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Analyses of Yield Gaps for the production of wheat and barley in Norway

Potential to increase yields on existing farmland

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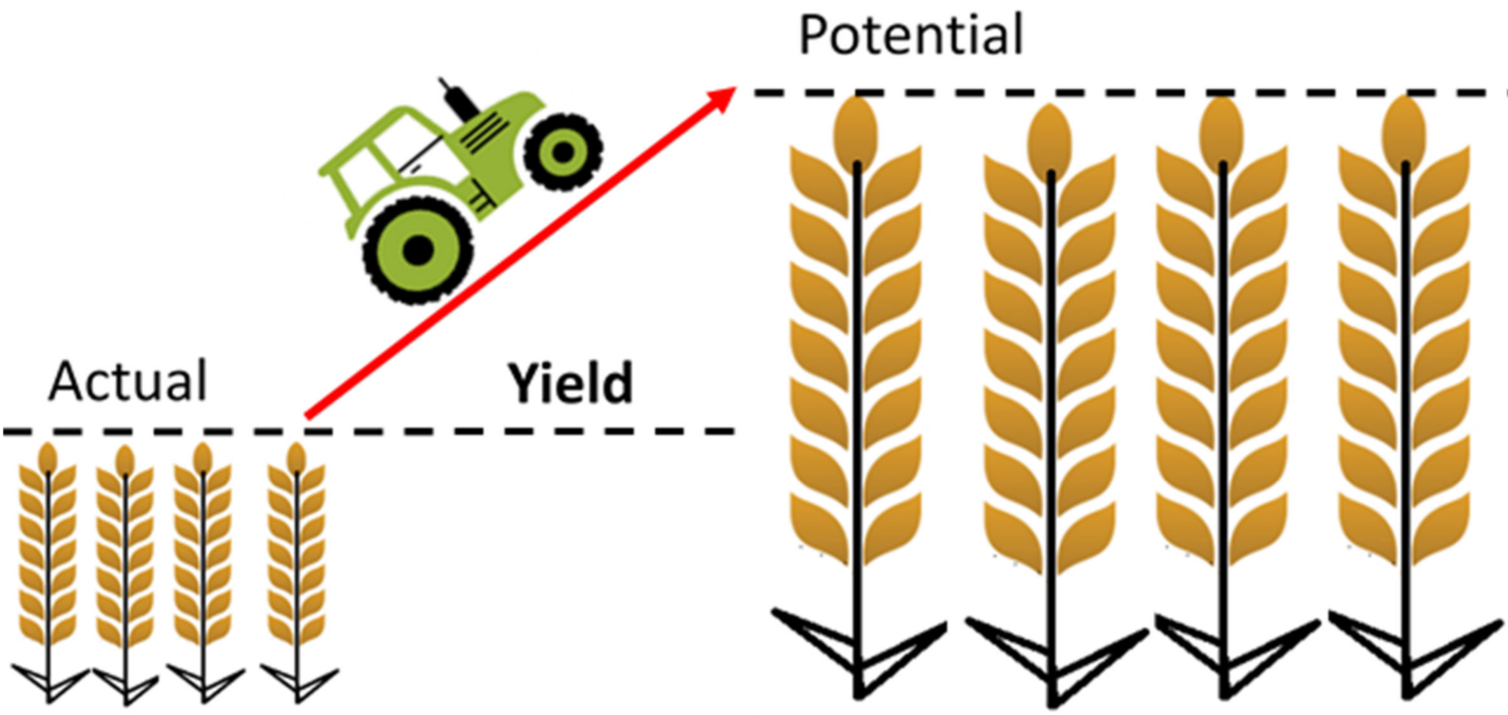

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TITTEL/TITLE

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Summary

An increase in cereal production in Norway is important for national food security and fulfilling the aim of increased food production. Since the early 1990's, both reduced cereal area and stagnating yields have been reported. A sustainable yield increase on existing arable land is an important strategy to increase cereal production globally, but also in Norway.

Yield gap (Yg) describes the difference between theoretical yield potential and yields harvested on farm. Yg analyses have gained international interest recently, as a methodology to determine the potential to increase cereal production. This has resulted in the development of the «Global Yield Gap Atlas» (GYGA) in which results from the different countries are published continuously. The analyses are based on standardized protocols to calculate both yield potential and yield gap and have been led by Wageningen University (WUR). Scientists, the grain industry and society require better knowledge about (a) the theoretical yield potential that can be expected in different region based on natural resources and (b) the efficiency of production in different regions. The methods used are based on the GYGA- methodology.

The yield gap analysis of Norwegian cereal production was done in close cooperation with WUR. This is the first-time simulation of the theoretical yield potential for cereals in Norway has been done. The results compare the calculated yield potential to actual yields achieved in different crops and regions. The use of standardized protocols and defined time series enables a comparison between different counties and regions.

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The simulations show that the Yg in Norway is larger than both the European average and most other Nordic countries. This analysis also allows for a discussion of bottlenecks in cereal production which should be addressed to increase yields in the future. Higher yields in Norway will help to reduce import and increase self-sufficiency for a future which will most likely be characterized by large challenges for the global food production in general. Increased yields are also an important factor for improving the economic situation for cereal producers. Further, this will be the basis for increased investments in technology and soil improvement measures, which again can improve yields. A sustainable closure of the yield gap will contribute to better utilization of input factors and thereby reduce the carbon footprint of Norwegian cereal production.

Sammendrag

En økning av kornproduksjonen i Norge er viktig for matsikkerheten og for å møte de nasjonale landbrukspolitiske mål om økt matproduksjon. Men siden 1990-tallet er det rapportert både synkende kornareal og stagnerende avlinger. En bærekraftig økning av produksjon på eksisterende areal er en viktig strategi for å øke kornproduksjonen globalt, og også for lokal produksjon i Norge. Avlingsgapet, avledet fra det engelske «Yield Gap», uttrykker forskjellen mellom teoretisk oppnåelige avlinger og de som tas i praktisk dyrking. Analyser av avlingsgapet har hatt betydelig oppmerksomhet i den internasjonale forskningen i senere tid, med mål om å identifisere uutnyttet potensiale for økt kornproduksjon. Dette har resultert i etableringen av det «Global Yield gap atlas» (GYGA) der resultater fra ulike land og/eller regioner blir fortløpende publisert. Analysene er basert på standardiserte protokoller for å beregne teoretisk oppnåelige avlinger og for analyser av avlingsgapet. Universitet i Wageningen (WUR) har hatt en ledende rolle i dette arbeidet. Både forskere, kornbransjen og samfunnet trenger mer kunnskap om (a) hvor store avlinger vi potensielt kan ta i ulike regioner ut fra naturgitte vilkår og (b) effektiviteten av ulike agronomiske tiltak og samspill mellom disse. Metodikken som er bygget opp i GYGA-nettverket kan brukes for å få økt kunnskap om dette.

Gjennom samarbeid med WUR er det gjort analyser av avlingsgapet i norsk kornproduksjon. Det er første gang at teoretisk avlingspotensial har blitt simulert for kornarter i Norge. Et av målene har vært å bruke resultatene for å identifisere avlingsbegrensende faktorer og uutnyttet avlingspotensial i Norge. Slike analyser kan gi nødvendig kunnskapsgrunnlag for mer presise vurderinger av de viktigste flaskehalsene i produksjonen og for å treffe effektive avlingsforbedrende tiltak. Men siden det brukes standardiserte protokoller og definerte tidsperioder kan det også gjøres sammenligninger med andre land og regioner. Analysene viser at avlingsgapet i Norge er større enn både europeisk gjennomsnitt og gapet i de fleste ande Nordiske land.

Resultatene fra denne studien gir et godt utgangspunkt for videre arbeid med å øke avlingene i norsk kornproduksjon. Det er påvist et stort ‘avlingsgap’, men det indikerer også potensial for forbedringer. Norge er et av de få landene i verden som trolig kan profitere av klimaendringene og har et potensial til å øke produksjonen. Høyere avlinger i Norge kan dermed hjelpe til å minske import og øke selvforsyningsgraden i Norge for en framtid som trolig vil gi større utfordringer for global matproduksjon og mer varierende avlinger og priser.

Økte avlinger vil også være en ‘vinn- vinn situasjon’ og en viktig forutsetning for å oppnå en forbedret økonomisk utvikling for kornprodusentene. Dette gir grunnlag for økte investeringer i både jordforbedrende tiltak og teknologisk utstyr som kan øke avlingene ytterligere. En bærekraftig reduksjon av avlingsgapet kan også bidra til en forbedret utnytelse av innsatsfaktorene og hjelpe til å minske landbrukets karbonfotavtrykk.

De gode kornavlingene de siste årene bekrefter at også små endringer kan gi mye utslag om forholdene er riktige. Dette er positivt og burde være en motivasjon til å fortsette denne innsatsen.

LAND/COUNTRY:	Norway
FYLKE/COUNTY:	Whole country

GODKJENT /APPROVED	PROSJEKTLEDER /PROJECT LEADER
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Preface

In the course of the need for a sustainable increase in food production the estimation of the yield gap- as the difference between theoretical yield potential and practical yields on a farm level- and the possibility to increase yields on excisting farm land is gaining interest. The study presented here has its origin in the AGROPRO "Agronomy for increased food production. Challenges and solutions" funded by the Norwegian Research Council (Project number 22530) which ended in 2017. This work has been a cooperation of different scientists over the last 3 years.

Apelsvoll 14.01.2020

T. Seehusen

Content

1 Introduction

Increasing cereal grain production is important to meet global food security challenges, but stagnating grain yields during recent periods are reported from many countries. An important strategy is to increase the crop yield on existing farmland, often referred to as sustainable intensification. The Global Yield Gap and Water Productivity Atlas (GYGA) aims to produce robust estimates of untapped production potential from crop simulation models based on current climate and available soil and water resources. These simulations are based on standard and transparent protocols to be used for specific crops over regions or countries in order to identify the main yield constraints and areas with unexploited yield potential.

Increasing grain production in Norway is important to meet the national goals for food production, but since 1990 the average cereal production has been significantly decreased as a result of both decreasing areas and stagnating grain yields. More knowledge is needed about the yield potential of the Norwegian cereal areas, in order to identify more precisely main yield constraints, to prioritize research, and to increase the efficiency of agronomic measures. This was partly background for the interdisciplinary project AGROPRO "Agronomy for increased food production. Challenges and solutions" funded by the Norwegian Research Council (project number 22530 in the Bionær Programme 2013- 2017). Agropro initiated a study of yield gap reported in Uhlen et al. (2017). At the same time TempAg: "Collaborative Research Network on Sustainable Temperate Agriculture" was established. The Norwegian Ministry of Agriculture and Food supported Norwegian collaboration in the network by funding to NIBIO ("Kunnskapsmidler"). One of the pilot activities in TempAg was international cooperation on Yield gap analyses. Researchers participating in AGROPRO joined with the network in TempAg for knowledge about GYGA methodology for studying yield gap.

The aim of the present study was to use the GYGA methodology to analyze yield potential and yield gap in wheat and barley for the main cereal producing areas in Norway. A secondary aim was to contribute with data from Norway to the Global Yield Gap Atlas (www.yieldgap.org). This report gives an overview over the work that has been done recently to determine yield gap in Norway and puts this into relation to the overall cereal production in Norway.

2 Background and key data on cereal production in Norway

2.1 The cereal production in Norway since 1950

The cereal area in Norway increased from 150 000 ha in 1950 to about 350 000 ha in 1990. This large increase in cereal area was a result of the Norwegian Agricultural policy after the second world war to increase domestic food production. The main strategy was to utilize the agricultural areas well suited for cereals in the southeast for cereal production, whereas the more hilly areas further north and west, as well as at higher altitudes, were to be used for grassland/animal production. This agricultural policy is referred to as the 'Channelisation policy' (Arnoldussen et al. 2014). This policy has been successful in giving increased food production. However, it relied to a large extent upon monocultural rotations in the cereal areas, and high cereal prices were necessary to motivate farmers to make the changes in production system. As a result of this, there was a steady and large increase in cereal production in Norway from 1950 until the mid-eighties. During this period the cereal yields increased constantly. Wheat yields were more than doubled and yields of barley and oats increased by nearly 100% (Stabbetorp 2017). This increase was due to progress in crop management and developments in machinery, along with improved varieties and breeding for increased yield potential. Among these, breeding progress is considered to have been the most important, especially for wheat (Stabbetorp 2017). Simultaneously, both the amount of production and the quality of wheat has improved steadily, which has increased the amount of Norwegian flour used in bakeries (Flø et al. 2017). Increased crop protection measures have reduced losses from weeds, pests and diseases. The cereal demand also changed during this period, due to the increasing use of feed concentrates in animal husbandry. Furthermore, increased meat consumption has led to a continual increase in the demand for cereals for animal feed.

However, since the early 1990's, the cereal area have been declining and production has stagnated (SSB, landbruksdirektoratet). There may be several different reasons for this. Changes in agricultural policy from mid-1980 with adjustments in subsidies from support per kg grain to a partly area-based system (subsidies given for both area in production and the quantity delivered) may have led to less effort among farmers to maximize yield. Together with decreasing cereal prices and increasing prices for input factors (e.g. fertilizer) and machinery, this has reduced the profitability of cereal production (Hoel et al. 2013, Stabbetorp 2017). The numbers of both farms and farmers have declined, while the number of part-time farmers, who often have their main education and income from professions other than farming, has increased (Hoel et al. 2013). At the same time, there has been more focus on reducing the environmental impact of agricultural production, which may in some cases conflict with higher yields. Measures against erosion, such as the transition to reduced soil tillage, may have had a negative effect on yields in the short term, but are expected to have positive long-term effects, such as reduced leaching and reduced deep soil compaction (Knight et al. 2012).

2.2 Cereal production in Norway today

The Norwegian cereal area is today about 285 000 ha distributed between 12900 farms. The three counties Akershus, Østfold and Hedmark, located in southeast Norway account for approximately 60% of the cereal area. Vestfold, Buskerud and Oppland cover 22 %, while Trøndelag has about 16% of the cereal area. Together these counties include 95 % of the Norwegian cereal area (Figure 1). The main cereals grown are spring varieties of barley (47%), wheat (26%) and oats (22%). The area of winter

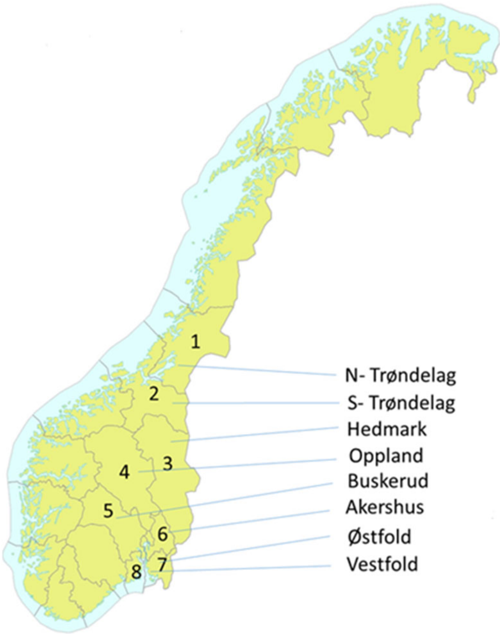


Figure 1. The main cereal-growing counties in Norway.

cereals (primarily wheat and rye) varies, reflecting the autumn sowing conditions, which differ from year to year (SSB). Winter rye and triticale are grown on a limited area. The cereals are typically grown in the flattest areas, and mono-cereal production systems dominate. Thus, rotations including only cereals are common, and with inclusion of oilseed rape, field peas and other crops as potato and vegetables in some cases. Barley is the most commonly grown cereal, especially in Central Norway (Trøndelag) due to its early ripening properties. Barley is also the dominating cereal in Hedmark, while Akershus, Østfold and Vestfold have together 70% of the wheat area. Østfold is the largest wheat-producing county, with 35% of the total wheat area. Norwegian cereal yields vary by approximately 30-40% per year, mostly due to varying weather conditions (Flø et al. 2017).

2.3 Cereal area and total cereal production from 2003 to 2013

The yield gap analyses presented in this report are based on data from the period 2003-2013. Therefore, the cereal area and total cereal production during this period are presented here in more detail.

Although there has been some variation between years, the overall trend is declining production and area (Figure 2) (SSB, 2015). Since 2013, the cereal area has continued to decline somewhat, whilst there were some seasons with comparatively high yields.

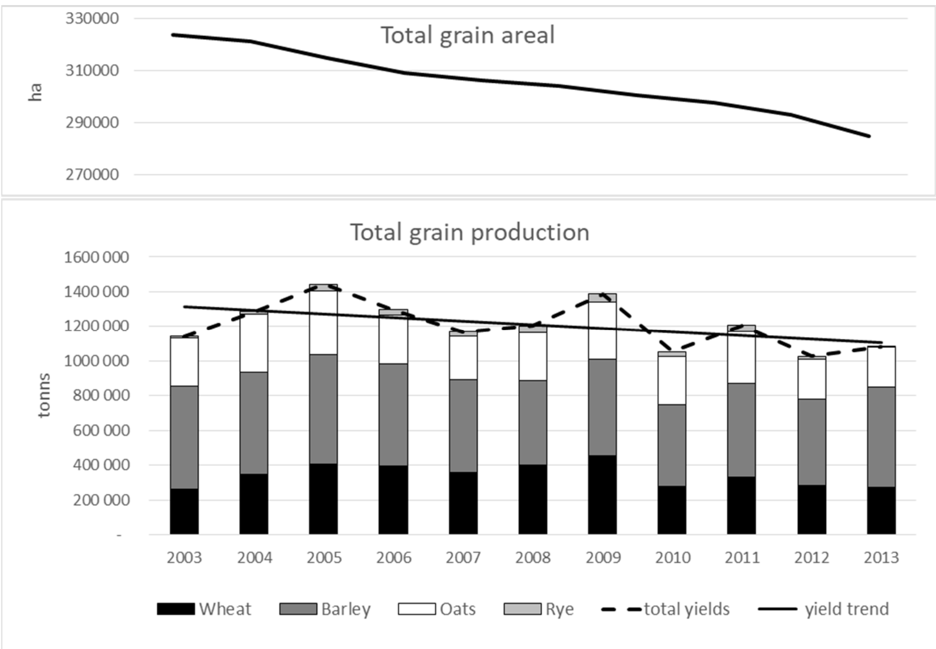


Figure 2: Total grain area (ha) and production (tonns) for the period from 2003-2013 for the different cereals

The area that is taken out of the cereal production is mainly transferred into grasslands (Eldby and Thuen 2016), as well as areas used for residential and industrial buildings, or road and rail traffic constructions (Landbruksdirektoratet 2018). This problem is not limited to Norway, as declining cereal area can also be found in other countries within the EU 28 (Eurostat 2018, www.yieldgap.org).

Key figures about cereals and areas:

1 hectare equals 10,000 m². We can produce ca. 500 g wheat per m² (average yield in Norway). This is enough for the production of one loaf of bread. To produce one loaf per day all year, 365 m² are needed (jordvern.no).

In 2012, Norway had approximately 0.23 hectares arable land per capita. This is the lowest level amongst the Nordic region (Table 1) and only slightly more than that expected to be needed to satisfy the food security needs of one person (0.14ha) (Bröcker and Moritz 2009). The global average cereal consumption per person and year equals ca. 67 kg (feed not included) (Fuglestad and Thuen 2017).

2.4 Farm number and size

In Norway, the number of cereal producing farms (cereals and oilseed) has been reduced from ca. 21 400 in 2000 to ca. 10 400 in 2018, which means a reduction of 50%. In the period 2003 to 2016 this was mostly due to smaller farms going out of business (<49ha) while the number of farms >50 ha increased. This led to an increase in average farm size from 18 ha (2003) to about 25 ha in 2018 (SSB 2019). By 2012, 65% of the Norwegian cereals were produced on farms bigger than 30 ha (Vagstad et al. 2013). Even so, Norway is the country within of the Nordic region which has the smallest amounts of both arable land and cereal area (Table 1) (Olesen 2014). Average field size is comparatively small and approximately 25% of the cereals in Norway are grown in fields less than 2.5 ha (Vagstad et al. 2013).

Table 1: Structure key indicators and utilized agricultural area in the Nordic region for the years 2000 and 2010 (Eurostat 2013, www.yieldgap.org).

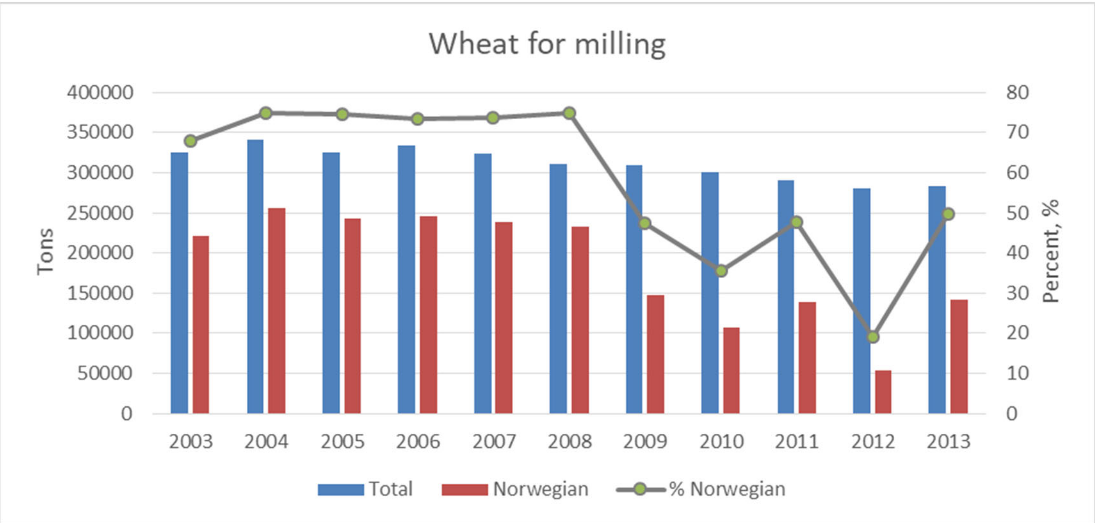
	Total farmland area	Arable land	Cereal area	Total farm	Average farm size	Area per person
2000	(million ha)	%	%	number	ha	ha
Denmark	2.64	94	55	57830	45.7	0.50
Sweden	3.07	88	38	81410	37.7	0.35
Finland	2.19	99	53	81190	27.3	0.43
Norway	1.04	62	32	70740	14.7	0.23
2010						
Denmark	2.65	91	56	42100	62.9	0.48
Sweden	3.07	85	31	71090	43.1	0.33
Finland	2.29	98	44	63870	35.9	0.43
Norway	1.01	56	30	46620	21.6	0.21

2.5 Use of cereals and quality

Most of the cereal production in Norway is used for animal feed, and this proportion exceeds 80% in most years. However, the production of wheat and rye is aimed at human consumption, and the proportions that meet food grade quality are used for milling. For wheat, the most important quality criteria are test weight, falling number and crude protein content. Furthermore, the Norwegian milling industry requires relatively strong gluten. Norwegian spring wheat varieties with strong gluten are available, and are sought-after by the industry. The winter wheat varieties typically have weaker gluten and a lower protein content. Thus, the proportion of winter wheat in the Norwegian flour blends is limited. Low Falling Number is a common quality fault, due to the predominately wet weather conditions in Norway prior to harvest. Additionally, it has been challenging in some years to reach the required protein content for winter wheat. As a consequence, the proportion of wheat used for milling varies from year to year, due to both the variation in total production and the proportion that meets food grade requirements. Figure 3A shows the proportion of Norwegian grown wheat that was used for milling during 2003-2013. Achieving a high production of wheat for milling is important to increase self- suffiency in Norway. Even though the wheat production in some years approaches the demand for milling, the highest proportion of Norwegian wheat in the flour blends has been around 70% until now, and this was achieved during 2004 - 2008. In challenging seasons, this proportion is lower. For the 2011 harvest with frequent rain during maturation and harvest, only 20% Norwegian wheat could be used for milling during 2011/2012 (Figure 3). The seasons 2009 - 2013 were all challenging with low proportions of wheat that met food grade. In the period after 2013, the proportion of Norwegian wheat in the milling blends has increased, but not to the level seen during 2004-2008.

Wheat that does not meet milling requirements is used for animal feed. The Norwegian cereal production approached the demand for cereals in the feed concentrates in the early 2000's. Thereafter the gap between production and demand has grown, partly due to the above-mentioned reductions in cereal production, partly due to increased demand and use of feed concentrates as well as consumption of meat and dairy products in Norway (www.fk.no).

A



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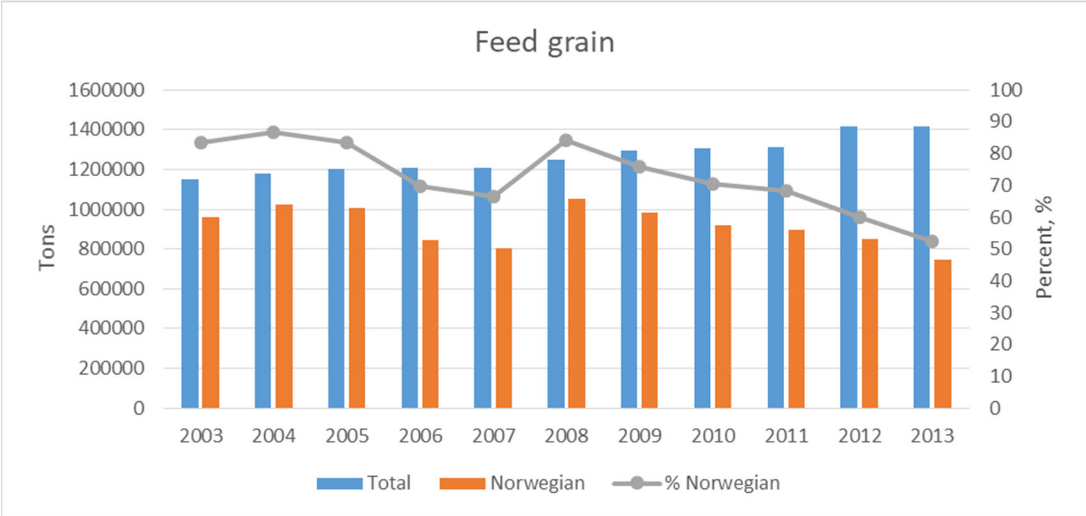


Figure 3. Total demand and the proportion of Norwegian wheat for milling (A), and of grain for feed consentrates (B) for the period 2003-2013. (Data: Norske Felleskjøp, www.fk.no).

Figure 3B shows the quantities of Norwegian-produced cereals used for feed concentrates compared to the total usage. The figure indicates a decline in Norwegian production in the recent period, reflecting the reduced production area as well as the stagnating cereal yields. Furthermore, changes in the chemical composition in the feed requirements for high-yielding animal production (e.g. high-yielding milking cows) have led to higher imports of other feed ingredients, thus reducing the demand for Norwegian cereals. However, the last decade has shown an increasing demand for Norwegian cereals for feed, in particular for wheat.

Climate in Norway

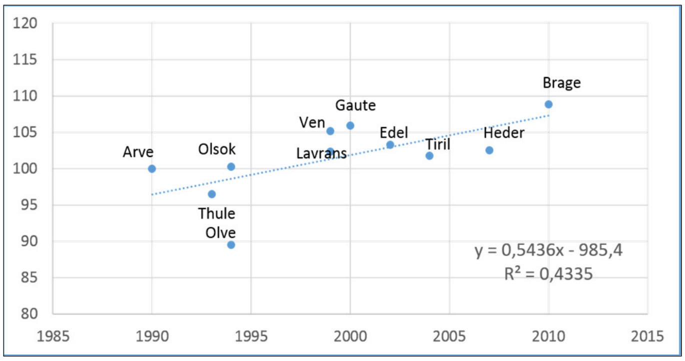
The natural variations in climate in Norway are large, both in terms of time and locality. Although temperatures are higher than in other areas on the same latitude, due to impacts of the Gulf-stream, the premisses for cereal production are nevertheless challenging, mostly due to low temperature and high precipitation. The short length of the growing season is an important limitation for an extension of the cereal area, both northwards and to higher altitude. This creates the need for varieties which can exploit a shorter growing season than in most other cereal-producing countries. Early-maturing varieties normally have a lower yield potential. Norwegian cereal production is facing both economical and biological limitations which results in comparatively low yields and high costs compared to other more southerly countries with intensive cereal production. More details about climate and climate scenarios can be found in Hanssen-Bauer, Førland et al. (2015).

2.6 Genetic improvements and yield potential in varieties

Cereal breeding has been conducted in Norway since 1900 in spring barley and oats, as well as in spring and winter wheat. Lillemo et al. (2009) analyzed the genetic gain in new varieties of barley in Central Norway from 1946-2010. They found relatively modest yield increases (0.25% per year) in varieties released before 1960, but this was followed by a period of more frequent release of new varieties and a higher rate of yield increase (0.79% per year) in the five decades after 1960. Based on the methodology of Lillemo et al. (2009) and data from official variety trials 1985-2015, the annual yield increase due to genetic gain in new varieties was estimated to 0,8% in spring wheat , whilst that of spring barley in both Eastern and Central Norway, was estimated to 0.4-0.6 % (Figure 4, Appendix 1-6). Similar improvements in genetic gain are reported from other European countries. As an example, the average genetic gain for wheat after the second world war in the UK has progressed more than 0.5% per year (Knight et al. 2012).

Hence, relatively strong and continued genetic gain in yield is achieved through release of new varieties in Norway, also in the recent decades after 1990. This means that the stagnating yields seen from the 1990's are not due to a lack of yield increases in new varieties, and that there is an unexploited yield potential in the varieties currently used in Norway.

A



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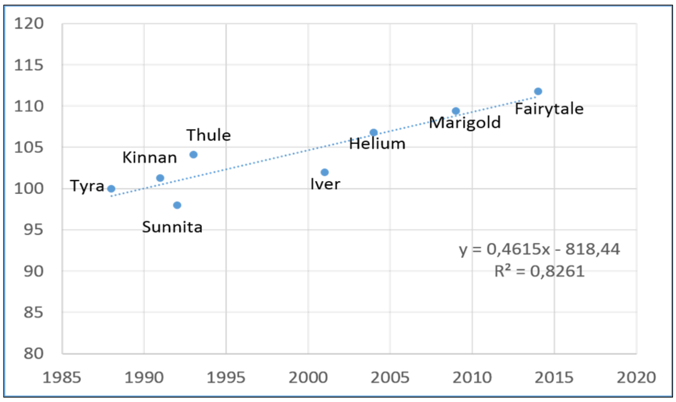

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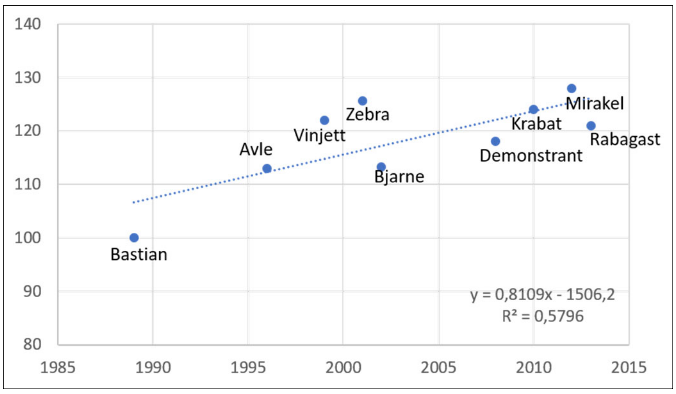

Figure 4. Relative yield differences of new varieties plotted against the year of release. Data are based on the official variety trials with early barley varieties for Trøndelag (A), late barley varieties at Østlandet (B) and spring wheat at Østlandet (C). Relative yields are calculated against Arve (early barley), Tyra (late barley), and Bastian (spring wheat).

Increasing population and land use

Norway

The population of Norway today is about 5.3 million (SSB 2019, https://www.ssb.no/befolkning/faktaside/befolkningen) and is expected to reach 5.5 million people in 2030 (SSB). Assuming the same diet and the same degree of self-sufficiency, cereal yields need to increase by 20% within 2030, which means that production must be increased by 265.000 tonnes (+ 900kg/ha) (Vagstad et al. 2013). It is a political aim in Norway to maintain or increase food self-sufficiency (Matdepartement 2016).

The agricultural land covers only 3.7% of the total land area. Only one third of this area can be used for cereal production. Many areas suitable for cereal production are located within or close to growing urban areas. Thus there are often conflicting interests in the use of these areas. In 2018 ca. 360 ha were converted to other uses in Norway which is lower than granted by the government (400 ha). This is a slight reduce from 2017 where 390 ha were converted (Kostra 2018). Although this is less than in some other parts of Europe (e.g. ca. 110 ha/day in Germany) (Bröcker and Moritz 2009), it is still a lot compared to the limited amount of arable land in Norway.

There is a strong connection between conversion of farmland and urban areas in Norway. Over 50% of the converted area was within a 1 km radius outside urban areas. Residential areas (26%) and the agricultural holdings themselves (22%) accounted for the highest amounts of converted area (Gundersen et al. 2017).

International

World population is projected to increase by ca. 35% by 2050. This will require up to 100% increase in food production, assuming that current trends in diets, consumption and income continue (Tilman et al. 2002, Lin and Huybers 2012, Van Wart et al. 2013).

On a world basis there are ca. 14 billion hectares land surface, of which only 11% (1.5 billion hectares) are suitable for agricultural production (Gundersen et al. 2017). In 1950, there were ca. 5100 m^2 per person, while it is expected that this figure will be reduced to 2000 m^2 by 2050. This is a significant reduction, that will lead to shortages in arable land especially in developing countries. Already today there is a growing imbalance in the amount of arable land per person. It is 2.5 times as high in the industrialized countries as in the rest of the world. Today urban areas cover approximately 250 million hectares (2 % of the available global area). This is expected to increase to 420 million hectares within the year 2050. This growth is mainly at the expense of arable land, and the loss of arable lands is compensated for by clearing forests. Between 1961 and 2007, the global amount of arable land increased by 11% (150 million hectares). If the global food demand continues to increase to the same extent, an additional area between 320 million hectares (size of India) and 850 million hectares (size of Brazil) will need to be cleared within 2050 (Bröcker and Moritz 2009, Chemnitz and Weigelt 2015).

3 Need for higher production on limited area-international perspective

3.1 European production

Europe accounts for around 20% of the global cereal production (Schils et al. 2018) and is thereby one of the largest and most productive suppliers of food and fiber. Yields are higher in Europe than the world average (Olesen and Bindi 2002, Olesen et al. 2011, Lin and Huybers 2012). Cereals are traded on the world market, where there is an increasing global demand and competition. Possibilities to increase yields in the high-yielding regions of Europe are therefore also of global interest. The discussion about Yield gap (Yg) should therefore also consider the global situation and cannot be limited to the situation in Europe.

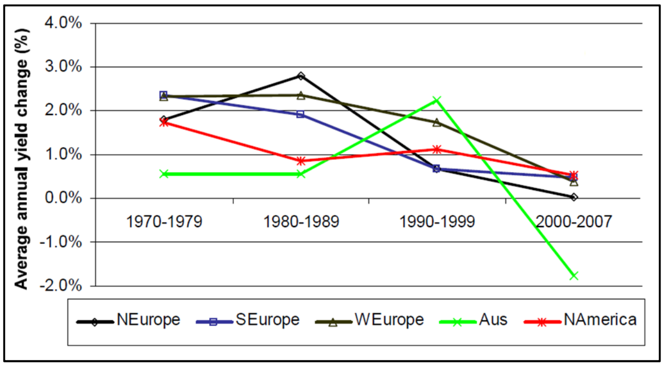

Figure 5. Average annual percentage change of wheat yields (t/ha) in advanced economies (Hengsdijk and Langeveld 2009)

Trends of stagnating yields and reduced yield gain are reported from different regions (Hengsdijk and Langeveld 2009) (Figure 5) and also (European) countries like Denmark, France, Great Britain and others (Spink et al. 2009, Brisson et al. 2010, Petersen et al. 2010, Lin and Huybers 2012, Schils et al. 2018). Although the trends are similar, the reasons for the Yg may vary from country to country and region to region. A considerable amount of work on Yg has been done recently, much of it within cereals (www.yieldgap.org.)

3.2 Need for increased food production

Cereals are one of the most important food sources in the world, both for food and feed (Arnoldussen et al. 2014) and there is an increasing global demand for cereals of approximately of 2% per year (Fuglestad and Thuen 2017) (Figure 6).

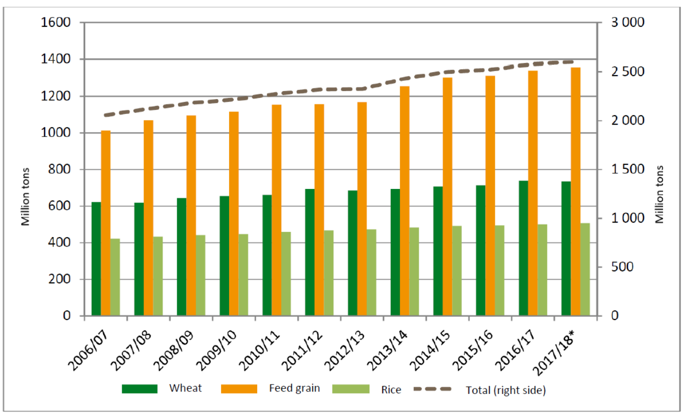

Figure 6. Cereal consumption in the world, estimated for 2017/2018 (Fuglestad and Thuen 2017)

At the same time, there is an increasing global demand for other crop products in the transition towards a low-fossil-carbon economy. This may, at least on a global basis, be in conflict with cereal and food production (Amundson et al. 2015, Schils et al. 2018). Calculations show that every hectare of existing cropland will be needed to produce yields that are substantially higher than current yields (Van Ittersum, Cassmann et al. 2013). Increasing production could either be achieved by (a) expanding the crop production area, (b) raising crop yields on existing farmland, or (c) a combination of both (Vagstad et al. 2013, Van Wart et al. 2013). While there are significant possibilities to close YG in many parts of the world (e.g. Eastern Europe) by improving nutrient use, water supply and plant protection (Foley et al. 2011), these possibilities may be more limited in the Western Europe, since these factors are often close to their optimum (Tilman et al. 2002).

Expanding the production area is often not possible in developed countries of the temperate zone, due to geographical limitation and/ or high costs since the most productive areas are already in production (Tilman et al. 2002, Foley et al. 2011). Additionally, a lot of prime agricultural land is converted to other uses such as urban, industrial and recreational uses (Lal 2013). A large percentage of the global land suitable for agriculture is already under cultivation. Therefore expanding area either occurs on marginal land, which is unlikely to sustain high yields, or as a redistribution of agricultural land towards the tropics, mostly at the expense of natural (rain-) forest (Foley et al. 2011, Tilman et al. 2011). Deforestation and cultivation reduce biodiversity, increase greenhouse gas emissions and depleting critical ecosystem services (Tilman et al. 2002, Foley et al. 2011, Van Wart et al. 2013).

Both costs and benefits from agricultural intensification vary greatly, often depending on geographic conditions and agronomic practices (Foley et al. 2011). Food production may be much more expensive in some of the marginal or tropic countries compared to production on areas that are already in use, if the costs for deforestation and other environmental consequences are taken into consideration (FAO 2015).

Land grabbing

The EU is today's largest user of farmland outside its own borders and is currently using ca. 640 mill. hectares. This equals about 1.5 times the (total-) area of all 28 states of the EU. These areas are mostly located in the former Russian Union, Latin America or South East Asia, countries that may already have problems in securing their own food supply (Bröcker and Moritz 2009, Chemnitz and Weigelt 2015).

3.3 Climate change and future scenarios

Climate change and its associated changes in temperature and precipitation are projected to impact crop productivity and product quality in most regions of the world. On a world basis, climate change could also be responsible for some of the yield stagnation since the 1990's, as shown by Lobell et al. (2011). Their studies estimate that the average global wheat yields could have been approximately 5% higher in the period 1980-2008 if there had been no negative climate effects (Figure 7). This 5% loss equals roughly the current wheat production of France (33 MT).

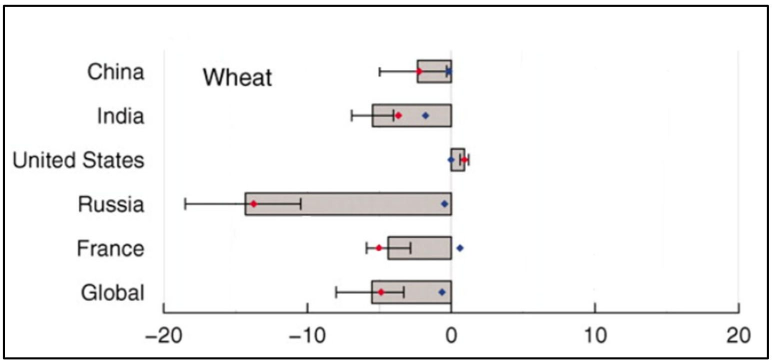

Figure 7. **Estimated net impact of climate change for 1980–2008 on crop yields in the major wheat-producing countries and for the overall global wheat production, expressed as percent of average yield. Gray bars show median estimate; error bars show 5% to 95% confidence interval. Red and blue dots show median estimate of the impacts from temperature and precipitation trends, respectively (Lobell, Schlenker et al. 2011).**

Effects of climate change on cereal production will vary between regions. Countries in the southern hemisphere are expected to suffer more than those in the northern hemisphere (Kang and Banga 2013). According to the climate models, Norway is among the few areas in Europe where an overall positive effect of climate change on agricultural production is expected, mostly due to an extension of the growth season (Olesen and Bindi 2002, Olesen et al. 2011, Seehusen et al. 2016).

Assuming that adaptation to climate change will be successful, e.g. by adaptation of crop varieties and management to control periods with increased precipitation, there is a potential to increase cereal production in Norway during the next decades (Seehusen et al. 2016). Norway may therefore be one of the countries that could possibly increase its yields. This would reduce the need for imports, and thus may contribute to relax the situation on the world market. Higher cereal production in Norway would support the UN sustainable development goal 2, 'zero hunger' (https://sustainabledevelopment.un.org/#).

4 Yield Gap analyses

Analyses of Yield Gaps (Yg) are gaining scientific attention, as the estimation and explanation of Yg reveals the potential for sustainable intensification of agricultural systems without extension of existing farmland. Sustainable intensification, including the closing of Yg on currently available agricultural land has been pin- pointed as one possible way to meet the future food demand. Yield gaps can be analyzed on different levels (FAO 2015). YG analyses on a country level could be useful in order to compare different geographic regions. Yg analyses on a cropping system level give the opportunity to compare different systems in terms of e.g. efficiency. Yg analyses at farm level can contribute to better understand how Yg can be closed at a practical level, and if so, under which production, economic and environmental conditions (Beza et al. 2016).

4.1 Potential and average yield

The possibility to increase cereal production under current production practices depends on the potential yield (Yp), which is defined as the maximum attainable yield of a crop cultivar when grown under optimal growing conditions and management practice. This includes non-limiting water and nutrient supply and efficient control of biotic and abiotic stresses (Van Ittersum et al. 2013, Van Wart et al. 2013) (Fig. 1a). Furthermore, this potential yield is location-specific, because of the variation in climatic conditions. Yield potential is expected to be independent of soil type since both water and nutrients can be applied through management. Details can be found in Van Ittersum et al. (2013).

For rainfed crops, water-limited potential yield (Yw) can be used, defined equivalent to Yp but where the crop growth is also limited by water supply as determined by precipitation, the water-holding capacity of the soil, as well as rooting depths and field topography (runoff).

The actual yield (Ya) is defined as the yield actually achieved by farmers.

Differences between the actual yields (Ya) achieved by the farmers, calculated as averages for specific regions and time periods, and the potential yield (Yp or Yw) are referred to as the yield gap (Yg) (Van Ittersum et al. 2013) (Figure 8).

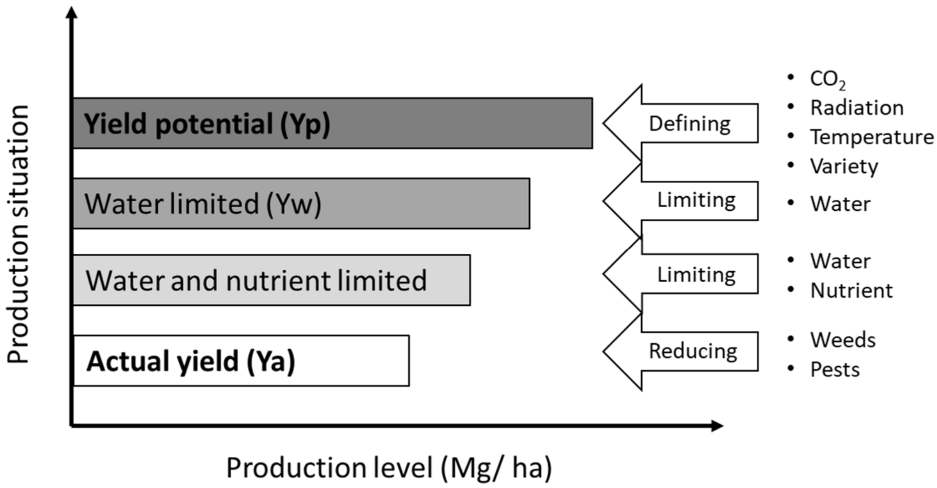

Figure 8. Different production levels determined by growth factors grouped as defining, limiting and reducing factors. Yield potential (Yp) of irrigated crops without growth limitations (water etc.) from planting to maturity. For crops grown under rainfed conditions the water limited yield (Yw) represents the ceiling yield. Actual yield (Ya) as average yield achieved by farmers on farm level. Yield gap (Yg) is the difference between Ya and Yp or Yw (modified after (Van Ittersum et al. 2013).

4.2 Exploitable yield

Under practical conditions on a farmer's level, it is nearly impossible to achieve perfection in plant production necessary to achieve Yp or Yw. This is mostly due to: (a) variable weather conditions with great uncertainty such as temperature, rainfall, wind etc.; (b) applied inputs not being cost-effective since yield responses follow diminishing returns when actual yields approach ceiling yields; and (c) limitations caused by fertilizer and chemical plant protection regulations aimed at reducing the environmental impact of agricultural production (Figure 9) (Van Ittersum et al. 2013, Van Wart et al. 2013). There may therefore be valid ecological and economic reasons to aim at closing yield gaps at lower yield levels than Yp. Studies show that average regional yields often level out, when yields reach 70- 80% of Yp, and that only few pass beyond this point (Lobell et al. 2009). Therefore, 80% of the potential yield (Yw) is often referred to as the exploitable yield (Y_{ex}). The exploitable yield gap (Yg_{ex}), defined as the difference between Ya and Y_{ex} (Figure 9), is therefore expected to be of the greatest practical interest in the context of improving agricultural production (FAO 2015). In this study we therefore show both the absolute (Table 3.) and the exploitable yield gap.

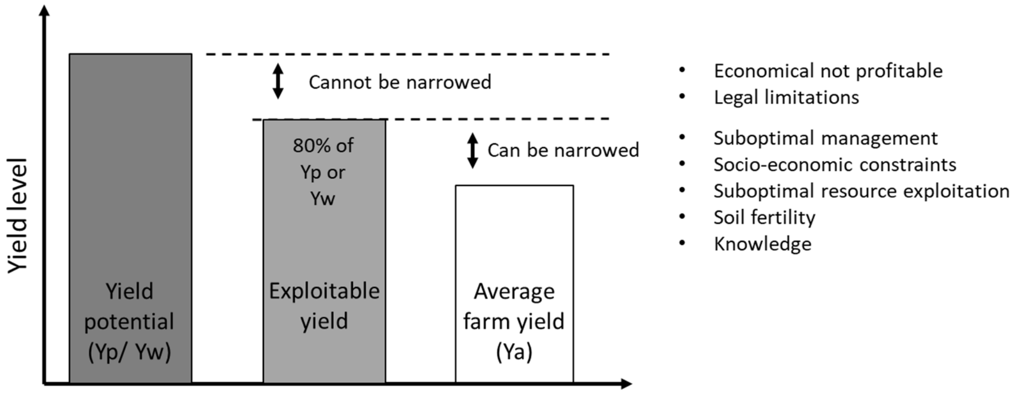

Figure 9. The exploitable yield gap describes the difference between the exploitable yield (80% of Yp/ Yw) and average yields (at farm level) modified after (Van Ittersum et al. 2013)

TempAg and Global Yield Gap Analyses (GYGA)

TempAg is an international research collaboration network established in order to increase the impact of agricultural research and inform-policy making in the world's temperate regions. The main aims of TempAg are (a) to increase the impact and return on investment in national research programs, (b) to bring together national competencies and work to meet goals of transnational mutual interest, (c) optimize land management for food production and other ecosystem services and (d) increase sustainability and improve food productivity. More about TempAg can be found at: www.tempag.net

When TempAg was established in 2015 three pilot activites (themes) were initiated.

Theme 3: Sustainable improvement of food productivity at the farm and enterprise level. This activity is focused on addressing yield gaps, resource use efficiency and environmental impact. Through quantification of yield and water productivity gaps for major crops in temperate countries (using the Global Yield Gap Atlas), this work has now delivered preliminary data identifying some of the underlying root causes of yield gaps in the temperate region.

The international Global Yield Gap and Water Productivity Atlas (GYGA) (www.yieldgap.org) provides robust estimates of untapped crop production potential on existing farmland based on current climate and available soil and water resources. Since the data and potentials for the different regions are modelled following the same procedure, results from the atlas can serve to (a) identify yield gaps and regions with the greatest potential for increasing yields and food self- sufficiency, (b) compare these regions, (c) assess how much extra land clearing or food import will be needed to meet future demand and (d), investigate impact of climate change, land use and environmental footprint of agriculture. More information can be found under: www.yieldgap.org.

Through the Global Yield Gap and Water Productivity Atlas (GYGA), methodology and standard protocols for assessing Yp, Yw, and Yg in different crops, regions and countries have been established. Analyses of Yg can be used to get deeper insight in yield constrains and unexploited potential for yield increases. Simulations of Yp and Yw in present and future climate can also be used to predict consequences of climate change and for the upscaling of results to foresee future yields and food security.

5 Data collection for the Norwegian GYGA analyses

For performing yield gap analyses for Norwegian cereal production the project group in Agropro inititated cooperation with Rene Schils at WUR (Wageningen University and Research) in the Netherlands, responsible for the GYGA analyses. The nessesary data was collected by the Agropro group in Norway, and the simulations and Yg analyses were performed by Rene Schils in the course of the 'yield gap' project with the aim of calculating yield gaps in different countries in the temperate climate zone. In order to be able to compare the different countries, the same GYGA methodology was used for all countries, also for Norway. Climate and soil data were collected from European databases. More details about the methodology and the data used can be found on the following site: www.yieldgap.org/web/guest/methods-overview. The time period selected for the analyses was 2003-2013 in all cases.

5.1 Yield potential

Simulations of potential yields (Yp and Yw) for calculation of yield gaps using the GYGA methodology (Yp and Yw) were done for spring- and winter wheat in Eastern Norway (Østlandet), and for spring barley for Eastern and Central Norway (Østlandet and Trøndelag). The two regions cover more than 90% of the harvested area of these cereals. Both regions were defined as being within the climate zone 1902 according to the GYGA criterias set for growing degree days, aridity and temperature seasonality (http://www.yieldgap.org/web/guest/methods-weather-data). The weather stations Oslo (NOR066) and Værnes/Trondheim (NOR027) were selected to represent the two regions. Soil data for Norway were collected from the Eurosoil database. Simulations of Yp and Yw were performed according to the standardized procedure developed for the Global Yield Gap Atlas (GYGA) (Van Ittersum et al. 2013, Van Wart et al. 2013, Schils et al. 2018). The difference between Yp and Yw (Figure 8) may vary with time since there may occur years with dry conditions (e.g. 2018) where water may be limiting. This would enlarge the difference between Yp and Yw. Anyhow, only small differences between Yp and Yw were found during the research period (2003-2013) (Table 3). Yw is therefor assumed to be the potential yield.

5.2 Actual yields

Actual (Farmers') yields (Ya) were collected from SSB (www.ssb.no). Means for the two main regions, Østlandet and Trøndelag, were calculated as averages of yields from the counties Østfold, Akershus, Hedmark, Oppland and Buskerud, and for Sør- and Nord-Trøndelag, respectively (Figure 1). The wheat yield data from SSB are not split between spring and winter wheat. Additional data were therefore provided from SSB to achieve Ya data for both crops. These additional data were based on wheat deliveries from all farms with only spring wheat or only winter wheat at Østlandet, and averages were calculated for the period 2003-2013.

5.3 Data from variety trials

Yield data from the variety trials were collected from yearly publications (Åssveen et al. 2004, Åssveen et al. 2014). The data were used to calculate the average yields from the variety trials to be compared with the simulated potential yields in the Yg analyses for the whole period. Averages of the main market varieties were used, comprising *Tiril*, *Tyra* and *Edel* for barley in Trøndelag, and *Tiril*, *Tyra* and *Helium* for barley at Østlandet. For spring wheat at Østlandet the calculated averages were based on the varieties *Bjarne* and *Zebra*, and for winter wheat *Magnifik*, *Olivin*, *Finans* and *Elvis*.

A selection of yield data from individual field trials that were outstandingly high-yielding, referred to as the “best variety trials”, were kindly provided by NIBIO (pers. comm. Annbjørg Øverli Kristoffersen). These data were used for comparisons with the simulated Yp and Yw, as they were considered close to the potential for the respective regions.

5.4 Phenological data

The phenological data requested for the GYGA simulations of Yp and Yw were sowing date (DOP), date of emergence (DOE), date of anthesis (DOA) and date of yellow ripeness (DOM). Sowing dates were collected from 1) research farms in several regions (Vollebekk Research Farm, NMBU at Ås, Øsaker Research Farm, NLR at Sarpsborg, and Kvithamar Research Station, NIBIO at Stjørdal), and 2) from the JOVA Experiments (Beckmann and Eggestad 2016) located at three different sites (Ås, Romerike and Ringsaker). Based on the data from all these locations, the first possible day for sowing was calculated for the period 2003-2013. The other phenological data (DOE, DOA, and DOM) were calculated based on an earlier established model for phenological development in spring wheat and spring barley (Bleken, unpublished) (Table 2, Appendix 7-9). The mean daily temperatures were collected from NIBIO weather stations for the whole period. Weather stations used were Ås, Kise, Kvithamar, Øsaker and Årnes.

Table 2. The model parameters for calculation DOE, DOA and DOM (Bleken, unpublished).

		Sowing - Emergence		Emergence – Heading		Heading – Physiological maturity	
Location	Cereal	T-Base	T-Sum	T-Base	T-Sum	T-Base	T-Sum
Vollebekk, Ås	Barley	-1.57	139	-3.8	825	4.94	387
Kvithamar, Stjørdal	Barley	-1.57	139	-3.50	757	4.94	387
Vollebekk, Ås	Wheat	-1.6	140	1.06	626	5.81	423

6 Simulations of Yield potential and calculation of the exploitable Yield Gap (Yg)

6.1 Yield Gap in Norway

Table 3. Simulations of potential yields (Yp) and calculations of yield gap (Yg) based on the period 2003-2013. Yields are given in Kg/ha, 15% moisture. GYGA CZ= climate zone chosen for simulation in global yield gap atlas.

Cereal	GYGA CZ	Region	Yp Kg/ha	Yw Kg/ha	Ya* Kg/ha	Yg (Yw-Ya) Kg/ha	Yg %
Spring Wheat	1902	ØST1	7508	7472	4120	3352	45
Winter wheat	1902	ØST	10129	9411	4647	4763	51
Spring Barley	1902	TRØ2	6279	6251	3409	2842	45
Spring Barley	1902	ØST	7291	6617	3697	2920	44

*1 Østlandet, 2 Trøndelag * Calculated from SSB data*

The results from the simulations of potential yields and calculations of yield gaps are given in table 3. Supplementary data to tables and figures are given in appendix.

The calculated total yield gaps were approximately 3000 kg/ha (45%) for the spring cereals (Table 3), and 4700 kg/ha for winter wheat (51%). The simulated Yw compared to Ya and results from variety trials, and the calculated Yg and Y_{ex} are described for each cereal and region (Figures 10-13).

6.1.1 Spring wheat (Østlandet)

For spring wheat, an average Yw of 7500 kg/ha was calculated. The average yield in the variety trials was 2200 kg (29%) lower than Yw. The best variety trials were 700 kg/ha (9%) lower than Yw on average, but they approached Yw in 2008 and 2012. The exploitable yield (defined as 80% of the Yw) was approximately 6000 kg/ha (dotted line) which gave an exploitable yield gap (Yg_{ex}) of 1900 kg/ha (31%) (Figure 10, Appendix 10, 11, 16).

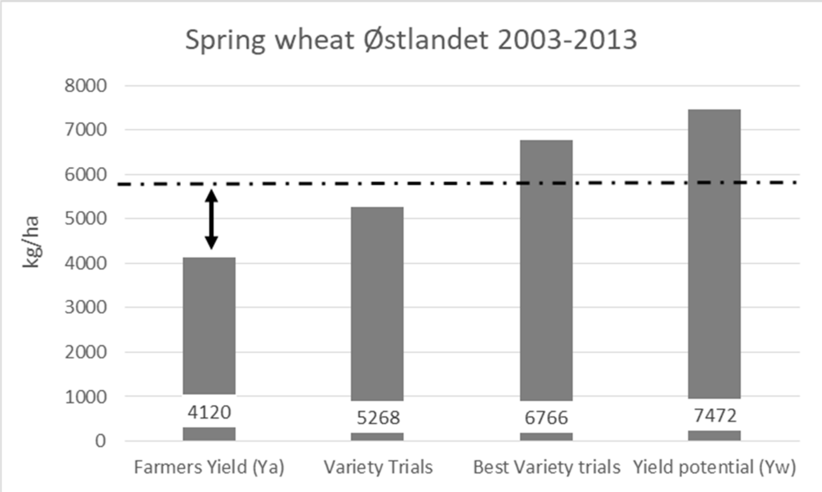

Figure 10. **Farmers yield (Ya), average yields from variety trials, average yields from the best yielding variety trials and calculated yield potential (Yw) for spring wheat in the region Østlandet for the period 2003-2013 in kg/ha at 15% moisture. Dotted line is the exploitable yield, defined as 80% of the Yp. Exploitable yield gap make up the difference between exploitable yield and Ya.**

6.1.2 Winter wheat (Østlandet)

The yields for winter wheat are shown in figure 11. The average yield in the variety trials was 3100 kg (33%) lower than Yw. The best variety trials were 720 kg/ha (8%) lower than Yw on average. The exploitable yield was 7500 kg/ha (dotted line) which gave an exploitable yield gap (Yg_{ex}) of 2900 kg/ha (38%) (Figure 11, Appendix 10 and 12, 17).

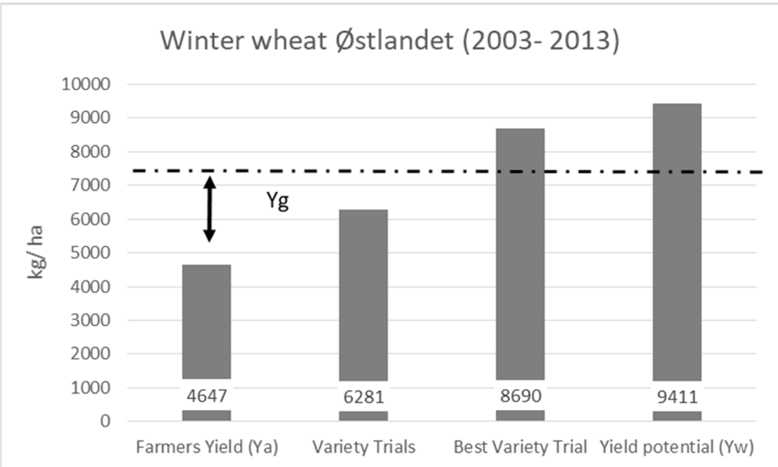

Figure 11. **Farmers yield (Ya), average yields from variety trials, average yields from the best yielding variety trials and calculated yield potential (Yw) for winter wheat in the region Østlandet for the period 2003-2013 in kg/ha at 15% moisture. Dotted line is the exploitable yield, defined as 80% of the Yp. Exploitable yield gap make up the difference between exploitable yield and Ya.**

6.1.3 Spring barley

Østlandet:

In this region (Figure 12), the average yield in the variety trials was 1400 kg (21%) lower than Yw. The best variety trials however were 60 kg/ha (1%) higher than Yw on average and about 950 kg/ha higher in the year 2010. The exploitable yield was about 5300 kg/ha (dotted line) which gave an exploitable yield gap (Yg_{ex}) of 1600 kg/ha (30%) (Figure 12, Appendix 14, 18).

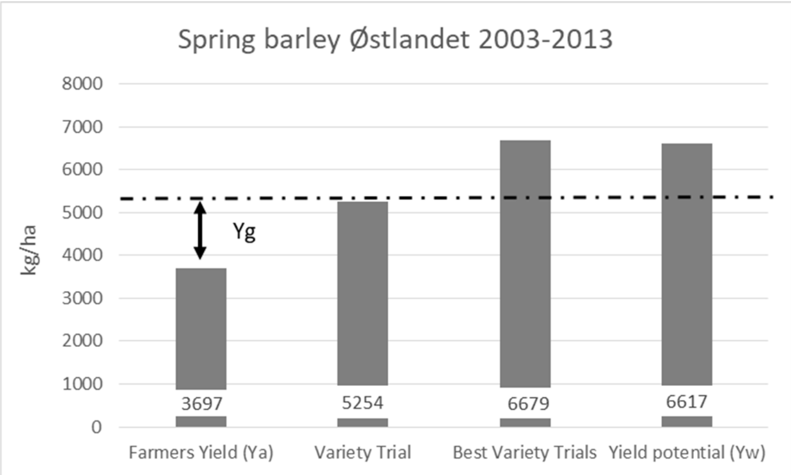

Figure 12. **Farmers yield (Ya), average yields from variety trials, average yields from the best yielding variety trials and calculated yield potential (Yw) for spring barley in the region Østlandet for the period 2003-2013 in kg/ha at 15% moisture. Dotted line is the exploitable yield, defined as 80% of the Yp. Exploitable yield gap make up the difference between exploitable yield and Ya.**

Trøndelag:

In this region (Figure 13), the average yield in the variety trials was 1500 kg/ha (24%) lower than Yw, but here the best variety trials gave yields 1000 kg/ha (16%) higher than Yw on average and 2800 kg higher than Yw in the year 2010. The exploitable yield was about 5000 kg/ha (dotted line) which gave an exploitable yield gap (Yg_{ex}) of 1300 kg/ha (32%) (Figure 13, Appendix 15, 18).

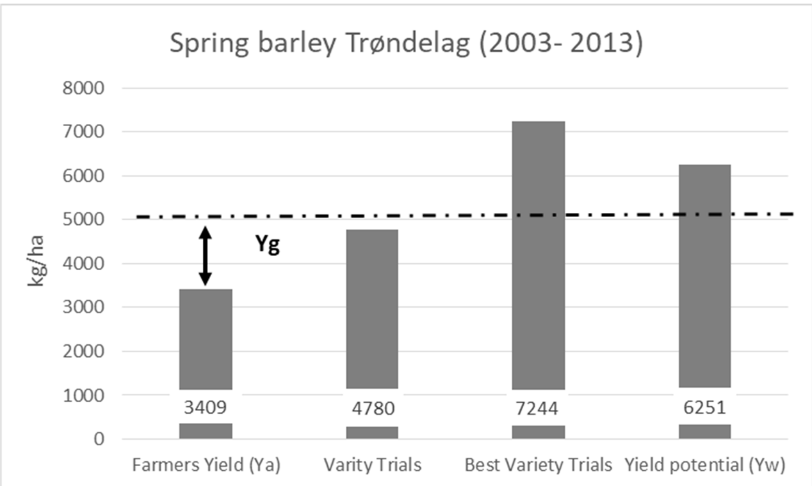

Figure 13. **Farmers yield (Ya), average yields from variety trials, average yields from the best yielding variety trials and calculated yield potential (Yw) for spring barley in the region Østlandet for the period 2003-2013 in kg/ha at 15% moisture. Dotted line is the exploitable yield, defined as 80% of the Yp. Exploitable yield gap make up the difference between exploitable yield and Ya.**

Comparison for spring barley between region Østlandet and Trøndelag:

The simulated Yw for spring barley was 6600 kg/ha for Østlandet and only slightly lower in Trøndelag, 6300 kg/ha. The calculated Yg was 2900 kg/ha for Østlandet and 2800 kg/daa for Trøndelag. The yields from the official variety trials were higher at Østlandet. The best variety trials were however highest in Trøndelag (7200 kg/ha) and exceeded Yw in some of the field trials. The variety trials also showed a larger variation in yield between seasons in Trøndelag compared to Østlandet (Appendix 11 and 12). The region Trøndelag, being the most northerly region with significant cereal production in Norway (64° N), normally has a cooler climate and higher precipitation during the growing season. Trøndelag also experiences more difficult weather conditions during harvesting due to more frequent precipitation, which can decrease quality as well as harvested yields. The lower temperatures in Trøndelag will normally give later maturity and later harvest. The lower temperatures affect phenological development and will cause longer duration of the development phases. However, the time to anthesis can partly be compensated for by photo-period responses, depending on the variety. The lower temperatures in Trøndelag will often give prolonged grain-filling and potentially larger grains. On the other hand, the region often challenged by more severe disease infestations due to the humid climate, that in many cases will reduce grain size and grain yield. However, in seasons with optimal growth conditions and with good management practice, it is possible to achieve high yields in the Trøndelag region, as these best variety trials have shown.

6.2 Yield gaps in the Nordic region

In context with the GYGA, yield gaps have been analyzed for other countries within the Nordic region (Table 4 and 5). This work has been done for winter wheat and spring barley, but not for spring wheat. While there was little difference between the yield potential (Yp) and water limited yield potential (Yw) in Norway during the research period, this difference seems to be of greater importance in some of the other countries (e.g. Denmark). In this comparison, Yg is therefore calculated as the difference between Yp and Ya rather than the difference between Yw and Ya as done in the previous section (6.1) (Table 4 and 5).

Table 4. Yield potential, actual yields and yield gaps for winter wheat for Denmark, Sweden, Finland* and Norway for the period 2003-2013. Total yield gap (Yg) as difference between Yp and Ya. Yp= yield potential, Yw= water limited yield potential, Y_{ex} = exploitable yield (www.yieldgap.org).**

2003-2013	Yp	Yw	Y_{ex} (80% of Yp)	Ya	Yg	total Yg %	Yg_{ex} %
Denmark	11.3	8.1	9.0	7.1	4.1	37	21
Sweden	11.0	8.7	8.7	6.2	4.7	43	29
Finland*	7.8	7.4	6.2	3.7	4.1	53	41
Norway**	10.1	9.4	7.5	4.6	4.7	51	38

**Finland combined 15% winter wheat, 85% spring wheat*

***Norway numbers from our own simulation (Table 3)*

Table 5. Yield potential, actual yields and yield gaps for spring barley for Denmark, Sweden, Finland and Norway for the period 2003-2013. Total yield gap (Yg) as difference between Yp and Ya. Yp= yield potential, Yw= water limited yield potential, Y_{ex} exploitable yield (www.yieldgap.org).

2003-2013	Yp	Yw	Y_{ex} (80% of Yp)	Ya	Yg	total Yg %	YG_{ex} %
Denmark	8.7	7.7	6.9	5.1	3.6	42	27
Sweden	7.4	6.8	5.9	4.4	3.0	40	25
Finland	7.1	6.7	5.6	3.5	3.5	50	38
Norway	6.7	6.4	5.3	3.7	3.0	44	31

As tables 4 and 5 show, Norway has the lowest yield potential and second lowest actual yields in both winter wheat and spring barley. This results in the second highest yield gap in the Nordic region for both types of cereals.

7 Discussion

Actual cereal yields are in general low in Norway compared to the European average, but they are also lower than in most of the other Nordic countries (Table 4). This is mostly due to a short growing season, unfavourable patterns of precipitation and the predominance of spring cereals (Seehusen et al. 2016). The variation in actual yields between years is large, and is due to variations in the weather conditions affecting the time of sowing and precipitation patterns in relation to plant water requirements as two important factors for yield performance. Results from this report show that yield improvements linked to plant breeding in spring wheat and spring barley have continuously increased, whereas actual yields have stagnated since 2000. This indicates that there is an unexploited potential to increase yields of wheat and barley in Norway.

7.1 Yield gap analyzes using GYGA methodology

Potential yields: Only minor differences were found between yield potential (Yp) and water limited yield (Yw) for both barley at Østlandet and Trøndelag and for spring wheat for the period 2003-2013. This difference is less pronounced than in some other Northern countries (Tables 4 and 5). This indicates that soil moisture in Norway has been sufficient to a large extent during this period with no severe droughts that would limit Yw.

As shown in section 5, simulations of Yp and Yw were performed for spring barley for the regions Østlandet and Trøndelag, and for spring and winter wheat at Østlandet. These simulations are based on the definition of climate zone according to the GYGA methodology to 1902 (growing degree days, aridity index, temperature seasonality) for both regions (Van Wart et al. 2013) . Furthermore, the simulations are based on phenological data from varieties that are grown in Norway and adapted to the climatic conditions. For barley, varieties of similar maturity class were used in the simulations for both regions, corresponding to the medium early maturity class. Also for spring wheat, the phenological data were based on the earlier varieties. As both regions were classified as being in the same climate zone, similar sowing dates were used for both regions in the simulations. This is a simplification made in order to be able to model potential yields according to the GYGA methodology, and which in this study may have given more similar results for the two regions.

Field trials and exploitable yield: The variety trials used to verify the results from the modelling were conducted in the same regions and time period (2003- 2013) and thus performed under the same seasonal weather conditions and with management similar to farm practice.

It is often found that variety trials give higher yield than farmer's yields (actual yield). This is mainly because trial plots are normally located on the best areas within the field, with minor variation in e.g. soil type, and because they are performed under conditions in which production factors are well controlled. Trial yields may in some cases be achieved at a relatively high input level and cost, which, transferred to farm level may incur undesirable environmental and economic costs (Knight et al. 2012). Furthermore, field trials often get more attention by farmers or research technicians than do "normal" fields, which may lead to better production conditions. On the other hand, advantages of new technology may be easier to obtain on a field under practical conditions than on small trial plots. As opposed to farmer practice, variety trials, such as the trials used in this study, are seldom treated against diseases, which may lead to lower trial yields (Strand 1994).

In any case, the results from the best yield trials approached the Yw values in several cases, indicating that the simulated Yw is expected to be of correct magnitude and therefore suitable to determine Yg. Furthermore, the comparison between the exploitable yield and the average results of the field trials (Figures 10-13) reveals that it should be possible for the best farmers to produce up to the exploitable yield in years with optimal growing conditions.

Differences in YG Norway:

Wheat: Winter wheat showed the highest Yg among the cereals studied, which is surprising. It should be noted, that the Ya data showed low yields in the period 2009-2013 (data not shown). This was evident for all the cereals, and in both regions for barley, but most pronounced for the winter wheat. The reasons cannot be fully explained but it has to be kept in mind that growing winter wheat can be challenging in Norway mostly due to difficult autumn conditions, which may lead to late sowing, problems with plant establishment and winter survival. This was also the case in many years between 2003 and 2013. In addition, the seasons were characterized by high and frequent precipitation, severe disease infestations, challenging harvest and also relatively poor grain quality.

It should be noted that significant increases in Ya of winter wheat were achieved in the seasons 2014 and 2015. In these seasons, several farmers achieved winter wheat yields of 10 tonnes/ ha, showing that winter wheat has a high yield potential also under Norwegian conditions. The fact that the best variety trials in wheat were on average only less than 10% lower than simulated Yw, or in some cases even approached Yw, indicates that it is possible to produce high wheat yields also under Norwegian climate conditions. In light of this, the (exploitable) Yg of at least 31% (spring wheat) found here seems to be high.

Barley: It is interesting to note that roughly similar levels were found for Østlandet and Trøndelag for both Yw and Ya, whereas the average of the official variety trials was higher at Østlandet. The average of the best variety trials were however highest in Trøndelag (6780 kg/ha), and approached and even exceeded Yw in some field trials. The variety trials showed a larger variation in yield between seasons in Trøndelag compared to Østlandet. The region Trøndelag normally has a cooler climate with higher precipitation during the growing season which can decrease the harvestable yields as well as the quality. The lower temperatures during tillering, ear differentiation and also grain-filling will prolong the duration of these phases and can increase the yield components number of grains/m^2 and grain weight. Thus, so long as varieties in the same maturity class are compared, and the harvesting conditions are good, similar or even higher Yw could be expected in Trøndelag compared to Østlandet, which support the GYGA simulation results.

Trends in Yg:

Due to the shortness of the period studied (2003-2013), it is difficult to identify any trends in yield gap. The genetic gains in yield due to new varieties have in the period 1992-2014 indicated yearly improvements from 0.5 % - 0.8 % per year. For barley, yield increases could be expected due to the release of the high-yielding barley varieties *Edel, Helium, Marigold* and in particular *Brage* and *Fairytale*. For the period 2003-2013, *Helium* increased its market share from 1.1% in 2007 to 22.5% in 2013. *Brage* and *Fairytale* were recently released and had not reached significant market shares until 2013. For spring wheat, *Zebra* released in 2002 was very high yielding, and only small yield increases were obtained in some of the later released varieties. Thus, it can be expected, that yield increases due to new varieties have had relatively low impact on the actual yields in the period 2003-2013. It could be expected however, that yield increases will appear in coming seasons with an increasing market share of newly released high-yieding varieties.

In Norway, there have recently (since 2013) been quite high cereal yields (exception 2018) (Appendix 19). During the years after 2013 the practical yields (Ya) have been higher than average for the period 2003-2013 in all years in both Østlandet and Trøndelag (exception 2015 in Trøndelag). There have been some years with favorable weather conditions for cereal production after 2013. This has led to early seeding in combination with good weather conditions throughout the growing season. This is also reflected in the results from the field trials, which also have been higher than before 2013. This supports the effect of good climate conditions.

A period of at least 10 years is suggested to give a representative choice of data including necessary yearly variation. Theoretically, the simulated yield potential (Yw) should therefore also be valid for future seasons as long as there are no exceeding variation compared to the input data. Such variation, possibly induced by e.g. climate change, could be earlier seeding or use of varities with a different growing phenology. If the yield gap for the recent years (after 2013) is calculated based on the simulated yield potential for the season 2003- 2013, the yield gap would have been reduced in recent years (Appendix 19).

Although there is indication for that the overall production trend is still negative (Berntsen et al. 2018), the recent yield increase implies that also small changes (e.g. agronomic changes) contribute to increased yields if the overall conditions are favorable. This is positive and should be a motivation to continue this effort.

Yield gap in Norway compared to other European countries:

The mean annual (total) yield gap for both wheat and barley has been described to be around 42% for the whole of Europe, but much less in North Western Europe (Schils et al. 2018). Our results show that the total Yg (difference between Yw and Ya) in Norway is between 3 % units (spring barley and spring wheat) and 9% units higher (winter wheat) than the European average (Table 3). It is also essentially higher (+15% units for spring barley, spring wheat and +21% units for winter wheat, table 3) than in Western Europe, where total Yg´s are on average expected to be below 30% (Schils et al. 2018). There is also evidence that the Yg in Norway is higher than in other Nordic countries (Tables 4 +5) (www.yieldgap.org).

When comparing YG in European production in general, it is important to consider the large heterogeneity of Europe`s agricultural landscape. Europe also has a wide geographic extent, comprising a variety of farm structures and intensities combined with pronounced differences in environmental conditions (Schils et al. 2018). There are also large structural and organizational differences in farm size and production intensity between the Nordic countries (Table 1), which may contribute to a higher production in our neighbouring countries. It is important to note that the result of the modelled yield potential is based on the availability, choice and quality of data that is used as input to the models (e.g. soil type, yield data), and that this may vary between countries.

7.2 Potential for increased Norwegian cereal production

The data presented in this report reveal a noteworthy potential to increase yields in Norway. This would be advantageous in different ways. Yield increase in the period between 1960 and 1990 was in large measure based on variety improvements, increased use of mineral fertilizer and chemical plant protection ('green revolution'). This would probably not be possible to the same extent today, mainly due to increased environmental focus and reduced profitability in cereal production. Closing the yield gap, also in Norway, is therefore mainly a question of improving input efficiency by a more precise application and a better exploitation of fertilizer and plant protection, by e.g. improving both timing and techniques for spreading or spraying rather than increasing input. Agronomic measures that have a positive effect on yields will often also have positive environmental effects, e.g. the avoidance of soil compaction, improved drainage and better exploitation of fertilizer (Uhlen et al. 2017). Higher yields per area could improve resource use efficiency and would be an important contribution to reduce the environmental footprint of cereal production in Norway (Korsaeth et al. 2014). This would also support the UN sustainable development goal Nr. 13 ('climate action') (https://sustainabledevelopment.un.org/#.). Simultaneously farmers and related industries would profit from higher yields. Higher profitability would give room for investments and the possibility to adopt more advanced production technologies. Investments and adaption of new strategies and technology could help to increase yields further and contribute to increased sustainability.

Higher national production would be an important step in securing food security and increase independency of the world market. The (exploitable) yield gap of ca. 30% presented in this study reveals a potential to reduce the amount of 30% grain import for human consumption and feed grain in Norway (section 2), but also to fulfill the political aim of increasing cereal yields by at least 20% within the year 2030 .

Yield gap analyses focus on the total yield, described as kg ha^{-1} (Van Ittersum et al. 2013) (Figure 8 and 9). Even if the data presented in this report reveal a potential for increased self- sufficiency in Norway, it will not be possible to compensate for all cereal import, mostly due to the need for high quality cereals for bread production (Eldby and Thuen 2016). However, higher yields are still favourable since cereals that are not suitable for the baking industry can be used as feed and thereby reduce the need for import of cereal and other forage crops.

In order to close the yield gap, it is important to determine the limitations in Norwegian cereal production. Several recent reports have described trends in cereal production and possibilities to increase cereal yields in Norway e.g. (Hoel et al. 2013, Vagstad et al. 2013, Arnoldussen et al. 2014). There are many ongoing field trials and data on the effects of fertilizer, plant protection etc. on yields, but there has until now, not been any quantitative analysis of the reasons for stagnating yields and YG in Norway. The most recent Norwegian report (Uhlen et al. 2017) summarized several agronomic factors and their assumed influence on yield. This study assumes a potential yield increase of 24%, mostly by reducing agronomic constraints such as soil compaction, poor drainage and poor crop rotation.

Earlier studies (Hoel et al. 2013, Vagstad et al. 2013, López Porrero 2016) show an unrevealed potential in improving both socio-economic factors (e.g. education, motivation and income) and technical factors. It should be noted that the difference between Ya and Yg_{ex} (Figure 9) indicates the exploitable yield gap under prevailing socio-economic conditions (Hengsdijk and Langeveld 2009). The exploitable yield, described as 80% of the yield potential, could be changed to a certain extent by e.g. changing legislation, reducing price for input factors or improving farmer incomes. A closure of the current yield gap therefore needs a more complete approach by taking into consideration both agronomical, organizational, technical and socio-economic factors.

8 Conclusion

In this report potential yields and yield gaps in Norwegian cereal production of spring, winter wheat and spring barley using GYGA methodology are calculated. Results are published on the GYGA website. Comparatively large Ygs were found for all cereals. These are essentially higher than in Western Europe and in most other Nordic countries. This reveals a potential to improve yields and close Yg by increasing yields on existing arable land in Norway. Higher yields and an increased exploitation of input factors could increase profitability and improve farmer incomes. This may strengthen cereal production in Norway and give room for investments in modern technology. This again may further increase yields and reduce negative environmental effects. Nevertheless, closing the yield gap is an ambitious aim, which needs serious investments in research but also political adjustments to unlock the unrevealed potential. Further studies over a longer period would therefore be of interest, in order to reveal trends in Yg over time. It will be important to further estimate the reasons for the comparatively high Yg in Norway, but also to support and guide farmers with the aim of closing the yield gap.

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Appendix: Keydata

Appendix 1. Barley yields (early varieties) from variety trials 1992 – 2014 in Trøndelag. Data are based on Åssveen et al. (2003, 2015), given in kg/daa, and are used for calculations of yield improvements due to release of new varieties. Check varieties are marked in bold.

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	
Arve	**457**	**440**	**381**	**368**	**388**	**412**	**384**	**418**	**387**	**326**	**492**	
Thule	484	431	358	316	338	396	392	410	391	293	487	
Olsok	448	422	385	353	404	408	399	414	402	323	472	
Olve	448	370	324	313	345	363	346	368	375	297		
Gaute				353	411	428	415	464	430	368	492	
Lavrans					458	400	407	414	402	333	472	
Ven					427	391	415	451	441	333	522	
Tiril										**352**	**457**	
Heder												
Edel												
Brage												

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Arve	**386**	**466**										
Thule												
Olsok	417	471										
Olve												
Gaute												
Lavrans	421	438										
Ven	417	452										
Tiril	**425**	**466**	**427**	**522**	**422**	**551**	**442**	**376**	**392**	**497**	**438**	**525**
Heder		452	427	480	430	534	455	395	443	477	464	536
Edel				475	452	557	433	432	404	502	447	525
Brage					452	584	473	402	435	517	486	546

Appendix 2. Barley yields (late varieties) from variety trials 1992 – 2014 in Trøndelag. Data are based on Åssveen et al. (2003, 2015), given in kg/daa, and are used for calculations of yield improvements due to release of new varieties. Check varieties are marked in bold.

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	
Tyra	**455**	**431**	**355**	**339**	**421**	**439**	**388**	**441**	**423**	**352**	**494**	
Sunnita		418	351	346	417	479	380	428	427	366	464	
Thule		457	391	349	425	483	404	441	431			
Olve			351	349	400	439	372	392	406		440	
Iver							392	467	423	370	484	
Edel									478	380	529	
Helium												
Marigold												
Fairytail												

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Tyra	**475**	**461**	**424**	**483**	**562**	**551**	**463**	**443**	**430**	**440**	**429**	**584**
Sunnita	451											
Thule												
Olve												
Iver	489	475	449	483	556	579	472	425	452	462	433	596
Edel	523	530	513	570	573	617	458	505	400	502	446	526
Helium				478	534	606	505	430	477	484	498	596
Marigold				502	573	612	472	412	499	506	506	619
Fairytail									520	493	489	637

Appendix 3. Barley yields (early varieties) from variety trials 1992 – 2014 at Østlandet. Data are based on Åssveen et al. (2003, 2015), given in kg/daa, and are use for calculations of yield improvements due to release of new varieties. Check varieties are marked in bold.

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	
Arve	513	575	507	512	545	548	523	511	487	511	462	
Olsok	472	541	466	497	550			480	472	491	462	
Ven					600	564	554	552	521	511	439	
Lavrans					529	564	513	531	482	511	490	
Edel								583	550	547	485	
Tiril										537	485	
Heder												
Brage												
Tyra	**427**	**554**	**428**	**479**	**602**	**577**	**563**	**585**	**523**	**566**	**455**	

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Arve	472	533	535	517	555							
Olsok	458	522	540	527	511							
Ven	486	517	567	558	549							
Lavrans	505	506	535	522	572							
Edel	614	721	654	595	550	601	471	512	374	461	468	562
Tiril	496	512	544	536	550	578	481	522	445	480	450	516
Heder			598	536	561	578	495	543	490	475	477	562
Brage					600	653	524	559	463	538	477	578
Tyra	**534**	**638**	**554**	**522**	**467**	**642**	**494**	**494**	**459**	**463**	**488**	**547**

Appendix 4. Barley yields (late varieties) from variety trials 1992 – 2014 at Østlandet. Data are based on Åssveen et al. (2003, 2015), given in kg/daa, and are used for calculations of yield improvements due to release of new varieties. Check varieties are marked in bold.

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Tyra	**427**	**554**	**428**	**479**	**602**	**577**	**563**	**585**	**523**	**566**	**455**
Sunnita	418	548	415	469	578	571	501	556	518	526	501
Kinnan	418	587	428	517	602	571	552	573	539	566	501
Thule		587	437	508	620	589	563	614	570		
Iver							586	585	549	583	487
Helium							586	585	549	583	487
Marigold											
Fairytail											

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Tyra	**534**	**638**	**554**	**522**	**467**	**642**	**494**	**494**	**459**	**463**	**488**	**547**
Sunnita	513	612	532	501	467							
Kinnan	539	612	560	506	509							
Thule												
Iver	539	657	571	532	472	629	504	514	454	463	493	558
Helium	539	657	632	538	532	642	514	484	487	477	493	629
Marigold				564	551	661	519	524	491	500	566	629
Fairytail									519	509	537	624

Appendix 5. Yields of spring wheat from variety trials 1992 – 2014 at Østlandet. Data are based on Åssveen et al. (2003,2015), given in kg/daa, and are used for calculations of yield improvements due to release of new varieties. Check varieties are marked in bold.

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Avle	391	534	453	571	597	550	613	597	515	527	462
Bastian	**364**	**470**	**403**	**508**	**519**	**545**	**484**	**496**	**443**	**495**	**420**
Vinjett			412	640	639	627	644	609	572	580	550
Zebra						594		615	592	574	582
Bjarne								591	530	553	499
Demonstrant											
Krabat											
Mirakel											
Rabagast											

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Avle												
Bastian	**461**	**460**	**575**	**425**	**439**	**509**						
Vinjett												
Zebra	597	603	617	529	506	619	462	588	503	543	557	503
Bjarne	524	548	593	477	477	553	405	**520**	**412**	**468**	**489**	**457**
Demonstrant			635	510	534	647	474	572	470	548	538	526
Krabat					506	597	458	562	457	524	528	526
Mirakel							474	572	461	571	528	512
Rabagast								556	420	510	523	503

Appendix 6. Improvements in yields versus year of release for new varieties. Calculations is based on variety trials in spring wheat and barley during the period 1992 – 2014.

Cereal	Region	Variety trials	Linear regression equation (relative yield vs year of release)	R^2
Spring barley	Trøndelag	Early varieties, Trøndelag 1992-2014	Y = 0,543x - 985	0,43
Spring barley	Trøndelag	Late varieties, Trøndelag 1992-2014	Y = 0,627x - 1150	0,68
Spring barley	Østlandet	Early varieties, Østlandet 1992-2014	Y = 0,542x - 980	0,70
Spring barley	Østlandet	Late varieties, Østlandet 1992-2014	Y = 0,462x - 818	0,83
Spring wheat	Østlandet	Østlandet 1992-2014	Y = 0,811x - 1506	0,58

Appendix 7: Phenological data for barley 2003 – 2013 used for in the GYGA simulations. Data include dates for sowing, emergence, heading and yellow ripening, given as date and day number. Date of sowing is based on empirical data, while date of emergence, heading/anthesis and yellow ripeness is calculated from growth model (Bleken, unpublished).

			Sowing		Emergence		Heading			Yellow ripeness	
Location	Region	Year	Day no	Date	Day no	Date	Day No	Date		Day no	Date
Kvithamar	Trøndelag	2003	136	15.mai	147	26.mai	192	10.jul		222	09.aug
Kvithamar	Trøndelag	2004	117	26.apr	128	07.mai	183	01.jul		221	08.aug
Kvithamar	Trøndelag	2005	128	07.mai	144	23.mai	191	09.jul		231	18.aug
Kvithamar	Trøndelag	2006	131	10.mai	145	24.mai	192	10.jul		227	14.aug
Kvithamar	Trøndelag	2007	127	06.mai	142	21.mai	186	04.jul		221	08.aug
Kvithamar	Trøndelag	2008	118	27.apr	129	08.mai	180	28.jun		217	04.aug
Kvithamar	Trøndelag	2009	127	06.mai	140	19.mai	187	05.jul		223	10.aug
Kvithamar	Trøndelag	2010	133	12.mai	145	24.mai	195	13.jul		231	18.aug
Kvithamar	Trøndelag	2011	127	06.mai	137	16.mai	184	02.jul		221	08.aug
Kvithamar	Trøndelag	2012	129	08.mai	143	22.mai	192	10.jul		236	23.aug
Kvithamar	Trøndelag	2013	138	17.mai	146	25.mai	190	08.jul		231	18.aug
Bye/Kolsrud	Østlandet	2003	133	12.mai	147	26.mai	192	10.jul		222	09.aug
Bye/Kolsrud	Østlandet	2004	127	06.mai	138	17.mai	190		08.jul	225	12.aug
Bye/Kolsrud	Østlandet	2005	127	06.mai	143	22.mai	192		09.jul	226	13.aug
Bye/Kolsrud	Østlandet	2006	133	12.mai	148	27.mai	192		09.jul	221	08.aug
Bye/Kolsrud	Østlandet	2007	124	03.mai	138	17.mai	185		03.jul	221	08.aug
Bye/Kolsrud	Østlandet	2008	129	08.mai	143	22.mai	190		08.jul	225	12.aug
Bye/Kolsrud	Østlandet	2009	129	08.mai	142	21.mai	188		06.jul	225	12.aug
Bye/Kolsrud	Østlandet	2010	129	08.mai	143	22.mai	191		09.jul	225	12.aug
Bye/Kolsrud	Østlandet	2011	122	30.apr	135	14.mai	185		03.jul	219	06.aug
Bye/Kolsrud	Østlandet	2012	126	05.mai	142	21.mai	190		08.jul	229	16.aug
Bye/Kolsrud	Østlandet	2013	133	12.mai	144	23.mai	191		09.jul	223	10.aug
Ås	Østlandet	2003	114	23.apr	131	10.mai	181	29.jun		212	30.jul
Ås	Østlandet	2004	111	20.apr	125	04.mai	176	24.jun		205	23.jul
Ås	Østlandet	2005	113	22.apr	129	08.mai	183	01.jul		223	10.aug
Ås	Østlandet	2006	124	03.mai	133	12.mai	183	01.jul		214	01.aug
Ås	Østlandet	2007	100	09.apr	117	26.apr	170	18.jun		199	17.jul

Ås	Østlandet	2008	122	01.mai	132	11.mai	181	29.jun	221	08.aug
Ås	Østlandet	2009	120	29.apr	133	12.mai	182	30.jun	216	03.aug
Ås	Østlandet	2010	116	25.apr	134	13.mai	183	01.jul	215	02.aug
Ås	Østlandet	2011	119	28.apr	132	11.mai	182	30.jun	215	02.aug
Ås	Østlandet	2012	118	27.apr	133	12.mai	183	01.jul	216	03.aug
Ås	Østlandet	2013	137	16.mai	145	24.mai	191	09.jul	222	09.aug
Øsaker	Østlandet	2003	113	22.apr	130	09.mai	180	28.jun	211	29.jul
Øsaker	Østlandet	2004	122	01.mai	131	10.mai	182	30.jun	223	10.aug
Øsaker	Østlandet	2005	112	21.apr	128	07.mai	182	30.jun	213	31.jul
Øsaker	Østlandet	2006	128	07.mai	137	16.mai	185	03.jul	215	02.aug
Øsaker	Østlandet	2007	99	08.apr	116	25.mai	168	16.jun	203	21.jul
Øsaker	Østlandet	2008	121	30.apr	131	10.mai	179	27.jun	215	02.aug
Øsaker	Østlandet	2009	117	26.apr	128	07.mai	179	27.jun	210	28.jul
Øsaker	Østlandet	2010	113	22.apr	131	10.mai	181	29.jun	214	01.aug
Øsaker	Østlandet	2011	118	27.apr	130	09.mai	179	27.jun	213	31.jul
Øsaker	Østlandet	2012	127	05.mai	141	20.mai	188	06.jul	228	15.aug
Øsaker	Østlandet	2013	142	21.mai	151	30.mai	196	14.jul	226	13.aug

Appendix 8. Phenological data for spring wheat 2003 – 2013 used for in the GYGA simulations. Data include dates for sowing, emergence, heading and yellow ripening, given as date and day number. Date of sowing is based on empirical data, while date of emergence, heading/anthesis and yellow ripeness is calculated from growth model (Bleken, unpublished).

			Sowing		Emergence		Heading		Anthesis		Yellow ripeness	
Location	Region	Year	Day no	Date	Day no	Date	Day No	Date	Day No	Date	Day no	Date
Bye/Kolsrud	Østlandet	2003	133	12.mai	147	26.mai	193	11.jul	196	14.jul	227	14.aug
Bye/Kolsrud	Østlandet	2004	127	06.mai	138	17.mai	194	12.jul	198	16.jul	234	21.aug
Bye/Kolsrud	Østlandet	2005	127	06.mai	143	22.mai	194	12.jul	196	14.jul	236	23.aug
Bye/Kolsrud	Østlandet	2006	133	12.mai	148	27.mai	193	11.jul	196	14.jul	227	14.aug
Bye/Kolsrud	Østlandet	2007	124	03.mai	138	17.mai	188	06.jul	191	09.jul	230	17.aug
Bye/Kolsrud	Østlandet	2008	129	08.mai	143	22.mai	193	11.jul	196	14.jul	235	22.aug
Bye/Kolsrud	Østlandet	2009	129	08.mai	142	21.mai	191	09.jul	194	12.jul	237	24.aug
Bye/Kolsrud	Østlandet	2010	129	08.mai	143	22.mai	194	12.jul	197	15.jul	234	21.aug
Bye/Kolsrud	Østlandet	2011	122	30.apr	135	14.mai	188	06.jul	191	09.jul	229	16.aug
Bye/Kolsrud	Østlandet	2012	126	05.mai	142	21.mai	193	11.jul	197	15.jul	240	27.aug
Bye/Kolsrud	Østlandet	2013	133	12.mai	144	23.mai	193	11.jul	197	15.jul	232	19.aug
Ås	Østlandet	2003	114	23.apr	131	10.mai	183	01.jul	187	05.jul	219	06.aug
Ås	Østlandet	2004	111	20.apr	125	04.mai	180	28.jun	183	01.jul	224	11.aug
Ås	Østlandet	2005	113	22.apr	129	08.mai	187	05.jul	190	08.jul	226	13.aug
Ås	Østlandet	2006	124	03.mai	133	12.mai	186	04.jul	189	07.jul	219	06.aug
Ås	Østlandet	2007	100	09.apr	117	26.apr	175	23.jun	179	27.jun	223	10.aug
Ås	Østlandet	2008	122	01.mai	132	11.mai	184	02.jul	187	05.jul	223	10.aug
Ås	Østlandet	2009	120	29.apr	133	12.mai	184	02.jul	186	04.jul	224	11.aug
Ås	Østlandet	2010	116	25.apr	134	13.mai	186	04.jul	189	07.jul	226	13.aug
Ås	Østlandet	2011	119	28.apr	132	11.mai	184	02.jul	187	05.jul	222	09.aug
Ås	Østlandet	2012	118	27.apr	133	12.mai	187	05.jul	190	08.jul	232	19.aug
Ås	Østlandet	2013	137	16.mai	145	24.mai	192	10.jul	196	14.jul	230	17.aug
Øsaker	Østlandet	2003	113	22.apr	130	09.mai	183	01.jul	186	04.jul	228	15.aug
Øsaker	Østlandet	2004	122	01.mai	131	10.mai	186	04.jul	190	08.jul	229	16.aug
Øsaker	Østlandet	2005	112	21.apr	128	07.mai	187	05.jul	189	07.jul	228	15.aug

Øsaker	Østlandet	2006	128	07.mai	137	16.mai	187	05.jul	190	08.jul	222	09.aug
Øsaker	Østlandet	2007	99	08.apr	116	25.mai	173	21.jun	176	24.jul	220	07.aug
Øsaker	Østlandet	2008	121	30.apr	131	10.mai	182	30.jun	185	03.jul	223	10.aug
Øsaker	Østlandet	2009	117	26.apr	128	07.mai	182	30.jun	184	02.jul	223	10.aug
Øsaker	Østlandet	2010	113	22.apr	131	10.mai	184	02.jul	188	06.jul	225	12.aug
Øsaker	Østlandet	2011	118	27.apr	130	09.mai	182	30.jul	185	03.jul	221	08.aug
Øsaker	Østlandet	2012	127	05.mai	141	20.mai	190	08.jul	194	12.jul	241	28.aug
Øsaker	Østlandet	2013	142	21.mai	151	30.mai	197	15.jul	200	18.jul	238	25.aug

Appendix 9. Phenological data for winter wheat 2003 – 2013 used for in the GYGA simulations. Data include dates for heading and yellow ripening, given as date and day number. Data are based on recordings from field trails at Østlandet.

Year	Heading day no	Heading date	YR day no	YR data
2003	171	19.jun	216	03.aug
2004	164	12.jun	209	27.jul
2005	173	21.jun	219	06.aug
2006	175	23.jun	218	05.aug
2007	162	11.jun	213	31.jul
2008	164	12.jun	214	01.aug
2009	171	19.jun	218	05.aug
2010	178	26.jun	224	11.aug
2011	164	12.jun	213	31.jul
2012	169	17.jun	224	11.aug
2013	174	22.jun	221	08.aug

Appendix 10. Yield data (average farm yields) for spring and winter wheat (special report from SSB, unpublished).

Year	Spring wheat Kg/ha	Winter wheat Kg/ha
2003	4330	4990
2004	4255	5202
2005	4690	5307
2006	3873	4773
2007	4160	4881
2008	4449	5614
2009	3384	3486
2010	4307	5144
2011	3860	3644
2012	4144	4219
2013	3871	3858
Mean	4120	4647

Appendix 11. Average farm yields and yields from variety trials compared to simulated water-limited yield potential for spring wheat at Østlandet. Data are given in kg/ha at 15% moisture.

Year	Average farm yield	Bjarne	Zebra	Mean varieties[1]	Best Variety trials[2]	Yw
2003	4330	5240	5970	5605		7063
2004	4255	5480	6030	5755		6870
2005	4690	5930	6170	6050		6983
2006	3873	4770	5290	5030	5620	6979
2007	4160	4770	5060	4915	6130	7984
2008	4449	5530	6190	5860	7740	8124
2009	3384	4050	4620	4335	6350	7640
2010	4307	5200	5880	5540	7200	7199
2011	3860	4120	5030	4575	6470	7955
2012	4144	4680	5430	5055	7760	8240
2013	3871	4890	5570	5230	6860	7159
Mean	4120			5268	6766	7472

[1] *Average yield of the varieties Bjarne and Zebra, dominating at Østlandet in 2003-2013.* [2] *Average yield from the most high-yielding (best) variety trials, given as averages of all varieties included.*

Appendix 12. Average farm yields and yields from variety trials compared to simulated water-limited yield potential for winter wheat at Østlandet. Data are given in kg/ha at 15% moisture.

Year	Ya	Magnifik	Olivin	Finans	Ellvis	Variety trial	Best variety trial	Yw
2003	4990	6998	7190			7094		8009
2004	5202	7314	7176	7245		7245		10316
2005	5307	6373	6439	6373		6395		8081
2006	4773	7109	6973	7244		7109		8351
2007	4881	6220	5722	6220		6054	8280	10228
2008	5614	7980	8379	8618		8326	10420	10875
2009	3486	4579	4386	5109	4531	4760	7600	8087
2010	5144	5880	5940	5640	6180	5920	8880	8986
2011	3644	4451	4023	3938	4580	4301		10205
2012	4219		6053	6240	6739	6343	8290	11302
2013	3858	3914	5811	5041	6108	5548		9075
Mean	4647					6281	8690	9411

Appendix 13. Barley Yield data (average farm yield). Data from the main barley producing counties, and calculated averages for the regions Østlandet and Trøndelag.

Year	S-Trøndelag	N-Trøndelag	Trøndelag	Østfold	Buskerud	Vestfold	Telemark	Akershus	Hedmark	Oppland	Østlandet
2003	3620	3220	3420	3320	3560	3650	2970	3270	4090	3690	3597
2004	3890	3680	3785	4310	3980	4000	3720	4470	4990	4300	4342
2005	3520	2880	3200	3960	3570	3950	3290	3660	4030	3660	3805
2006	3760	3390	3575	3710	2880	3420	3090	3350	3990	3000	3392
2007	3160	2490	2825	3550	3030	3320	2540	3650	4510	3890	3658
2008	4420	4070	4245	4320	3670	4120	3640	4220	4760	4160	4208
2009	3610	3380	3495	3690	2930	3450	3010	3240	3590	3320	3370
2010	3330	2640	2985	4410	3880	4680	4050	3750	4130	3650	4083
2011	3160	3040	3100	3740	2870	3590	2130	3520	3630	3010	3393
2012	3540	3930	3735	3830	3430	3690	3350	3080	4020	3670	3620
2013	3080	3190	3135	3130	3150	2870	2370	3060	3920	3060	3198
Mean	3554	3265	3409	3815	3359	3704	3105	3570	4151	3583	3697

Appendix 14. Average farm yields and yields from variety trials compared to simulated water-limited yield potential for barley at Østlandet. Data are given in kg/ha at 15% moisture.

Year	Average farm yield	Tiril	Tyra	Helium	Mean varieties[1]	Best varity trials[2]	Yw
2003	3597	4960	5340	5390	5230		6441
2004	4342	5120	6380	6570	6023		5455
2005	3805	5440	5540	6310	5763		6226
2006	3392	5360	5220	5370	5317	6780	6266
2007	3658	5500	4670	5320	5163	6390	7064
2008	4208	5780	6420	6420	6207	7540	7299
2009	3370	4810	4940	5140	4963	5960	6870
2010	4083	5220	4940	4840	5000	7510	6562
2011	3393	4450	4590	4860	4633	6260	7092
2012	3620	4800	4630	4760	4730	6550	7443
2013	3198	4500	4880	4920	4767	6440	6072
Mean	3697	5085	5232	5445	5254	6679	6617

[1] Average yield of the varieties Tiril, Tyra and Helium, dominating at Østlandet in 2003-2013. [2] Average yield from the most high-yielding (best) variety trials, given as averages of all varieties included.

Appendix 15. Average farm yields and yields from variety trials compared to simulated water-limited yield potential for barley in Trøndelag. Data are given in kg/ha at 15% moisture.

Year	Average farm yield	Tyra	Tiril	Edel	Mean varieties[1]	Best variety trials[2]	Yw
2003	3420	475	425	523	4743		5704
2004	3785	461	466	530	4857		5744
2005	3200	424	427	513	4547		5818
2006	3575	483	522	569	5247		6258
2007	2825	562	422	573	5190	6490	6332
2008	4245	551	551	617	5730	7840	6551
2009	3495	463	442	458	4543	7040	6202
2010	2985	443	376	505	4413	8880	6087
2011	3100	430	392	400	4073	6970	7060
2012	3735	440	497	502	4797	8250	6820
2013	3135	429	438	466	4443	5240	6185
Mean	3409				4780	7244	6251

[1] Average yield of the varieties Tyra, Tiril and Edel, dominating in Trøndelag in 2003-2013. [2] Average yield from the most high-yielding (best) variety trials, given as averages of all varieties included.

Appendix 16. Yearly simulations of potential yield (Yp) and water limited potential yield (Yw) based on GYGA methodology for spring wheat. Climate zone, weather station code and phenological data are given.

SIM_SPRING_WHEAT_STAT_YEAR											
COUNTRY_NAME	CZ[1]	STATCODE[2]	Yr[3]	DOP[4]	DOE[5]	DOA[6]	DOM[7]	Yp	Yw	Yp (15% moisture)	Yw (15% moisture)
Norway	1902	NOR066	2003	119	135	187	222	6059	6004	7128	7063
Norway	1902	NOR066	2004	119	129	188	226	6305	5839	7418	6870
Norway	1902	NOR066	2005	119	134	191	231	6300	5935	7412	6983
Norway	1902	NOR066	2006	119	131	186	220	6320	5932	7435	6979
Norway	1902	NOR066	2007	119	131	186	226	6786	6786	7984	7984
Norway	1902	NOR066	2008	119	129	186	225	6913	6905	8133	8124
Norway	1902	NOR066	2009	119	131	186	227	6509	6494	7658	7640
Norway	1902	NOR066	2010	119	137	190	228	6121	6119	7201	7199
Norway	1902	NOR066	2011	119	132	186	225	6761	6762	7954	7955
Norway	1902	NOR066	2012	119	135	193	235	7004	7004	8240	8240
Norway	1902	NOR066	2013	119	133	186	223	6737	6086	7926	7159
Mean 2003-13								6529	6352	7681	7472

[1] Climate zone, defined by GYGA, [2] Code for weather station; NORD066 = Oslo, [3] Year, [4] Day of planting, [5] Day of emergence, [6] Day of anthesis, [7] Day of maturity

Phenological data are gives as day number from 1. of January.

Appendix 17. Yearly simulations of potential yield (Yp) and water limited potential yield (Yw) based on GYGA methodology for winter wheat. Climate zone, weather station code and phenological data are given.

SIM_WINTER_WHEAT_STAT_YEAR									
COUNTRY_NAME	CZ	STATCODE	Yr	DOA	DOM	Yp	Yw	Yp (15% moisture)	Yw (15% moisture)
Norway	1902	NOR066	2003	171	216	7334	6808	8628	8009
Norway	1902	NOR066	2004	154	209	9254	8769	10887	10316
Norway	1902	NOR066	2005	173	219	8315	6869	9782	8081
Norway	1902	NOR066	2006	175	218	8171	7098	9613	8351
Norway	1902	NOR066	2007	162	213	9134	8694	10746	10229
Norway	1902	NOR066	2008	164	214	9988	9244	11751	10875
Norway	1902	NOR066	2009	171	218	7956	6874	9360	8087
Norway	1902	NOR066	2010	178	224	7935	7638	9335	8986
Norway	1902	NOR066	2011	164	213	8670	8674	10200	10205
Norway	1902	NOR066	2012	169	224	9592	9607	11285	11302
Norway	1902	NOR066	2013	174	221	8361	7717	9836	9079
						8610	7999	10129	9411

[1] Climate zone, defined by GYGA, [2] Code for weather station; NORD066 = Oslo, [3] Year, [4] Day of planting, [5] Day of emergence, [6] Day of anthesis, [7] Day of maturity

Phenological data are gives as day number from 1. of January.

Appendix 18. Yearly simulations of potential yield (Yp) and water limited potential yield (Yw) based on GYGA methodology for spring barley. Climate zone, weather station code and phenological data are given.

SIM_SPRING_BARLEY_STAT_YEAR											
COUNTRY_NAME	CZ	STATCODE	Yr	DOP	DOE	DOA	DOM	Yp	Yw	Yp (15% moisture)	Yw (15% moisture)
Norway	1902	NOR027	2003	127	138	186	219	5038	4848	5927	5704
Norway	1902	NOR027	2004	127	134	193	228	5139	4882	6046	5744
Norway	1902	NOR027	2005	127	142	190	231	5386	4945	6336	5818
Norway	1902	NOR027	2006	127	137	189	225	5564	5320	6546	6258
Norway	1902	NOR027	2007	127	140	186	223	5528	5382	6504	6332
Norway	1902	NOR027	2008	127	136	187	224	5897	5568	6938	6551
Norway	1902	NOR027	2009	127	137	186	222	5277	5272	6208	6202
Norway	1902	NOR027	2010	127	139	192	228	5178	5174	6092	6087
Norway	1902	NOR027	2011	127	133	184	221	6001	6001	7060	7060
Norway	1902	NOR027	2012	127	138	190	231	5797	5797	6820	6820
Norway	1902	NOR027	2013	127	135	178	216	5257	5257	6188	6185
Mean		Trøndelag						5460	5313	6424	6251
Norway	1902	NOR066	2003	127	139	187	222	5536	5475	6513	6441
Norway	1902	NOR066	2004	127	134	189	226	5296	4636	6231	5455
Norway	1902	NOR066	2005	127	141	191	230	5572	5292	6555	6226
Norway	1902	NOR066	2006	127	135	186	219	5735	5326	6747	6266
Norway	1902	NOR066	2007	127	140	188	227	6004	6005	7064	7064
Norway	1902	NOR066	2008	127	135	187	225	6204	6204	7299	7299
Norway	1902	NOR066	2009	127	138	186	226	5858	5839	6892	6870
Norway	1902	NOR066	2010	127	139	189	227	5579	5578	6564	6562
Norway	1902	NOR066	2011	127	135	185	222	6028	6028	7092	7092
Norway	1902	NOR066	2012	127	140	192	233	6326	6326	7442	7443
Norway	1902	NOR066	2013	127	137	185	221	6027	5161	7091	6072
Mean		Østlandet						5833	5625	6863	6617

[1] Climate zone, defined by GYGA, [2] Code for weather station; NORD066 = Oslo, [3] Year, [4] Day of planting, [5] Day of emergence, [6] Day of anthesis, [7] Day of maturity

Phenological data are gives as day number from 1. of January.

Appendix 19. Results from field trials and practical yields for barley for the recent years in relation to trial period.

Barley Østlandet	2003-2013	2014	2015	2016	2017	2018	2019
Yp (2003-2013)	729						
Yw (2003-2013)	661						
Yex	529						
Field trials	525	574	583	587	591	431	600
Ya	370	437	474	487	457		
Yg total	292						
%	44						
Yg ex	156						
%	30						
Barley Trøndelag	2003-2013	2014	2015	2016	2017	2018	2019
Yp (2003-2013)	679						
Yw (2003-2013)	625						
Yex	500						
Field trials	478	566	548	520	505	404	564
Ya	341	398	322	416	364		
Yg total	284						
%	45						
Yg ex	130						
%	32						

Yield from field trials from variety trials (Nape 1103) and Ya from Randby 2019 https://www.fylkesmannen.no/nb/vestfold-og-telemark/landbruk-og-mat/jordbruk/

NIBIO
NORSK INSTITUTT FOR
BIOØKONOMI

Norsk institutt for bioøkonomi (NIBIO) ble opprettet 1. juli 2015 som en fusjon av Bioforsk, Norsk institutt for landbruksøkonomisk forskning (NILF) og Norsk institutt for skog og landskap.

Bioøkonomi baserer seg på utnyttelse og forvaltning av biologiske ressurser fra jord og hav, fremfor en fossil økonomi som er basert på kull, olje og gass. NIBIO skal være nasjonalt ledende for utvikling av kunnskap om bioøkonomi.

Gjennom forskning og kunnskapsproduksjon skal instituttet bidra til matsikkerhet, bærekraftig ressursforvaltning, innovasjon og verdiskaping innenfor verdikjedene for mat, skog og andre biobaserte næringer. Instituttet skal levere forskning, forvaltningsstøtte og kunnskap til anvendelse i nasjonal beredskap, forvaltning, næringsliv og samfunnet for øvrig.

NIBIO er eid av Landbruks- og matdepartementet som et forvaltningsorgan med særskilte fullmakter og eget styre. Hovedkontoret er på Ås. Instituttet har flere regionale enheter og et avdelingskontor i Oslo.

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