvestable seeds if the plant did not have to survive winter. However, the carbon is not spent and lost. Some of it can be reallocated into new growth in the following seasons providing a resource that decreases the cost of producing photosynthetic tissues subsequent years (DeHaan, Van Tassel and Cox, 2004).

The extensive root system of perennials penetrates a greater soil volume and have therefore an increased access to water and nutrients. As a result, the plant is less likely to suffer limitations of growth due to water and nutrient availability close to the soil suface. Compared to annuals, perennial grasses also continue to grow past harvest time and start sprouting earlier in spring, which increase the total biomass production (DeHaan, Van Tassel and Cox, 2004). A larger biomass contributes to a higher yield potential since yield in cereals is highly dependent on total photosynthetic biomass of the plant (Parry *et al*., 2011).

Agriculture

According to Bell *et al*. (2008) two different approaches to cultivating perennial wheat has been suggested; either as a one-purpose grain crop for milling or feed, or as a dual-purpose grain-and-forage crop. Dual-purpose wheat can be used as a forage reserve during dry years with forage shortage, thus stabilize the farming system on mixed production farms. It is not ideal as a permanent feed source since grain yield is greatly reduced by heavy grazing and better forage grasses are available for cultivation as a single purpose forage crop (Bell *et al.*, 2008).

Since functional varieties of perennial wheat are not yet developed, not much is known about suitable agricultural practices. It is reasonable to believe that establishment of the crop would not differ remarkably from the establishment of annual crops although the importance of good establishment and early weed control increases in a perennial system. Input costs of establishment are expected to decrease due to investment costs of fuel and seed being divided over several years. To generate a surplus for the farmer the crop therefore does not need to provide quite as high yields as long as there is a similar demand for the product (Bell *et al.*, 2008).

Modeling of single purpose grain crop and dual purpose grain-and-forage crop for Australian conditions show that dual-purpose wheat is beneficial for the farmer under certain conditions. One-purpose wheat would however need to provide almost as high yields as annual wheat to be feasible with today's prices – which at least initially is unlikely (Bell *et al.*, 2008).

Perennial pastures and native grasslands have been shown to have very high nutrient use efficiency and to successfully recirculate nitrogen within the biomass, thereby reducing leaching and the need for fertilizer (Crews, 2004). If this proves to be the case also for perennial wheat it further reduces the costs of cultivation and might also limit environmental problems associated with nitrogen fertilization and leaching. It has been suggested that perennial wheat should be cultivated in polyculture stands together with *Fabaceae*-species to decrease the need for nitrogen fertilization further by utilizing the N-fixation properties of the companion species (Crews, 2004). However, a lot of work concerning the development of such a cropping system remains before it can be introduced to the general farming community.

One of the main problems that perennial cereals aim to counteract is erosion associated with tillage and exposed topsoil, and loss of soil fertility associated with poor soil structure, nutrient run-off and decreased carbon content in the soil (Jackson, 2002). By reducing the time the soil is without cover and limit the amount of tillage needed, problems with erosion is expected to decrease.

The positive effects of a perennial crop on soil fertility also leads to improved health of the crop. Perennial relatives are often the source of resistance genes in annual crops (Cox, Garrett and Bockus, 2005). However, a perennial crop is generally more exposed to disease compared to an annual crop due to the long time frame for potential infection and the presence of host material during the whole year. The pathogen pressure in a field is greatly reduced by tillage, but when cultivating a perennial this is only possible certain years and other measures might become necessary to protect the crop from disease if the plant's biological resistance is not sufficient to keep the crop healthy.

The pathogen species are in turn affected by stand structure, host ecology and subsequent differences in micro-flora. Several of the important pathogens of today such as *Rhizoctonia solani* and *Gaeumannomyces graminis* var. *tritici* become suppressed by the competition in an undisturbed soil with a large micro-flora diversity and a greater number of earthworms (Cox, Garrett and Bockus, 2005). The initial crosses of wheat and wild wheat relatives already tested in fields have showed resistance to many common diseases such as *Puccinia tritica, Puccinia graminis, Cephalosporium gramineum, Tapesia yallundae* and wheat streak mosaic, among others (Cox *et al*., 2002). It is likely that we will face changes in disease pressure with these new crops; some diseases might become less problematic but pathogens that depend on live tissue for winter survival might become more abundant (Cox, Garrett and Bockus, 2005).

In order to counteract the pathogen friendly conditions in perennial stands, Cox, Garrett and Bockus (2005) suggests investigating the potential of using fire and grazing as disease management strategies. Both methods remove plant material, making the environment less favorable for many pathogens.

Breeding work

Methods and plant material

There are two main strategies for finding useful breeds; through crossbreeding existing annual grains with related perennial species ("wide hybridization"), and through domestication of wild perennial species (Cox *et al*., 2010). The first method has the advantage of providing a shortcut for the domestication process. Any wild species domesticated today will lack, by comparison, several thousand years of selection for agricultural traits such as fast germination, shortened dormancy, sizable seeds and favorable nutrition and baking characteristics.

The main drawback of wide hybridization is the difficulty to create and identify fertile offspring since the differences in chromosome configuration between the species involved result in many offspring that are unable to reproduce. Advances in hybridization and selection techniques have made it possible to create fertile lines from initially infertile hybrids with poor chromosome pairing but the process is painstakingly inefficient (Cox *et al.*, 2006).

Modern wheat *Triticum aestivum* is a hexaploid derived from the primitive *T. monococcum* and has several wild relatives with which crosses have been tested. For an outline of the genetic and evolutionary relationships see figure 1. Among others *Thinopyrum* sps. provide hybrids that are at least partially fertile (Cox *et al.*, 2010). The two species *Th. elongatum* and *Th. ponticum* was earlier considered as one species under the name *Agropyron elongatum*, which makes notations for pedigrees of particular crosses by *A. elongatum* unreliable (Cai, Jones and Murray, 2001).

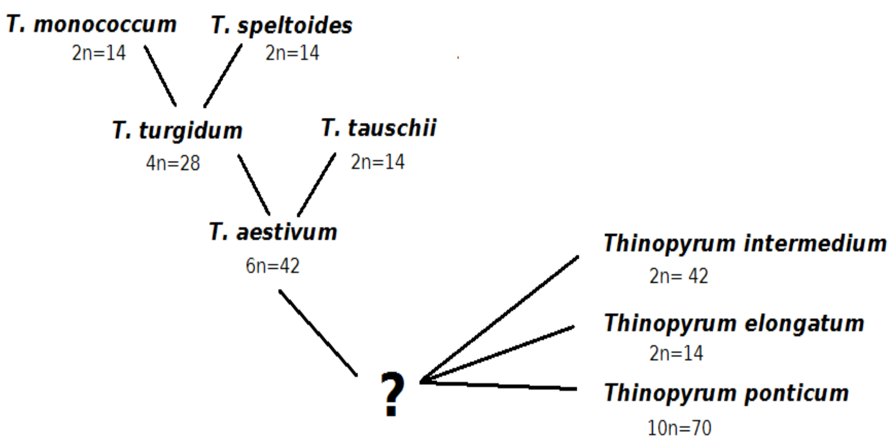

Figure 1: The relationships between wheat species

Perenniality is a complex characteristic that is regulated and facilitated by a great many interacting genes in the plant. Several hybridization trials have shown that the level of perenniality in wheat crosses is dosage dependent on genome transferred by the perennial parent, indicating that perenniality is a quantitative trait (Thomas, Thomas and Ougham, 2000). Genes affecting perenniality are also located on several chromosomes which further complicate breeding work (DeHaan, Van Tassel and Cox, 2004). As such, it is with today's knowledge not possible to directly transfer appropriate genes to the hybrid and traditional breeding methods must be deployed, although genome mapping and chromosome analysis provide helpful tools in the process (Cox *et al.*, 2006).

Different crosses retain different chromosomes from their different parents. This means that when working with hybrid offspring, very few are mutually compatible for further breeding (Cox *et al*., 2002). A successful hybrid must both have the high fertility and the agricultural traits from wheat, combined with the life history trait of its wild parent. Selection for many traits simultaneously makes breeding progress slow even when viable plant material is available for selection (Cox *et al.*, 2006).

Breeding results

Post-sexual cycle regrowth, ie. the presence of live and active undifferentiated meristems after grain harvest, has been induced in spring wheat by introducing one chromosome from *Th. elongatum* (Lammer *et al*., 2004). The resulting strain has been used to analyze the regulation of traits associated with perenniality. Annual wheat senescence completely upon ripening but the introduced chromosome transfers a trait of maintaining live meristems able to produce new tillers (Lammer *et al*., 2004).

Post-sexual cycle regrowth is important for perenniality but is not sufficient since the plants proved sensitive to winter conditions. In order to create perennial wheat that also survive cold or drought, many other crosses and backcrosses have been attempted.

Cai, Jones and Murray (2001) found that three of their tested strains regrew after harvest and produced seed the following year. One of them “AgCs” was a cross between hexaploid spring wheat and diploid *Thinopyrum elongatum* and carried 21 pairs of chromosomes from wheat and 7 pairs from *Thinopyrum*. It was not sufficiently winter hardy and many plants did not survive winter. The individuals that did survive regrew and set seed the following summer. The other two both had unknown pedigrees (within *ThinopyrumXTriticum*) and both carried 18 pairs of chromosomes from wheat, 7 pairs from *Thinopyrum* and 3 translocated pairs from the cross. Both did better in field conditions and these two hybrids proved more stable from generation to generation than AgCs. The genome analysis indicated that while AgCs inherits its perennial characteristics from *Th. elongatum*, the other two most likely inherit their perenniality from *Th. ponticum.*

In another test by Murphy *et al.* (2009:1) 31 breeding lines from backcrosses between wheat and spring wheat/*Th. elongatum*-hybrids at F_5-F_6 were evaluated in field conditions during the years of 2005-2007. The rate of post-sexual cycle regrowth varied greatly and was not dependent on location. However, none of the strains survived the winter, despite doing so during earlier phases of breeding. The authors indicate that the particular year had provided unusually harsh winter conditions. Yield of the perennial strains were measured as 20-93 % of the annual controls for the first harvest, with a mean of 44 %. No negative relationship could be found between perenniality and grain yield, which suggests that simultaneous selection for both traits is possible.

Jaikumar *et al.* (2012) tested four selected breeding lines of wheat and spring wheat/*Th. elongatum*-hybrids against two standard varieties in 2008-2010. The perennial strains did provide a second harvest but the experiment was not continued any further due to poor regrowth in the fall of 2010. The average 1st year yield where 48 % compared to annuals, with lower kernel size, fewer tillers and lower harvest index. They did however find that 2nd year perennials yielded at similar levels as their first year. They also grew markedly taller than annuals and 1st year perennials, resulting in a similar or greater biomass.

Hayes *et al.* (2012) have conducted a large scale test of almost 200 different lines of perennial wheat, obtained from a variety of sources, during the years 2008-2011. This study found that the scientific community has developed a broad range of hybrids with varying pedigrees and very different characteristics. They did not find any relationship between 1st season harvest and post-sexual cycle regrowth but they did find weak negative relationships between 1st season harvest index and post-sexual cycle regrowth. In general, resistance to diseases was good, grains were very small and the quality of grain was acceptable, although variation was large between lines in all characteristics. Particular lines were able to combine longevity and high grain yield and three of the hybrids managed to survive and produce seed every year of the four year experiment.

From the genome analysis Hayes *et al.* (2012) managed to find an association between longevity and the presence of at least one whole genome equivalent (14 chromosomes) from the perennial parent, resulting in 56 chromosomes when the wheat parent is hexaploid (see figure 2). However, many lines with 56 chromosomes still failed to survive. The exact composition of the interesting varieties is yet to be determined and the high variability suggests that interaction between the genomes influence longevity. The great range of each characteristic can also facilitate selected breeding for desirable traits, and the authors state that such an attempt is likely to be successful.

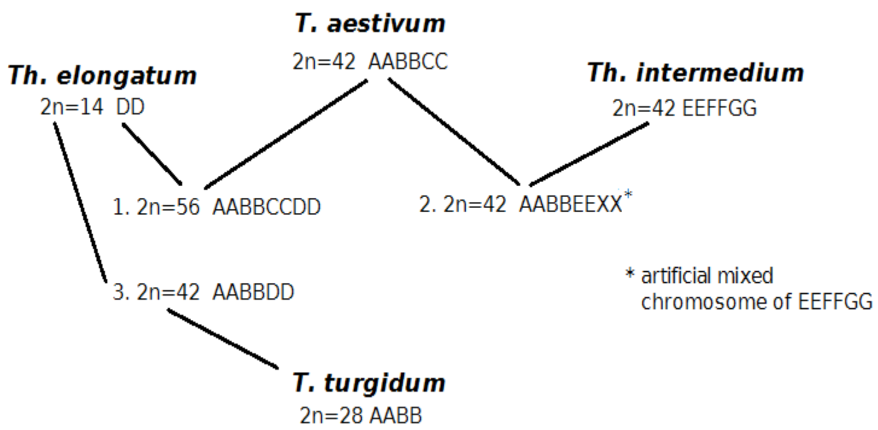

Figure 2: The genome of three existing crosses that exhibit perenniality

Almost all of the strains that have been evaluated so far have low yield levels (Cai, Jones and Murray, 2001, Murphy *et al.*, 2009:1, Jaikumar *et al.*, 2012, Hayes *et al.*, 2012). To better understand the yield potential of perennial wheat Jaikumar *et al.* (2014) have tested whether perennial wheat yield is source or sink-limited, and concluded that perennial wheat today provide yields much lower than they potentially could considering their large photosynthetic biomass. According to Hayes *et al*. (2012), there is a great variation between different hybrids of many yield factors, which provides ample genetic material for selection.

Some tests have also been done to evaluate the disease resistance of the hybrids created so far. Cox *et al*., (2005) tested two varieties of wheat X wheatgrass and found that resistance against tan spot *Pyrenophora tritici-repentis* was equivalent to that of annual wheat cultivars considered resistant and resistance to barley yellow dwarf virus was good in one of the strains. However, both strands were susceptible to take all *Gaeumannomyces graminis* var. *tritici* and wheat streak mosaic virus.

In another test, Cox, Murray and Jones (2002) found that six of the 24 different lines of wheat hybrids tested (of varying pedigrees) were resistant to all three tested diseases; eyespot *Tapesia yallundae*, cephalosporium stripe *Cephalosporium gramineum* and wheat streak mosaic virus.

Murphy *et al*., (2009:2) have investigated the nutritional value of 31 strains of perennial wheat. They found that the content of Ca, Mg, P, Cu, Fe, Mn and Zn were higher in perennial wheat than in the annual controls and that the relative uptake of minerals differed from the patterns seen in annual wheat. For the perennial no relationship could be found for grain yield versus mineral content whereas for annual wheat there was a negative relationship. The baking tests showed that perennial wheat have lower flour yield and lower loaf volume but shorter mixing time and greater protein content creating a product that has higher nutritional value but is less desirable from a bread baking perspective. The authors identify potential for other uses such as pastries and noodles, and suggest that problems with threshability and seed shattering is possible to overcome by selective breeding due to the high variability within range of tested strains and that the alleles involved are already known.

4 Discussion

Perennial wheat as a solution

Despite the fact that perennial wheat is not yet a cultivated crop, some conclusions have been possible to make anyway. Several independent trials (mentioned above) have showed that it is biologically possible to create a perennial hybrid of wheat and wheatgrass. Such a crop would provide better utilization of available water and nutrients, and have a greater stress tolerance compared to annual varieties. From the tested strains it seems possible to develop perennial wheat cultivars with high pathogen resistance, minimizing the need for fungicides and chemical seed treatments. Considering that several harvests are possible for each establishment it would require less fuel per unit of food produced, as well as reducing the risk of erosion.

The effects of perennial wheat on soil fertility, biodiversity and ecosystems are harder to evaluate. Experiences from other perennial grass crops such as forage indicate that the continuous plant coverage and large root biomass in a soil undisturbed by tillage is beneficial for both soil fertility and biodiversity, and it is reasonable to assume similar properties of a perennial wheat crop. What is clear is that soils prone to erosion are best protected when covered by live plant matter. By reducing land degradation through prevention of soil loss, the agro-ecosystem is sustained.

When comparing the yield levels measured in the initial trials conducted so far with that of standard wheat varieties, the breeding work is disappointing. However, it is important to remember that perennial wheat hasn't been selected for grain yield yet and that there is a great variation in yield levels within the total population. The low harvest index of the first tested crosses should be possible to improve just as traditional breeding has improved the yields of conventional wheat, at least to some degree.

But even with a lower harvest index, the longer effective growing season and resulting larger biomass provides a good potential for harvests in the range of the highly selected modern cultivars. Yield potential of perennial wheat can exceed annual wheat if the increase in above ground biomass exceeds the costs associated with surviving between growth periods. Perennial wheat cultivars with conventional yield levels are however far from realization as of today.

The varieties investigated so far have proven to have good nutritional value even though some technical and agronomical traits (such as baking characteristics and milling properties) are sub-par. But from a world nutrition point of view, it seems unlikely that perennial wheat will be able to "feed the world" since it is far from exceeding annual wheat when it comes to yield levels and land area is a limited resource in itself.

Perhaps the greatest benefit of cultivating perennial wheat comes from preventing negative impacts rather than competing in yield levels. For areas where conventional agriculture is problematic due to erosion, drought, salinization or other environmental problems it could provide a valuable and more sustainable alternative than annual crops.

With lower input costs the perennial wheat might be a viable alternative for the farmer despite lower yields, dependent on the market balance of supply and demand. It can, as a dual-purpose crop, contribute to stability of fodder supply at local level, decreasing the pressure on grazing areas and mitigating major draught events. Perennial wheat might also provide positive external effects which from a socioeconomic perspective can motivate subsidies, improving the option for the farmer further.

Challenges for perennial wheat

The main challenge for introducing a commercial perennial variety continues to be suitable plant material. Even through the breeding work carried out so far indicate great possibilities for the future, there is a lot of work still to do. Success in breeding a suitable variety is limited by the slow process of traditional breeding with very little progress per year. It might also be that the hybrids created so far is not sufficient for providing the genetic material needed.

Perennial wheat seems most suitable for fields with poor growth conditions, where it might become a better crop than annual cereals due to low input costs, good soil protection characteristics and high drought tolerance. It is still too early to carry out any methodical trials for developing proper agricultural practices though.

Two different approaches are feasible; either developing cultivars with large vegetative re-growth aimed as a dual purpose crop or developing cultivars with dormancy after the grain harvest. The dormancy-alternative is the one that has been investigated most extensively so far. Without dormancy it is unlikely for the crop to survive harsh winter conditions, but perhaps it is not necessary for cultivation in areas where the off season is due to low precipitation rather than low temperatures.

Winter hardiness is the one characteristic that seems the most problematic at this stage. Plenty of crosses show post reproductive cycle re-growth but few survive into the next season, particular with harsher winter conditions. Developing proper winter hardiness is key to providing a welcome crop choice for farmers looking for a cereal that can thrive under less than perfect conditions whereas pathogen resistance and management techniques seems less problematic due to the positive results from already tested strains.

The low yield levels of existing breeding lines is also a challenge of course, but as mentioned under '*Breeding results*' the existing crosses show good potential for reasonable yield levels. Other characteristics are more pressing, i.e. the quality of the crop. As it seems today, perennial wheat will not be able to replace annual wheat as the high quality commodity used for baking bread due to the different protein composition. Instead, it can be used for unleaved products such as noodles, crackers and so forth.

Many agricultural traits that are part of the domestication of wild plants must be addressed with this new crop. It includes shedding tendency, tiller structure, presence of chaff et cetera. This will, of course, take considerable effort and time. It will also be a challenge to introduce a new product to consumers. The industry must be willing to develop new distribution channels and we must overcome the cultural barriers in the traditions of what to eat.

The same cultural barriers might be an obstacle also on farm level, with farmers hesitant to try new crops and preferring to keep to traditional farming methods, or even within academia where research efforts might not be dedicated to perennial grain due to priorities elsewhere. At the same time, it is important that public institutions dedicate funds for this type of research since private investment is unlikely in a crop that doesn't need to be re-sown as conventional and doesn't need large amounts of market inputs.

Suggestions for further research

In my opinion, the research efforts for developing perennial wheat should initially focus on creating a broad genetic base of interbreedable hybrids. The genome analyses have indicated that the hybridization of regular wheat and *Thinopyrium sps.* is difficult in terms of genome compatibility between strains, and therefore it is important to have a good foundation with high genetic diversity within compatible strains as raw material for further selective breeding.

With high genetic diversity within the crop population, it is less likely that a future dead end will occur. This will require long term investments and it is likely that the first commercially available seed might take longer to introduce with this approach compared to a dedicated focus on finding a single suitable cross but if the new crop is to have a long term chance of providing new varieties and continually improved field performance, this foundation is necessary.

A broad variance within the crop is also a way of mitigating some of the problems associated with the conventional breeding work of cereals, like boom and bust-cycles for new cultivars with regards to pathogen resistance. For the long term success of perennial wheat as a sustainable and viable grain crop it is essential with a wide range of traits within the available gene pool for future breeding work regarding pathogen resistance, yield improvements and technical characteristics.

Since perennial wheat is intended to have high persistence in the field, it might benefit from cultivation in heterogenic fields due to the limiting effect this has on the spreading of pathogens within the stand, and this will also require that a broad range of cultivars are available for the farmer.

Secondly, initial selection should focus on the purely biological aspects of the plant, such as winter hardiness, drought tolerance and plant health. Selection for agricultural traits such as quality parameters and yield should only come later when the hybrid is stable and vital. Selective breeding for cultivar properties will be possible as long as the desired traits exist within the gene pool, but it will be more difficult and time consuming to introduce new genetic material to the hybrid once the F1-F6 stage has passed.

5 Reference list

Bell, L. B., *et al.* (2008). A preliminary whole-farm analysis of perennial wheat in an Australian dryland farming system. *Agricultural Systems*, Vol. 96, pp. 166-174

Cai, X., Jones, S.S., Murray, T.D. (2001). Molecular cytogenetic characterization of Thinopyrum genomes conferring perennial growth habit in wheat – Thinopyrum amphiploids. *Plant Breeding,* Vol. 120, pp. 21-26

Cox, C.M., Murray, T.D., Jones, S.S. (2002). Perennial Wheat Germ Plasm Lines Resistant to Eyespot, Cephalosprium Stripe, an d Wheat Streak Mosaic. *Plant Disease,* Vol. 86, pp. 1043-1048

Cox, C.M., Garrett, K.A., Bockus, W.W. (2005). Meeting the challenge of disease management in perennial grain cropping sytems. *Renewable Agriculture and Food Systems,* Vol. 20, Issue: 1, pp. 15-24

Cox, C.M., *et al.* (2005). Reactions of Perennial Grain Accessions to Four Major Cereal Pathogens of the Great Plains. *Plant Disease,* Vol. 89, pp. 1235-1240

Cox, T.S., *et al.* (2002). Breeding Perennial Grain Crops. *Critical Reviews in Plant Sciences,* Vol. 21, Issue: 2, pp. 59-91

Cox, T.S. *et al.* (2006). Prospects for Developing Perennial Grain Crops. *Bioscience,* Vol. 56, Issue: 6, pp. 649-659

Cox, T.S., *et al.* (2010). Progress in breeding perennial grains. *Crop and Pasture Science,* Vol. 61, Issue: 7, pp. 513-521

Crews, T.E. (2004). Perennial crops and endogenous nutrient supplies. *Renewable Agriculture and Food Systems,* Vol. 20, Issue: 1, pp. 25-37

DeHaan, L.R., Van Tassel, D.L., Cox, T.S. (2004). Perennial grain crops: A synthesis of ecology and plant breeding. *Renewable Agriculture and Food Systems* Vol. 20, Issue: 1, pp. 5-14

DeWet, J.M.J. (1981). Grasses and the Culture History of Man. *Annals of the Missouri Botanical Garden,* Vol. 68, Issue: 1, pp. 87-104

FAO (Food and Agriculture organization of the United Nations) *FAOSTAT database.* faostat3.fao.org/go/to/compare/Q/QC/E [2014-05-29]

Field, C. (2001). Sharing the Garden. *Science*, Vol. 294, pp 2490-2491

Merlet, M., Jamart, C. and L'Orphelin, S. (2014). *Land and Water Rights Hotspot.* Food and Agriculture Organisation of the United Nations

Gifford, M., *et al.* (1984). Crop productivity and photoassimilate partitioning. *Science,* Vol. 225, Issue: 4664, pp 801-808

Hayes, R.C., *et al.* (2012). Perennial cereal crops: An initial evaluation of wheat derivatives. *Field Crops Research,* Vol. 133, pp. 68-89

Jackson, W. (2002). Natural systems agriculture: a truly radical alternative. *Agriculture, Ecosystems & Environment ,* Vol. 88, pp. 11-117

Jaikumar, N.S., *et al.* (2012). Agronomic Assessment of Perennial Wheat and Perennial Rye as Cereal Crops. *Agronomy Journal,* Vol. 104, Issue: 6, pp. 1716-1726

Jaikumar, N.S., *et al.* (2014). Photosynthetic Responses in Annual Rye, Perennial Wheat, and Perennial Rye Subjected to Modest Source:Sink Ration Changes. *Crop Science,* Vol. 54, pp. 274-283

Lammer, D., *et al.* (2004). A single chromosome addition from Thinopyrum elongatum confers a polycarpic, perennial habit to annnual wheat. *Journal of Experimental Botany*, Vol. 55, Issue: 403, pp. 1715-1720

Maydup, M.L., *et al.* (2012). The contribution of green parts of the ear to grain filling in old and modern cultivars of bread wheat (Triticum aestivum L.): Evidence for genetic gains over the past century. *Field Crops Research,* Vol. 134, pp. 208-215

Murphy, K.M., *et al.* (2009:1). Post-sexual cycle regrowth and grain yield in Thinopyrum elongatum × Triticum aestivum amphiploids. *Plant Breeding,* Vol. 129, pp. 480-483

Murphy, K.M., *et al.* (2009:2). Nutritional and quality characteristics expressed in 31 perennial wheat breeding lines. *Renewable Agriculture and Food Systems,* Vol. 24, Issue: 4, pp. 285-292

Parry, M., *et al.* (2011). Raising yield potential of wheat. II. Increasing photosynthetic capacity and efficiency. *Journal of Experimental Botany,* Vol. 62, Issue: 2, pp. 453-467

Reynolds, M., *et al.* (2009). Raising yield potential in wheat. *Journal of Experimental Botany,* Vol. 60, Issue: 7, pp. 1899-1918

Rydberg, T. (2012). Land is a Prerequisite for Food Production. In: Jacobsson, C. (Ed.) *Sustainable agriculture*, Uppsala: Elanders, pp. 16-18

Thomas, H., Thomas, H.M., Ougham, H. (2000). Annuality, perenniality and cell death. *Journal of Experimental Botany,* Vol. 51, Issue: 352, pp. 1781-1788

Zhang, Y., *et al.* (2011). *Potential of Perennial Crop on Environmental Sustainability of Agriculture,* Proceedings from the 3rd International Conference on Environmental Science and Information Technology, Harbin Normal University, Harbin, China