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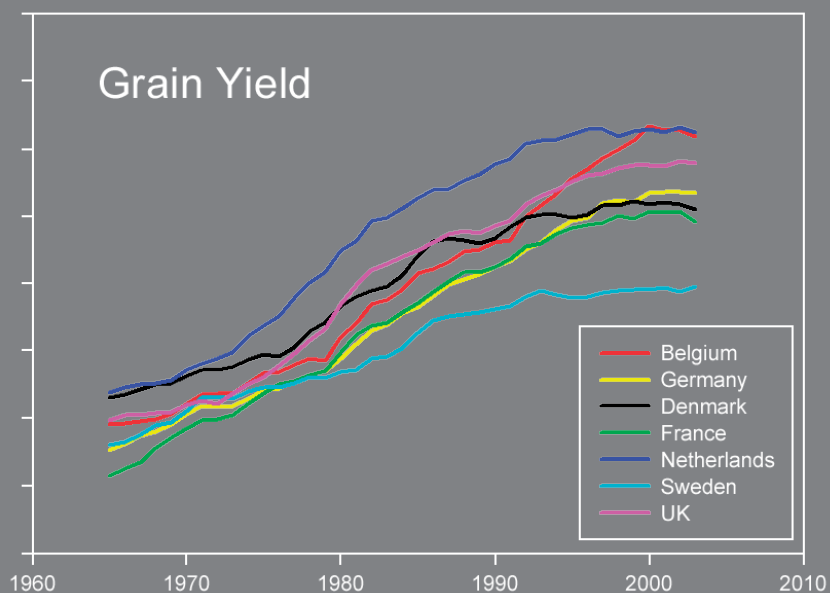
CAUSES OF YIELD STAGNATION IN WINTER WHEAT IN DENMARK

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Preface

This report is the result of a joint project between the Faculty of Agricultural Sciences (DJF), Aarhus University, and the Knowledge Centre for Agriculture at the Danish Agricultural Advisory Service (DAAS). The project was initiated by a workshop on 1st April 2008 which set the framework for the working groups. The outcome from the working groups was presented at the second workshop on 4th November 2008.

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Summary

The national grain yield of winter wheat in Denmark increased from 43 dt/ha in the 1960s to 71 dt/ha after 2000. However, the recent annual yield increase and the average national yield in Denmark are lagging behind trends in other north-western European countries (Belgium, France, Germany, the Netherlands and UK). This is a cause of concern, not only for the farmers in Denmark, but also for the society in general, since increasing grain yields is a precondition for further growth in agricultural production and exports.

The average annual yield increases of winter wheat in Denmark was 0.8 dt/ha during the past four decades, but the increase has been uneven, and close to zero particularly since the end of the 1990s. However, stagnating yields is not a Danish issue only, but a phenomenon that has been observed for the other north-western European countries since 2000.

The aim of this study was to identify changes in environmental conditions, breeding progress and agricultural practices that may explain the stagnating yields. The analyses included effect of soil type, climate and external factors, breeding and genetics, fertilization, crop protection, crop rotation, and farm management and technology. Technology was treated in relation to soil tillage and soil compaction, but also involved considerations on farm management. In general, the number of available dataset was limited, and the opportunity for analysis and interpretation of individual factors was often restricted by the impact on yield being affected by several simultaneous and inseparable factors.

Only a few factors were considered to have increased the yield potential, in particularly breeding, but several factors have had a negative impact on grain yield of winter wheat. Thus, the reduction in nitrogen fertilizer use and the way that this restriction has been imposed was estimated to reduce the yield. Animal manure being applied to a large part of the wheat area causes direct crop damages by trampling plus some yield reduction due to long-term soil compaction. There has been a trend towards a higher proportion of winter wheat in the crop rotations increasing the frequency of wheat after wheat, which cause increased risk of yield losses due to soil-borne diseases, e.g. take-all. An increase in use of reduced tillage systems is also assumed to have reduced grain yields. A reduction in general consumption of fungicides is assumed to largely outweigh the benefits of more efficient fungicides.

In total, these factors should have resulted in increases in grain yield of winter wheat of 2 to 10 dt/ha over the period 1990 to 2006, but the national grain yield of winter wheat only increased by approximately 3.1 dt/ha. This gap of up to 7 dt/ha between achieved and estimated yield increases may partly be explained by the low cereal grain prices during this period, which is likely to have reduced management intensity, in particular by reducing number of working hours and costs of consumables. However, owing to lack of data we were not able to account properly for such effects of management intensity. Annual yield increases may have failed due to the wider use of animal manures and implementation of statutory orders related

to protection of the environment causing suboptimal rates of these nutrient sources. Also the increased frequency of winter wheat cropping with a clear tendency to continuously cropping may be an overlooked issue as a poor crop rotation significantly increases the negative impact of pests (weeds, insects, fungus and viras).

Some of the estimated causes of yield losses will likely persist, in particular those related to reductions in nitrogen fertilizer rates, application of manure to a larger proportion of the wheat area and the higher frequency of wheat after wheat in the rotations. Once introduced such effects would not be expected to take place in the future, meaning that the annually yield increases caused by breeding should turn up more clearly in the national grain yields in the future. However, this requires a continuous effort on improving crop management at the farm level.

Sammendrag

I Danmark steg det gennemsnitlige udbytte af vinterhvede fra 43 hkg/ha i 1960'erne til 71 hkg/ha efter år 2000. Imidlertid er de årlige udbyttestigninger aftaget i de seneste år, og det gennemsnitlige udbytte i Danmark halter bagefter udviklingen i andre nordvesteuropæiske lande (Belgien, Frankrig, Tyskland, Holland og Storbritannien). Dette giver anledning til bekymring, ikke kun blandt danske landmænd, men også i samfundet generelt, da stigende kerneudbytte er en forudsætning for yderligere vækst i landbrugsproduktionen og eksporten.

De gennemsnitlige årlige udbyttestigninger i vinterhvede i Danmark har været 0,8 hkg/ha i løbet af de seneste fire årtier, men stigningen har været ujævn og tæt på nul især siden slutningen af 1990'erne. Dog er stagnerende udbytter ikke alene et dansk problem, men et fænomen, der også er observeret i de øvrige nordvesteuropæiske lande siden år 2000.

Formålet med denne undersøgelse var at identificere ændringer i miljøforholdene, forædling og dyrkningsmetoder, der kan forklare de stagnerende udbytter. Analyserne omfattede effekt af jordtype, klima og eksterne faktorer, forædling og genetik, gødskning, plantebeskyttelse, sædskifte, samt driftsmetoder og teknologi. Teknologi behandles primært i forhold til jordbearbejdning og jordpakning, men også i tilknytning til ændringer i driftsmetoder. Generelt var omfanget af tilgængelige datasæt begrænset, og muligheden for analyse og fortolkning af de enkelte faktorer var ofte begrænset, idet udbyttet ofte påvirkes af flere samtidige og uadskillelige faktorer.

Kun nogle få faktorer anses for at have øget udbyttepotentiale, primært fremgangen forårsaget af forædlingsarbejdet, mens flere faktorer har haft en negativ indvirkning på udviklingen af kerneudbytte af vinterhvede. Således kan der estimeres en udbyttereduktion som følge af implementering af reducerede normer for anvendelse af kvælstofgødning. Anvendelse af husdyrgødning til en stor del af hvedearealet forårsager direkte afgrødeskader som følge af kørsel plus indirekte udbyttetab på grund af langvarig jordpakning. Der har været en tendens øget dyrkning af hvede efter hvede, og den højere hyppighed af vinterhvede i sædskiftet øger risikoen for udbyttetab som følge af jordbårne sygdomme, f.eks. goldfodsyge. En øget anvendelse af reduceret jordbearbejdning antages også at have reduceret kerneudbyttet. En reduktion i det generelle forbrug af fungicider antages at stort set at opveje fordelene ved mere effektive fungicider.

Samlet set burde disse faktorer have resulteret i udbyttestigninger på 2 to 10 hkg/ha i perioden 1990 til 2006, men på landsplan steg kerneudbytte af vinterhvede kun med ca. 3,1 hkg/ha. Denne forskel på op til 7 hkg/ha mellem opnået og anslåede udbyttestigninger kan til dels forklares med lave kornpriser i denne periode, som sandsynligvis har reduceret dyrkningsintensiteten, navnlig ved at reducere antallet af arbejdstimer og omkostninger til hjælpematerialer. På grund af manglende data har vi ikke været i stand til at redegøre detaljeret for sådanne effekter af ændret dyrkningspraksis. Udeblivelse af årlige udbyttestigninger kan skyldes ud-

bredt anvendelse af husdyrgødning og gennemførelse af reguleringer til beskyttelse af miljøet, som kan have forårsaget suboptimal anvendelse af næringsstoffer i husdyrgødningen. Også den øgede frekvens af vinterhvede i sædskiftet med en klar tendens til ensidig korndyrkning kan være et overset problem, idet et dårligt sædskifte øger den negative virkning af skadedyr (ukrudt, insekter, svampe og vira).

Nogle af de anslåede årsager til stagnerende udbytter i vinterhvede vil sandsynligvis forblive permanente, navnlig effekten af reducerede kvælstofnormer, anvendelse af husdyrgødning på en større del af hvedearealet og højere frekvens af hvede efter hvede i sædskiftet. Effekten af disse tiltag forventes ikke at påvirke udbyttet yderligere fremover, hvilket giver en formodning om, at årlige udbyttestigninger på grundlag af forædlingsfremgang igen vil vise sig i udbyttet på landsplan. Dette kræver imidlertid en fortsat indsats for optimering af dyrkningstiltagene på bedriftsniveau.

1. Causes of winter wheat yield changes since 1990

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1.1 Introduction

The national grain yield of winter wheat in Denmark increased from 43 dt/ha in the 1960s to 71 dt/ha at the turn of the millennium (Chapter 2, Figure 2.1). Before 1970 the national yield in Denmark was comparable to the yield in the Netherlands and surpassed the yields in Belgium and the UK by 4 dt/ha, Germany by 8 dt/ha and France by 12 dt/ha. During the 1980s and 1990s growth in the Danish national yields lagged behind those of the other countries. Since the turn of the millennium the national yield of winter wheat in Denmark has been surpassed by yields in the Netherlands and Belgium by 11 dt/ha, have been overtaken by yields in Germany and the UK, and been caught up by the French national yields.

The average annual yield increase was 0.8 dt/ha from 1961 to 2007, but the increase has been uneven, and close to zero, particularly since the end of the 1990s. This is a cause of concern, not only for the farmers in Denmark, but also for society in general, since an increasing grain yield is a precondition for further growth in agricultural production of food, feed and bioenergy. However, stagnating yields are not a Danish issue only, but a phenomenon that has been observed in other North-west European countries since the late 1990s (Chapter 2, Figure 2.4).

The aim of this study was to identify changes in environmental conditions, breeding progress or agricultural practices that may explain the stagnating yields. The analyses include effects of soil type, climate and external factors, breeding and genetics, fertilization, crop protection, crop rotation, technology and farm management. Technology was treated in relation to soil tillage and soil compaction, but also involved considerations on farm management. In general, the number of available datasets was limited, and the opportunity for analysis and interpretation of individual factors was often restricted by the impact on yield being affected by several simultaneous and inseparable factors. None of the datasets available had been established with the purpose of answering the question raised. Some of the analyses in the report covered several decades, but in this chapter we restrict our summary of yield changes to the period since 1990.

1.2 Changes and impacts

The national winter wheat grain yields in Denmark increased by 0.18 dt/ha/year over the period 1990 to 2009, but this figure increased to 0.30 dt/ha/year, when yields were corrected for effects of climatic variation (Chapter 3). A similar analysis based on data from normally

treated plots from more than 6000 field experiments on winter wheat in Denmark over the period 1992 to 2008 showed climate-corrected yield annual increases of 0.71 and 0.47 dt/ha for sandy and loamy soils, respectively (Kristensen et al., 2010). This indicates that the causes of stagnating yields were less manifest in the more controlled field experiments than at the national scale.

Soil type
Until 1980 winter wheat accounted for 3% of the agricultural area in Denmark, but increased to 25% at the beginning of the 1990s. This development is quite different from other North-west European countries (Belgium, Germany, France, Netherlands and Sweden), where the total area cultivated with wheat has been more or less stable since the 1970s. Originally, winter wheat in Denmark was grown mostly on loamy soils (sandy loam, 10-15% clay), but later also on lighter textured soils (loamy sand soils) (Olesen et al., 2000). Even though less suitable soils were included for wheat cultivation during the 1980s and the first half of the 1990s, yield increases were still significant. The proportion of arable land used for winter wheat has been constant since the mid 1990s, indicating little change in the soil types used for wheat, with only minor influence of soil type on the stagnating yields in winter wheat since the end of the 1990s. It is noticeable that farmers in the county of Storstrøm with the highest share of sandy loams have been able to maintain significant annual yield increases for a longer period and thereby produce by far the highest yields (Chapter 2). The difference in annual yield increases between the remaining counties was insignificant.

Crop rotation
Since 2000 the area with winter wheat has occupied 8-40% of the arable land in the different counties, indicating differences in crop rotations between counties. The highest proportion of winter wheat has been in counties dominated by loamy soils and typically with a large proportion of cereals in the crop rotations. The large proportion of cereal cropping has forced winter wheat onto less favourable positions in the crop rotation. Wheat has appeared more often in the crop rotation since the beginning of the 1990s (Figure 1.1) with even a large frequency of continuous wheat cropping, but examination of this issue requires more detailed datasets than were available for this study.

Environment
The external factors that have a direct influence on crop growth and grain yield in winter wheat include climate (temperature, precipitation, and global radiation), atmospheric concentrations of carbon dioxide (CO_2) and ozone (O_3), and ultraviolet radiation (UV-B, 320-280 nm). The mean temperature has increased during recent decades, and average summer and winter temperatures during 2000-08 were 1.1 to 1.5 °C above the average temperature 1961-90, respectively. In addition there has been a weak tendency for increased winter precipitation, whereas summer precipitation remained unchanged. The number of sunshine hours during winter was larger during the past two decades compared with the average for 1961-90, whereas the number of sunshine hours during the summer was unchanged.
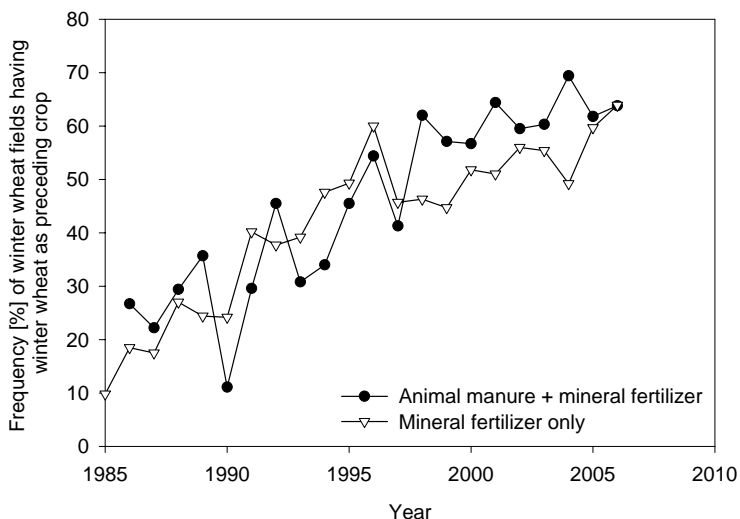
Figure 1.1 Frequency of fields with winter wheat having wheat as the preceding crop expressed as a percentage of all preceding crops. The frequency is shown for two farm types using datasets A and B described in Chapter 5.
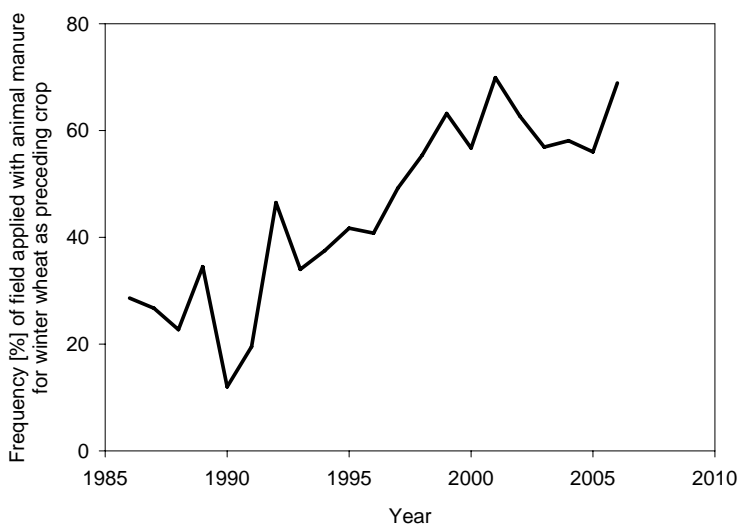
Figure 1.2 Frequency of fields with winter wheat receiving animal manure when winter wheat was the preceding crop. The frequency is shown for a farm type using animal manure plus mineral fertilizer (dataset B described in Chapter 5).

A multiple regression analysis was applied for the average national grain yields during 1990-2008, and the effects of the winter temperature (linear and quadratic effect), winter precipita-

tion, spring sunshine hours and maximum summer temperature were found to affect grain yields. In this way a climate-normalised annual yield increase of 0.30 dt/ha was estimated. The estimated yield increase without correction for climate variability was 0.18 dt/ha/year (Chapter 3). Thus changes in climate over this period have caused yield decreases of 0.12 dt/ha/year.

The annual increase in atmospheric CO_2 concentration in the past four decades corresponds to nearly 2 ppmv. The primary response of plants to rising atmospheric CO_2 concentrations is to increase resource use efficiencies of global radiation, water and nitrogen. During 1990-2008 an accumulated change of 30 ppmv was recorded, corresponding to an estimated annual yield increase of 0.16 dt/ha.

Since the biospheric O_3 concentration at ground level has remained unchanged in Denmark, this factor could not have affected grain yields of winter wheat. However, depletion of stratospheric O_3 has caused an increase in the UV-B radiation of 6-14%. A negative impact of increased UV-B radiation cannot be excluded, but the effect is very difficult to quantify.

Breeding and genetics

The winter wheat varieties in the marketed assortment have continuously been replaced and a variety has typically been on the market for only for 3-5 years. The most dominating varieties during time made up more than 90% of the market. The number of sites for variety field-testing in Denmark has been reduced over time and since the mid 1990s the field tests have typically been carried out at only a few well-managed sites on loamy soils. This choice of sites for variety tests may cause some bias when estimating the contribution from breeding progress and the problem is illustrated by the difference between the weak growth in national yields and the maintained high yield increases for the county of Storstrøm mentioned earlier. However, an annual yield increase of 0.9 dt/ha expresses the estimated potential due to breeding progress during 1980-2007 (Chapter 4), and this progress seems to be stable over the entire period.

The estimate of yield progress used here was derived by comparing yields of new against older varieties acting as reference. This has the advantage of providing an estimate of the effect of genetic differences only. However, yields of reference varieties may decline over time due to their diminishing resistance to fungi and other pathogens or reduced adaptability to changes in the environment. This risk has been observed for rice varieties in the Philippines (Peng et al., 2000), and may also have been valid for winter wheat reference varieties in Denmark, even though insignificant yield trends were observed for the periods where the varieties served as references (Chapter 4). The effect of resistance breakdown or reduced adaptability in reference varieties would be to overestimate the plant breeding progress.

An alternative way to estimate breeding progress is to assess the yield trend from optimally managed field experiments. Using this approach Fischer & Edmeades (2010) arrived at an

annual yield progress of 0.6 dt/ha for winter wheat in the UK. Peltonen-Sainio et al. (2009) similarly estimated annual genetic yield progress of 0.5 dt/ha for winter wheat in Finland. With this approach, however, genetic improvement can be confounded with changes in the environment. During the last 20 years, increasing temperatures are likely to have affected yield, in most cases leading to yield reductions (Lobell and Field, 2007; Kristensen et al., 2010). The estimates of annual yield increases for UK and Finland may therefore underestimate the genetic improvement, which thus most likely lies somewhere between 0.6 and 0.9 dt/ha per year.

Animal manure

The Danish parliament has passed several action plans with the aim of reducing the environmental effects of agricultural nitrogen (N) use. To fulfil this aim, the statutory order on nitrogen fertilization is divided into two parts: one setting out standard N rates for each crop, and the other a substitution rate for N in animal manures that has to be taken into account when observing the standard N rate. These regulations have, together with statutory orders regarding application method and timing, significantly reduced the application rate of animal manure and reduced the concurrent use of nitrogen, phosphorus and potassium in mineral fertilizers. The rate of plant-available N applied was reduced by 43 kg N/ha for combined use of animal manure and mineral fertilizer (Chapter 5). However, the rate of plant-available N in the 1990s was clearly supra-optimal. Therefore, available data were not suitable for assessing how the reduced N rates from changes in legislation had affected grain yield. Today the rate of plant-available N applied in combinations of animal manure and mineral fertilizer converge to the N rate for mineral fertilizer.

Since the mid 1990s trailing hoses have commonly been used for spring application of animal slurry in winter wheat. The working width and capacity of slurry tankers have increased over time, and a much larger proportion of the wheat area now receives animal slurry compared with 1990 (Figure 1.2). The additional yield loss due to crop damage caused by trampling from by the larger slurry application equipment was estimated at 1.2 dt/ha since 1990 (Chapter 5).

Nitrogen fertilizer

Using a theoretical approach to yield response functions, a dataset of recorded N rates on farms from 1985-2007, and a set of 115 experimental yield-to-N rate responses obtained during the years 1998-2007, we estimated a yield reduction of 2.1-3.1 dt/ha caused by the introduction of standard N rates plus the subsequent reduction of standard N rates, in practice corresponding to 16-19 kg N/ha (Chapter 5). The experiments on yield-to-N rate responses were located in well-managed fields and received the same treatments as the surrounding fields in terms of chemical spraying and choice of variety. Therefore, any changes in breeding progress or changes in optimal N fertilizer requirement observed over time should in principle have been included in the yield obtained by the annual fertilizer experiments.

In the context of yield changes in the period since 1990, the long-term effect of reduced standard N rates implemented in 1999 is considered to be of minor importance as the yield effect was supposed to be in the order of 0.4 dt/ha (Chapter 5). Despite some changes in fertilization rates for some nutrients other than N, we were not able to demonstrate any effect on the yield of winter wheat (Chapter 5).

Plant protection - diseases
The most yield-reducing epidemic disease in winter wheat was Septoria leaf blotch (*Septoria tritici*), but also powdery mildew (*Blumeria graminis*) reduced yields significantly, particularly on sandy soils. In some seasons, there may be severe attacks of stripe rust (*Puccinia striiformis*) and leaf rust (*Puccinia triticina*), and in fields with minimum tillage, tan spot (*Drechslera tritici-repentis*) and fusarium head blight (*Fusarium spp.*) may influence yields and grain quality. Disease control gives on average a yield increase of about 10%, but this effect varies considerably in time and space, depending on weather and the cultivars grown. No consistent increase in disease pressure could be observed.

The potential yield increase since the beginning of the 1990s due to the introduction and development of strobilurins was estimated at 5-6 dt/ha (Chapter 6). Simultaneously, the focus on net yield rather than gross yield in crop protection has reduced the yield by 4-5 dt/ha.

Take-all (*Gaeumannomyces graminis*) can be a serious soil-borne root pathogen, particularly in 2nd and 3rd year wheat. Monitoring data describing the development of the disease are not available, but an analysis of 6039 winter wheat experiments showed that the percentage of experiments having wheat as the preceding crop increased from 20-30% at the beginning of the 1990s to 40-50% since year 2000. The average grain yield of winter wheat was 4 dt/ha higher with preceding crops other than wheat (Chapter 6), but the difference could be 10 dt/ha if broadleaved crops preceded the winter wheat (Knudsen, 2010). Based on Figure 1.1 showing the share of 2nd (plus 3rd) year winter wheat it was assumed that 60% of the area cultivated with winter wheat was affected by take-all, causing a weighted average yield reduction of 2.4 dt/ha since 1990.

Plant protection – insects
The frequency of attacks by aphids (primarily *Sitobion avenae*) seems to have been reduced from 1992-2008 (Chapter 6). Aphids may cause significant yield losses when attacks surpassing the thresholds are left untreated. Control of orange wheat blossom midge (*Sitodiplosis mosellana*) was found to counteract a yield loss of 1.3 dt/ha, when the preceding crop was wheat. Assuming 60% of the fields with winter wheat have wheat as the preceding crop and half of the cases are treated, the average effect may be in the order 0.4 dt/ha. Barley yellow dwarf virus (BYDV) and field slugs (*Deroceras* sp.) are, in general, not regarded as serious problems that could explain the observed stagnating yields.

Plant protection - weeds
Increased weed frequencies particularly for grass species have been reported, and this may have had a negative impact on the grain yield of winter wheat. Also the use of herbicides in winter wheat increased since 2000. Although early sowing increases the weed biomass of grass species and the potential yield loss, our analysis did not support the hypothesis that increased density of Wind Bentgrass (*Apera spica-venti*) contributed to reducing yields in winter wheat.

Plant protection – growth regulators
Chlormequat-chloride was the most widely used plant growth regulator in winter wheat, and apart from hoarding in a few years the treatment frequency has been quite low (0.1-0.3) since the mid 1990s (Chapter 6). Varieties resistant to lodging and lower N rates were assumed to reduce the need for application of growth regulators to support the strength of the straw and avoid lodging. Changes in growth regulators have therefore not affected wheat yields.

Soil tillage
Primary soil tillage has several purposes, including incorporation of crop residues and manures for enhanced turn-over, facilitation of root growth, water infiltration and soil aeration by loosening the top-soil, and suppression of weeds and pests. Traditionally mouldboard ploughing has been extensively used, but since the end of the 1990s non-inversion tillage systems have been introduced, which may be successfully applied in well-managed crop rotations with only minor weed problems. Occurrence of grass weeds and infestation with take-all in rotations with multiple wheat crops in non-inversion tillage systems may cause yield losses of 8-12 dt/ha. Reduced tillage was estimated to have been practised on less than 10% of the arable land. Experiments on reduced tillage compared with mouldboard ploughing showed average yield reductions in winter wheat of 2-4 dt/ha, which translates into a yield reduction of about 0.2 dt/ha over the period since 1990, assuming that this is practised on about 5% of the land cropped with winter wheat.

The purpose of secondary tillage is to create a seedbed optimized for germination and early growth. PTO-driven harrows were introduced at the end of the 1980s and became very popular. Although the PTO-driven harrows could not be seen to directly affect yields compared with the formerly used time harrows, the PTO-driven harrows can operate in suboptimal situations and may thereby have reduced the quality of the seedbed. Reducing operation costs and expanding the time slot for field operations has been the primary driver for the increasing use of reduced tillage systems and PTO-driven harrows.

Soil compaction
Heavy tractors and trailers induce high stresses in the subsoil and cause permanent soil compaction under wet soil conditions. Stresses of more than ~50 kPa at depths below 50 cm should be avoided. For large low-pressure tyres, this threshold corresponds to a maximum wheel load of 3.5 t, while older non-optimal tyres or modern tyres inflated for highway traffic

reach the threshold at loads of ~2 t. Today the wheel load in practice greatly exceeds this threshold, particularly for slurry application equipment. No commercially marketed slurry tanker has wheel loads below 5 t, and the load of the rear wheel of tractors is even higher. The permanent yield reduction from compaction of deep subsoil layers was estimated at 2.5% across a range of soil types in humid climates. A comparison of an optimized and a non-optimized system of slurry application predicted a short-term additional yield reduction of ~6%. These predictions derive mainly from spring-sown crops and with lower wheel loads than in modern agriculture. Although these predictions are uncertain, they point to a yield reduction from slurry application in modern agriculture of 8.5% as compared to a soil-optimized spreading strategy. For an average yield of 70 dt/ha, this corresponds to 6 dt/ha. Assuming that half the winter wheat area frequently received animal slurry and that the spreading strategy was suboptimal for one third of this area, the reduction due to compaction corresponded to 1 dt/ha over the period since 1990.

Farm management
The yields of winter wheat vary considerably between farms, indicating that much of the variation may be related to management, but data is unsuitable for a more detailed explanation. The relationship between wheat yields and farm management was not necessarily well confined. The price of wheat grain has decreased since the mid 1980s, which means that the grain yield is of lees relative importance for total farm economy. Farmers have focused on the reduction of costs, working hours and consumables. This may have resulted in suboptimal timing of operations and reduced input rates in wheat cropping, but optimized farm net profits. There has also been a structural change towards larger farm and field sizes, which potentially means less effort to manage the crop according to soil and field variability. Also farmer's specialization in e.g. animal production may give field related management a lower priority. However, increased knowledge and improved decision support systems may have aided the management of winter wheat. In general, less focus on the cropping in the field has reduced the yield of winter wheat in recent decades. However, these general considerations on management intensity were mostly covered by the management changes described above, and no specific effect of farm management was therefore included in the estimated effects on wheat yields.

1.3 Summary of impacts
Estimates of annual changes are converted to absolute values by multiplying by 17 seasons to represent the period 1990-2006. There may be some uncertainty in this conversion, but also in the absolute estimates due to (minor) differences in cutting-off periods. The estimated yield effects for the period are summarized in Table 1.1.

Table 1.1 Estimated effects of environmental, genetic and management factors on yield of winter wheat for the period 1990-2006 (17 years). Factors not estimated to have any effect on yield are not shown. Positive values show increased yield and negative values show decreases.

	Change in wheat yield [dt/ha]
Climate	-2.0
CO_2	2.7
Breeding	10.2-15.3
Application of animal slurry	-1.2
Nitrogen rate restrictions, short term	-3.1 to -2.1
Nitrogen rate restrictions, long term	-0.4
Improved fungicides	5.0 to 6.0
Focus on net yield in crop protection	-5.0 to -4.0
Soil-borne diseases (more monoculture)	-2.4
Orange wheat blossom midge	-0.4
More reduced tillage	-0.2
Subsoil compaction	-1.0
Sum of all factors	2.2 to 10.3
Observed national yield increase	3.1
Gap (estimated minus achieved yield increase)	-0.9 to 7.2

A few factors have increased the yield potential, in particularly breeding, but several factors have had a negative impact on grain yield of winter wheat. In total, these factors should have resulted in increases in grain yield of winter wheat of 2.2 to 10.3 dt/ha over the period 1990 to 2006. In reality the yield from the national statistics only increased by approximately 3.1 dt/ha.

When the national yields were corrected for climatic variation (i.e., assuming no climatic trend), an annual yield increase of 0.30 dt/ha was obtained. This should be compared to esti-mated climate-corrected annual yield increases of 0.71 and 0.47 dt/ha for sandy and loamy soils, respectively, from well-managed field experiments (Kristensen et al., 2010). Over the entire period from 1990 to 2006 this difference between national statistics and field experi-mental data amounts to 7.0 and 2.9 dt/ha for sandy and loamy soils, respectively. These field experiments have been well managed and are not likely to have been negatively affected by trampling damages caused by manure application equipment (-1.2 dt/ha) or from reduced till-age (-0.2 dt/ha). It is therefore likely that other improved management factors may have sus-tained yield improvements in the experiments, whereas this is probably not the case for the winter wheat area in general.

The gap of up to 7 dt/ha (Table 1.1) between achieved and estimated yield increases may partly be explained by the low cereal grain prices during this period (Finger, 2010), which are likely to have reduced management intensity, in particular by reducing the number of working hours and costs of consumables. Such effects of management intensity were not properly ac-

counted for in the estimates in Table 1.1. This could for example have affected the efficiency of pest, disease and weed control and thus the yields obtained in practice. Besides this, the increased frequency of winter wheat cropping with a tendency towards continuous cropping may be an overlooked but important issue, as a poor crop rotation significantly increases the negative impact of weeds, pests and diseases, e.g. the incidence of take-all in crop rotations with a high frequency of wheat causes yield losses of up to 25%. Winter wheat yielded on average 10% more following a broadleaved crop than when it was preceded by winter wheat (Knudsen, 2010).

Stagnating winter wheat yields have also been observed in most other European countries, where this has also caused some concern. The low grain prices may similarly have affected the management intensity and thus the yields obtained there. However, for some of the central and south European countries higher temperatures and more frequent drought periods may also have contributed to lower yield increases or even yield reductions (Brisson et al., 2010; Olesen et al., 2011; Peltonen-Sainio et al., 2010).

Finger (2010) attributed the slowing of yield decreases in Switzerland to changes in agricultural policy towards environmentally friendly cereal production. In particular, there has in Switzerland been a large drive towards organic farming, where yields are generally smaller. There was thus an increase in the area of wheat under extensive production from 25% in 1992 to 45% in 1997, whereafter it has remained stable. In Denmark the area with organic cultivated winter wheat constitutes less than 0.5% of the total winter wheat area, and the smaller yields due to conversion to organic farming can therefore not have affected overall national yields.

Standard N rates introduced in 1993 and restricted standard N rates introduced in 1999 have often been mentioned in the Danish debate as the main cause of reduced yields. However, Table 1.1 shows that these regulations may only be blamed for a minor part of the yield reductions amounting to about a third of the effect of breeding. Parallel to these regulations the statutory substitution rate of N in manure at farm level was gradually increased during the period 1993 to 2003 (Figure 5.1). The on-farm substitution rate for different types of animal manures are aggregated values based on 1) field experiments, 2) a supplement due to extra mineralization in crops with a long growing season, and 3) an estimated residual effect of organic N, and weighed by likely application methods and application times (Petersen & Sørensen, 2008). The objectives of the regulations are to reduce environmentally harmful losses due to ammonia volatilization and/or nitrate leaching, and to increase the utilization of N in animal manures. These regulations affect the amount of mineral N fertilizer that the farmer is allowed to apply, which is the parameter used for the official control.

The incentive to make more N available to the crop may be obtained by handling manure according to good farming practice. However, no official control of the utilization of animal manure N is applied, and the farmer may give this a lower priority, depending on the cost-

benefit relationships on the farm, including the prices for plant and animal products. Conditions for slurry application in winter wheat may frequently be suboptimal, since the capacity of application equipment (typically trail hoses) are often optimized with respect to non-nutritional parameters (e.g. acreage to manage, employees working hours, prohibited application on Sundays and public holidays) without taking varying weather conditions during April-May into account. Thus, suboptimal slurry application in practice may have reduced the amount of available N for winter wheat more than anticipated, and possibly also has a smaller effect on environmental protection than expected.

The impact of the two above-mentioned regulations (reduced standard N rates and substitution rate of N in manures) depends on the farm type, which varies between counties. For example, the county of Storstrøm has by far the smallest livestock density at half the national average of both pigs and cattle (Petersen & Sørensen, 2008). In addition, the pig density in the county of Storstrøm has been stable since the 1980s, whereas the density has increased in most other counties (Petersen & Sørensen, 2008). Owing to this and assuming that the animal manure is applied to the crops best able to utilize the N (spring-sown crops) it is most likely that the winter wheat in the county of Storstrøm was fertilized with mineral N to a higher extent than in counties with a higher livestock density. Thus, in Storstrøm, the impact of environmental regulations regarding agricultural use of N may be related to (reduced) standard N rates rather than substitution rates for N in manures. This impact of the regulations may explain that the yields in the county of Storstrøm continued to increase in the late 1990s, and that suboptimal manure management has caused poorer yield increases since 1990 in counties having a high livestock density.

1.4 Perspectives
A range of different factors has affected winter wheat yields in Denmark. These factors are different in nature and will therefore also have likely different effects in future.

There was a considerable difference between yields obtained in well-managed field experiments and the yields obtained in practice expressed by the national average. Some part of this gap between attainable and actual yields may be explained by changes in factors that have a negative impact on the yield of winter wheat (Table 1.1), but there is still a difference of up to 7 dt/ha. However, in 2008 the national average yield was 79 dt/ha, or 8 dt/ha more than the average of the past decade, indicating that the yield increase obtained by breeding can still be realised in practice, when other conditions such as climate and management are favourable.

Some of the estimated causes of yield losses will likely persist, in particular those related to reductions in nitrogen fertilizer rates, application of manure to a larger proportion of the wheat area and the higher frequency of wheat following wheat in the rotations. However, yield reductions from these factors would not be expected to increase in the future, meaning that the persistent yield increases from breeding should be reflected more clearly in the na-

tional grain yields. This requires a continuous and persistent effort in improving crop management at the farm and field level. Higher grain yields in the future may also require increases in nitrogen availability for the crop, in particular when grain protein concentrations are to be maintained (Jones et al., 2010).

Given that agroenvironmental regulations are not likely to be eased, there is a need to further focus on crop management practices with the purpose of 1) increasing the nitrogen use efficiency of manures and 2) controlling weeds, pests and diseases. Firstly, increasing the nitrogen use efficiency of manures will directly increase grain yields, since the Danish regulations force general nitrogen fertilisation rates below the economically optimal. However, there are options for improving nitrogen use efficiency in manures, e.g. by technologies that reduce ammonia emissions (e.g. slurry acidification) or increase the availability of nitrogen in the manure (e.g. anaerobic digestion) (Petersen & Sørensen, 2008). Also an increased focus on proper timing of manure application may improve the nitrogen use efficiency and grain yields. Related to the nitrogen use efficiency is also an increase of nitrogen uptake in the autumn that will have both an environmental impact by reducing the nitrogen leaching potential and increase the capability of the crop to remobilize nitrogen for early growth in the spring. Secondly, crop protection problems are probably best dealt with through improved crop rotations, which would mean less second-year wheat. Alternatively, winter wheat in monoculture should be restricted to those fields and soil types, where this poses the fewest problems.

The analysis presented here could not fully explain the underlining drivers of changes in national crop yields, since the available data simply do not allow this. Grain and input prices are probably the main factors that indirectly affect farm and crop management, but relatively little are known about how price expectations affect crop management and the resulting yield effects, and it is obvious that this management topic calls for further study. However, in the long term a better understanding of the fundamentals of genetic improvement is needed to direct plant breeding and to estimate the potential for future yield increases. Current estimates show that it should be possible to sustain yield increases from breeding progress for at least the next few decades (Foulkes et al., 2007; Reynolds et al., 2009; Fischer & Edmeades, 2010), but whether this results in higher actual yields depends on farm and crop management (Ransom et al., 2007). There is currently little evidence of changes in the ability of soils to sustain high crop yields, and new experiments on effects of soil compaction and soil organic matter on crop yield are needed. More information on how management of manure and method for application in practice affects winter wheat yield is needed to support advice and improve crop nutrient management. Likewise, better data are needed from actual crop rotations including winter wheat in Denmark to identify the extent to which yields can be improved by having more favourable pre-crops or alternative crop rotations.

1.5 References

Brisson, N., Gate, P., Gouache , D., Charmet, G., Oury, F.-X. & Huard, F. (2010) Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. Field Crop Res. 119, 201-212.

Finger, R. (2010) Evidence of slowing yield growth – The example of Swiss cereal yields. Food Policy 35, 175-182.

Fischer, R.A. & Edmeades, G.O. (2010) Breeding and cereal yield progress. Crop Sci. 50, S-85-S98.

Foulkes, M.J., Snape, J.W., Shearman, V.J., Reynolds, M.P., Gaju, O. & Sylvester-Bradley, R. (2007) Genetic progress in yield potential in wheat: recent advances and future prospects. J. Agric. Sci. 145, 17-29.

Jones, H., Clarke, S., Haigh, Z., Pearce, H. & Wolfe, M. (2010) The effect of the year of wheat variety release on productivity and stability of performance of two organic and two non-organic farms. J. Agric. Sci. 148, 303-317.

Knudsen, L. (2010) Udbytter i markforsøg fra 2000 til 2009. Artikel nr. 114. LandbrugsInfo. http://www.landbrugsinfo.dk/Planteavl/Afgroeder/Korn/Vinterhvede/Sider/pl_10_114.aspx.

Kristensen, K., Schelde, K. & Olesen, J.E. (2010) Winter wheat yield response to climate variability in Denmark. J. Agric. Sci. (in press).

Lobell, D.B. & Field, C.B. (2007) Global scale climate-crop yield relationships and the impacts of recent warming. Environ. Res. Let. 2, 014002.

Olesen, J.E., Bøcher, P.K. & Jensen, T. (2000) Comparison of scales of climate and soil data for aggregating simulated yields of winter wheat. Agric. Ecosyst. Environ. 82, 213-228.

Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B, Peltonen-Saino, P., Rossi, F., Kozyra, J. & Micale, F. (2011) Impacts and adaptation of European crop production systems to climate change. *European Journal of Agronomy* (in press).

Peltonen-Sainio, P., Jauhianinen, L. & Laurila, I.P. (2009) Cereal yield trends in northern European conditions: Changes in yield potential and its realisation. Field Crops Research 110, 85-90.

Peng, S., Laza, R.C., Visperas, R.M., Sanico, A.L., Cassman, K.G. & Khush, G.S. (2000) Grain yield of rice cultivars and lines developed in the Philippines since 1966. Crop Sci. 40, 307-314.

Peltonen-Sainio, P., Jauhianinen, J., Trnka, M., Olesen, J.E., Calanca, P.L., Eckersten, H., Eitzinger, J., Gobin, A., Kersebaum, C., Kozyra, J., Kumar, S., Marta, A.D., Micale, F., Schaap, B., Seguin, B. & Skjelvåg, A. (2010) Coincidence of variation in yield and climate in Europe. *Agriculture, Ecosystems & Environment* (in press).

Petersen, J. & Sørensen, P. (2008) Gødningsvirkning af kvælstof i husdyrgødning – Grundlag for fastsættelse af substitutionskrav. DJF rapport nr. 138, Aarhus Universitet, Det Jordbrugsvidenskabelige Fakultet, Tjele.

Ransom, J.K., Endres, G.J. & Schatz, B.G. (2007) Sustainable improvement of wheat yield potential: the role of crop management. J. Agric. Sci. 145, 55-61.

Reynolds, M., Foulkes, M.J., Slafer, G.A., Berry, P., Parry, M.A.J., Snape, J.W. & Angus, W.J. (2009) Raising yield potential in wheat. J. Exp. Bot. 60, 1899-1918.

2 Yield trends in Denmark and North-west European countries

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2.1 Introduction

Improvements in winter wheat varieties, subsidiary materials and management technologies have on average caused an annual yield increase of 1.0 dt ha^{-1} in North-west European countries since the beginning of the 1960s. However, this annual yield increase seems to have stagnated during the last decade. Is this a Danish problem or a common European problem? The aim is to examine the annual yield increases in North-west European countries, and examine differences between counties within Denmark.

2.2 Materials and methods

We used two datasets on grain yield of winter wheat to analyse the problem. The first dataset was extracted from FAO Statistics (http://faostat.fao.org/site/567/default.aspx#ancor accessed September 2008). Yields of (winter) wheat and cultivated areas were selected for Belgium, Denmark, Germany, France, Netherlands, Sweden and United Kingdom for 1961-2007 (Figure 2.1). Until 1999 inclusive data for Belgium were extracted from Belgium-Luxembourg and afterwards for Belgium. Germany became a sovereign state in 1990 and data before 1989
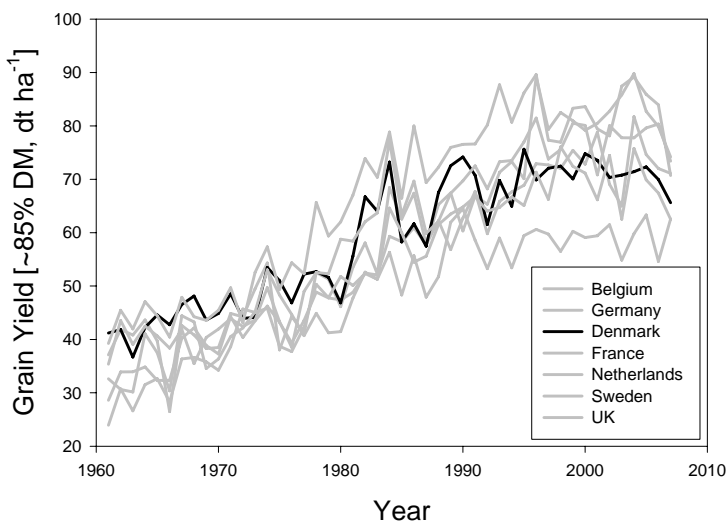

Figure 2.1 Grain yield of winter wheat in North-west European countries during 1961-2007. FAO Statistics (http://faostat.fao.org/site/567/default.aspx#ancor accessed September 2008).

were summed by FAO separately for the German Democratic Republic and Federal Republic of Germany. The FAO data are based on national reports.

The second dataset was obtained from Statistics Denmark (http://www.statbank.dk, StatBank Denmark, Table HST7 for 1990-2006 supplied with comparable data for 1970-1989) (Figure 2.2). Yields from 2001 and onwards are 85% dry matter. Yields during 1985-2000 are re-corded with 84% dry matter but adjusted to 85% dry matter. Yields before 1985 may be with variable dry matter content, but assumed to be in the range 82-86% dry matter. The recorded yields are based on farmers' reports. About 10% of the farmers are selected for a stratified inquiry. The national average yield enters the FAO Statistics.
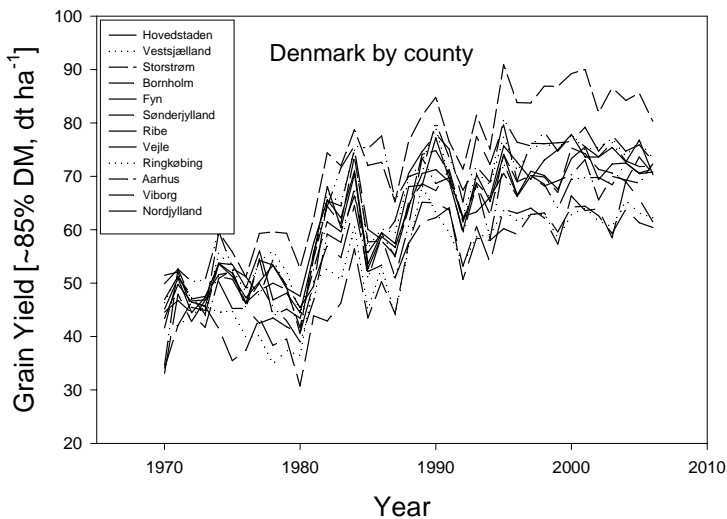
Figure 2.2 Grain yield of winter wheat in the counties of Denmark during 1970-2006 (StatBank Den-mark Table HST7 for 1990-2006 supplied with comparable data for 1970-1989).

2.3 Results and discussion

2.3.1 First approach
A straightforward approach was to describe the yields over time by a linear function. How-ever, it is clear that a linear function will not be the best fit for the data. It was hypothesized that two linear but discontinuous functions may be better. The point at which the two linear functions are discontinued may be related to the implementation of environmental action plans on nutrients or the use of pesticides. Several action plans were implemented during the 1990s and after the millennium, making it difficult to select *the* event that objectively points to the cause of discontinuity. Alternatively a quadratic or an exponential function may give satisfactory fits, but these functions have parameters that are difficult to interpret. Due to

these problems, particularly determining the point of discontinuity this first approach in ana-lysing the yield increases over time was rejected.

2.3.2 Second approach

It is clear that the annual yield increase has to be calculated as an average of several years due to significant variation in the yield from year to year. Using 9 years in calculation of a moving mean may smooth the yield data. However, this does not solve the problem of determining the point of discontinuity. Therefore a moving regression was applied:

$$Y = \mu + \alpha_{country} + (\beta + \gamma_{country}) \times year + \varepsilon ,$$

using country as class variable and year as continues variable. The regression included 9 years and the countries/counties in the respective dataset. The midpoint year equals zero within this 9 year interval of year$\in$[-4, …, 4], and the midpoint year were used for the corresponding Gregorian calendar year when plotting the estimates. The regression was performed from first year to (last year-9) moving 1 year for each calculation. The parameter sum $\beta+\gamma_{country}$ give the yield trend for each country (or county depending on the dataset). The parameter sum $\mu+\alpha_{country}$ give the mean yield for each country for the midpoint year. This approach is objec-tive and solves the problems associated with the first approach.

2.3.3 Development in North-west European countries

The moving means (Figure 2.3) clearly show differences in the average yields ($\mu+\alpha_{country}$). Farmers in the Netherlands have been able to produce by far the highest yield during mid 1970s to the mid 1990s, but farmers in Belgium are now able to compete for the first place. The farmers in Sweden have since mid 1980s obtained the lowest yield. Around 1970 the Danish yields were comparable with the yields obtained in the Netherlands, but during the 1980s and 1990s the Danish yields are lagging behind. These changes are analyzed further using the annual yield increases.

The moving estimate of annual yield increases ($\beta+\gamma_{country}$) is shown in Figure 2.4 together with the probability for a null-hypothesis of the common slope (T-test) and for the signifi-cance of the $\gamma_{country}$ parameter (F-test). The common slope based on nine years observations was significant different from zero in most years, except 1999, 2000, 2002 and 2003 where ProbT>0.1, and the common slope even tended to be negative for the midpoint year 2003 (0.3 dt ha^{-1} year^{-1}, P=0.13). In most years the parameter $\gamma_{country}$ is not significant different indicat-ing a common slope is able to describe data, except during midpoint years 1976-80 and 1992-1997. The annual yield increases of >1 dt ha^{-1} around 1980 (Figure 2.4) is caused by the yield peak in the early 1980s (Figure 2.1) presumably caused by introduction of varieties with dwarf genes. The significance in the parameter $\gamma_{country}$ during 1976-80 (Figure 2.4) is assumed to be related to a delayed introduction of dwarf genes in some countries, probably linked
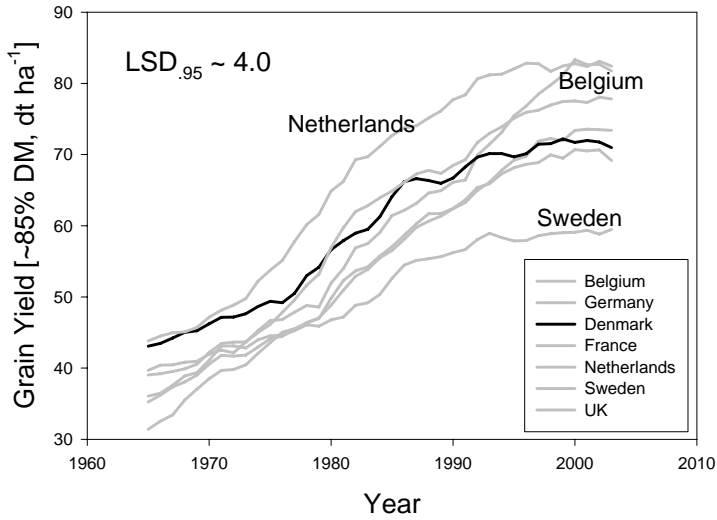
Figure 2.3 Moving means of winter wheat grain yield in North-west European countries. The LSD value for the difference between countries is an average of LSD values estimated by the moving regressions.
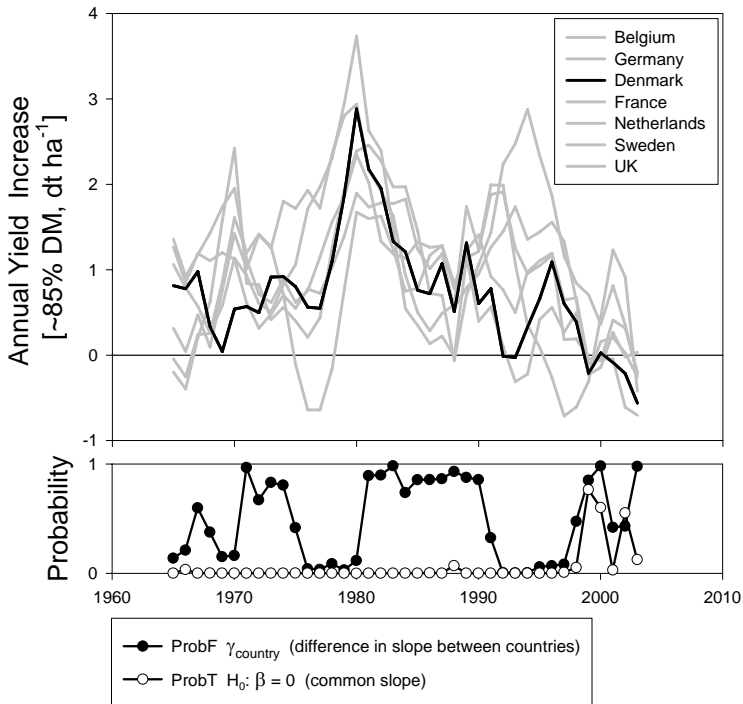

Figure 2.4 Moving estimate of annual yield increase of winter wheat in North-west European countries (top) and probabilities (bottom).

to the lack of winter hardiness in the new varieties. During these midpoint years the average annual yield increase was 2.35 and 2.54 dt ha^{-1} in the Netherlands and the UK, respectively, compared t with 1.39 dt ha^{-1} obtained in Denmark.

During the midpoint years 1992-97 the difference in annual yield increase is particularly caused by a high annual increase in Belgium, in average 2.16 dt ha^{-1} (Figure 2.4). However, significant annual yield increases were also obtained in Germany (1992-97, average 1.48 dt ha^{-1}), the Netherlands (1992-93, average 1.53 dt ha^{-1}), UK (1992-1996, average 1.28 dt ha^{-1}), and France (1992-97, average 0.86 dt ha^{-1}). In Denmark, significant but less annual yield increases were obtained in three midpoint years (1995-97, average 0.78 dt ha^{-1}) and the estimates were zero in two years (1992-93, average -0.02 dt ha^{-1}). The smaller rate of annual yield increases in Denmark during the midpoint years 1976-80 and 1992-97 explained much of the change in the moving means in Figure 2.3.

Since 1998 the slopes were neither significantly different from zero nor significantly different from country to country. This indicates that stagnating annual yield increases since 1998 are not a particularly Danish issue, but a North-west European issue. Figure 2.4 indicates that the annual yield increase on average has become steady smaller since 1980.

2.3.4 Development in Denmark

At the beginning of the 1970s the area cropped with winter wheat accounted for 80,000 ha, but this has increased to 670,000 ha in 2006, corresponding to approx. 25% of the arable land in Denmark (EuroStat, http://epp.eurostat.ec.europa.eu, data APRO_CPP_CROP). This development is quite different from the other North-west European countries (Belgium, Germany, France, Netherlands and Sweden) where the total wheat area has been more or less stable during the same period (Figure 2.5). However, there has been a shift from spring to winter wheat varieties in some countries. Until the middle of 1970s spring wheat accounted for 40% of the total wheat area in Belgium and Netherlands, and 30% in Denmark. A shift towards winter wheat was recognised in Sweden in the beginning of the 1980s. The EuroStat data do not enable a distinction between spring and winter wheat in Germany and the UK. Today winter wheat accounts for >95% of the total wheat area in all countries in Figure 2.5 except Sweden where the proportion is about 90%. Since the 1970s the total wheat area has doubled in the UK and increased five-fold in Denmark (Figure 2.5).

In the 1970s the growing of winter wheat in Denmark mainly took place on the most clayey soils (sandy loam, 10-15% clay), but today the wheat is also cropped on lighter textured soils (loamy sand soils). In the county of Ribe the area with winter wheat was larger in the 1990s than today (Figure 2.6), but the soil in this county may be too light-textured even when irrigation is carried out.

The area with winter wheat in 2006 varies between 8-40% of the arable land in the counties indicating differences in the crop rotation (Figure 2.7). The highest proportion of winter wheat is in counties dominated by the loamiest soils typically cropped with cereal crop rotations.
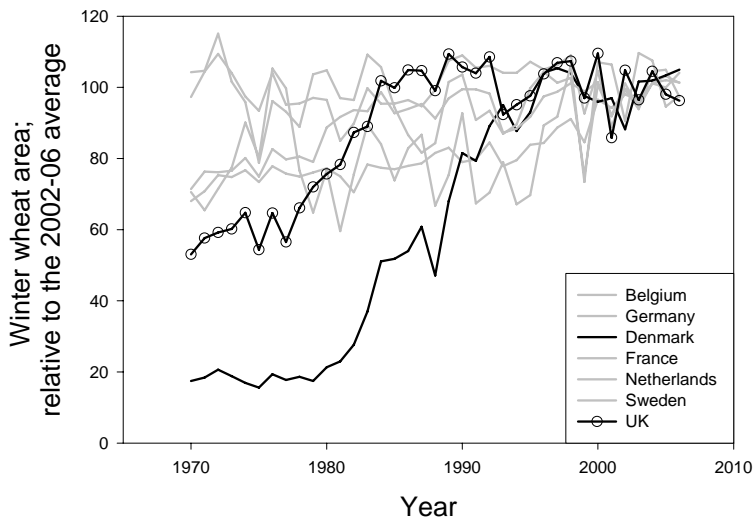
Figure 2.5 The area cropped with wheat in proportion to the 2002-06 average total wheat area in North-west European countries. (FAO Statistics, http://faostat.fao.org/site/567/default.aspx#ancor accessed September 2008).
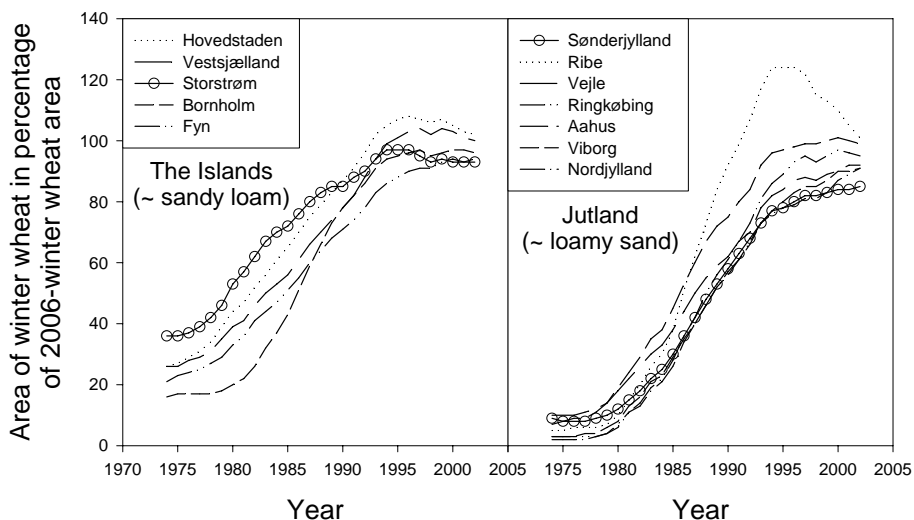
Figure 2.6 The area cropped with winter wheat in proportion to the 2006-winter wheat area in counties of Denmark (Statistics Denmark).

The moving means (Figure 2.8) clearly show differences in the average yields between counties. Farmers in the county of Storstrøm have been able to produce by far the highest yield. However, assuming that the capability of the farmers is independent of county, the parallel curves in Figure 2.8 indicate that the mean county yield is related to county properties such as soil type and climate rather than management.
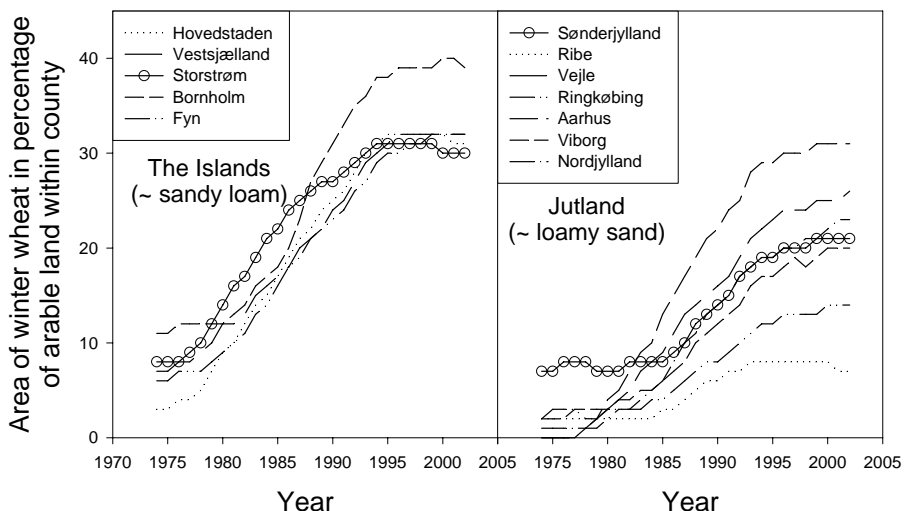
Figure 2.7 The area cropped with winter wheat in proportion to the arable land in the counties (Statistics Denmark).
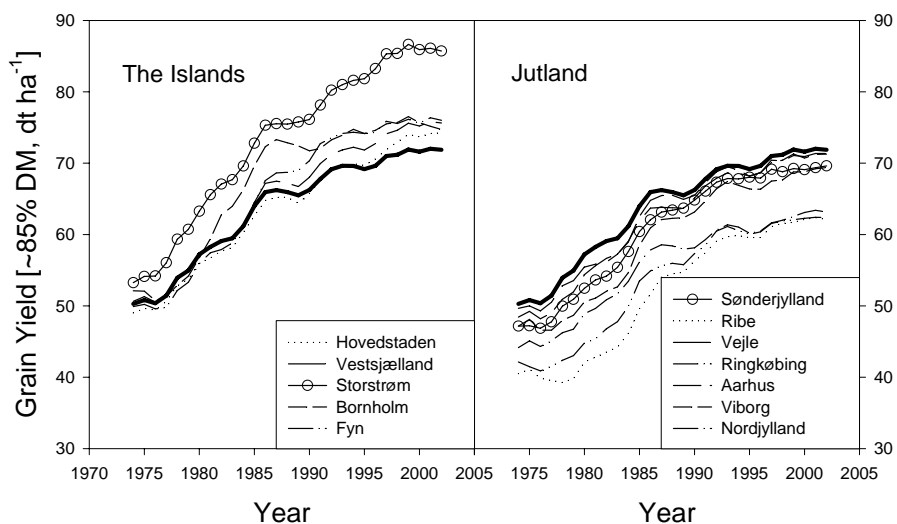
Figure 2.8 Moving means of winter wheat grain yield in the counties of Denmark. Bold line represent overall county mean. A LSD value of 4.7 averaged over the moving regressions was calculated for the difference between counties.

The moving estimate of annual yield increases ($\beta+\gamma_{country}$) is shown in Figure 2.9 together with the probability for a null-hypothesis of the common slope (T-test) and for the significance of the $\gamma_{country}$ parameter (F-test). The parameter $\gamma_{country}$ is insignificant, except during 1974-75 and 2002, indicating that a common slope is able to describe data in most years. The annual yield increase for the county of Bornholm seems to differ from the other counties during the 1980s, but not significantly. In 1975, 1977, 1992-93, 1999 and 2001-02 the T-test (ProbT>0.1) shows that the common slope is not significantly different from zero. The highest standard errors were obtained in years where the common slope is significant, indicating that the insignificance is not due to high standard errors. Thus, stagnating annual yield increases have also occurred in the past.
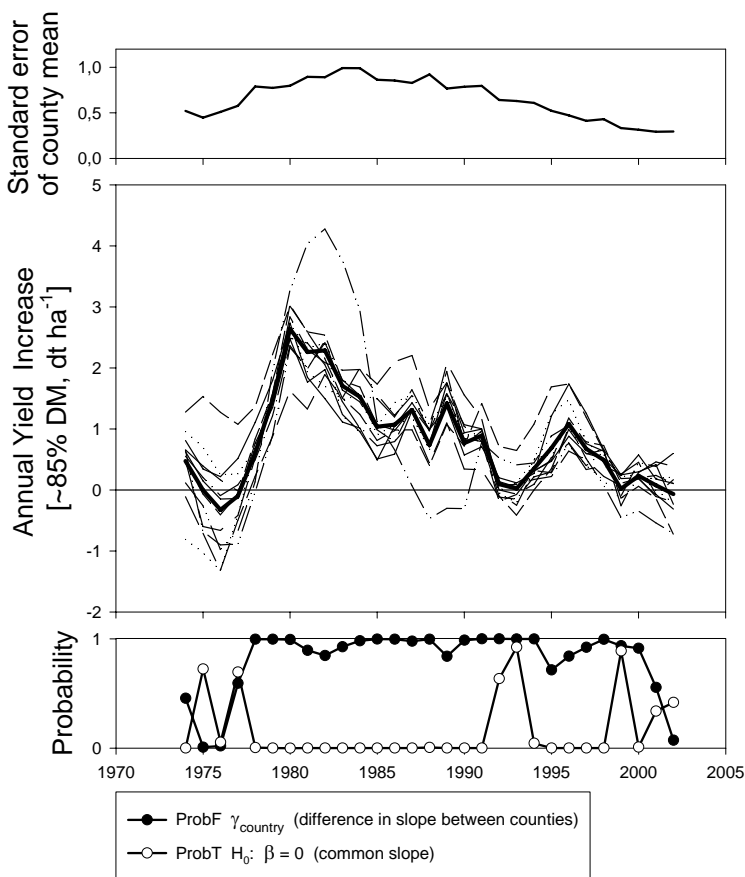
Figure 2.9 Moving estimate of annual yield increase of winter wheat in the counties of Denmark (middle), standard error of county mean annual yield increase (top) and probabilities (bottom). The bold line represents county mean annual yield increase.

In case of a significant $\gamma_{country}$ parameter it would have been relevant to relate differences to either soil type or crop rotation characteristics within the counties. However, this could not have been examined further by these data due to only one observation per county and year. The reason for the significant $\gamma_{country}$ parameter in 2002 is an annual yield increase of 0.60 dt ha^{-1} in the county of Viborg and a decrease of 0.40 dt ha^{-1} on average in the counties of Bornholm, Fyn, Hovedstaden, Ribe, Storstrøm and Vestsjælland.

2.4 Conclusions

Stagnating annual yield increases

- are not at new phenomenon,
- are not a Danish issue only, and
- are not related to county.

The absence of significance of the county-related annual yield increase (the class variable $\gamma_{country}$) in the Danish dataset reduces the possibility to obtain significance for an interpretable variable such as soil type or crop rotation by replacing the simple class variable. Even the use of other class variables representing county would be biased either in the selection or in the judgement of county characteristics. In addition, county characteristics may be confounded, e.g. by soil type and use of animal manure. Increased winter wheat cropping has forced the crop onto less favourable soil types and to less favourable places in the crop rotation, but examination of these issues requires other datasets with more detailed information.

3 Environmental changes and impacts on yield of winter wheat

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The external environment affects crop yield directly and indirectly by affecting the duration of growth, growth rate, allocation of total growth to grains and through affecting the conditions for harvesting and thereby the harvest losses. Some of the external influences act through other biotic factors such as pests and diseases. These effects are treated in other chapters. This chapter therefore focuses on those external factors that directly influence crop growth and grain yield in winter wheat. This includes climate, CO_2, ozone and UV-B radiation.

3.1 Climate

Most of Europe has experienced increases in the surface air temperature during 1901 to 2005, which amounts to 0.9 °C in annual mean temperature over the entire continent (Kjellström, 2004; Alcamo et al., 2007). However, the recent period shows a trend considerably higher than the mean trend (+0.4°C/decade for the period 1977-2001, Jones and Moberg, 2003). Temperatures are increasing more in winter than in summer (EEA, 2004; Jones and Moberg, 2003). An increase of temperature variability has been observed, primarily due to increase in warm extremes (Klein Tank and Können, 2003). In Denmark, both summer and winter temperatures have increased during the recent decades (Figure 3.1), and average winter and summer temperatures have over the period 2000 to 2008 been 1.5 and 1.1 °C higher, respectively, than normal for the period 1961-90. The MAXIMUM of the average annual summer season (April to July) temperature during 1961-90 was 12.5 °C. It is worth noting that 8 of the 18 years since 1990 had summer season temperatures that exceeded 12.5 °C.

There are indications of changes in the rainfall pattern over Europe as indicated by the frequency of drought events during spring and early summer. There has been an increase in frequency of droughts in large parts of Western and Eastern Europe, with particularly large increases in the Mediterranean region (Trenberth et al., 2007). Mean annual precipitation is increasing in most of the Atlantic and Northern Europe and decreasing along the Mediterranean (Klein Tank et al., 2002). An increase in mean precipitation per wet day has been observed in most parts of the continent, even in areas getting drier (Frich et al., 2002; Klein Tank et al., 2002). In Denmark, there has been a tendency for an increase in winter precipitation over recent decades, whereas summer rainfall on average has not changed (Figure 3.1).

The main changes in climate have occurred for temperature and rainfall. However, there are also indications of minor changes in global radiation in Denmark (Figure 3.1). The number of sunshine hours during winter has increased over the past two decades, whereas there has been

no significant trend in summer sunshine hours. However, that largest number of sunshine hours in summer over the period was observed in 2008.
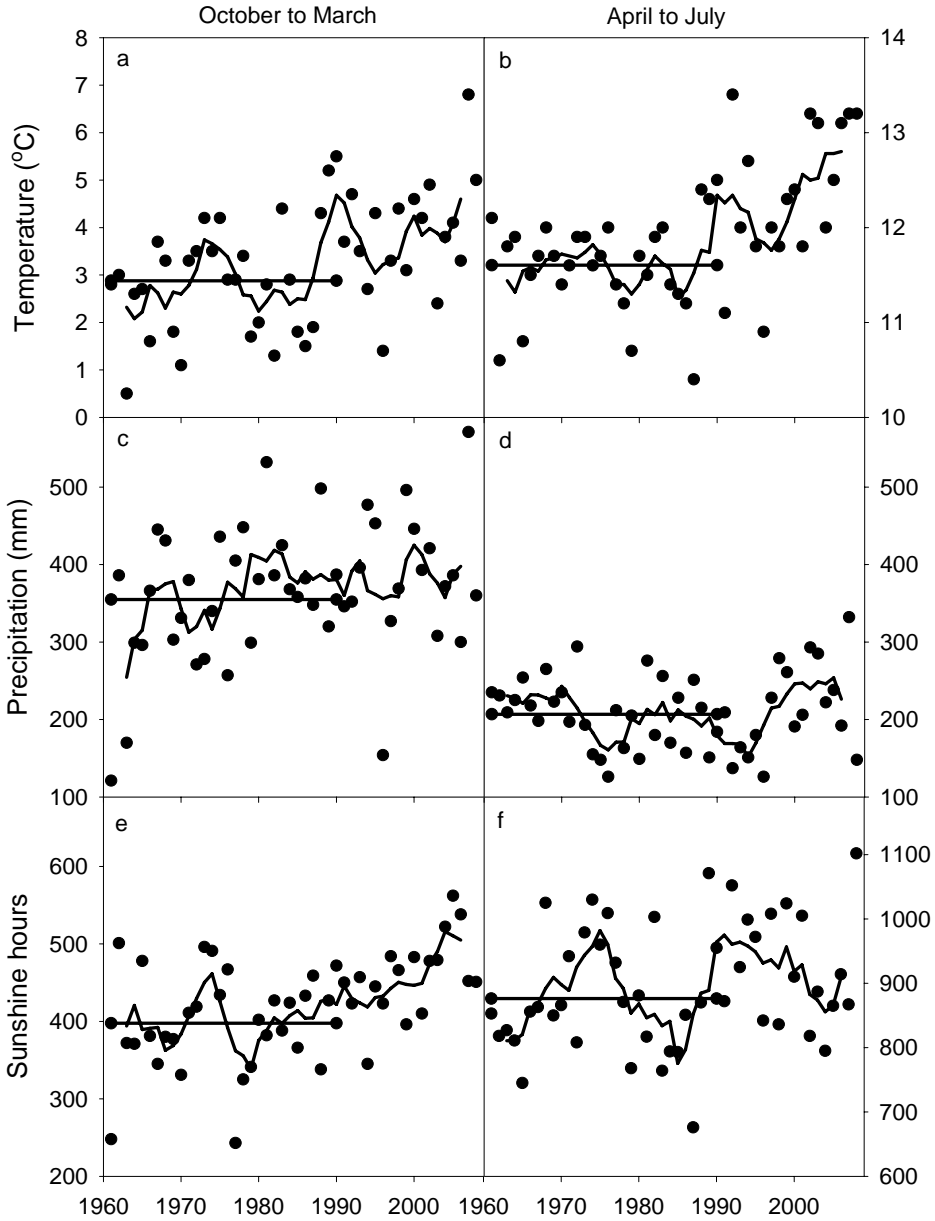
Figure 3.1 Observed mean temperature, precipitation and sunshine hours over Denmark for winter (October to March) (a, c, e) and summer (April to July) (b, d, f). The curve shows a five-year moving average, and the horizontal line shows the mean for the normal period 1961-1990. Note differences in scale between winter (left) and summer (right).

Temperature and rainfall influences crop yield through a range of biophysical processes (Olesen and Bindi, 2002). Temperature affects crop yield through effects on growth rate and on plant development. At low temperatures (less than about 10 °C) photosynthesis will be restricted by temperatures, and low temperatures will also delay development of the crop canopy and thereby delay the period with maximum light interception. However, the primary influence of temperature is on crop development. At higher temperatures, the start of active growth is advanced, plants develop faster, and this reduces crop duration for most annual crops. In wheat, an increase by 1 °C during grain fill reduces the length of this phase by 5%, and yield declines by a similar amount (Olesen et al., 2000a). Maize and soybean yields in the United States between 1982 and 1989 decreased by 17 percent with each 1 °C increase in growing season mean temperature (Lobell and Asner, 2003). There are also clear indications that increasing temperatures are causing grain yield reductions globally (Lobell and Field, 2007).
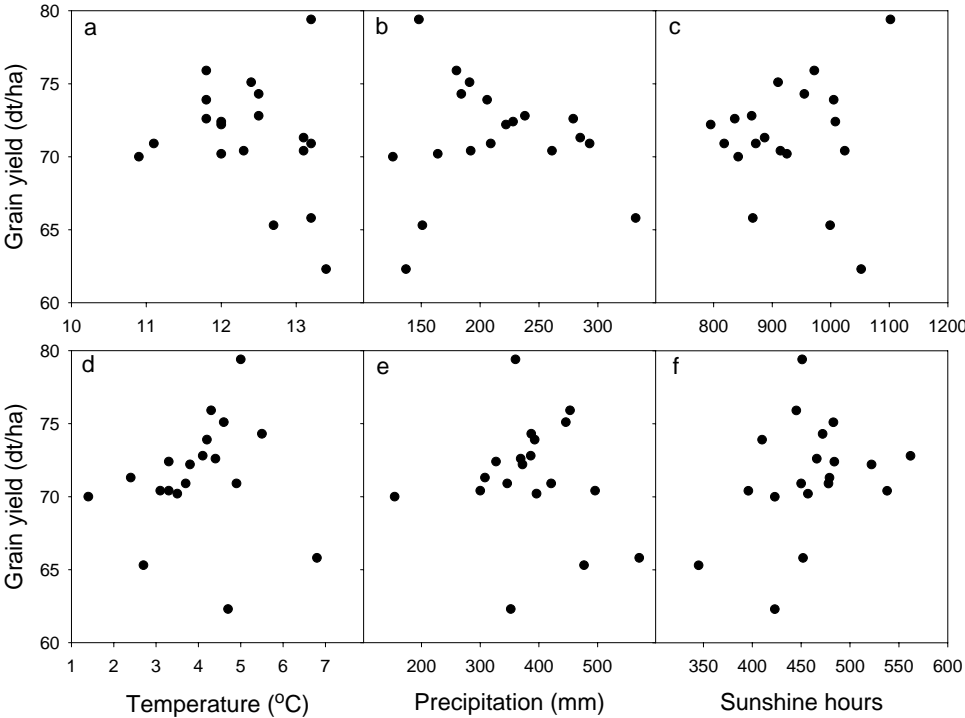
Figure 3.2 Observed national average grain yield of winter wheat in Denmark versus temperature, precipitation and sunshine hours during summer (April to July) (a, b, c) and versus temperature, precipitation and sunshine hours during winter (October to March) (d, e, f).

Olesen et al. (2000a) analysed grain yield of winter wheat from 1971 to 1997 at seven Danish experimental stations. The yield data were first detrended and then correlated with monthly values of temperature, rainfall and solar radiation. Yields were positively correlated with tem-

peratures during autumn and winter, whereas summer temperatures had no influence. Precipitation did not influence yields, except for rainfall during July, which had a negative effect on yield. Solar radiation had a positive effect on yield in April, but otherwise did not affect yields. In another study, Olesen et al. (2000b) correlated regional winter wheat yields in Denmark with seasonal temperature and precipitation, and found a slightly positive effect of temperature during April to July on grain yield.

An analysis of the effects of winter and summer temperature, precipitation and sunshine hours on national average grain yield of winter wheat is presented in Figure 3.2. There is no significant correlation between any of these climatic variables and grain yield. However, there is an indication of lower yields in years with higher summer temperatures. This is contrast to the findings of Olesen et al. (2000b) for the period 1971-97. However, the reason may be a nonlinear response, where the recent very warm years exceed the optimum. A similar optimum temperature was found in model-simulated yield of winter wheat over Europe (Olesen et al., 2007).

One of the reasons for the lack of significant correlations between climate parameters and grain yield could be that several climatic variables simultaneously affect crop growth and that this effect may differ between developmental phases thus obscuring the effect of individual climate variables. A multiple regression analysis was therefore performed on national grain yield data from Denmark for 1990 to 2008. The growing season was divided into three periods: 1) winter (October to March), 2) spring (April to May), and 3) summer (June to July). Several climate variables for these periods were tested, but only those shown in Table 3.1 were found to significantly affect grain yield. A yield trend described as an effect of year was also included in the analysis.

There was a significant yield increase over the period 1990 to 2008, when the yield data were corrected for variation in temperature, precipitation and sunshine hours in the individual years. This annual yield increase was estimated at 0.3 dt/ha, which is considerably less than for the period 1970 to 1995, where an annual yield increase of 1.0 to 1.5 dt/ha was estimated (Olesen et al., 2000a).

There was a non-linear response of grain yield to mean winter temperature (Figure 3.3). The highest yields were observed for winter temperatures around 4 °C. Winter temperatures likely affect two important processes affecting grain yield. Higher winter temperatures enhance crop development leading to earlier appearance of final leaves as illustrated in Figure 3.4 using data from the monitoring network for plant diseases in Denmark. The date of flag leaf appearance varied more than three weeks and this variation was largely determined by winter temperatures. An earlier appearance of the final leaves shortens the period that the crop has available for developing its canopy, thus reducing the capacity to intercept radiation. The period

Table 3.1 Multiple regression of national grain yield (dt/ha) of winter wheat in Denmark on year and climate variables for winter (October to March), spring (April to May) and summer (June to July) for the period 1990 to 2008. The following overall statistics were obtained for the model: $R^2 = 0.63$, RMSE = 2.91. The P-value shows a test of whether the estimate is significantly different from zero. Temperature is mean temperature (°C), maximum temperature is mean of daily maximum temperature (°C), sunshine is sunshine hours, and precipitation is sum of precipitation (mm).

Variable	Estimate	P-value
Intercept	70.0	0.043
Year	0.30	0.036
Temperature (winter)	6.19	0.039
Temperature^2 (winter)	-0.753	0.034
Precipitation (winter)	-0.019	0.080
Sunshine hours (spring)	0.042	0.025
Maximum temperature (summer)	-1.055	0.062
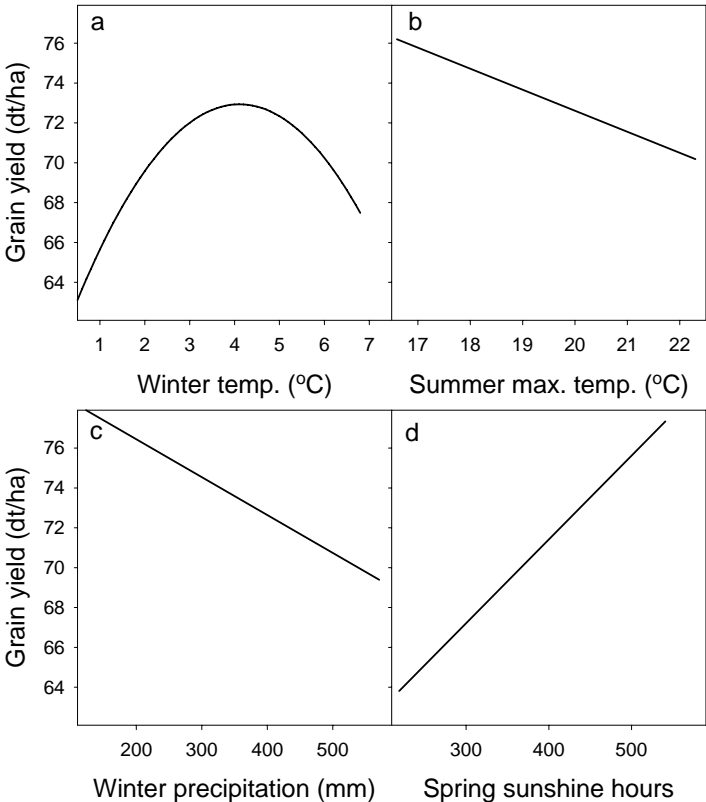
Figure 3.3 Estimated responses of winter wheat grain yield to variation in climate parameters (range for 1961-2008). The responses were estimated using the regression equation shown in Table 3.1 for year 2000 using the average climatic conditions for all other climate parameters than the one in question.

for developing tillers and ears is also reduced, possibly also reducing the sinks for carbohydrates during grain-filling. When this vegetative period becomes too short, it negatively affects the yield potential, and this is the likely explanation for high winter temperatures resulting in lower yields. Low winter temperatures can also lead to low grain yields in winter wheat (Figure 3.3a). This can partly be explained by very low winter temperatures giving rise to frost or cold damage. However, the most likely reason is that cold winters restrict root growth during the winter, since the development of deep root systems is primarily controlled by soil temperature. Cold temperatures therefore result in a too shallow root system of the winter wheat in spring, which makes the crop more susceptible to drought.
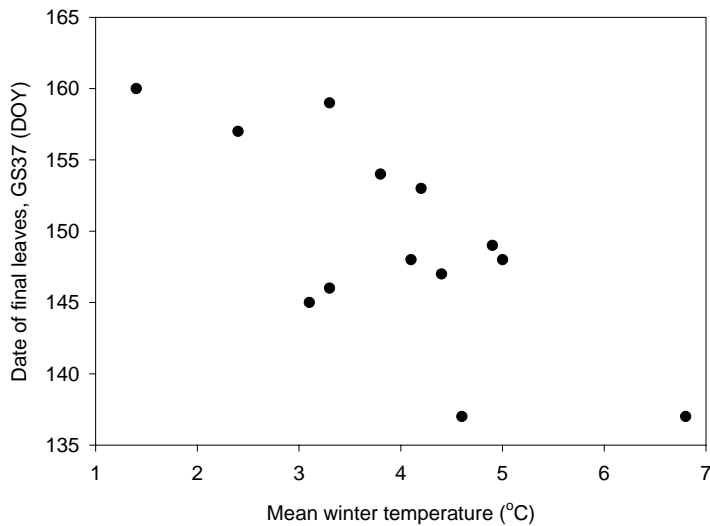
Figure 3.4 Date of flag leaf appearance (corresponding to growth stage 37) in winter wheat for the years 1996 to 2008 in the Danish monitoring network for plant disease versus mean winter temperature (October to March).

Higher summer maximum temperatures reduce crop yield. There are two likely explanations for this. Higher temperatures during the summer period will reduce the duration of the grain-filling period, which shortens the period available for accumulating dry matter in the grain. The second explanation is that high maximum temperatures are associated with high vapour pressure deficits and large evaporative demands, which may lead to temporary water shortages and stomatal closure that reduces net assimilation. Water shortage during anthesis is particularly critical as ovules are aborted.

Increasing winter precipitation reduces grain yield (Figure 3.3c). A reason for this could be that high winter precipitation is associated with high nitrate leaching, which reduces the availability of nitrogen for the crop in the following year. On soils with insufficient drainage, wet winters may also restrict root development making the crop more susceptible to early drought.

High solar radiation in spring (April and May) has a large beneficial effect on grain yield (Figure 3.3d). This is most likely a direct effect of solar radiation on crop photosynthesis, which during this period further stimulates growth of the roots and leaves, resulting in a dense crop canopy and also a large resource of carbohydrate and nitrogen reserves in the crop for later transfer to the grain.

The analysis also shows that precipitation during the spring and summer period does not come out as an important factor. On most sandy loams and loams, winter wheat establishes a very deep root system, which means that water shortages and most droughts do not result in yield losses. However, in some years with early droughts yield losses may occur, in particular in late sown crops, where root growth is delayed resulting in water shortages. On sandy soils drought effects are much more likely to occur. However, winter wheat is commonly irrigated on these soils in Denmark.

The estimated yield trend for the period 1990 to 2008 was 0.18 dt/ha/yr without adjusting for climate effects, whereas the yield trend was 0.30 dt/ha/year when climatic differences between years were included. This means that climatic variation, in particular increasing temperatures, has reduced yields by about 2.2 dt/ha over the 18 year period from 1990 to 2008.

3.2 CO_2

Atmospheric CO_2 concentrations affect crop growth and yield in several ways. Therefore, the observed increase in CO_2 concentration may also have affected yield of winter wheat in Denmark. CO_2 concentrations are increasing due to the global emissions of CO_2 from fossil fuel combustion and from land use changes. The change in atmospheric CO_2 concentration in recent years corresponds to about 2 ppmv per year (Figure 3.5).

Plant photosynthesis has long been known to respond to atmospheric CO_2 concentration. However, this response depends on the photosynthetic pathway of the plants. The response is thus much smaller in C_4-plants (tropical plants including maize) compared with C_3-plants (e.g. wheat) (Fuhrer, 2003). The photosynthesis in C_3-plants is stimulated by enhanced CO_2 concentrations through reductions in photorespiration.

The second primary effect of CO_2 enrichment on plants is to reduce stomatal aperture and density, which causes a reduction in stomatal conductance and thus transpiration. An average reduction of 20% of stomatal conductance has been found with a doubling of the current CO_2 concentration (Drake et al., 1997). However, effects of soil water availability and leaf area index reduce the impact on total transpiration.

There is a third primary effect of CO_2 enrichment, which is the reduction of dark respiration because CO_2 and O_2 are mutually competitive substrates on the ribulose biphosphate carboxy-

lase (Rubisco) enzyme for ribulose biphosphate (RuBP) followed by a reduction in activity of respiratory enzymes (Ogren, 1984; Bunce, 1994). Maintenance respiration has been found to be reduced by 20% for a doubling of the current atmospheric CO_2 concentration (Drake et al., 1997).
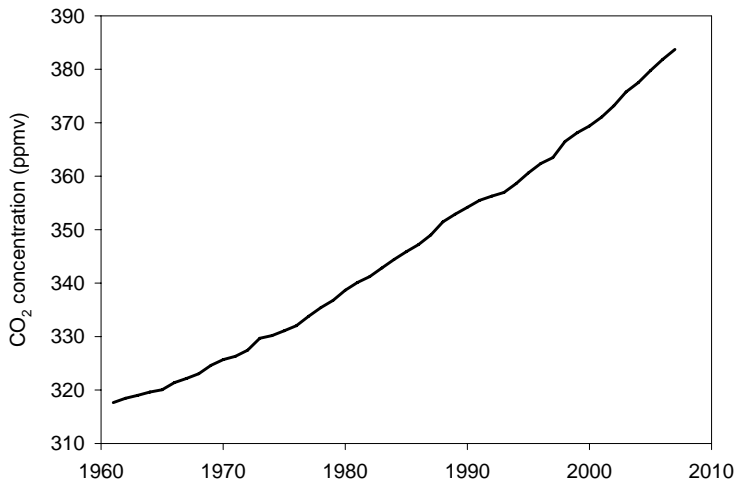
Figure 3.5 Average annual CO_2 concentrations measured at Mauna Loa in Hawaii.

The resulting effects of these primary responses of plants to rising atmospheric CO_2 concentration are increasing resource use efficiencies for radiation, water and nitrogen. The highest response is seen for water use efficiency, which is affected positively by all three factors. The observed response of grain yield in wheat to variation in CO_2 concentration is illustrated in Figure 3.6. This graph draws on data from 12 whole-season studies with different CO_2 concentrations under a wide range of experimental conditions, from pots in growth chambers or glasshouses to open top chambers (OTC) or free air CO_2 enrichment (FACE) facilities (Olesen and Bindi, 2000). Figure 3.6 shows a mean yield increase of 28% for a doubling of current CO_2 concentrations.

Recent estimates of the yield benefit from increasing CO_2 are smaller than earlier ones (Ainsworth and Long, 2005), and the average annual increase of the next decades is marginal compared with what has been achieved through conventional crop management and breeding (Berntsen et al., 2006). Some model studies of CO_2 effects are based on results from enclosure studies from the 1980s that exaggerate the effects of increased CO_2 on plant production (Long et al., 2006). These model predictions should be considered with caution, since they may substantially overestimate the positive yield effects of increased CO_2.

During the period 1990 to 2008 the atmospheric CO_2 concentration has increased by about 30 ppmv, corresponding to an increase of 8%. Using the relationship show in Figure 3.6, this

converts into an increase in grain yield increase of 4% over the period or about 0.16 dt/ha per year (75 dt/ha×0.04/18 years).
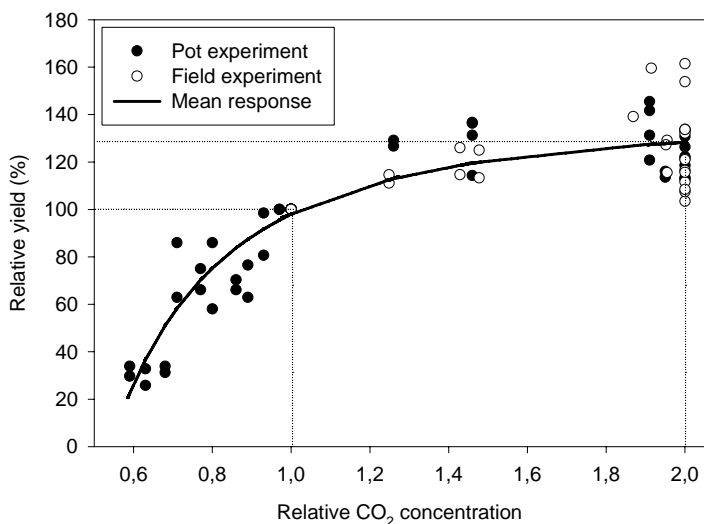
Figure 3.6 Relative effects of CO_2 concentration on wheat grain yield in experiments. Ambient CO_2 is set to 1. Open symbols represent data from field experiments, filled symbols represent data from pot or glasshouse experiments. The solid line shows the mean estimated response (Olesen and Bindi, 2002).

3.3 Ozone

Ozone (O_3) is a major secondary air pollutant, produced by a complex series of photochemical reactions from primary precursor emissions of nitrogen oxides and volatile organic compounds (Ashmore, 2005). There is evidence of an increase in global background ozone concentrations, which will lead to significant changes in global ozone exposure over this century, during which direct and indirect effects of other changes in the global atmosphere will also modify plant responses to ozone (Pleijel et al., 1997). Ambient concentrations of the pollutant are known to decrease the productivity of a wide range of crops in many parts of the world (Musselman and Lefohn, 2007, Pleijel et al., 2006).

It has been shown that ozone can cause a range of effects including visible leaf injury, growth and yield reductions, and altered sensitivity to biotic and abiotic stresses (Fuhrer et al., 1997). However, there are important interactions with increasing CO_2 concentrations that may modify future ozone impacts. Changes in water availability, temperature and nutrient cycling may also interact with changing ozone exposure. Second-order interactions, for example, with the likelihood and severity of insect pest outbreaks, also need to be considered.

Wheat has been known as a species sensitive to O_3 (Ainsworth et al., 2008). Yield reductions induced by exposure to the pollutant have been reported in glasshouse and field studies

(Wang et al., 2005), with responses dependent upon concentration, timing and duration of O_3 exposure and other environmental factors, as well as on the cultivar and cultural practices.

Ozone impacts at the whole-plant level have received considerable attention (Ashmore, 2005). Reductions in productivity were found to be related to increased non-structural carbohydrate contents of source leaves and inhibited carbon export to sinks such as roots. The expected consequences are: (1) changes in hydraulic function of roots leading to altered whole-plant water relations; (2) reductions in carbon transfer from the plant to the soil; (3) altered soil nutrient uptake by the roots.

Long-term effects of ozone on annual crops result from the cumulative impact of ozone taken up over the course of a single growing season. It is well known that increasing O_3 levels at ambient CO_2 cause a decline in yield either via direct effects (i.e. on Rubisco) on one or more reproductive growth stages or via indirect effects originating from injury to the vegetative organs and subsequent reductions in assimilate availability and partitioning (Shankar and Neeliah, 2005). These processes are affected by early senescence (Gelang et al., 2000). A compilation of data from an EU-wide study showed that an ozone-induced reduction of green leaf area duration was a general effect in wheat (Piikki et al., 2008).

Considerable evidence suggests that ozone uptake is decreased by elevated CO_2 (Piikki et al., 2008). Experiments with wheat demonstrated that the positive effect of elevated CO_2 on yield was larger in an atmosphere containing elevated levels of ozone (Heagle et al., 2000), possibly due to ozone exclusion, rather than increased detoxification capacity. However, the two processes act together as shown in plants treated with elevated CO_2, where ozone uptake is reduced and the availability of carbon for detoxification is increased (Heagle et al., 2000).

The trends of ozone in eight environments in Denmark are shown in Figure 3.7. Annual average concentrations have kept stable during the period since 1992. However, there is an indication of reductions in maximum ozone concentrations.

Annual averages of ozone concentrations for three rural areas in Denmark are shown in Figure 3.8. The data indicate a slight decline in concentrations in the period. In two recent detailed studies, the losses of crops in Denmark caused by high ozone levels have been estimated for the years 1989 to 1998 (Ostromsky et al., 2001; Zlatev et al., 2001). The results indicated yield loss rates of 5 to 10 % in the years investigated. However, since ozone levels have not been increasing in Denmark, this is not a likely explanation for the stagnating grain yields.
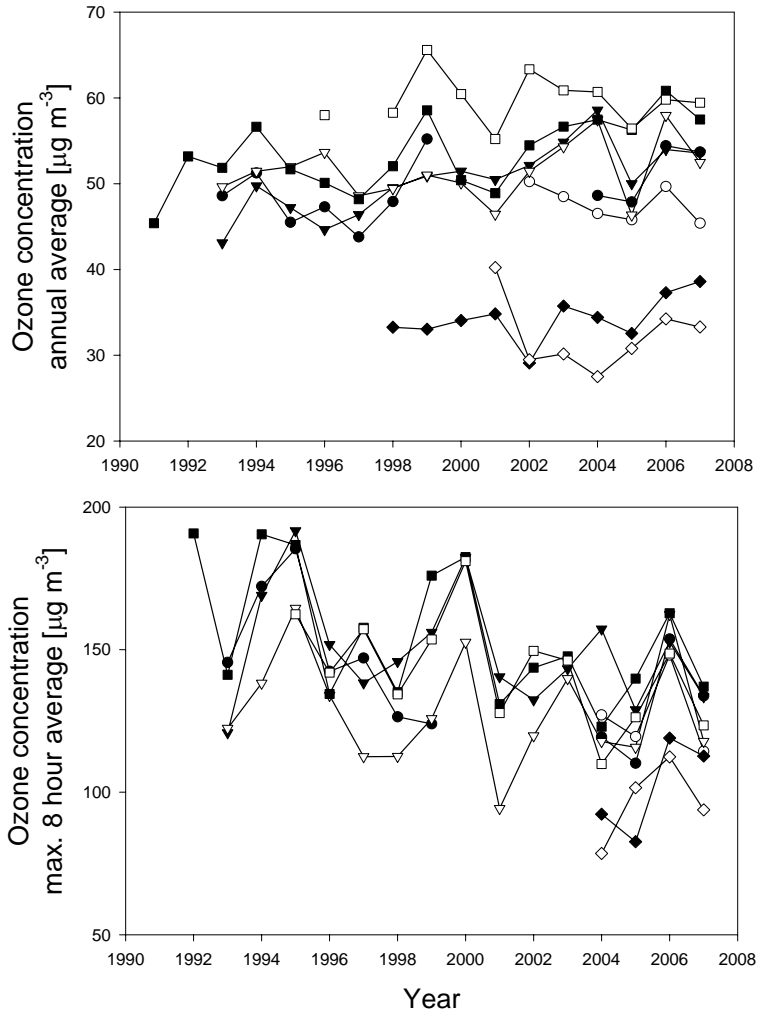
Figure 3.7 Annual average values (above) and the max. 8 hour average value (below) of ozone in eight environments in Denmark (six city environments: Copenhage (3 sites), Odense, Aalborg, Århus, and two rural environments Lille Valby and Kelsnor). The latter is calculated as hourly 8 hour running averages according to the provisions in the EU Council Directive (EC, 2002) (Redraw from Kemp et al., 2008).
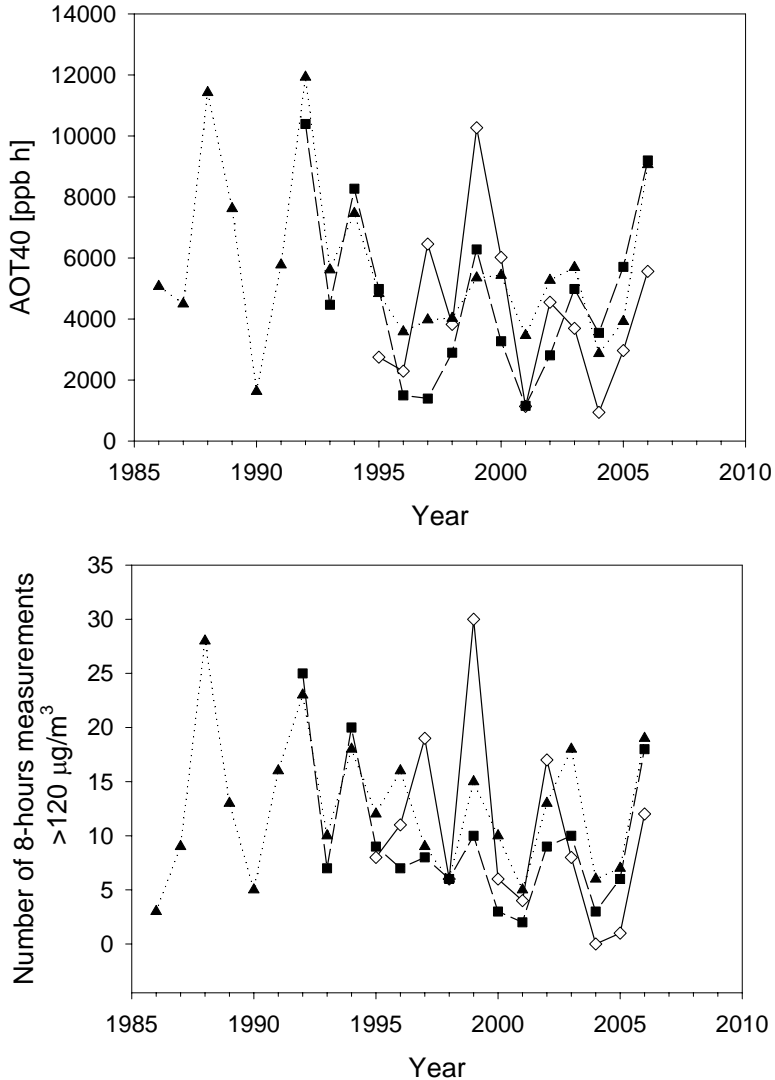
Figure 3.8 Accumulated exposure Over a Threshold of 40 ppb (AOT40; ppb h) values recorded from 8-20 CET from May to July according to EU regulation (2002/3/EC) (above) and number of 8-hours measurements above 120 μg/m^3 (below) at three rural environments (Keldsnor Fyr at South Langeland; Ulborg in West Jutland near Ulfborg and Lille Valby near Roskilde) (Above figure is re-draw from Ellermann et al., 2006, below figure pers. comm.).

3.4 UV-B radiation

The solar radiation at the top of the Earth's atmosphere contains a significant amount of radiation of wavelengths shorter, and therefore more energetic, than that of visible light (400-700 nm). Wavelengths in the range 100-400 nm constitute the ultraviolet (UV) spectral region.

The shortest of these wavelengths (UV-C, 100-280 nm) are essentially blocked by atmospheric oxygen (O_2) and ozone (O_3). Wavelengths in the UV-B range (280-315 nm) are absorbed efficiently by O_3, while UV-A wavelengths (315-400 nm) are absorbed only weakly by O_3 and are therefore more easily transmitted to the Earth's surface (Madronich et al., 1998).

Scientific assessment of ozone depletion provides clear evidence that stratospheric O_3 for the period of 1997–2001 was 3–6% less than the pre-1980 average values. Due to this depletion, UV-B radiation on the Earth's surface has increased since early 1980s by 6–14 %. This has increased the concern over the ecological implications of increasing UV-B radiation on agricultural production (Hakala et al., 2002). To date, a wide range of biochemical, physiological, morphological, anatomical and growth responses of plants have been reported in response to elevated UV-B radiation (Feng et al., 2007).

On continued exposure to UV-B, leaves show chlorotic and necrotic patches, which are attributed to the decrease in leaf chlorophyll content. Such symptoms are not unique to UV-B radiation as plants deficient in mineral nutrients and those exposed to ozone also produce similar symptoms (Krupa, 2003a, b).

Numerous studies have been done to study the impact of UV-B radiation on crop growth (Calderini et al., 2008). Overall, enhanced UV-B radiation has been shown to reduce the elongation rates of both main- and side tillers, resulting in more compact and shorter plants. Leaf area was reduced under enhanced UV-B radiation due to reduction in cell size, cell number or both (Hakala et al., 2002). UV-B radiation may change the allocation of biomass to root systems (Caldwell et al., 2007), and these changes can be much larger than changes in the plant shoot system.

Wheat is a potentially UV-B sensitive species (Li et al., 1998). UV-B radiation modifies the floral morphology and affects reproductive processes that lead to final yield formation. It has been shown that pollen germination and pollen tube growth were inhibited by exposure to enhanced UV-B (Shukla et al., 2002) limiting the yield forming capability. Delays in development and decrease in plant height were observed at early tillering stage under UV-B treatment (Li et al., 1998). UV-B radiation changed crop canopy structure by decreasing the total number of tillers produced and increasing dead shoot number, resulted in fewer head-bearing shoots at ripening stage, and decreased biomass and yield (Zheng et al., 2003). UV-B radiation decreased the area of the last leaf and leaf area index. This resulted in yield reductions under UV-B (Yuan et al., 2000).

There are only measurements at Danish Meteorological Institute of UV-B radiation for the past 10 years, and there is in Europe in general a lack of long-term monitoring data for UV-B. The UV-B radiation depends on many factors, including solar elevation, cloud cover, thickness of the stratospheric ozone layer and aerosols. Ground-based measuring stations have re-

corded increases in the amount of UV radiation in recent years. Increased UV radiation will continue until recovery of the stratospheric ozone layer is complete. Higher effects of UV-B radiation reducing yields in recent years therefore cannot be excluded, but are also very difficult to quantify.

3.5 Conclusions

All the mentioned external factors (climate, CO_2, ozone and UV-B) may have affected winter wheat yields over the past two decades. Of these factors, it is easiest to quantify the effects of climate and CO_2. The yield depleting effects of ozone may have be slightly decreased in recent years, whereas the effect of UV-B radiation has probably been stable or increased slightly.

The response functions for climatic variables in Table 3.1 and of atmospheric CO_2 in Figure 3.6 allow the observed grain yields to be corrected for these effects. Figure 3.9 shows corrected national grain yields, which have been adjusted to the average climate for 1961-90 and to the atmospheric CO_2 concentration in 1990. The result is a yield has remained remarkably stable over the period since 1996.
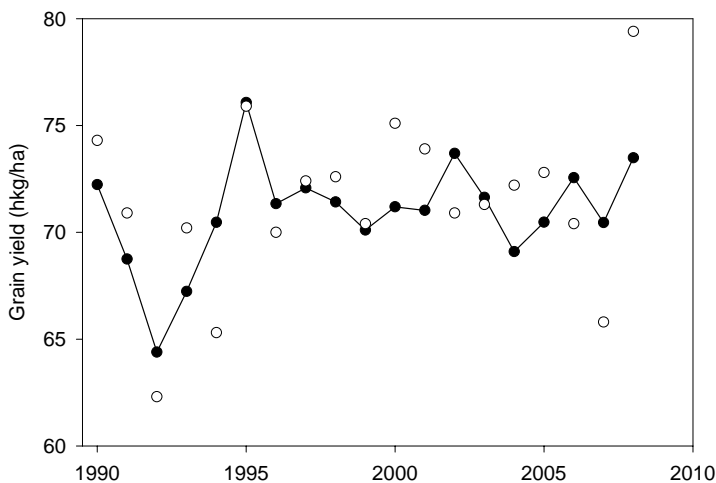
Figure 3.9 National average grain yield of winter wheat in Denmark (open symbols) and corrected for effect of climate and increased atmospheric CO_2 (filled symbols).

The changes in climate over the period 1990 to 2008 were estimated to have reduced winter wheat grain yield by 0.12 dt/ha/yr. This should be compared to an anticipated yield increase of 0.16 dt/ha/yr from rising atmospheric CO_2 concentration. The result is a negligible effect of climate and CO_2 on wheat yields.

3.6 References

Ainsworth, E.A. & Long, S.P. (2005) What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. New Phytol. 165, 351-372.

Ainsworth, E.A., Rogers, A. & Leakey, A.D.B. (2008) Targets for crop biotechnology in a future high-CO_2 and high-O_3 world. Plant Physiology 147, 13-19.

Alcamo, J., Moreno, J.M., Nováky, B., Bindi, M., Corobov, R., Devoy, R.J.N., Giannakopoulos, C., Martin, E., Olesen, J.E. & Shvidenko, A. (2007) Europe. In Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds). Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, p. 541-580.

Ashmore, M.R. (2005) Assessing the future global impacts of ozone on vegetation. Plant Cell Environ. 28, 949-964.

Berntsen, J., Petersen, B.M. & Olesen, J.E. (2006) Simulating trends in crop yield and soil carbon in a long-term experiment - effects of rising CO_2, N deposition and improved cultivation. Plant Soil 287, 235-245.

Bunce, J.A. (1994) Responses of respiration to increasing atmospheric carbon dioxide concentrations. Physiol. Plant. 90, 427-430.

Calderini, D.F., Lizana, X.C., Hess, S., Jobet, C.R. & Zuniga, J.A. (2008) Grain yield and quality of wheat under increased ultraviolet radiation (UV-B) at later stages of the crop cycle. J. Agric. Sci. 146, 57-64.

Caldwell, M.M., Bornman, J.F., Ballare, C.L., Flint, S.D. & Kulandaivelu, G. (2007) Terrestrial ecosystems, increased solar ultraviolet radiation, and interactions with bother climate change factors. Photochem. Photobiol. Sci. 6, 252-266.

Drake, B.G., Gonzalez-Meier, M.A. & Long, S.P. (1997) More efficient plants: a consequence of rising CO_2? Ann. Rev. Plant Physiol. Plant Mol. Biol. 48, 609-639.

EEA (2003) Europe's Environment: the third assessment. European Environment Agency, Copenhagen. 343 pp.

EEA, 2004. Impacts of Europe's changing climate: An indicator-based assessment. EEA Report No 2/2004, European Environment Agency, Copenhagen, Denmark, 107 pp.

Ellermann, T., Andersen, H.V., Bossi, R., Christensen, J., Frohn, L.M., Geels, C., Kemp, K., Løfstrøm, P., Mogensen, B.B. & Monies, C. (2007) Atmosfærisk deposition 2006. NOVANA. Danmarks Miljøundersøgelser, Aarhus Universitet, Faglig rapport fra DMU nr. 645, 62 pp.

Feng, H.Y., Li, S.W., Xue, L.G., An, L.Z. & Wang, X.F. (2007) The interactive effects of enhanced UV-B radiation and soil drought on spring wheat. S. African J. Bot. 73, 429-434.

Frich, P., Alexander, L.V., Della-Marta, P., Gleason, B., Haylock, M., Tank, A.M.G.K. & Peterson, T. (2002) Observed coherent changes in climatic extremes during the second half of the twentieth century. Climate Res. 19, 193-212.

Fuhrer, J. (2003) Agroecosystem responses to combinations of elevated CO_2, ozone, and

global climate change. Agric. Ecosyst. Environ. 97, 1-20.

Fuhrer, J., Skärby, L. & Ashmore, M.R. (1997) Critical levels for ozone effects on vegetation in Europe. Environ. Poll. 97, 91-106.

Gelang, J., Pleijel, H., Sild, E., Danielsson, H., Younis, S. & Sellden, G. (2000) Rate and duration of grain filling in relation to flag leaf senescence and grain yield in spring wheat (*Triticum aestivum*) exposed to different concentrations of ozone. Physiol. Plant. 110, 366-375.

Hakala, K., Jauhiainen, L., Koskela, T., Kayhko, P. & Vorne, V. (2002) Sensitivity of crops to increased ultraviolet radiation in northern growing conditions. J. Agron. Crop Sci. 188, 8-18.

Heagle, A.S., Miller, J.E. & Pursley, W.A. (2000) Growth and yield responses of winter wheat to mixtures of ozone and carbon dioxide. Crop Sci. 40, 1656-1664.

Jones, P.D. & Moberg, A. (2003) Hemispheric and large scale surface air temperature variations: an extensive revision and an update to 2001. J. Clim. 16, 206-223.

Kemp, K., Ellermann, T., Brandt, J., Christensen, J., Ketzel, M. & Jensen, S.S. (2008) The Danish Air Quality Monitoring Programme. Annual Summary for 2007. NERI Technical Report No. 681. National Environmental Research Institute, University of Aarhus.

Kjellström, E. (2004) Recent and future signatures of climate change in Europe. Ambio 33:193-198.

Klein Tank, A.M.G. & Können, G.P. (2003) Trends in indices of daily temperature and precipitation extremes in Europe. J. Clim. 16, 3665-3680.

Klein Tank, A.M.G. et al. (2002) Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. Int. J. Clim. 22:1441-1453.

Krupa, S. (2003a) Atmosphere and agriculture in the new millennium. Environ. Poll. 126, 293-300.

Krupa, S.V. (2003b) Joint effects of elevated levels of ultraviolet-B radiation, carbon dioxide and ozone on plants. Photochem. Photobiol. 78, 535-542.

Li, Y.A., Yue, M. & Wang, X.L. (1998) Effects of enhanced ultraviolet-B radiation on crop structure, growth and yield components of spring wheat under field conditions. Field Crops Res. 57, 253-263.

Lobell, D.B. & Asner, G.P. (2003) Climate and management contributions to recent trends in U.S. agricultural yields. Science 299, 1032.

Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Nösberger, J. & Ort, D.R. (2006) Food for thought: Lower-than-expected crop yield stimulation with rising CO_2 concentrations. Science 312, 1918-1921.

Madronich, S., McKenzie, R.L., Bjorn, L.O. & Caldwell, M.M. (1998) Changes in biologically active ultraviolet radiation reaching the Earth's surface. J. Photochem. Photobiol. B-Biology 46, 5-19.

Musselman, R.C. & Lefohn, A.S. (2007) The use of critical levels for determining plant response to ozone in Europe and in North America. Thescientificworldjournal **7**, 15-21.

Ogren, W.L. (1984) Photorespiration: pathways, regulation, and modification. Annu. Plant Physiol. 35, 415-442.

Olesen, J.E. & Bindi, M. (2002) Consequences of climate change for European agricultural productivity, land use and policy. Eur. J. Agron. 16, 239-262.

Olesen, J.E., Jensen, T. & Petersen, J. (2000a) Sensitivity of field-scale winter wheat production in Denmark to climate variability and climate change. Clim. Res. 15:221-238.

Olesen, J.E., Bøcher, P.K. & Jensen, T. (2000b) Comparison of scales of climate and soil data for aggregating simulated yields of winter wheat. Agric. Ecosyst. Environ. 82, 213-228.

Olesen, J.E., Carter, T.R., Diaz-Ambrona, C.H., Fronzek, S., Heidmann, T., Hickler, T., Holt, T., Minguez, M.I., Morales, P., Palutikov, J., Quemada, M., Ruiz-Ramos, M., Rubæk, G., Sau, F., Smith, B. & Sykes, M. (2007) Uncertainties in projected impacts of climate change on European agriculture and ecosystems based on scenarios from regional climate models. Clim. Change 81 (suppl. 1), 123-143.

Ostromsky, T., Dimov, I., Tzvetanov, I. & Zlatev, Z. (2001) Estimation of the wheat losses caused by the tropospheric ozone in Bulgaria and Denmark. In: Numerical Analysis and Its Applications, pp. 636-643.

Piikki, K., De Temmerman, L., Ojanpera, K., Danielsson, H. & Pleijel, H. (2008) The grain quality of spring wheat (Triticum aestivum L.) in relation to elevated ozone uptake and carbon dioxide exposure. Eur. J. Agron. 28, 245-254.

Pleijel, H., Ojanpera, K. & Mortensen, L. (1997) Effects of tropospheric ozone on the yield and grain protein content of spring wheat (*Triticum aestivum* L) in the Nordic countries. Acta Agric. Scand. Sect. B Soi Plant Sci., 47, 20-25.

Pleijel, H., Eriksen, A.B., Danielsson, H., Bondesson, N. & Sellden, G. (2006) Differential ozone sensitivity in an old and a modem Swedish wheat cultivar - grain yield and quality, leaf chlorophyll and stomatal conductance. Environ. Exp. Bot. 56, 63-71.

Shankar, B.& Neeliah, H. (2005) Tropospheric ozone and winter wheat production in England and Wales: A note. J. Agric. Econ. 56, 145-151.

Shukla, U.C., Joshi, P.C. & Kakkar, P. (2002) Synergistic action of ultraviolet-B radiation and cadmium on the growth of wheat seedlings. Ecotoxicol. Environ. Safety 51, 90-96.

Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Tank, A.K., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Soden, B. & Zhai, P. (2007) Observations: Surface and atmospheric climate change. In Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tigor, M. & Miller, H.L. (eds) Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA. p. 235-336.

Wang, H.X., Kiang, C.S., Tang, X.Y., Zhou, X.J. & Chameides, W.L. (2005) Surface ozone: A likely threat to crops in Yangtze delta of China. Atmos. Environ. 39, 3843-3850.

Yuan, L., Yanqun, Z., Haiyan, C., Jianjun, C., Jilong, Y. & Zhide, H. (2000) Intraspecific responses in crop growth and yield of 20 wheat cultivars to enhanced ultraviolet-B radiation under field conditions. Field Crops Res. 67, 25-33.

Zheng, Y.F., Gao, W., Slusser, J.R., Grant, R.H. & Wang, C.H. (2003) Yield and yield formation of field winter wheat in response to supplemental solar ultraviolet-B radiation. Agric. Forest Meteorol. 120, 279-283.

Zlatev, Z., Dimov, I., Ostromsky, T., Geernaert, G., Tzvetanov, I. & Bastrup-Birk, A. (2001) Calculating losses of crops in Denmark caused by high ozone levels. Environ. Model. Assess. 6, 35-55.

4 Breeding and genetics

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4.1 Introduction

When analyzing the contribution of breeding and genetics to yield development in winter wheat over time, it is important to take into account the changes in conditions to which the development of new varieties have to adapt. The yield potential is a complex character that can be bred for in itself, but the realization of the potential will always be constrained by environmental limitations, such as nutrient availability and exposures to stress. There are two major cereal breeders in Denmark (Sejet Plant Breeding and Nordic Seed), and so the breeding of new winter wheat varieties is performed under national environmental and regulatory constraints. Similarly, cultivars from abroad will usually be subject to Danish trial conditions before being sold on the Danish market.

The breeding efforts must adapt to changes in the aim of developing new, higher yielding varieties. The introduction of dwarf genes in 1987/88 follows this aim, but also introduces a switch from tall to very short wheat varieties. Discussions of utilization of nutrient and water resources in the soil during the 1990s turn the breeder to focus on varieties with larger root mass which implies varieties with more vegetative biomass causing taller varieties. Another factor leading to taller varieties during the 1990s was increasing disease incidents caused by Septoria. Taller plants appear to have lesser risk of fatal infection by this fungal disease. Introduction of strobilurine fungicides in 1998 gives opportunity for extended grain filling period, and utilization of this yield potential may also be included in the breeding aim. The introduction of the Dutch variety Ritmo, which dominated the market in the late 1990s meant an increased tillering, also contributing to the total yield of the wheat plant. With a better resistance to Wheat Eyespot *(Pseudocercosporella herpotrichoides)* added, Ritmo has become the ancestor to all the new Danish varieties that dominate the market today.

Overall, there is a clear picture that the Danish breeding efforts during the last three decades have been modified to meet the challenges from the changes in growing conditions for winter wheat in Denmark. The aim of this paper is to assess whether these breeding efforts, in spite of the challenges, have kept up with the demand for sustained increases in yield potential of new winter wheat varieties.

4.2 Data and method

The yields of the 4-10 highest-yielding varieties in the National Field Trials are by regression compared with the yield of eight corresponding reference varieties during 1980-2008. This

regression analysis makes us able to estimate the improvement in yields contributed by the new high-yielding varieties. The total number of winter wheat varieties in the trials differed amongst years, but it increased considerably throughout the whole period. The fraction of high-yielding varieties (4, 7, or 10) represents *c*. 20 % of the total number of varieties in the trials. The variety composition of the highest-yielding varieties obviously changed from year to year; however, there was a clear tendency for many varieties to be included in this group for more years before being replaced.

The yields are an average of up to 10 national trials per year. Before 2004 the winter wheat varieties were tested in up to four trial series. Data from before 2004, when the introduction of alpha design enabled all trials to be joined in one series, is therefore adjusted by the trial reference mixture to make a comparison between all years, trials, and varieties possible. The variety Hereward, which is used as reference for a long period (1992-2008) was only included in 5 of 10 trials from 2002. The trial reference mixture was used to correlate the yield between trial series and thereby enabling the comparison with the high yielding varieties in all the trials.
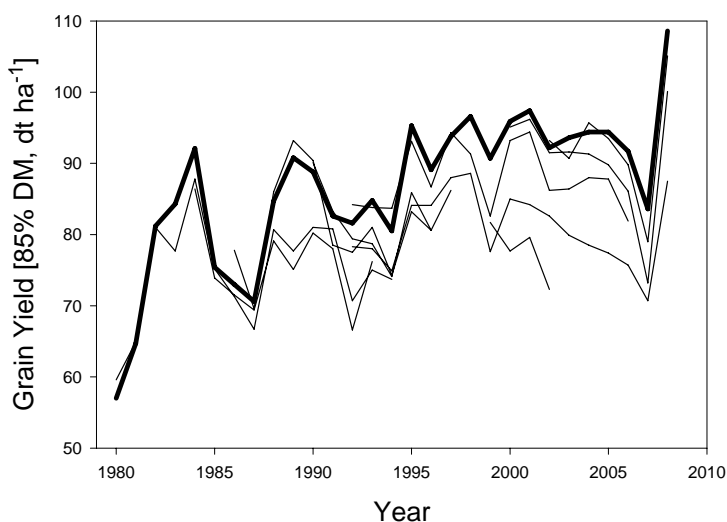
Figure 4.1 The yield of the 4-10 highest yielding varieties in test (bold line) compared to reference varieties (Kraka, Kosack, Sleipner, Pepital, Hereward, Ritmo, Hattrick and Smuggler) participating in national trials for several years (National Field Trials). The periods for reference varieties appear from Table 2.

In addition to the data from the National Field Trials, two minor trials focussing directly on the breeding effects on yield (yields of old varieties under comtemporary growing conditions) were included in the data analysis (an unpublished study from Nordic Seed 2007-2008, and Kjærsgaard et al. (2002)).

4.3 Analysis

If the yields of the reference varieties decreased over years due to e.g. break-down of the disease resistance, the slope of the regression of yield on year for each indivual reference variety should be negative. However, table 1 shows that none of the reference varieties had a statistically significant tendency to a higher or lower yield over the years. On the other hand, the highest-yielding varieties significantly increase in yield over years.

Table 4.1 Annual yield increase for reference varieties.

Variety	Slope [dt/ha/y]	*P* value
Kraka	0.41	0.37
Kosack	0.04	0.87
Sleipner	-0.04	0.96
Pepital	-0.30	0.73
Hereward	-0.14	0.59
Ritmo	0.01	0.97
Hattrick	-1.03	0.33
Smuggler	0.23	0.89
4-10 highest yielding	0.93	<0.001

For the span of years covered by each individual reference variety a regression analysis was made for the relative yield of the 4-10 highest-yielding varieties. This showed that the relative yield of the 4-10 highest-yieldning varieties increased significantly when compared to all reference varieties but Smuggler (Figure 2 and Table 2). From Figure 2, it is evident throughout the whole period that the yield of the high-yielding varieties was equal to the yield of the reference variety at the time it was adobted as reference, but that the group of high-yielding varieties gradually out-competes the reference variety when new high-yielding varieties enter the group of 4-10 highest yielding varieties. The slopes do not differ significantly amongst the different reference varieties. The new and highest-yielding varieties contributed with an average yield improvement of 1.1 % per year (1980-2008). This corresponds to an improvement of yield between 82 and c. 100 kg per hectare per year in comparison with the mean yield of the reference varieties in the period.

In a study on yields of old varieties under comtemporary growing conditions, two years' trials at the Nordic Seed breeding station near Odder showed an improvement in yield corresponding to 0.5 % per annum, when the old variety Kraka was compared to the current reference mixture (4 varieties), which is also used as reference mixture in the national yield trials. But with the 10 highest-yielding varieties in the national yield trials doing around 3 % better than the same reference mixture in the same two year period, the improvement per year since Kraka might in fact be a bit better, with an estimated improvement corresponding to 0.6 % per annum. Kjærsgaard et al. (2001) found the same improvement in yield per annum, when comparing the variety Kraka to the twelve year younger variety Ritmo in trials at Sealand. In

comparison, Öfversten et al. (2004) found, on the basis of the Finnish statutory variety test, that new varieties contributed to an annual yield increase of 0.63 % in winter wheat and 0.97 % per anno in winter rye.
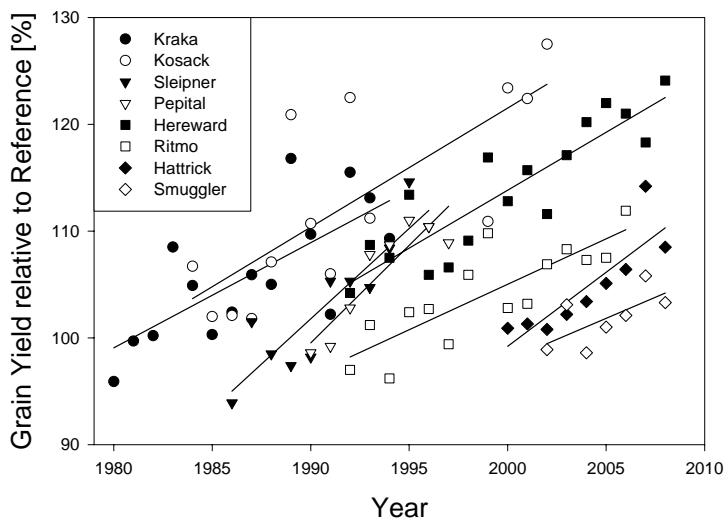
Figure 4.2 Yield of the 4-10 highest yielding varieties in the national field trials relative to the reference varieties (Kraka, Kosack, Sleipner, Pepital, Hereward, Ritmo, Hattrick and Smuggler) covering different periods (National Field Trials). The periods for reference varieties appear from Table 2.

Table 4.2 Relative annual yield increase of 4-10 higest yielding varieties.

Reference variety	Period	Slope [%]	*P* value	Mean yield in period [dt/ha]	Yield improvement [kg/ha/year]
Kraka	1980-1994	0.98	<0.001	74.9	82
Kosack	1984-1993/ 1999-2002	1.11	<0.001	76.3	84
Sleipner	1986-1996	1.69	<0.001	81.1	89
Pepital	1990-1997	1.83	0.002	82.3	91
Hereward	1992-2008	1.09	<0.001	80.9	89
Ritmo	1992-2006	0.85	<0.001	87.8	97
Hattrick	2000-2008	1.39	0.005	90.5	100
Smuggler	2002-2008	0.79	0.260	92.4	102
Mean		1.1			92

This analysis is based on yields of winter wheat varieties in well-conducted trials in the period 1980-2008. How these yields translate into the yields of common Danish agriculture during the same period is another question, to which the answer depends, first of all, on the choice of varieties by the farmers and also on common agricultural practices. Based on the amounts of

certified sowing seeds sold, as reported by the Danish Plant Directorate every year (www.pdir.dk), there is a lag of at least four years from their first appearance in the National Field Trials until new high-yielding varieties get their break-throughs as commonly grown varieties. Furthermore, the choice of varieties can be based on other reasons than pure yield, for example quality or disease resistance. For instance, the sowing seed data shows that in the year 2002 the share of sowing seeds from varieties that in previous years had been part of the group of high-yielding varieties, as defined in this analysis, had fallen to a minimum of around 50 %. After 2006, the high-yielding varieties have comprised more than 90 % of the sowing seed sold, and it seems that the new and taller winter wheat varieties with a presumably better ability to take up nitrogen are gaining importance in common agricultural practice.

4.4 Future winter wheat yields – what to expect?

It is the nature of wheat breeding that new varieties should exceed, or at least equal, older varietes with regard to yield levels. However, an increase in the yield potential can be more or less directly pursued in the breeding process, in the way that primary selection criteria will often be focussed on qualitative characters such as resistance to important diseases. Breeding directly for yield requires a focus on a range of yield components in order to optimize the combined effects of these. Sylvester-Bradley et al. (2005) estimated the theoretical maximal wheat yield under British conditions to approximate 19.2 t/ha, which indicates the maximal yield also under Danish conditions. Thus, targeted approaches to increase wheat yields substantially above the current levels should still be plausible.

The yield increases observed over the last 50 years are mostly attributed to increases in harvest index that in modern varieties approximates an apparent maximum around 0.6 (Fisher 2007). However, Fisher (2007) also noted that many of the best north European winter wheats, with a harvest index at around 0.45-0.50, are still well below this limit, leaving lots of space for improvement. Future increases in yield need to rely on increases in total biomass while maintaining an efficient re-allocation of photosynthates to the grain, i.e. a high harvest index. Foulkes et al. (2007) suggested that this can be achieved through different targeted optimizations: i) a better rooting system for efficient water and nutrient uptake; ii) extension of the stem-elongation phase in order to increase the accumulation of pre-anthesis water soluble carbohydrates in the stems; iii) optimization of photosynthesis and radiation use efficency either via changes in plant architecture or directly via higher specificity for carboxylation by Rubisco, regulation of Rubisco activation, or ribulose bisphosphate regeneration (see also Parry et al. 2007); and iv) development of strong sinks to efficiently absorb photosynthates during the grain filling period, i.e. setting of a high number of kernels at anthesis. Overall, an important element for the combination of high biomass and high harvest index is the delaying of senescence processes (Gregersen et al. 2008) that should secure the re-allocation of photosynthates and nutrients to the grain.

There is considerable evidence that biomass increases have been associated with specific introductions of alien genes into wheat germplasm in the last decades, which has been extensively used in wheat breeding programmes across the world (Foulkes et al. 2007; Reynolds et al. 2001). However, the complexity of the yield traits makes targeted selection difficult. Anticipated future insights into the genetic and molecular regulation of these complex traits will presumably provide means for a more efficient selection. Studies in rice (e.g. Xue et al. 2007; Wang et al. 2008) have shown that several yield components, although quantitative of nature, are relatively simply governed by single genes, for example genes that have large effects on grain size and weight, plant height, and grains per panicle. This holds promises as well for wheat breeding. When the wheat genome sequence eventually becomes available (www.wheatgenome.org), the characterization of important yield-determining genes could form the basis for development of molecular markers that can assist their efficient exploitation in breeding programmes.

Detailed characterization of yield-determining genes could also, in the longer term, form the basis for genetic modification, by up- or down-regulation of gene activities in order to achieve yield increases. This could be exploited in e.g. a cisgenesis approach (Rommens et al. 2007), where only the plant's own genes are used during the genetic engineering.

The introduction and use of wheat hybrids will possibly increase yield, as hybrids can achieve a higher harvest index, biomass and yields through combining yield components from their parents (Evans, 1993). Grain yield data from 1975 to 1995 from four North American locations, selected and analyzed by relative yield indices, indicated an 11% advantage of hybrids over pure lines. In European studies the levels of heterosis for grain yield averaged 5% to more than 10% (Kindred & Gooding, 2005). In 2006 the wheat hybrid Hysun was the highest yielding variety in the National Field Trials. The hybrid variety was, however, excluded the following year because of 40 percent mother plants in the plots. In 2008 another hybrid variety, Hymack, did not exceed the trial reference mixture in the National Field Trials (www.sortinfo.dk).

4.5 Conclusion
For the period 1980 to 2008, the analysis indicated that breeding and genetics have contributed with an annual yield increase of up to 1.1 %. The results might indicate, that the Danish cereal breeders have adapted to the new conditions very quickly, e.g. with new and taller winter wheat varieties with presumably better abilities to take up nitrogen, as an answer to the reduced nitrogen quotas in Denmark. The estimation is that there are still possibilities for improving winter wheat yields considerably, but that this will rely on targeted breeding efforts on the genetic combination of yield components, possibly by the help of new technologies such as the development of molecular markers.

4.6 References

Evans, L.T. (1993) Crop Evolution, Adaptation, and Yield. Cambridge University Press, Cambridge.

Fischer, R. A. (2007) Understanding the physiological basis of yield potential in wheat. Journal of Agricultural Science 145, 99-113.

Foulkes, M.J., Snape, J.W., Shearman, V.J., Reynolds, M.P., Gaju, O. & Sylvester-Bradley, R. (2007) Genetic progress in yield potential in wheat: recent advances and future prospects. Journal of Agricultural Science, Cambridge 145, 17-29.

Gregersen, P.L., Holm, P.B. & Krupinska, K. (2008) Leaf senescence and nutrient remobilisation in barley and wheat. Plant Biology 10, 37-49.

Kindred, D.R. & Gooding, M.J. (2005) Heterosis for yield and its physiological determinants in wheat. Euphytica 142, 149-159.

Kjærsgaard, J. (2002) Planteavlsberetning 2002, LandboCentrum, Møllevej 15, DK-4140 Borup.

Kjærsgaard, J. (2001) Planteavlsberetning 2001, LandboCentrum, Møllevej 15, DK-4140 Borup.

Parry, M.A.J., Madgwick, P.J., Carvahlo, J.F.C. & Andralojc, P. (2007) Prospects for increasing photosynthesis by overcoming the limitations of Rubisco. Journal of Agricultural Science 145, 31-43.

Reynolds, M.P., Calderini, D.F., Condon, A.G. & Rajaram, S. (2001) Physiological basis of yield gains in wheat associated with the LR19 translocation from Agropyron elongatum. Euphytica 119, 137-141.

Rommens, C.M., Haring, M.A., Swords, K., Davies, H.V. & Belknap, W.R. (2007) The intragenic approach as a new extension to traditional plant breeding. Trends in Plant Science 12, 397-403.

Sylvester-Bradley, R., Faulkes, J. & Reynolds, M. (2005) Future wheat yields: Evidence, theory and conjecture. Yields of farmed species, constraints and opportunities in the 21st century. In: R. Sylvester-Bradley & J. Wiseman (Eds.) Nottingham University Press, UK. 651 pp.

Wang, E., Wang, J., Zhu, X., Hao, W., Wang, L., Li, Q., Zhang, L., He, W., Lu, B., Lin, H., Ma, H., Zhang, G. & He, Z. (2008) Control of rice grain-filling and yield by a gene with a potential signature of domestication. Nature Genetics 40, 1370-1374.

Xue, W., Xing, Y., Weng, X., Zhao, Y., Tang, W., Wang, L., Zhou, H., Yu, S., Xu, C., Li, X. & Zhang, Q. (2008) Natural variation in Ghd7 is an important regulator of heading date and yield potential in rice. Nat Genet 40, 761-767.

Öfversten, J., Jauhiainen, L. & Kangas, A. (2004) Contribution of new varieties to cereal yields in Finland between 1973 and 2003. The Journal of Agricultural Science (2004)), 142:3:281-287 - Cambridge Univ Press.

5 Changes in fertilization practice and impact on yield of winter wheat

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5.1 Introduction

The Danish Parliament passed *Actions plans for the aquatic environment* in 1987, 1998 and 2004, a *Plan for Sustainable Agriculture* in 1991, and an *Action Plan to reduce Ammonia Emission* in 2001. As a result of the plans, The Danish Plant Directorate was authorized by the Minister of Food, Agriculture and Fisheries to lay down statutory orders on the agricultural use of nitrogen (N) with the aim of reducing nitrate leaching from fields. The annual statutory order is divided into two parts for nitrogen: one setting out standard N rates for each crop, and the other concerning a substitution rate for N in animal manures that has to be taken into account in observing the standard N rate.

Introduction of standard N rates was decided in 1992 and took effect starting with the 1993/94 growing season. The standard N rates depend on soil type, irrigation, and preceding crop, and are defined as the N rate required to obtain economically optimal yields. To meet the Nitrate Directive (EEC, 1991) the second *Action Plan for the Aquatic Environment* from 1998 stipulates a suboptimal N rate for crops (Mikkelsen et al., 2005; Kronvang et al., 2008). Thus reduced standard N rates corresponding to *c.* 90% of the N rate for economically optimal yields have been prescribed in Denmark since 1999 (see Textbox 1). The substitution rate for N in animal manures took effect starting with the 1993/94 growing season, and it has been tightened gradually ever since (Figure 5.1). The substitution rates include the first year and the residual fertilizer values. These regulations have, together with statutory orders determined by the Danish Environmental Protection Agency (DEPA) regarding application time and method, caused significant changes in the use of N in animal manure and mineral fertilizers. A detailed description of implemented regulations is given by Mikkelsen et al. (2005) and Kronvang et al. (2008), but the most important DEPA statutory order regarding winter wheat is the ban of slurry application in the autumn (from harvest to 1st February), taking effect from July 1993.

The overall question on how changes in fertilization practice may have affected winter wheat grain yields may be divided into two: The first question is how the N rate for winter wheat has changed. Here it is important to consider the N source and separate the discussion for animal manure and mineral fertilizer as several measures aim to improve the utilization of N in animal manure. The second question is how the change in N rate has affected the grain yield. Before this question may be answered, we have to discuss some uncertainties in estimation yield response including the first-year effect and the long-term effect of varying N rate.
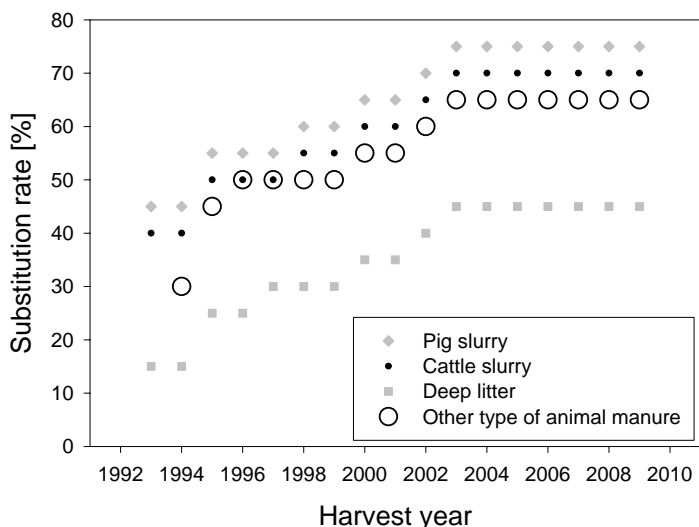
Figure 5.1 Changes of the legal substitution rate (From Petersen & Sørensen, 2008).

Textbox 1 Method of establishment of reduced standard N rates in Denmark based on working papers and notes from *The official committee on standard N rates, nitrogen prognosis and nitrogen in animal manures* (Normudvalget).

The *Plan for Sustainable Agriculture* in 1991 state obligatory fertilizer budgets at farm level. The statutory standard N rates (SNR) are from the growing season 1993/94 based on economically optimal N rates (EONR) obtained in annual field experiments carried out by DAAS using figures for the recent 10 years to reflect changes in agricultural practice, including breeding progress.

The *Action plan for the aquatic environment* 1998 (VMPII) set the national crop N demand by summarizing the SNR for each crop multiplied by its associated area for the growing season 1997/98. Subsequently the reduced standard N rates (RSNR) were defined as 90% of the SNR for individual crops. Due to changes in the fertilizer-crop price relation affecting the EONR, the reduction of the national N quota was 9.3-12.4% compared to the national crop N demand for the growing seasons 1999/2000 to 2003/04.

The *Action plan for the aquatic environment* 2004 (VMPIII) introduced two technical adjustments. 1) The available national N quota was adjusted according to changes in crop area and total culti-vated area using the growing season 2003/04 as basis year. 2) A binding whereby the summa-rized national N quota (sum of adjusted area multiplied by the RSNR) of succeeding years may not exceed the 2003/04 quota. Due to this binding, the individual RSNR were further and propor-tionally reduced to respect the 2003/04 ceiling.

Until the growing season 2004/05 the yield potential was not considered in the calculations, but included starting with the growing season 2005/06. As the statutory SNR are forecasts based on recordings in previous years adjustments for expected annual yield increases for the delay time were also taken into account. Although not explicitly mentioned in the political agreed document on VMPIII, these procedures were based on an interpretation of the agreement. This has caused that RSNR today are *c.* 14% below the EONR for all crops.

Even though the changes in the application of other nutrients do not exactly follow the changes in N application rate, answers can be derived from the discussion for N as changes in nutrient application rates are related to the use of animal manure and the increased awareness of the value of nutrients in manures, particularly phosphorus (P) and potassium (K).

5.2 National application rates of mineral fertilizers

The average national application rates of the major nutrients N and P in mineral fertilizer and animal manures were calculated by Grant et al. (2006) for 1985-2004 and Grant et al. (2007) for 1990-2004 plus preliminary values for 2005 and 2006. Grant et al. (2006, 2007) also calculated the amount of N and P removed by the crop at harvest.

National average application rates of N and P were supplemented with calculations made by The Danish Plant Directorate (2006) for the period 1960-1984. Grant et al. (2006, 2007) did not calculate application rate of K for mineral fertilizer or animal manures. Therefore the national average application rate for K in mineral fertilizer since 1960 originates from The Danish Plant Directorate (2006).

The figures from The Danish Plant Directorate include all uses of mineral fertilizers, including mineral fertilizer used in public parks, sports fields and private gardens. Consumption for these purposes, assumed to be 5,000 t N and 500 t P, are subtracted from the total consumption before calculating the national average application rate given by Grant et al. (2006, 2007).

The average application rate of N in animal manure has been stable during 1985-2006 (Figure 5.2). In contrast, the consumption of mineral fertilizer N has decreased concurrent with the introduction of regulations on the use of animal manure and an increased focus on the agricultural nitrogen cycle. Despite some inter-annual variation in the amount of N harvested in crops, the harvested amount seems to be largely independent of the legislative pressure (Figure 5.2).

The statutory orders derived by the actions plans concerns N, but the general awareness of utilization of nutrients in animal manure has, together with high a P-status in Danish soils, reduced the use of mineral fertilizer-P since 1980 (Maguire et al., 2009). During 1985-2001 the average application rate of P in animal manure was quite stable, followed by a clear decrease (Figure 5.2). This decrease was due to the introduction of changed feeding strategies foreseeing a claim on reduced P surplus introduced in 2004 by the third action plan for the aquatic environment (Poulsen & Rubæk, 2005). The amount of P harvested per hectare seems unaffected by the changes.

Similar to P the average application rate of K decreased, particularly since 1990, due the increasing focus on the utilization of nutrients in animal manure.
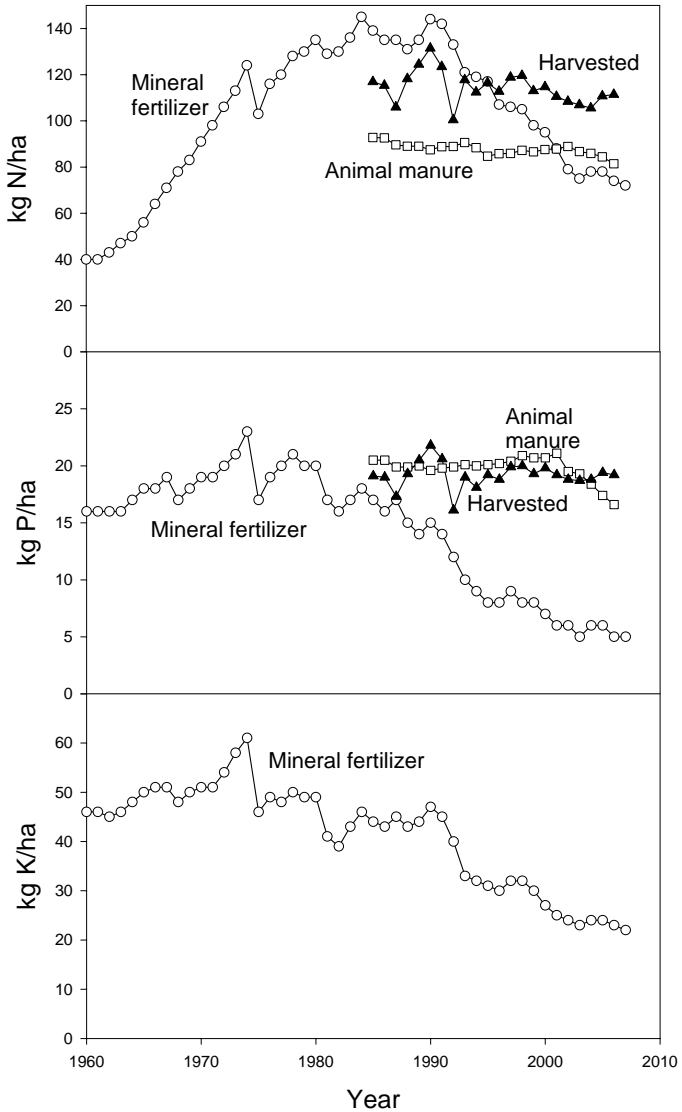
Figure 5.2 Average national rates of macronutrients applied in mineral fertilizer (○) and animal manure (□) together with the average harvested nitrogen per hectare (▲).

Can the figures for national averages be transferred to winter wheat? Even when setting up detailed formulas for calculation the nutrient rates applied for different crops, a transferring algorithm based on general assumptions has to be rejected. The main reasons are (i) significant differences between farms in the use of animal manure and mineral fertilizer due to their

specialization, (ii) farmers may prioritise differently in their allocation of N fertilizer to the crops in rotation, and (iii) the area cropped with winter wheat has increased considerably but to a varying extent across counties (Chap. 2).

Figures on sulphur (S), magnesium (Mg), copper (Cu) and boron (B) in mineral fertilizers are based on the total national consumption since the season 1992/93 given by The Danish Plant Directorate (2006). Fertilizers with Cu and B are used for specific purposes and Mg is also applied by the use of dolomite lime. These circumstances make national average application rates of little value in this context, since they do not necessarily reflect the use for winter wheat fertilization. Due to reduced S deposition from the atmosphere at the end of the 1980s, sulphur deficiency symptoms became more frequent at the beginning of 1990s (Pedersen, 1993). The availability of S in animal manure is low (Eriksen & Schnug, 1998) and S was introduced in most mineral fertilizers, typically N-fertilizers, and used for all types of crops. Since the mid 1990s the national average S application rate has been fairly constant within the range 18-21 kg/ha.

Lime is mainly used to neutralize the acidifying effect of N fertilizers. Therefore, the use of lime, in general, has changed proportional to the use of N fertilizers. In addition, the application of lime is not related specifically to winter wheat, but to the crop rotation and the soil acidity (see section 5.4.2). Thus, changes in the use of lime will not contribute to the explanation of stagnating winter wheat yields (data not shown).

5.3 Nitrogen rate and yield response

First we make some theoretical considerations regarding estimation of optimal N rates and the use of standards of N rates. Then we supplement the national statistics on fertilizer use with KVADRATNET-data on observed N rates applied for winter wheat. After a discussion on distinguishing the first-year effect and the long-term effect, we finally consider the impact of using equipment for application of animal manure.

Estimates of yield effects are based on 260 field experiments on N response carried out by the Danish Agricultural Advisory Service (DAAS) during 1998-2007 using six steps of 50 kg N/ha within 0-250 N kg/ha. The yield response of each individual experiment was estimated using a modified cubic polynomial function with plateau when the first inflection point was passed. Where a cubic function did not fit, a quadratic function was used. The experiments were all located in well-managed fields including pesticide treatments following the practice of the surrounding field. The varieties used in these experiments reflect the current market assortment incorporating the increased yield potential achieved through breeding. A subdataset (DAAS-sub) was formed including 115 field experiments having cereals or fallow as the preceding crop and a maximum annual animal manure N rate of 40 kg/ha in the preceding five years.

5.3.1 Theoretical approach

Setting the optimum rates of fertilization involves fitting a response function to the yield data obtained by applying increasing rates of fertilizer. Although several different functions are commonly used to describe the response, it is seldom explained why one function is selected over others (Cerrato & Blackmer, 1990). Despite high coefficients of determination (often R^2 >0.90), five response function have shown considerable disagreement in the economically optimal N rate estimated at a fixed grain to fertilizer price ratio (Cerrato & Blackmer, 1990). Using 27 Danish winter wheat experiments, the estimate of N rate for maximum yield differs by up to 50 kg N/ha using three yield response functions (Mortensen & Gordon, 2003). Thus, the choice of response function has a considerable impact on the optimal N rate.

When the response function is chosen the uncertainty of the estimated N rate for optimum yield has to be discussed. Using 533 experiments with increasing N rate Foldager (2000) estimated the N rate for optimal yield with 95% confidence limits to be ±12 kg N/ha for the most dominating combinations of preceding crop and soil type. A confidence interval of the same order was obtained using bootstrapping methods in a single experiment (Foldager, 2001). For less frequent combinations of preceding crop and soil type the confidence interval increased up to ±40 kg N/ha (Foldager, 2000).

The choice of response function influences the estimated N rate for optimal yield more than the uncertainty of the estimate. In field experiments, several factors influence the crop productivity, e.g. soil type, preceding crop and climate. Some of these factors may be taken into account in the statistical analyses for the yield to N rate response, but not all. Therefore, the response is not exclusively a cause and effect relation, but more or less a question of fitting a function to data. Thus user-friendly functions in terms of calculations but lacking agronomical interpretable parameters are used, e.g. a cubic polynomial function, whereas extension of a polynomial function (quadratic or cubic) to a non-linear function with a plateau may be more appropriate (Beattie et al., 2004). To compare estimates of N rates for economically optimal yield over time it is a natural prerequisite that the same function must be used throughout the time.

Estimating yield effects caused by changes in N-rate using the difference between two points at the same response curve may, in general, reduce the uncertainties due to the inter-relationship of the points. However, we have not analysed this topic further. Using the DAAS-dataset and a modified cubic polynomial function including a plateau, the N rate for economically optimal yield (EONR) was on average 28 kg N/ha less than for maximum biological yield (MBY) due to the cost of fertilizer and application causing a yield reduction of 0.6 dt/ha (Figure 5.3). When using the economically optimal N rate rather than the biological maximum we introduce the value of harvested grain and the cost of applied fertilizer (Chap. 10). These factors change over time and make comparisons more difficult. From a practical point of view, the economically optimal N rate (EONR) is the important parameter and has been used by DAAS for decades.
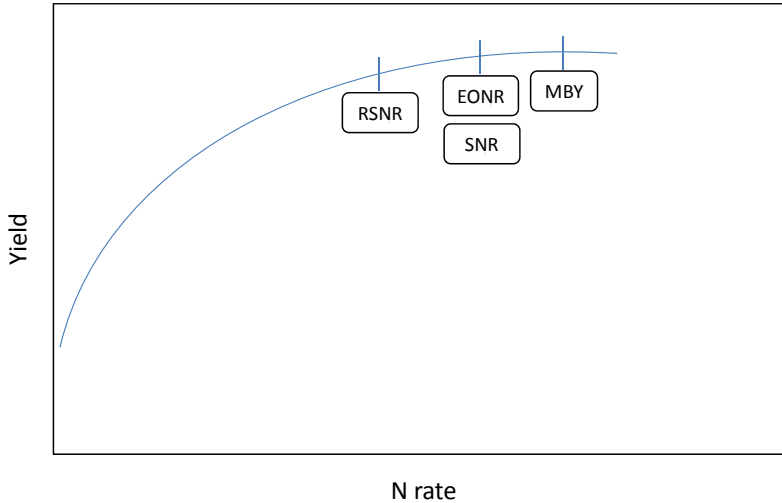
Figure 5.3. Outline of the relation between maximum biological yield (MBY), yield at economically optimal N rate (EONR) and yield at reduced standard N rate (RSNR). Standard N rate (SNR) is based on EONR. The concept of EONR, SNR and RSNR are explained in Textbox 1.

An estimate of the economically optimal N rate (EONR, Figure 5.3) is based on yield response curves obtained in previous years, but an estimate will not be able to exactly predict the economically optimal N rate of the succeeding year or of a specific field, even using the best advisory tool. The predicted N rate may be sub- or supra-optimal compared to the actual economically optimal N rate calculated after the growing season. Due to the asymmetry of the response function, the mean of sub- and supra-optimal N rates causes a yield loss. Although the statutory standard N rates (SNR, Figure 5.3) are established on the same basis as N rates recommended by the advisory service they leave less space for individual adjustments as the statutory order excludes the use of further advisory tools including farmers' experience. The difference in yields between the economically optimal N rate recorded after the growing season and statutory standard N rate was estimated at 1.1 dt/ha using the DAAS-dataset. However, the statutory standard N rates may not fully account for this loss, since neither advisors nor farmers will be able to predict accurately the actual yield response on individual fields in individual years. Therefore, we assume a yield loss of approximately 0.5 dt/ha using the statutory standard N rates rather than predictive economically optimal N rates adjusted for individual conditions.

The above-mentioned topics are general but the effect of reduced standard N rates is at the present a Danish issue only. Using the DAAS data on yield to N response in 260 field experiments and a grain to fertilizer price ratio of 1:5 we estimated 178 kg N/ha on average for the economically optimal N rate (EONR, Figure 5.3). The reduced standard N rate (RSNR, Figure 5.3) for the 260 experimental sites was 154 kg N/ha on average using the procedure

prescribed by the statutory order taking into account (i) the soil type, (ii) the effect of previous crop, (iii) the long-term effect of animal manure and (iv) the annual N prognosis. The difference between EONR and RSNR corresponds to -13% and the yield was reduced by 1.9 dt/ha. However, the standard N rates for each crop are controlled at farm level giving the farmer the opportunity to redistribute fertilizer N between crops and thereby make some individual adjustments of the N rates. Hence, the actual application N rate may depend on the farmers' decisions.

5.3.2 KVADRATNET-data

Observed figures for rates of animal manure and mineral fertilizer may be obtained from the KVADRATNET, which is a square grid of 7×7 km established by DAAS in the winter 1986/87 with the purpose of annual estimates on the content of mineral soil N in the spring. This systematic grid has 830 intersections on land, 590 of these are located on farmland. Each intersection is represented by a 50×50 m area managed by the farmer, who also annually reports on manure and fertilizer applications. Heidmann et al. (2001) drew attention to elements of uncertainty associated with the reporting: 1) Application rate, particularly for animal manure, 2) conversion to nutrient rate using standard values, and 3) the simple risk of notes on applications going missing.

The KVADRATNET data consist at present of 3300 observations on winter wheat. We selected the intersections points of the most important preceding crops (cereals, sugar beet, rape or peas) and the dominating soil types (JB nr. <9, according to the Danish soil classification system). Data control was omitted in this preliminary analysis, but a few recordings with zero application or missing values were deleted without further verification, indicating that some quality control is needed for more detailed analysis. Some of the deleted recordings may be due to organic farming conditions. The data did not give us the opportunity to distinguish between ordinary wheat for feeding and wheat for bread as the latter may allow a higher N rate to be applied. Bread wheat accounts for <10% of the area with winter wheat, and have a supplemental standard N rate of 30 kg N/ha. The remaining data were divided into two data sets: A) exclusively fertilized with mineral fertilizer N, and B) fertilized with animal manure plus mineral fertilizer N (Table 5.1).

Several changes in agricultural systems have taken place over time (e.g. area with winter wheat, livestock holdings and crop rotation), which adds noise to data and causes considerable variation. In a crop rotation including winter wheat, an intersection point may be redrawn systematically at intervals of 3-4 years, but as the crop preceding winter wheat more frequently has become winter wheat since the middle of the 1990s, which indicates continuous cropping, systematic redrawing has increased. This causes correlated data that may be considered as repeated measurements, and analysis on sub-datasets of intersection point redrawn ≥10 times may be more suitable to estimate changes over time as some random variation may be excluded. The datasets sub-A and sub-B reflect the typologies of winter wheat crops fertil-

ized with mineral fertilizer only and with a combination of animal manure and mineral fertilizer, respectively (Table 5.1).

Table 5.1 Overview of the datasets extracted from the KVADRATNET database for winter wheat.

	Dataset A Mineral fertilizer N exclusively	Dataset B Animal manure plus mineral fertilizer N
No. of observations	1374	1103
No. of intersection points	389	311
Dominating soil types *	JB6, JB7 and JB4	JB6, JB7 and JB4
Subdataset **	Dataset sub-A	Dataset sub-B
No. of observations	190	190
No. of intersection points	16	17
Dominating soil types *	JB7	JB6, JB7
Dominating county	Zeeland	Jutland

* JB no. according to the Danish soil classification system

** More than nine recordings of individual intersection points

To get the advantage of the repeated measurements we focus on the sub-datasets that both represent sandy loam soils but in two different regions of the country (Table 5.1). We focus on the changes comparing two periods: the past, from the beginning of the 1990s to 2000 (some variation in the starting year used depending on the dataset) *versus* today, the period 2001-06 (reduced standard N rates corresponding to *c.* 90% of the standard N rates). The figures of the 10, 25, 50, 75 and 90% fractiles give a general view of the data and we used the median to calculate N rates for different periods.

For intersection points without application of animal manure the mineral fertilizer N rate changed from 182 kg N/ha as an average of the median during 1991-2000 to 166 kg N/ha (corresponding to -9%) as an average of the median during 2003-06 using sub-dataset A (Figure 5.4). Using the full dataset A the reduction in N rate was in the same order, 19 kg N/ha (data not shown), but the changes in the average median value was from 175 to 156 kg N/ha (corresponding to -11%). In Figure 5.4 it is noticed that the values for the 50, 75 and 90% fractile are very close to each other for 2005/06, indicating a maximum N rate of 170 kg N/ha in practice under the conditions of reduced standard N rates. The maximum N rate during 1991-2000 (before and just after introduction of standard N rates) has been about 205 kg N/ha based on an average of the 90% fractile (Figure 5.4). This indicates a maximum decrease in the N rate of 17% compared with the situation before introduction of reduced standard N rates.
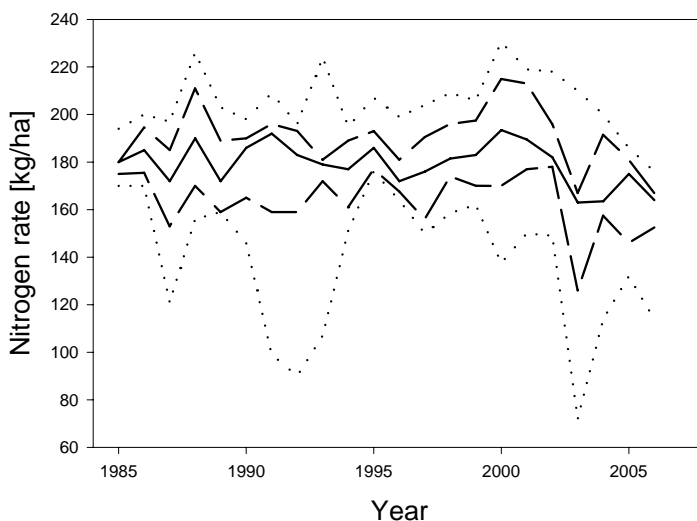
Figure 5.4 Fractiles of mineral fertilizer N rate for dataset sub-A (Table 3.1). Full line: 50% fractile, dashed lines: 25 and 75% fractiles, dotted lines: 10 and 90% fractiles.

Using these estimates the yield losses due to reduced standard N rates were estimated using the DAAS sub-set of 115 response curves. The yield was calculated for the application rates of 166 and 182 kg N/ha based on dataset sub-A for each response function. Using these pair-wise estimates the yield difference between the average median N rate during the past and of today was estimated at 1.4 dt/ha (standard deviation 0.87 dt/ha). Using the average median N rates for the full dataset A that has a higher variation than for sub-A, the yield reduction was estimated at 2.0 dt/ha (standard deviation 1.07 dt/ha).

In this way we have answered the question regarding the yield effect of reduced standard N rates where mineral fertilizer was used exclusively. Including animal manure the question is more complicated as there have been several changes in the substitution rate for N in different types of animal manures together with changes in claims regarding application time and method (Mikkelsen et al., 2005).

Using the full dataset B the maximum application rate of animal manure N has been reduced considerably fulfilling the aims of the implemented legislation. Since 1985 a steady reduction in the use of mineral fertilizer N in combination with animal manure has been observed (Figure 5.5).

Based on the repeated measurements in dataset sub-B the average of the median was calculated for two periods (Table 5.2). Converting the change in total-N rate applied in animal manure to mineral N corresponding to an ammonia-N:total-N ratio of 0.65, the overall change in N rate is $(22 + 33 \times 0.65) = 43$ kg N/ha. A similar figure is obtained using the full dataset B. The figure is twice the figure for using mineral fertilizer only. However, the change in mineral

fertilizer N rate is in the same order, and the change in animal manure N rate may be related to implementation of DEPA statutory orders fulfilling the Nitrate Directive.
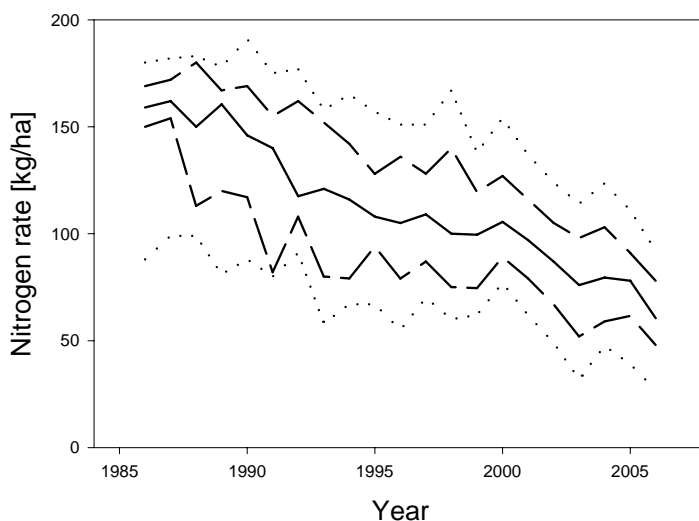
Figure 5.5 Fractiles of mineral fertilizer N application rate used in combination with animal manure, dataset B (Table 5.1). Full line: 50% fractile, dashed lines: 25 and 75% fractiles, dotted lines: 10 and 90% fractiles.

Table 5.2 Change in the median application rate of total-N in mineral fertilizer and animal manure at 17 intersection points using animal manure (Dataset sub-B). Based on the median shown in Figure 5.5. Figures for animal manure require further data control.

	Mineral fertilizer	Animal manure
1992-2000	102	158
2001-2006	80	125
Difference	22	33

The median N rate for the 17 intersection points using animal manure was 205 kg N/ha (102 + 158×0.65) as an average of 1992-2000. This rate is similar to the 90% fractile of the sub-A data for 16 intersection points receiving mineral fertilizer only, indicating that the N rates in the sub-B dataset have been supra-optimal in the past. The change from supra-optimal to optimal is included in the estimate of 43 kg N/ha, which therefore is an overestimation of the change from standard N rates to reduced standard N rates for farms using animal manure. However, this preliminary analysis indicates that data require further control regarding rate and time of animal manures application.

5.3.3 First-year contra long-term effect

The first-year yield response of N-rate is determined in one-year experiments with changing locations from year to year. Similar to the residual effects of organic amendments, the rate of mineral N may also have a residual effect caused by its influence on crop residues (roots and stubble) left in the soil. Although this effect of fertilizer N rate may be minor, the annual effects may accumulate over time. Due to statutory orders prescribing reduced standard N rates corresponding to *c.* 90% of the standard N rate for economically optimal yields, the long-term effect of a sustained reduction in fertilizer N rate on yield, N off-take and grain quality (protein content) has become an issue in the Danish environmental debate.

The long-term residual effect of mineral N fertilizer was examined in five long-term experiments (Askov, Jyndevad and Rønhave in Denmark and Orup and Fjärdingslöv in Sweden; Petersen et al., 2009). From these investigations, a spring barley grain yield decrease of 8×10^{-3} t/ha (kg N/ha)$^{-1}$ [= 8 kg grain (kg N)$^{-1}$] was on average estimated for an annual decrease in previous N rate accumulated during >35 years using mineral fertilizers. Petersen et al. (2009) did not detect any long-term effect of a sustained reduction in N rate on grain quality expressed as grain N concentration and grain weight.

Assuming a similar yield response in winter wheat but only accumulated for a period of 10 years (1999-2008) equivalent to a quarter of the previous time in the long-term experiments, a reduction of about 20 kg N/ha corresponds to a yield loss in the order of 0.4 dt/ha.

5.3.4 Application

The more widespread cropping of winter wheat during the 1980s increased the focus on using split applications to promote tillering and development of an effective crop canopy (Darwinkel, 1983; Ellen, 1987). Since the middle of the 1980s the fertilizer N application has been split with first rate mid March and second rate mid to late April. A split application yields on average 1-2 dt/ha more than a single application mid April (Pedersen, 2003; Olesen et al., 2003). However, varying results have been recorded, most likely due to a delay in the availability of the applied fertilizer caused by dry conditions, as discussed by Olesen et al. (1992).

Animal manure applied to winter wheat typically replace the second rate of mineral fertilizer as the soil typically is better able to carry the slurry tankers at the later application time (mid to late April). Less than 10% of the winter wheat area received animal manure in the spring before implementation of the environmental actions plans. Due to the ban on autumn application we assume that about 55% of the area cropped with winter wheat today receives animal manure in the spring, mainly as pig slurry applied by trailing hoses. This causes significant traffic damage to the crop in the wheel tracks depending on weather conditions, growth stage and the load of the wheels. In dry conditions Pedersen (1994) recorded a yield loss of 1-2 dt/ha averaged over seven experiments. Four experiments carried out in 2004 and repeated in 2005 gave a yield loss of 3.5 and 2.4 dt/ha, respectively, for a working width of 16 m and 65-

70 cm wide tyres (Pedersen, 2004, 2005). Using a yield loss of 2.5 dt/ha and an increase in spring-applied animal manure of 45%-point, the average yield loss due to traffic damages is estimated to 1.2 dt/ha.

5.3.5 Yield response to change in nitrogen application rates

Assuming the contributions in Table 5.3 are additive, the use of reduced standard N rates has an effect of 3.0 dt/ha based on the theoretical approach. However, the N rates used for the theoretical approach are less than the rate of 170 kg N/ha used in current practice. Thus we assumed that the theoretical approach overestimates the response. An effect of 1.4 dt/ha based on the fertilizer practice recorded in the KVADRATNET seems closer related to practice. On top of this comes the yield reduction due to using economically optimal N rates (0.6 dt/ha) and staturory standard rates (approximately 0.5 dt/ha), which according to Table 5.3 may result in a total yield loss of 2.5-3.1 dt/ha. This estimate is in the same order as the estimate exclusively based on the theoretical approach.

Table 5.3 Summarizing yield losses of winter wheat due to different aspects of N rate compared to maximum biological yield [dt/ha]. Estimates for KVADRATNET-data are based on the sub-datasets and in parentheses for the full datasets mentioned in Table 5.1.

Using	Theoretical approach	KVADRATNET-data
Economically optimal N rate	0.6	
Statutory standard N rate	Approx. 0.5	
Reduced standard N rate	1.9	1.4 (2.0)
Sum	3.0	2.5 (3.1)

A long-term effect of reduced standard N rates may presumably contribute with an additional loss of approximately 0.4 dt/ha, assuming that winter wheat respond in the same way as spring barley. However, in this context we do not include the long-term effect of reduced N in the total yield loss. The yield loss due to crop damages caused by traffic is estimated at 1.2 dt/ha on average. In total we estimated the effect of N rate/fertilization within the range 3.7-4.3 dt/ha.

5.4 Other nutrients

Animal manure is not exclusively an N source as other nutrients are applied with the manure. The change in the use of animal manure due to statutory orders on N therefore also affects the application of other nutrients. The topic may be examined using different sources of data, which have fewer details than for N.

5.4.1 KVADRATNET-data on phosphorus and potassium

Since 1985 farmers have accounted on P and K in animal manure, and dataset B (Table 5.1) clearly shows a reduced application rate of P and K in mineral fertilizers (Figure 5.6). This

effect on the use of mineral fertilizer is enhanced as animal manure is often used on winter wheat partly due to the increased area of winter wheat, and a more even distribution of animal manure between crops due to the statutory orders. Similar to N, the estimation of P and K applied in animal manure require further control regarding rate and time of manure application. For farmers exclusively using mineral fertilizer (Dataset A, Table 5.1) some reduction in mineral P fertilizer was also observed (Figure 5.6), but in contrast, the application rate of mineral K was largely unchanged during the period 1985-2006 at 46 kg K/ha on average.
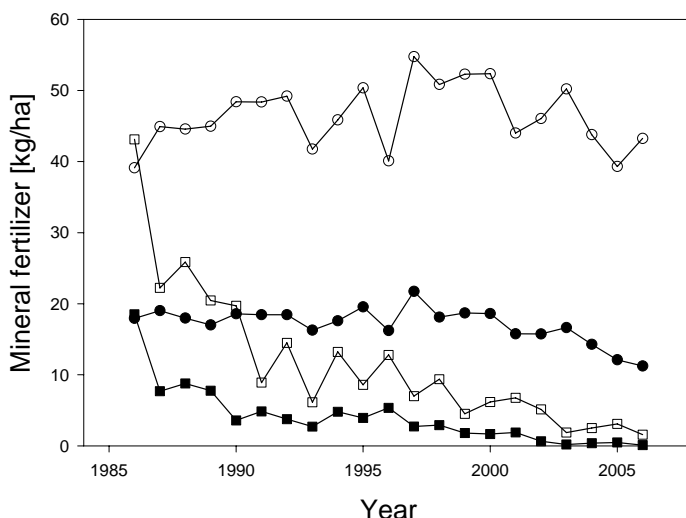
Figure 5.6 Average rates of mineral fertilizer P (●■) and K (○□). Farmers exclusively using mineral fertilizer (●○) and farmers using mineral fertilizer in addition to animal manure (■□) based on dataset A and B, respectively (Table 5.1).

5.4.2 Soil analysis and micronutrients

To maintain the soil fertility farmers examine the soil nutrient status by sampling with 4-7 years interval. The major part of soil analyses originate from this routinely sampling, but a minor part originate from particular fields with expected low values. Thus, recorded soil analysis data are not crop specific, but relate rather to crop rotation and soil type. Table 5.4 list the symbol, unit, threshold and extracting agent for the different soil parameters. The proportion of soil samples below the Rt, Kt or Cut thresholds has been less than 5% and unchanged during 1987-2007 based on the recordings collected by the Danish Agricultural Advisory Service (data not shown). We observe a decrease in the proportion of samples below the Mgt-thresholds until mid 1990s and a constant level afterwards (Figure 5.7). The clearest change was observed for Pt where the proportion of samples below the thresholds has increased since the end of the 1990s (Figure 5.7). The yield may be limited in fields having soil analysis below the thresholds but field experiments carried out in recent years seldom indicate significant yield response to applications of P, K and Mg.

Table 5.4 Parameters, symbol, units, extraction agent (Plantedirektoratet, 1994), thresholds and annual number of analyses (Danish Agricultural Advisory Service) for soil sampling in Denmark.

Parameter	Symbol	Unit	Threshold	Extracting agent	Annual number
Soil pH	Rt	pH(CaCl$_2$)+0.5	5.5	0.01 M CaCl$_2$	~ 100,000
P	Pt	mg P/100 g soil	2.0	0.5 M NaHCO$_3$ (Olsen –P)	~ 100,000
K	Kt	mg K/100 g soil	4.0	0.5 M NH$_4$-acetate	~ 100,000
Mg	Mgt	mg Mg/100 g soil	3.0	0.5 M NH$_4$-acetate	~ 100,000
Cu	Cut	mg Cu/1000 g soil	2.0	0.02 M EDTA	~ 10,000
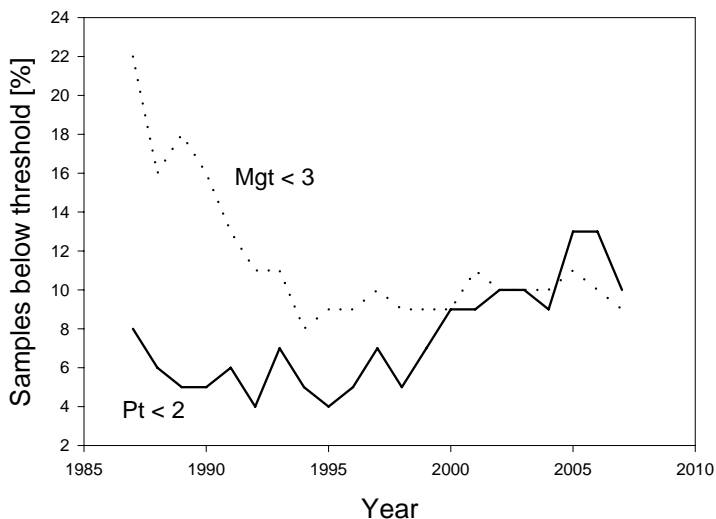
Figure 5.7 Change in the proportion of soil samples with Pt and Mgt below the threshold. Data collected by the Danish Agricultural Advisory Service 1987-2007.

5.4.3 Sulphur, manganese, copper and other micronutrients

In contrast to P and K that are applied to maintain soil pools and soil fertility causing an almost insignificant response to application rate (Bennetzen, 1985; Rubæk & Sibbesen, 2000), deficiency in S or Mn may have dramatic effects on growth and yield of winter wheat. The plant availability of S is associated to the mineralisation of organic matter, whereas availability of Mn is related to the soil redox potential.

In the 1990s most one-year experiments without sulphur application decreased the grain yield by 2 dt/ha compared to applications of 20 kg S/ha, but in some experiments the decrease was up to 10 dt/ha (Pedersen, 1999). Since the mid 1990s winter wheat has in general received sufficient S in mineral fertilizers and yield reduction due to S deficiency has been avoided.

In contrast to other nutrients, Mn deficiency occurs in the autumn and winter months and may cause chlorosis, and in serious cases wilting before the growing starts in spring. The symptoms typically occur in spots but fields are completely damaged in severe cases. This involves – partly – re-sowing of fields, reducing the economically yield significantly due to the cost of seeds and wages combined with lower-yielding spring crops. The effect of Mn is winter survival rather than a yield response during the growing season.

It is our impression that Mn deficiency problems have become more frequent and more severe, but we do not have data to support this. We are not able to separate an increased occurrence of Mn deficiency from the enlargement of the area grown with winter wheat (Chap. 2) or the changed use of animal manure. In addition, there are no data available on the consumption of Mn in Danish agriculture, but winter wheat is sprayed up to six times during the winter to avoid chlorosis.

Problems with Cu deficiency are mainly limited to coarse sandy soils, which partly explain the lower number of analysis (Table 5.4). From 1992/93 to 2006/07 the national consumption of Cu in mineral fertilizers decreased from 110 to 35 t/y (The Danish Plant Directorate, 2006). This may be due to increased awareness of Cu in animal manure and the fact that the use of pig manure increases the soil content of Cu (and Zn) (Gräber et al., 2005).

Field experiments carried out by DAAS during the last five years regarding foliar application of micronutrients (B, Cu, Fe, Mo, Mn & Zn) in the elongation phase of winter wheat very seldom results in significant yield increases (Pedersen, 2008). Thus, there is no indication that changes in fertilizer practice or consumption of S, Mn and Cu (or any other micronutrient) may have influenced winter wheat yields in recent decades.

5.5 Conclusions

Implementation of statutory orders on the agricultural use of animal manure and increased focus on nutrient cycling in agriculture has significantly reduced the application rate of animal manure, and increased utilization of the nutrients in animal manure has concurrently reduced the application rates of N, P and K in mineral fertilizer considerably. Using typologies for fertilization of winter wheat for estimation, the introduction of reduced standard N rates has reduced the rate by 16-19 kg N/ha when only mineral fertilizer is used. The reduction was 43 kg N/ha for combined use of animal manure and mineral fertilizer, but the starting point was a supra-optimal N rate. The equipment for spring application of animal manure causes crop damage reducing the yield of winter wheat. In total we estimated the effect of N rate/fertilization to be in the range 3.7-4.3 dt/ha. We were not able to demonstrate effects on winter wheat grain yield of changes resulting from nutrients other than N.

5.6 References

Beattie, B.R., Gordon, B.P., Mortensen, J.R. & Knudsen, L. (2004) Produktionens afhængighed af kvælstoftilførsel. Tidsskrift for Landøkonomi 4/2004, p. 55-64.

Bennetzen, F. (ed.) (1985) Oversigt over Landsforsøgene 1984. Landsudvalget for Planteavl, Aarhus.

Cerrato, M.E. & Blackmer, A.M. (1990) Comparison of Models for Describing Corn Yield Response to Nitrogen Fertilizer. Agronomy Journal 82, 138-143.

Darwinkel, A. (1983) Ear formation and grain yield of winter wheat as affected by time of nitrogen supply. Netherlands Journal of Agricultural Science 31 (3), 211-225.

EEC (1991) European Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31991L0676:EN:HTML

Ellen, J. (1987) Effects of plant density and nitrogen fertilization in winter wheat (Triticum aestivum L.). 1. Production pattern and grain yield. Netherlands Journal of Agricultural Science 35, 137-153.

Eriksen, J. & Schnug, E. (1998) The soil sulphur cycle. In: Schnug, E. (ed.) Sulphur in Agroecosystems, Kluwer Acedemic Publishers, The Netherlands.

Foldager, L. (2000) Usikkerhed på optimal kvælstofmængde – variansanalyse. Danish Institute of Agricultural Sciences, Department of Agricultural Systems. Internal Report 2000-05, 28 p. (In Danish)

Foldager, L. (2001) Usikkerhed på optimal kvælstofmængde fastsat ved enkeltforsøg – Bootstrap metoder. Danish Institute of Agricultural Sciences, Department of Agricultural Systems. Internal Report 2001-01, 23 p. (In Danish)

Grant, R., Blicher-Mathiesen, G., Pedersen, L.E., Jensen, P.G., Madsen, I., Hansen, B., Brüsch, W. & Thorling, L. (2007) Landovervågningsoplande 2006 NOVANA. Aarhus Universitet, Faglig rapport fra DMU nr. 640, 124 p.
http://www2.dmu.dk/Pub/FR640_LOOP.pdf

Grant, R., Blicher-Mathiesen, G., Jensen, P.G., Madsen, I., & Rasmussen, P. (2006) Landovervågningsoplande 2005 NOVANA. Miljøministeriet, Faglig rapport fra DMU nr. 594, 112 p. http://www2.dmu.dk/Pub/FR594.pdf

Gräber, I., Hansen, J.F., Olesen, S.E., Petersen, J., Østergaard, H.S. & Krogh, L. (2005) Accumulation of Copper and Zink in Danish Agricultural Soils in Intensive Pig Production Areas. Geografisk Tidsskrift, Danish Journal of Geography 105(2):15-22.

Heidmann, T., Nielsen, J., Olesen, S.E., Christensen, B.T. & Østergaard, H.S. (2001) Ændringer i indhold af kulstof og kvælstof i dyrket jord: Resultater fra Kvadratnettet 1987-1998. Danmarks JordbrugsForskning, DJF-rapport Markbrug nr. 54, 73 pp.

Kronvang, B., Andersen, H.E., Børgesen, C., Dalgaard. T., Larsen, S.E., Bøgestrand, J. & Blicher-Mathiasen, G. (2008) Effects of policy measures implemented in Denmark on nitrogen pollution of the aquatic environment. Environmental Science and Policy 11, 144-152.

Maguire, R.O., Rubæk, G.H., Haggard, B.E. & Foy, B.H. (2009) Critical Evaluation of the Implementation of Mitigations Options for Phosphorus from Field to Catchment Scales. Journal of Environmental Quality 38 (5), 1989-1997.

Mikkelsen, S., Iversen, T.M., Kjær, S. & Feenstra, P. (2005) The regulation of nutrient losses in Denmark to control aquatic pollution from agriculture. Evaluating Agri-Environmental Policies: Design, Practice and Results. OECD. pp. 295-208.

Mortensen, J.R. & Gordon, B.R. (2003) udbyttefunktioner i relation til normer for tilførsel af kvælstof. Tidsskrift for Landøkonomi 190, 338-350.

Olesen, J.E., Olsen, C.C., Petersen, J., Rasmussen, K.J., Secher, B.J.M., Jørgensen, L.N., Jensen, P.K., Vester, J. & Ersbøll, A. (1992) Udvikling af et dyrkningsprogram for vinterhvede. Grundlag for forskning og modeludvikling. (Redaktør: J. E. Olesen.) Tidsskr. Planteavl. Beretning nr. S2204, 185 pp.

Olesen, J.E., Jørgensen, L.N., Petersen, J. & Mortensen, J.V. (2003) Effects of rate and timing of nitrogen fertilizer on disease control by fungicides in winter wheat. 1. Grain yield and foliar disease control. J. Agri. Sci., Camb., 140, 1-13.

Pedersen, C.Aa. (ed.) (1993) Oversigt over Landsforsøgene 1993. Brabrand Bogtryk Aps.

Pedersen, C.Aa. (ed.) (1999) Oversigt over Landsforsøgene 1999. Scanprint A/S.

Pedersen, C.Aa. (ed.) (2003) Oversigt over Landsforsøgene 2003. Phønix-Trykkeriet A/S

Pedersen, C.Aa. (ed.) (2004) Oversigt over Landsforsøgene 2004. Scanprint a/s.

Pedersen, C.Aa. (ed.) (2005) Oversigt over Landsforsøgene 2005. Scanprint a/s.

Pedersen, J.B. (ed.) (2008) Oversigt over Landsforsøgene 2008. Scanprint a|s.

Petersen, J. & Sørensen, P. (2008) Fertilizer value of nitrogen in animal manures – Basis for determination of a legal substitution rate. Aarhus Universitet, Det Jordbrugsvidenskabelige Fakultet, DJF-rapport Markbrug nr. 138, 111 pp. In Danish with English summary. http://web.agrsci.dk/djfpublikation/index.asp?action=show&id=1047

Petersen, J., Thomsen, I.K., Mattsson, L., Hansen, E.M. & Christensen, B.T. (2009) Residual effect of mineral nitrogen fertilizer. Connecting different scales of nitrogen use in agriculture. The 16th N-workshop, Turin, Italy, 28th June-1st July 2009.

Plantedirektoratet (1994) Fælles arbejdsmetoder for jordbundsanalyser. Metode samling, upagineret.

Poulsen, H.D. & Rubæk, G.H. (2005) Fosfor i dansk landbrug – Omsætning, tab og virkemidler mod tab. Danmarks JordbrugsForskning, DJF-rapport Husdyrbrug nr. 68, 214 pp. http://web.agrsci.dk/djfpublikation/djfpdf/djfhu68.pdf

Rubæk, G.H. & Sibbesen, E. (2000) Long-term phosphorous fertilization – Effects on crop yield and soil phosphorous status. Danish Institute of Agricultural Sciences, DIAS-report Plant Production no. 31, 43 pp.

The Danish Plant Directorate (2006) Danmarks forbrug af handelsgødning 2004/05. 11p. http://pdir.fvm.dk/Admin/Public/Download.aspx?file=Files%2fFiler%2fTopmenu%2fPublikationer%2fStatistik%2f2005%2fforbrug_handelsgoedning_0405.pdf

6 The impact from crop protection on yields

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6.1 The impact from diseases and disease control

Several diseases occur regularly in wheat crops and fungicides are commonly applied in order to minimize the potential loss from attack. The most important and yield-reducing disease in winter wheat is Septoria leaf blotch (*Septoria tritici*), but also powdery mildew (*Blumeria graminis*) can reduce yields significantly particularly on sandy soils. In some seasons stripe rust (*Puccinia striiformis*) and leaf rust (*Puccinia triticina*) may give severe attack and in fields with minimum tillage tan spot (*Drechslera tritici-repentis*) and fusarium head blight (*Fusarium spp.)* may influence yields and grain quality.

The average yield increases from disease control in Danish winter wheat are about 10%, but they vary considerably across years, depending on the earliness of disease onset and actual disease severity levels in individual seasons. Variability of disease pressure is closely linked to climate and the susceptibility of cultivars grown.

In this chapter the potential influences from diseases on yields will be discussed with focus on three factors:
- Development of effectiveness and yield responses from fungicides
- Impact of low dose strategies on yield potential
- Development of disease pressure during the last 30 years

Before 1985 only limited data exist to describe the disease pressure and yield responses in the individual season. Therefore disease development and disease control in the last approx. 10 years will be described in most detail.

The topic concerning fungicides and dose strategies related to leaf diseases is discussed in section 6.1-6.4. Section 6.5 deals with diseases related to the crop rotation. An overall conclusion concerning diseases is made in section 6.6. Growth regulators and pests caused by insects are briefly mentioned in sections 6.7 and 6.8, respectively.

The trial material used in the analysis is mainly originating from fungicide trials with different strategies carried out by DAAS in the National Field Trials (Landsforsøgene), but also trial data from DJF are included.

6.1.1 General level of response to fungicides

In order to assess if there have been major changes in yield response to fungicides obtained in the many field trials carried out over the years (including variety trials), data from trials at the Danish Agricultural Advisory Service (DAAS) and the Faculty of Agricultural Sciences (DJF) at Aarhus University have been collected in Figure 6.1. The trials have been sprayed with authorized products using a total of 50-100 per cent of the normal standard dose. The annual average indicates major differences between years. The annual variation is due to different disease pressures influenced mainly by differences in climatic conditions, but varieties and fungicides used in the trials also play a major role. From 1971 to 1980 relatively few fungicides and trials were available, and yield increases in the range of 3-4 dt/ha were common using products like Maneb, Bayleton and Benlate. From 1981 when more effective and broad-spectrum fungicides were introduced, the yield increases rose by approximately 6 dt/ha. The data do not indicate a major change in response to fungicides since 1980 (Figure 6.1). The high yield response in the 1980s is highly influenced by severe yellow rust attacks in the later part of the 1980s and 1990 and very high Septoria levels in 1987 (Figure 6.1). Since 1990 especially Septoria has been dominant in the trials. Part of the high responses between 1998 and 2003 is also expected to be related to the introduction of the strobilurins in that period.
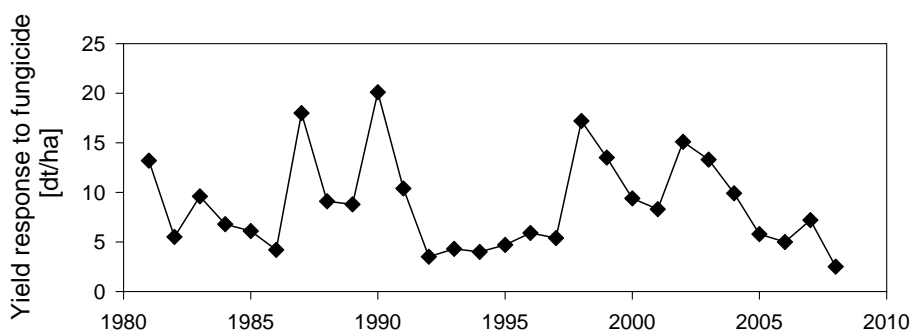
Figure 6.1 Differences in yield response to fungicides (gross yield, dt/ha) in winter wheat crops in individual years (1981-2008) based on a large number of trials carried out by DAAS (The National Field Trials) and DJF.

6.2 Development of effectiveness and yield responses from fungicides

6.2.1 Major fungicides used during the period

During the relevant period major changes in the use of actual fungicides have taken place. This has happened due to the development of new products as well as to development of fungicide resistance. Table 6.1 shows the development in the sale of the most important fungicides (active ingredients) used in winter wheat crops. The specific fungicides mainly used in practical winter wheat production are shown in Table 6.2.

Table 6.1 Sale (tonnes active ingredients) of the most important fungicides used in winter wheat crops (Miljøstyrelsen -pesticide statistics). A dash (-) indicates that the product was sold but the amount is not published.

Active ingredient	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
triadimenol/fon	-	-	9.2	18.1	36.4	42.0	22.5	12.5	7.7	6.7	0
prochloraz	-	-	104.6	170.3	157.4	94.1	90.7	57.1	26.9	27.3	29.4
fenpropimorph	-	155.5	223.2	328.4	366.1	339.5	365.2	332.3	317.8	286.6	196.5
propiconazole	-	-	78.2	100.4	108.1	114.9	109.5	88.7	84.4	98.0	67.4

Active ingredient	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
prochloraz	16.5	11.7	3.7	1.8	10.3	0.4	0.8	1.0	1.8	0	0
propiconazole	86.6	46.0	24.9	29.8	22.1	19.1	17.0	29.5	30.9	24.5	8.3
fenpropimorph	278.5	219.3	132.9	118.6	104.2	87.4	76.3	25.6	16.2	23.1	17.8
fenpropidin		7.3	39.7	5.2	11.7	0	18.6	93.0	67.8	29.9	22.8
tebuconazole	3.7	26.9	19.6	46.2	55.0	52.1	32.1	30.6	26.2	21.8	20.4
azoxystrobin		71.3	93.5	69.3	77.2	55.6	35.9	23.2	26.8	22.4	21.9
kresoximmethyl			22.8	2.2	3.2	0.7	0.8	0.9	0.7	0.5	0
pyraclostrobin						33.575	43.0	41.8	23.8	17.9	12.1
epoxiconazole							20.7	37.6	46.6	42.4	41.0
boscalid										8.9	18.8
prothioconazole										7.4	12.8

Table 6.2 The fungicides most used in winter wheat since 1970.

Year	Fungicides most used in winter wheat
1971-1980	Benlate (benomyl), Bayleton (triadimefon), Maneb
1981-1997	Tilt 250ec, Tilt turbo/ Tilt top (propiconazole)
1998	Amistar (azoxystrobin)
1999	Amistar (azoxystrobin), Mentor (kresoximmethyl)
2000	Amistar (azoxystrobin), Folicur (tebuconazole)
2001	Amistar (azoxystrobin), Folicur (tebuconazole)
2002	Comet (pyraclostrobin), Folicur (tebuconazole), (Amistar (azoxystrobin))
2003	Comet (pyraclostrobin), Opus (epoxiconazole)
2004	Comet (pyraclostrobin), Opus (epoxiconazole). Recommended decreased amount of Comet
2005	Opus (epoxiconazole), (Comet (pyraclostrobin))
2006	Opus (epoxiconazole), (Proline (prothioconazole))
2007	Opus (epoxiconazole), Bell (epoxiconazole + boscalid), Proline (prothioconazole)

Benzimidazoles (MBC) have been widely used in Denmark since the 1970s, and from the beginning of the 1980s, 65-80% of the winter cereal area was treated with these fungicides. The largest quantities were used for control of eyespot in cereals (*Oculimacula yallundae* and *O. cuformis*) and snow mould (*Michrodochium nivale*) in winter cereals. In the early and mid-1980s unacceptable control levels were found under field conditions, and laboratory tests showed widespread resistance on isolates from *O. yallundae, O. acuformis*, and *M. nivale*. The percentage of control of eyespot went from 80% in 1981 to 10% in 1984 (Jørgensen &

Thygesen, 2006). By 1986 the biological approval for single products as well as mixtures with benzimidazoles was withdrawn for eyespot in cereals, and labels were amended. As a consequence a dramatic drop in the treated area of winter cereals with these products took place.

Triazoles have generally given very cost-effective control of major cereal diseases for more than 25 years in Denmark. The use of triazoles increased significantly during the 1980s, and for many years propiconazole was the dominant active ingredient used for disease control in cereals. When first authorized, most of the triazoles were approved for control of powdery mildew in cereals in general. Today this efficacy is regarded as being relatively low with the exception of tebuconazole (Jørgensen & Thygesen, 2006).

The level of control of Septoria leaf blotch has been assessed in field trials since the beginning of the 1990s using two treatments with 1/3 of the full label rate of propiconazole. Overall, there has been a significant drop in efficacy, although annual variations should be noted. Epoxiconazole has only been authorized in Denmark since 2003 and prothioconazole since 2006. These two fungicides still provide effective control and yield responses, although a drop in efficacy from reduced rates of epoxiconazole have taken place since 2004.

Strobilurins were introduced in Denmark in 1998, and soon afterwards resistance to powdery mildew (*Blumeria graminis* f.sp. *tritici*) was found in wheat, which led to the amendment of the label recommendation. From spring 2003 to summer 2004 the level of G143A mutations in Septoria leaf blotch (*Mycosphaerella tritici*) in Denmark increased from 2.5% to 81% (Jørgensen & Thygesen, 2006). A similarly rapid development was found in many neighbouring countries. The significant yield benefit from the strobilurins found in relation to the newer triazoles had disappeared in wheat by 2004.

The major trend in fungicide use since 1990 in Figure 6.2 is expressed by the development in Treatment Frequency Index (TFI; regarding fungicides synonymously to Total Fungicide Input which is used occasionally) in use of triazoles (propiconazole, tebuconazole, epoxiconazole, etc.) and strobilurins (kresoxim-methyl, azoxystrobin, pyraclostrobin). Treatment Frequency Index is defined as the number of standard doses used. Fungicides containing triazoles have been the major group used during the last 25 years.
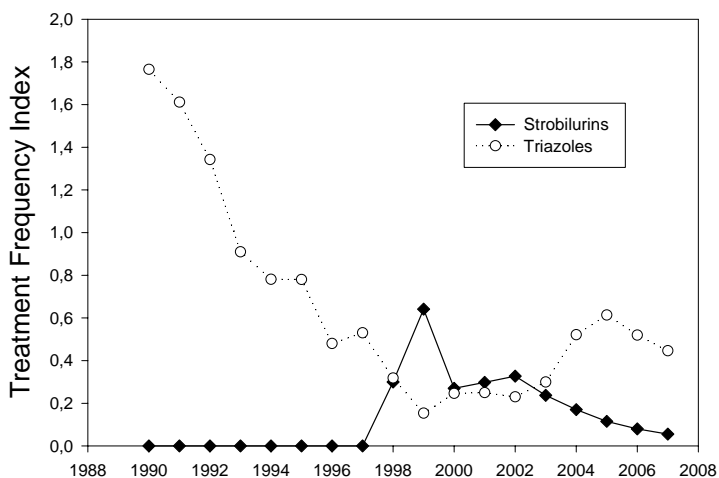
Figure 6.2 Treatment Frequency Index (TFI) for triazoles (plus mixtures with morpholines before 1998) and strobilurins measured in winter cereal (Miljøstyrelsen - Pesticide statistic).

6.2.2 Development in gross yield with different fungicides

From 1998-2007 the overall TFI for fungicides has been around 0.75, and therefore trials carried out by DAAS with this application rate were selected for the comparison of yield response between older and newer fungicides. Trials with fungicide treatments given in either a single or in two applications are used for this comparison (Table 6.3). In the single fungicide treatment 50-75% of the normal rate is typically applied around heading. The double-spraying strategies are in most cases based on a standard programme using about 25% of the normal dose at an early treatment (growth stage 31-32) followed by an ear application using around 50% of the normal rate. Investigations have shown that the first treatment only contributes little to the total yield increase from fungicide application. The treatment around heading contributes on average 85% of the total gross yield increase (Pedersen, 2007).

Table 6.3 Gross yield increase (dt/ha, weighted average) obtained from the use of different fungicides in the National Field Trials carried out by DAAS using 50-75% of standard rates in a single or a two-spray application strategy. Numbers of trials are shown in brackets.

Comparison of fungicides	One spray [dt/ha]	Two spray [dt/ha]
Amistar versus Tilt top 1998-2001	4.5 (129)	5.8 (123)
Comet versus Amistar 2002		2.3 (20)
Comet+Opus versus Amistar+Opus 2003	2.4 (10)	
Comet+Opus versus Opus 2003	3.4 (10)	
Comet+Opus versus Opus 2004-2006	0.1 (38)	
Bell, Proline versus Opus 2007	2.3 (18)	-

Replacing Tilt top (propiconazole) by the strobilurin Amistar (azoxystrobin) in 1998-2001 increased the gross yields for fungicide treatment by 5.2 dt/ha, which was estimated using data from the 1998-1999 trials. The trials focus on tests of new fungicides and strategies, and as a fungicide becomes less competitive and phased out it is no longer included in the trials. However, Figure 6.1 shows that the yield response to fungicide in 1998-1999 was higher than in 2000-2001, and therefore the response in gross yield in 2000-2001 was expected overall to be less than 5.2 dt/ha by replacing Tilt top with Amistar.

In 2002 the use of Amistar was replaced with another strobilurin Comet (pyraclostrobin). It appears that the gross yields increased by approx. 2.3 dt/ha. In 2003 the triazole Opus (epoxi-conazole) was introduced to the market, which in itself was much more effective than the old triazoles. In 2003 the yield response to the use of Comet+Opus in comparison to Opus was 3.4 dt/ha. But already in 2004-2006 this positive response had disappeared. This was due to the development of strobilurin resistance in Septoria. In 2007 the use of the new pesticides Proline (prothioconazole) and Bell (epoxiconazole + boscalid) resulted in an increase in gross yield response of approx. 2.3 dt/ha compared to Opus.

The differences between the different strategies in individual years are shown in Table 6.4, which includes data from DJF trial plans with triazoles, strobilurins as well as mixtures. This table shows the potential variations between products and years reflecting variations in dis-ease pressure. Figure 6.3 summarizes the differences in yield response with different fungi-cides tested at DJF. Only the first four columns are directly comparable as they originate from the same eight trials carried out in 2001-2002. The data for Opera after resistance develop-ment and for the two new products Bell/Proline rely on comparisons from other trials (Jørgen-sen, 2004). The figure supports the information from DAAS (Table 6.3). It shows a clear dif-ference in yield responses obtained from the use of the different fungicides. The data are summarized in Table 6.5.

Table 6.4 Yield and yield increases, dt/ha. Trial data from DJF (Jørgensen et al., 1998-2003).

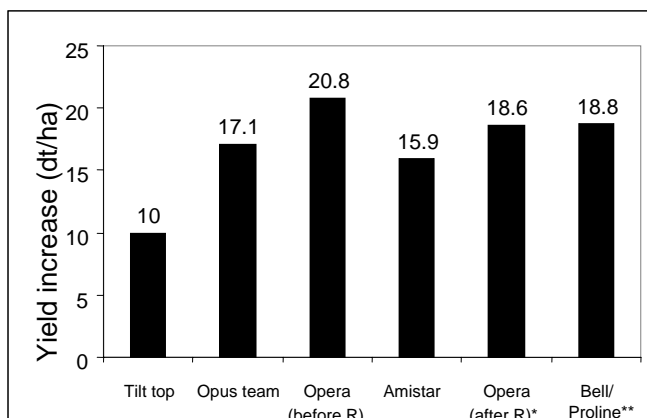| Product	1998	1999	2000	2001	2002	2003	1998-2003	2001-2003	2000-2002
Untreated	**62.8**	**84.9**	**78.2**	**82.3**	**67.6**	**67.3**	**73.9**	**72.4**	**75.2**
Tilt top 2×0.33	11.5	10.2	7.3	4.9	15.2	8.0	9.5	9.4	9.8
Opus team 2×0.5	23.3	20.7	15.3	10.6	23.5	15.3	18.1	16.4	18.7
Opera 2×0.5	-	-	-	14.0	27.7	20.0	-	20.6	-
Amistar 2×0.33	17.7	21.5	14.6	10.6	21.2	-	-	-	17.1
Comet 2×0.33	-	-	-	-	27.1	-	-	-	-
Amistar + Opus 2×(0.17+0.17)	-	-	-	-	-	16.5	-	-	-
No of trials	4	4	4	4	4	4	24	12	20

Figure 6.3 Yield differences between fungicides mainly based on a trial plan with a 2×1/3 rate of different products in 2001-2002. The trials are from DJF and cover situations with relatively high disease pressure.

*The yield benefit from Opera after strobe resistance compared to Opus team/Opus indicates a benefit of 1.5 dt/ha.

** The change from Opus team to Bell/Proline is based on registration trials with Bell compared to Opus team (2004), which has given a benefit of 1.7 dt/ha using data from ½ rate.

Table 6.5 Summarising changes in the yield increases from fungicides during the last 30 years.

Major changes in used products	Change in yield responses
From benzimidazoles (MBC) to propiconazole	6 dt/ha
From propiconazole to strobilurins (Amistar)	5 dt/ha
From Amistar to Comet	2-3 dt/ha
Strobilurin resistance	-2 dt /ha
Total results	11-12 dt/ha

6.2.3 Conclusion: Development of effectiveness and yield responses from fungicides

Trial data indicate a general increase in yield benefit following the development of more effective fungicides during the last 35 years.

- Introduction of broad-spectrum triazoles in the 1981/1982 increased the yield response to fungicides by 6 dt/ha compared to the use older fungicides, like benomyl.
- Introduction of the first strobilurins (Amistar) in 1998 increased the yield response to fungicides by 5 dt/ha compared to the use of triazoles.
- This was further increased by 2-3 dt/ha in 2002-2003 when pyraclostrobin was introduced, giving a total increase of approximately 7-8 dt/ha compared to Tilt products.
- Following the development of resistance to strobilurins this last increase was partly lost in 2004, but stabilized by epoxiconazole being introduced to the market, giving better yield responses than the first strobilurins used alone.

- The strength of the present fungicides (Bell, Proline, Opus) is today still up compared with the first strobilurins introduced, with a tendency that Bell and Proline are giving better responses than Opus used alone.
- Compared to the strobilurins at their best (Comet + Opus), the yield response of fungicide application is today, however, approximately 2 dt/ha less, compared to 2002-2003.
- The total potential gain from fungicide use today is around 11-12 dt/ha (Table 6.6) compared with 25-30 years ago. This increase reflects that the efficacy of the fungicides used today has improved significantly compared to products used in the late1970s.

6.3 Impact of low dose strategies on yield potential

Have we used too low doses of fungicides? This question is relevant because the gross yield typically increases with a higher dose of fungicides. In Denmark the net yields are traditionally always calculated in the trials, and the dose recommended to farmers is typically the dose that in most cases has given the highest net yield increase.

In general, the prices of fungicides are higher in Denmark than in other European countries because of the pesticide tax in Denmark (33%). This has an important effect on the economic optimum and may also be a contributory factor to the higher fungicide input and harvested yields in other countries than Denmark (Jørgensen et al. 2008). In Germany, UK and France the input measured in TFI is typically 2-3 times higher than in Denmark. but the actual cost of fungicides is typically only around twice that in Denmark.

6.3.1 Optimizing reduced doses

For more than 15 years Denmark has recommended appropriate and reduced doses of fungicides as part of an overall aim of reducing cost as well as impact on the environment from the use of pesticides. Common practice in Denmark is to treat winter crops one to three times per season depending on the cultivar and disease severity. Figure 6.4 shows the treatment frequency index (TFI).

The recommendations have been based on results where focus has been on optimizing the margin over fungicide cost rather than gross yield. Based on 32 field trials carried out between 2003 and 2006 comparing two treatments with full, half and quarter doses of Opus, the gross yield was reduced by 4-5 dt/ha from two full rates compared with a TFI around 0.75 (Figure 6.5) . Despite these results many data still support that the optimal economic input is around 0.5-1.0 TFI, as described below.
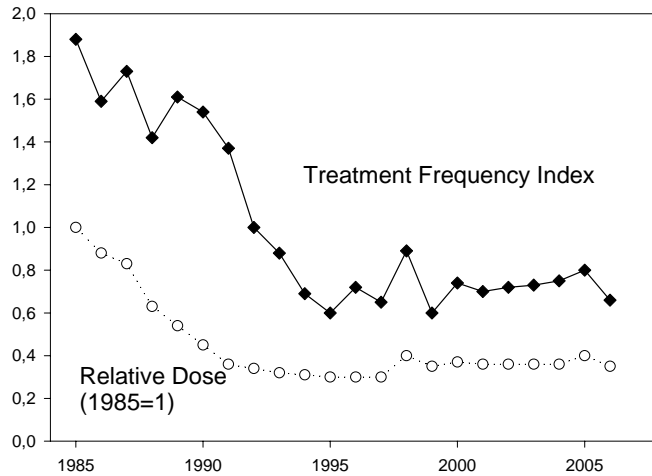
Figure 6.4 Changes in Treatment Frequency Index (TFI) and dose used per application in wheat from 1985 to 2004. (Miljøstyrelsen - Pesticide statistics).
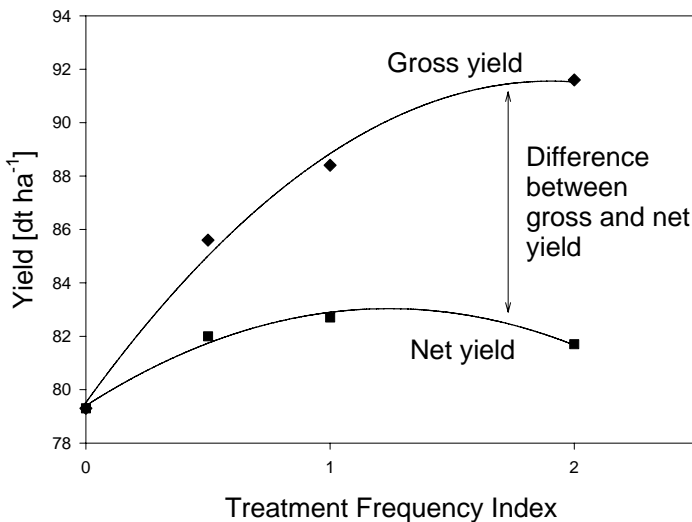
Figure 6.5 Yield response to different fungicide input in wheat using two treatments with either full, half or quarter rate of Opus/ Opus team (data from registration trials 2001-2005 carried out by DJF). Based on a grain price of 13.5 €/dt grain.

The optimal input with fungicides depends on the disease pressure and the climate in the individual season, but in particular the susceptibility of the cultivar plays a major role for the optimal input. The differences in margin between resistant and susceptible cultivars are largest in seasons with severe attacks of Septoria leaf blotch and yellow rust. The dose-response curves for ear treatments targeting control of Septoria leaf blotch and yield responses have

generally been very flat. This has been shown in many trials annually (Jørgensen et al., 2008; Pedersen, 2007). The economic optimum in resistant cultivars was a Treatment Frequency Index (TFI) between 0.25 and 0.5. On more susceptible cultivars, the optimum TFI was 0.5-0.9, and a 2-spray programme gave more flexibility with regard to the dose needed at the 2nd application. Figure 6.6 shows an example of calculated net yield gain in winter wheat in resistant (a) and susceptible cultivars (b) for selected strategies and two grain prices. The results are based on data from the National Field Trials in the Sjælland region 1999-2003.
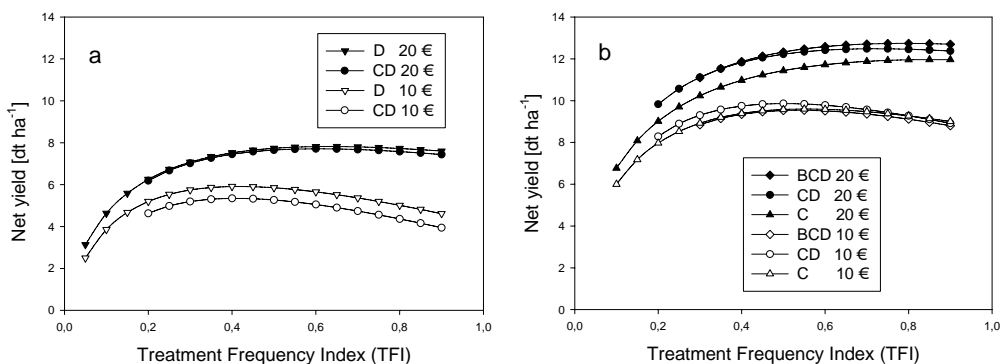
Figure 6.6 Calculated net yield gain in winter wheat in resistant (a) and susceptible cultivars (b) for selected strategies and two grain prices. The legends for fungicide strategies are ranked according to the most beneficial solutions. B: GS 32-36, C: GS 37-50, D: GS 51-64. Data based on 5 years trial data from the National Field Trials carried out by DAAS-region Sjælland.

6.3.2 Conclusion: Impact of low dose strategies on yield potential

The actual gross yield is not optimized using fungicides as focus has been based on net yields rather than gross yield. Many years' trials have shown that the best net yields are obtained by using reduced rates, typically between 0.4 and 0.75 depending on the year and level of resistance in the cultivar. The data have shown that the gross yield has been reduced by 4-5 dt/ha in the last 10-15 years due to the reduced treatment frequency policy in Denmark. From the point of view of the farmers' economy the low dose policy is, however, still believed to be a sensible policy.

6.4 Development of disease pressure during the last 30 years

The most important diseases in winter wheat are Septoria leaf blotch (*Septoria tritici*) followed by powdery mildew (*Blumeria graminis*), stripe rust (*Puccinia striiformis*), leaf rust (*Puccinia triticina*), tan spot (*Drechslera tritici-repentis*) and fusarium head blight (*Fusarium spp.*). For the period up to 1985 only limited data exist to describe the disease pressure in the individual season. Focus will therefore be on the last 10-20 years.

Variability of disease pressure is closely linked to climate and the susceptibility of cultivars grown. Figure 6.1 indicates the yield response found across the time periods. This figure does not indicate any major changes in yield responses looking over the whole period, but as described previously the annual variation is a result of disease pressure, cultivars as well as fungicides used.

6.4.1 Link between resistance level in cultivars and grown cultivars
One way to investigate changes in disease risk over the years is to combine existing information on grown cultivars in specific years with their actual resistance ranking using an index. In the computer program Crop Protection Online (CPO www.planteinfo.dk) all the varieties are assigned indices from 0-3 ranging from not susceptible to very susceptible (www.sortinfo.dk, Hagelskjær & Jørgensen, 2003).

Indexing varieties in susceptibility groups first started in 1999. Figure 6.7 shows the resistance index in winter wheat to the four leaf diseases that fungicide treatments can be aimed at. The resistance index is indicated as the average group in CPO (group 0-3) weighted with distribution of sold seed of the varieties that have been grown in Denmark. Therefore, the resistance index changes when changes occur in the distribution of varieties or if changes occur in the virulence profile of the pathogens (infection races). It can be noted that the resistance index has been rising (= falling susceptibility) against yellow rust and mildew, fairly unchanged variety resistance against Septoria (however, rising resistance over the last few years (variety Ambition)) but falling resistance level against brown rust.
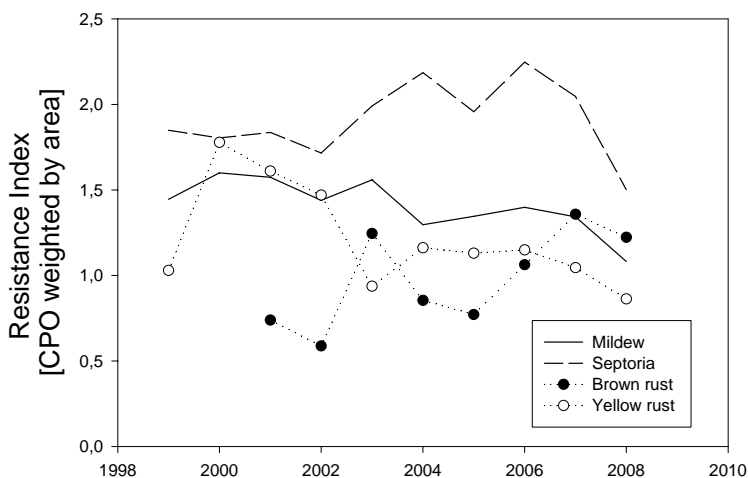
Figure 6.7 Resistance index in winter wheat to the four leaf diseases that fungicide treatments can be aimed at. (see text).

Data from the national monitoring network can also be used as a source of information, when one investigates the changes in disease risk – see Figure 6.8 (Nielsen 2008, Nielsen & Jensen 2008, Jørgensen et al., 2008; www.lr.dk/regnet). The septoria attacks vary annually but no specific trend in disease risk has been observed. The septoria attacks may seem severe, but it must be noted that registrations are made using percentage observations with > 25% attacked plants. Many plants are often attacked by Septoria, but the percentage coverage varies considerably over the years, even though there are 100% attacked plants.
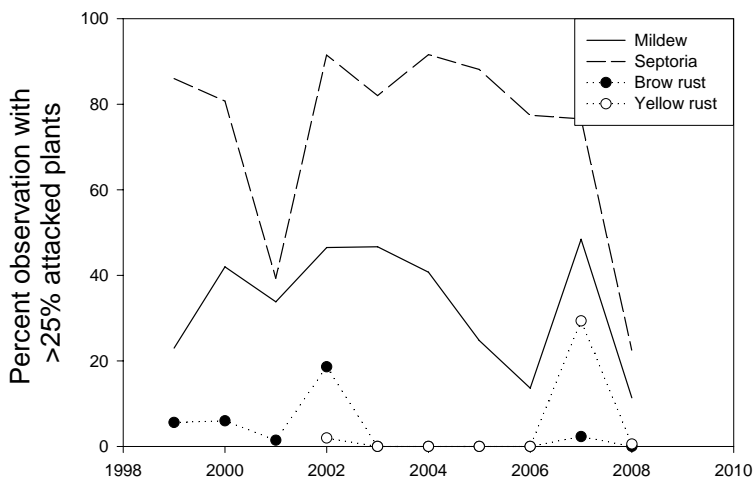
Figure 6.8 Data from the plant production advisers' monitoring network in 1999-2008 (www.lr.dk/regnet) in which registrations are made in untreated plots in the wheat varieties most commonly grown. The threshold for including data is >25% of plants attacked.
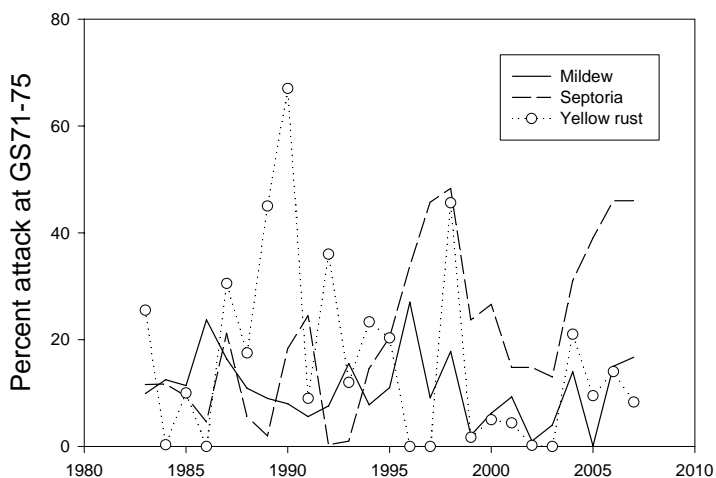
Figure 6.9 Data from the registration trials (DJF) in 1983-2007, in which assessments are made in untreated plots in commonly used wheat varieties. The data indicate a general increase in Septoria (from the early part of the 1980s and to the end of the 1990s) and a stable or reduced level of mildew and yellow rust.

The third source of information used to visualize any changes in disease pressure originates from DJF's registration trials, which have data back to 1982. Data in Figure 6.9 show an increase in Septoria leaf blotch from the early part of the 1980s. Before this period this disease was not recognized as a major problem. *Stagonospora nodorum* dominated up to 1982 when a major shift occurred to Septoria leaf blotch (*Septorio tritici*) in Denmark as well as in many other European countries. Since the end of the 1990s no sign of a further increase in the Septoria problem has been observed (Figures 6.7-6.9).

6.4.2 Conclusion: Development of disease pressure during the last 30 years

It can be concluded that the plant breeders have been capable of developing resistant varieties with competitive yields faster than the pathogen populations have changed during the last 10-year period. Therefore nothing indicates that the disease pressure has increased from 1999-2008.

The impact from development of significant attacks of Septoria leaf blotch since the early 1980s compared with the attack of *S. nodorum* prior to this period cannot be quantified. As the fungicides during the same period have become more effective, the disease is not believed to have had a major impact on the total yield level. With respect to other diseases no major changes have been found, which could have caused the stagnating yields.

6.5 Diseases related to the crop rotation

Take-all (*Gaeumannomyces graminis*) is regarded as a serious root pathogen, which is seen as a problem particularly in 2nd and 3rd year wheat. Certain years, e.g. 2007, had severe attacks with significant impact on yields. Mainly the weather, sowing time, and crop rotations are seen as influential factors. No specific monitoring data are available to describe a trend during the last 30 years.

Using data from DAAS trials it is suggested that the proportion of winter wheat grown with pre-crop winter wheat has increased significantly (Table 6.6). It appears that 20-30 per cent of the wheat trials had wheat as a pre-crop in the early 1990s, while wheat was the pre-crop in approx. 40-50 per cent of the trials in the last 6-7 years. These data support that there has been an increase in the fields at risk of take-all attacks. Excluding 262 trials with yields less than 45 dt/ha, the average winter wheat yield is 77 dt/ha with a pre-crop of winter wheat. With other pre-crops the average yield is 81 dt/ha.

Reduction in the N-rate applied for wheat may also facilitate an increase in take-all attacks as both the N-rate and N-type is described to have significant impact on take-all development (Gutteridge & Hammond-Kosack, 2008). It is therefore estimated that the fungus has caused larger yield losses in recent years than in previous years, but it is not possible to determine

precisely the extent of the loss. Severe attacks of take-all are known to reduce yields by 20-30% (Gutteridge & Hammond-Kosack 2008)

Table 6.6 Number of DAAS trials in winter wheat with winter wheat as a pre-crop in 1992-2008. in total 6039 trials.

Year	Number of trials	Per cent wheat trials with wheat as pre-crop	Yield with wheat as pre-crop [dt/ha]	Yield at another pre-crop [dt/ha]
1992	344	12.5	69.2	75.9
1993	336	19.3	78.1	77.6
1994	384	28.1	71.8	75.6
1995	473	31.9	76.6	83.3
1996	446	32.5	74.5	76.3
1997	486	35.8	77.1	80.6
1998	528	33.0	78.4	82.6
1999	505	36.8	75.5	78.9
2000	452	31.2	79.5	85.4
2001	400	35.5	80.1	85.9
2002	324	40.7	75.6	77.7
2003	279	40.9	74.3	78.4
2004	244	45.1	76.8	79.8
2005	251	47.4	74.6	81.3
2006	246	50.0	76.1	77.1
2007	172	40.1	72.9	75.4
2008	169	39.6	96.2	101.2
Average			76.9	80.8

6.6 Overall conclusion on disease control

There is no indication that less effective fungicides, too small doses of fungicides or an increasing disease pressure should play a major role for the stagnant wheat yields, which have been seen in recent years.

More effective fungicides have from the beginning of the 1980s until today resulted in a potential increase in yield responses during the period of approximately 11-12 dt/ha. Focus on net yields rather than gross yield was initiated around the end of the 1980s and has led to widespread use of reduced fungicide dosages. Calculations have shown that the gross yield may be reduced by 4-5 dt/ha due to the focus on economic optimums rather that gross yield. This policy is, however, still seen as being of benefit to the farmers' economy. In summary, the potential increase in yield responses during the period is assessed at approximately 6-8 dt/ha.

The cultivated varieties have not become more susceptible during the last 10 years, but have rather shown a decrease in susceptibility. *Septoria tritici* arrived as a new serious disease in the beginning of the 1980s and has since been the major target for fungicide treatments. This disease is, however, generally found to be controlled satisfactorily at farm level and is not believed to contribute to the stagnating yields.

6.7 Trend in the use of plant growth regulators

Compared to our neighbouring countries, Denmark has a low use of plant growth regulators (PGR) in wheat. The recommendations have generally been to treat only in high risk situations (variety, early sowing, etc.). The strict nitrogen policy practised in Denmark has also helped reduce the need for PGR.

The use of PGRs in winter wheat in Denmark has been very stable (0.1-0.3 TFI) during the last 20 years. CCC (chlormequat-chloride) is the most commonly used PGR in winter wheat. The dramatic changes seen in 1995 and 2001 are because farmers were increasing their stocks of pesticides due to risks of prohibitions and increased taxes on pesticides. After that time the use has levelled out again. In summary, lodging is not believed to have significantly added to the stagnation in yields.

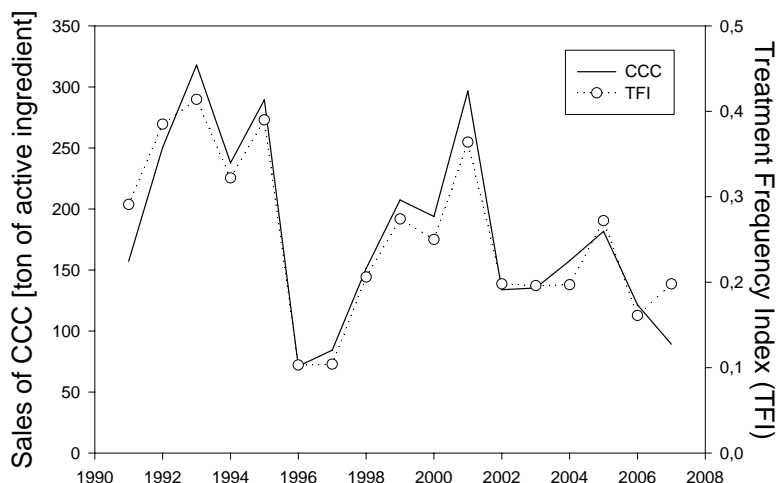**Figure 6.10** Sales of CCC (kg) and calculated TFI, as the main Plant Growth Regulator used in winter cereals (Miljøstyrelsen -Pesticide statistic).

6.8 Yield impact caused by insects

The most common and dominant pest in wheat is aphids – primarily *Sitobion avenae*. During the period 1906-1983 surveys were made of the distribution of aphids on the basis of data

input from the plant production advisers to DJF. The results show an increase in the distribution from the middle of the 1950s, followed by a fall from the beginning of the 1970s.

When one studies the results from the plant production advisers' registration and monitoring net (Nielsen, 2008; Nielsen & Jensen, 2008), which was initiated in the beginning of the 1990s, the distribution of aphids in wheat as a linear regression over the whole period 1992-2008 shows no increase, but rather a tendency for a fall in attack pressure (Figure 6.11). There are, of course, significant differences between individual years. The conclusion must, therefore, be that aphids cannot be the cause of stagnant yields in wheat.
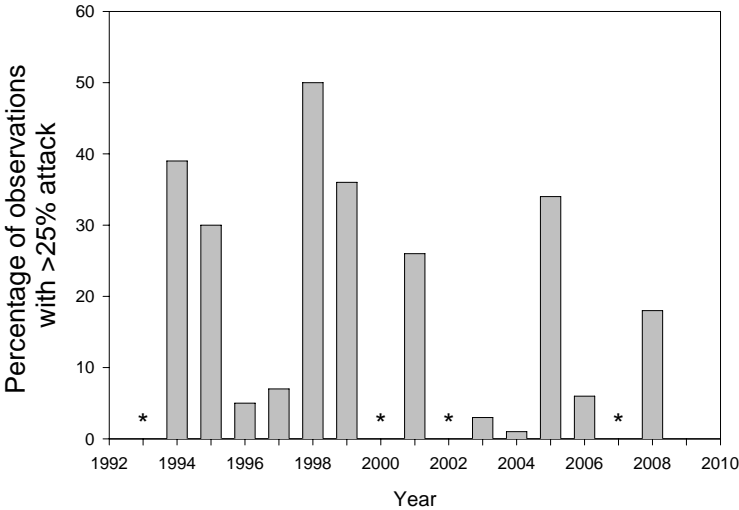
Figure 6.11 Percentages of observations with more than 25% attack of aphids in winter wheat in week 27, 1993-2008. An asterisk indicates that data are only available until week 26.

In recent years the orange wheat blossom midge (*Sitodiplosis mosellana)* has spread widely, and as a consequence of this the National Fields Trials initiated control in fields with pre-crop wheat in 2006. In 2006-2007 gross extra yields of 1.3 dt/ha on average were obtained from treatment against *Sitodiplosis mosellana*.

In recent years the distribution of the barley yellow dwarf virus (BYDV) has also increased. Apart from 2007 when many fields in the southern parts and costal areas suffered considerable yield losses, the attacks have appeared in only some localities. No specific monitoring data are available, but BYDV is not regarded, in general, as a reason for stagnant yields in wheat.

The occurrence of *Deroceras* sp. (field slugs) is estimated to have been more frequent in recent years as well. There are no estimates of the annual attacks, but the spread of *Deroceras* sp. during the last ten years is not considered so serious that it could have an effect on the yields, in general.

6.9 References

Miljøstyrelsen: Pesticide statistics (Bekæmpelsesmiddelstatistikken). 1986-2007.
    http://www.mst.dk/Bekaempelsesmidler/Pesticider/Regulering/Statistik.htm

Gutteridge, R.J. & Hammond-Kosack, K.E. (2008) Strategies for the control of take-all. Ce-real Pathosystems. Papers from BSPP presidential meeting, University of London, 16-17 dec. 2008. p 75-88.

Hagelskjær, L. & Jørgensen, L.N. (2003) A web-based decision support system for integrated management of diseases and pest s in cereals. European Plant Protection Organisation, EPPO Bulletin 33, 467-471.

Jørgensen, L.N., Nielsen, G.C., Ørum, J.E., Jensen, J.E. & Pinnschmidt, H.O. (2008) Integrat-ing Disease Control in Winter Wheat – Optimizing Fungicide Input. Outlooks on Pesti-cide Management, 19(5), 206-213

Jørgensen, L.N. (2004) Svampesygdomme i korn. DJF rapport 112. 21-94.

Jørgensen, L.N. & Thygesen, K. (2006) Fungicide resistance and its impact on recommenda-tions to farmers – experiences from Denmark AAB conference. Fungicide resistance: are we winning the battle but losing the war? Aspect of Applied Biology 78, 65-70

Jørgensen, L.N., Nielsen, B.J. & Saltofte, H. (2008) Sygdomsangreb 2007. In: Pesticidaf-prøvning 2007. Aarhus Universitet, Det Jordbrugsvidenskabelige Fakultet, DJF rapport Markbrug, nr. 133, p. 13-17.

Jørgensen, L.N., Ørum, J.E., Pinnschmidt, H.O. & Nielsen, G.C. (2007) Integrating disease control in winter wheat – optimizing fungicide input. In: Modern Fungicides and Anti-fungal Compounds V (Eds H. Dehne, H.B. Deising, U.Gisi, K.H. Kuck, P.E. Russel & H. Lyr). Braunschweig, Germany: DPG: Spectrum Phytomedicin, pp. 197-210

Jørgensen,L.N., Nielsen, G.C., Ørum, J.E. & E. Noe (2008) Controlling cereal disesae with reduced agrochemical inputs – a challenge for both growers and advisers. Cereal patho-systems. BSPP presidential meeting, London 16-17 dec 2008. 23-34

Nielsen, G.C. (2008) Forecast and monitoring systems in agricultural crops in Denmark, En-dure projekt RA 3.1.
    http://www.lr.dk/planteavl/informationsserier/aktuelt/Pl_aktuelt_09_293_b1.pdf

Nielsen, G.C & Jensen J.E. (2008) Forecast and monitoring systems in agricultural crops in Denmark, ENDURE international conference, La Grand Motte, France, 12th-15th Octo-ber 2008. http://www.endure-
    net-
    work.eu/international_conference_2008/abstracts_online/posters/p_53_monitoring_for_
    cereal_diseases_a_tool_for_adjusting_input_according_to_need

Nielsen, G.C. (2008) Registreringsnet 2008 – vinterhvede, artikel nr. 113, 2008 Landbrugsin-fo. http://www.lr.dk/planteavl/informationsserier/artikler/lpart113.htm

Pedersen, J.B. (2007) Oversigt over landsforsøgene, Dansk Landbrugsrådgivning. Flere år-gange (1980-2007).

7 Impact of weeds on yields in winter wheat

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7.1 Introduction

A recent weed survey revealed that within the last 15 years (from 1987-89 to 2001-04) weed frequency increased significantly in most arable crops including winter wheat (Andreasen & Stryhn, 2008). This is in contrast to the preceding period from 1964-69 to 1987-89 where weed frequency was reduced by up to 60% (Andreasen et al., 1996). The method used in the weed surveys does not provide any information on the density of the individual weed species but it can be assumed that an increase in frequency probably also reflects an increase in the average density.

In winter wheat the most notable change is a pronounced increase in the frequency of the grass weed species *Poa annua* and *Apera spica-vent*, but also winter annual broadleaved weed species like *Capsella bursa-pastoris, Galium aparine*, *Stellaria media*, *Veronica arvense* and *Viola arvensis* increased in frequency (Figure 7.1). Also the frequency of *Fallopia convolvulus* has increased. This species is a summer annual but also occurs in winter wheat and competes with the crop. The increased frequency of the abovementioned weed species can largely be attributed to an increased frequency of winter cereals, particularly winter wheat, in the crop rotation but in the case of *Poa annua* also the warmer and more humid winter climate that we have experienced within the last 10 years. Other grass weed species observed more frequently in winter wheat fields now than previously are *Alopecurus myosuroides* and *Bromus ssp.* but their overall frequency is still quite low. Also earlier sowing, reduced tillage (where practised), reduced herbicide dosages and lately reduced nitrogen quotas are supposed to have an effect.

Grass weed species are more competitive that most broadleaved weed species and farmers have responded to the changes in weed flora by intensifying the use of herbicides in winter cereals since 2001 following a period of reduced use of herbicides in winter cereals (Figure 7.2).

Nevertheless, in spite of the increased use of herbicides, average yield losses due to weeds may have increased and hence contributed to the observed stagnation in winter wheat yields. In order to examine this hypothesis we compiled a data set consisting of the results from 224 herbicide trials in winter wheat conducted by the Danish Agricultural Advisory Service over the last 10 years (1998 to 2007). From each experiment we selected one herbicide treatment considered to be a suitable choice for controlling the weed flora. The herbicides were applied at two doses; the recommended dose and a reduced dose. The experiments were classified as '*Apera spice-venti*', '*Poa annua*', 'dicot+grass weed' or 'dicot weed' trials according to the

dominant weed species in the experiments. Only the '*Apera spice-venti*' and '*Poa annua*' data were used in the subsequent analyses. In the following the data set will be referred to as the 'DAAS data set'.
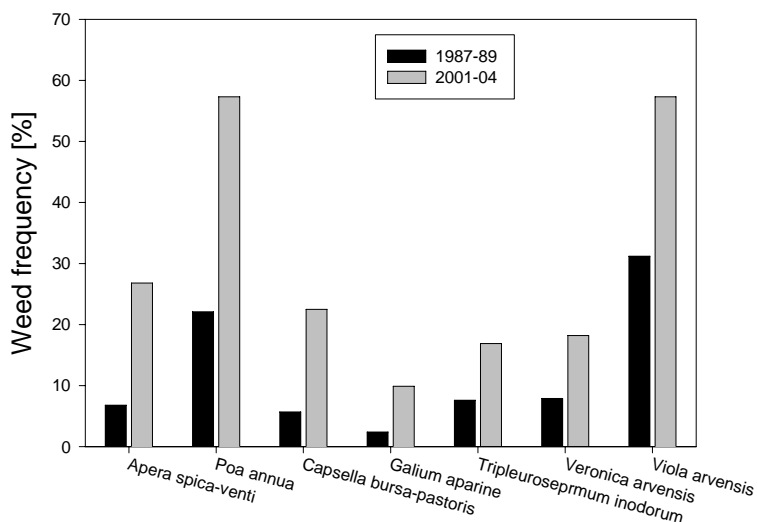
Figure 7.1 Observed weed frequencies of selected weed species in winter wheat in surveys conducted in 1987-98 and 2001-04. For all weed species the observed frequency in 2001-04 was statistically significantly higher than in 1987-89 (Andreasen & Stryhn, 2008).
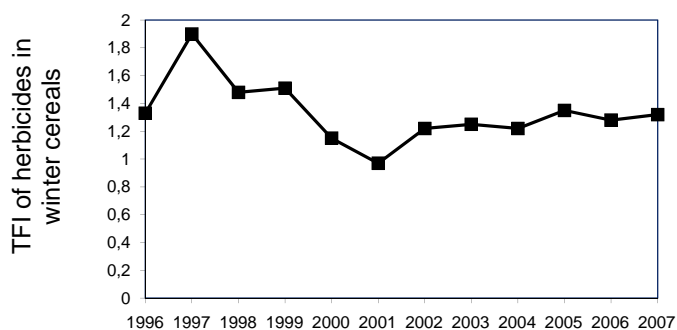
Figure 7.2 Treatment Frequency Index (TFI) of herbicides in winter cereals (winter wheat is *c*. 75% of the total area of winter cereals). Herbicide use in winter wheat is generally higher than in winter barley, winter rye and winter triticale.

Besides a shift in the weed flora, cropping practice has also changed. Nowadays winter wheat is often sown earlier than 10-15 years ago. It is generally believed that early sowing leads to increasing weed problems particularly with grass weeds which could also have led to increased yield losses.

To examine whether the observed changes in weed flora and cropping practice can have contributed to the stagnating yields in winter wheat we decided to examine the following hypotheses using the DAAS data set:

1. Early sowing leads to increasing problems particularly with grass weeds in winter wheat
2. Higher densities of grass weeds result in higher yield increases for weed control in winter wheat
3. More grass weeds survive herbicide treatments resulting in higher weed coverage at harvest

7.2 Hypothesis 1: Early sowing leads to increasing problems particularly with grass weeds in winter wheat

Numerous experiments have shown that late sowing of winter wheat reduced weed density/dry matter of grass weeds (Moss, 1985; Amann et al., 1992; Melander, 1995) and broad-leaved weeds (Christensen, 1993; Christensen et al., 1996; Olsen et al., 1997). Weeds generally have a higher temperature requirement for germination than winter wheat and the effect of late sowing can be attributed to an increased delay in weed germination relative to crop emergence. Melander (1995) found that delaying sowing by 14 days extended the time from the beginning to the end of germination of *Apera spica-venti*, reduced seed production but the effect on winter wheat yields was inconsistent. In the abovementioned studies early sowing was around 1 September, normal sowing was around 20 September while late sowing was 2-3 weeks later than normal sowing. Only one Danish study included early sowing (Olsen et al., 1997), while the other studies compared normal and late sowing.

Plotting grass weed density against sowing date for the data included in the DAAS data set did not reveal a clear relationship between sowing date and grass weed density (Figure 7.3).

Conclusion: Early sowing favours grass weeds resulting in higher weed biomass and thus higher potential yield losses if weeds are not controlled effectively.

Figure 7.3 Density of grass weeds *(Apera spica-venti* and *Poa annua*) in control plots versus sowing date in winter wheat herbicide trials carried out by the Danish Agricultural Advisory Service from 1998 to 2007. Data from experiments with less than 10 grass weeds per m^2 were omitted.
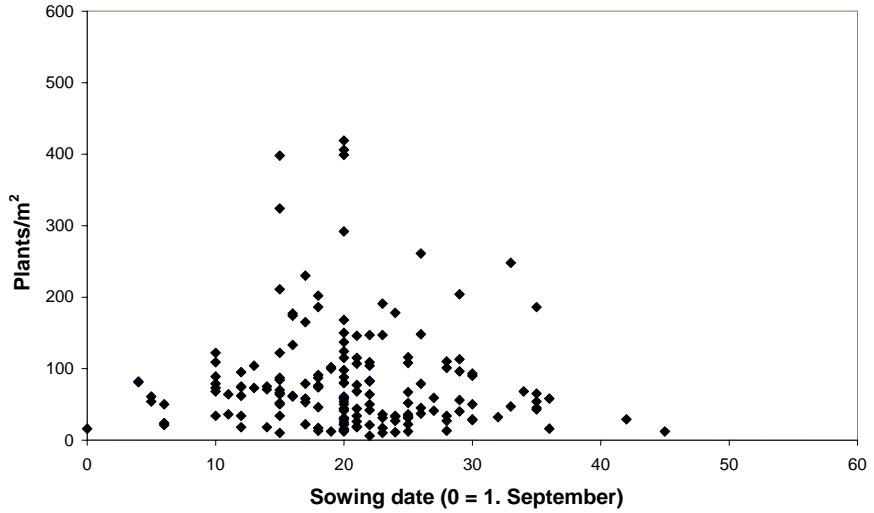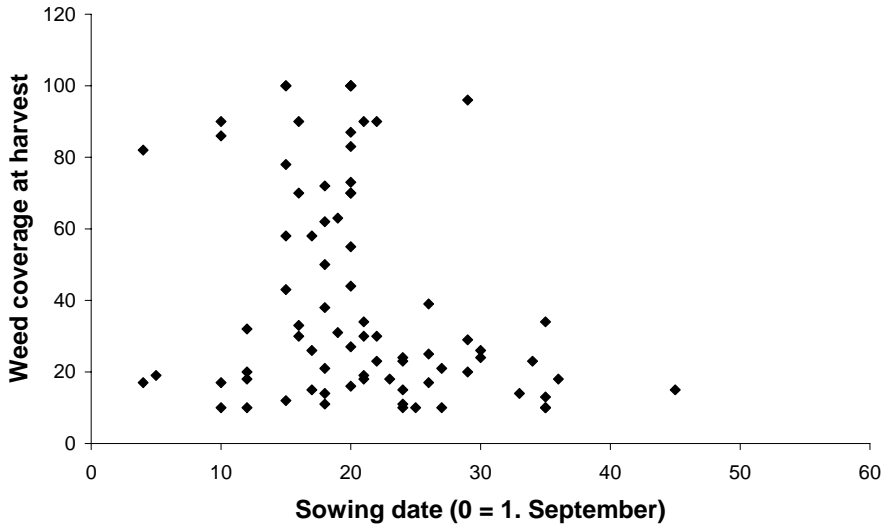

Figure 7.4 Grass weed coverage *(Apera spica-venti* and *Poa annua*) in control plots versus sowing date in winter wheat herbicide trials carried out by the Danish Agricultural Advisory Service from 1998 to 2007. Data from trials where the coverage of grass weeds at harvest was less 10% were omitted.

7.3 Hypothesis 2: Higher densities of grass weeds result in higher yield increases for weed control in winter wheat

Before examining the relation between weed density and effect of weed control we consider whether the weed density in the DAAS dataset is representative for winter wheat fields in Denmark. Using the DAAS data set we may suggest that grass weeds have not become a bigger problem during the last 10 years as no correlation was found plotting grass weed density against year (Figure 7.5). This is not in agreement with the conclusions of the aforementioned weed survey (Andreasen et al., 2008). The discrepancy may be caused by the fact that the increase in frequency of *Apera spica-venti* and *Poa annua* happened in the first part of the 1990s, i.e. prior to the 10-year period covered by the data set. Another and more likely explanation is that grass weed trials tend to be carried out in heavily infested fields, i.e. the weed densities in the trials do not reflect the general development in the grass weed situation in Danish winter wheat fields.
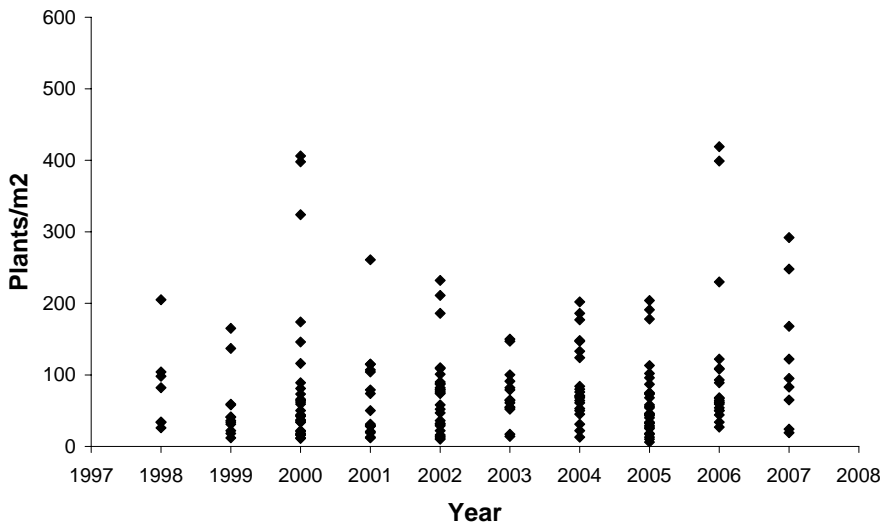
Figure 7.5 Grass weed density *(Apera spica-venti* and *Poa annua)* in control plots versus year in winter wheat herbicide trials carried out by the Danish Agricultural Advisory Service from 1998 to 2007.

Yield increase was positively correlated with *Apera spica-venti* density (Figure 7.6), but the regression was weak. The logarithmic equation suggests that very high densities will result in yield losses of ca. 32 dt/ha. Yield losses of 5 and 10 dt/ha occurred at densities of 5 and 13 plants/m^2, respectively. The analysis of the results from the treatments with reduced herbicide produced a very similar relationship suggesting that reducing herbicide doses did not increase yield losses. Our findings are in accordance with a similar analysis presented by Jensen & Petersen (2006), except that they predicted higher maximum yield losses.
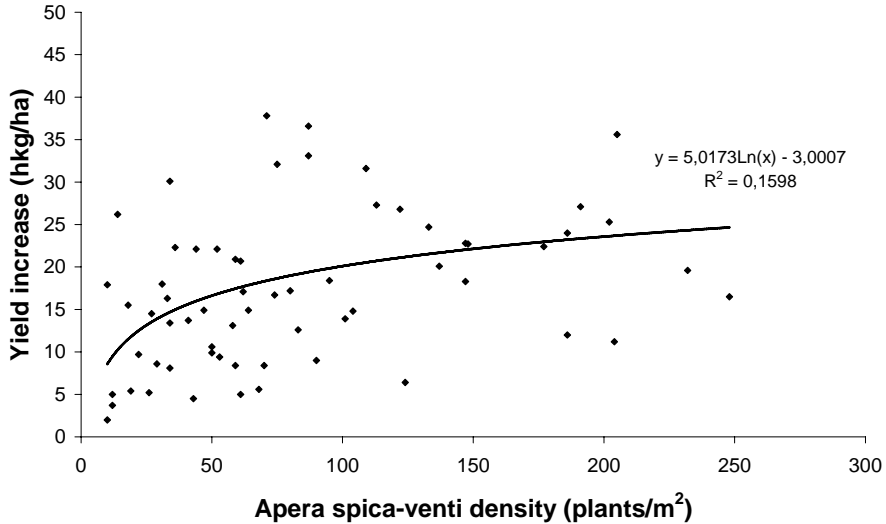
Figure 7.6 *Apera spica-venti* density in control plots versus yield increase following application of the recommended herbicide dose in winter wheat herbicide trials carried out by the Danish Agricultural Advisory Service from 1998 to 2007.

Conclusions: High grass weed densities resulted in higher yield increases following application of recommended and reduced herbicide doses, but the analysis of the DAAS data set could not confirm the hypothesis that grass weed densities have increased during the last 10 years.

7.4 Hypothesis 3: More grass weeds survive herbicide treatments resulting in higher weed coverage at harvest

A comparison of *Apera spica-venti* coverage at harvest against year did not reveal any significant correlation, although weed coverage tended to be higher in recent years than previously following application of reduced herbicide doses. The results may have been affected by the fact that *Apera spica-venti* often wilted and was partly vanished at harvest time, making it difficult to distinguish between this grass weed and other plant residues.

Figure 7.7 shows the effect of reduced herbicide doses versus year and it is obvious that unsatisfactory effects were more common in recent years than in the beginning of the 10-year period. It is likely that a reduced efficacy explains the observed trend towards higher weed coverage at harvest, although it should be stressed that environmental factors, in particular soil moisture, will be an important parameter determining whether surviving weeds will continue to grow during the summer.
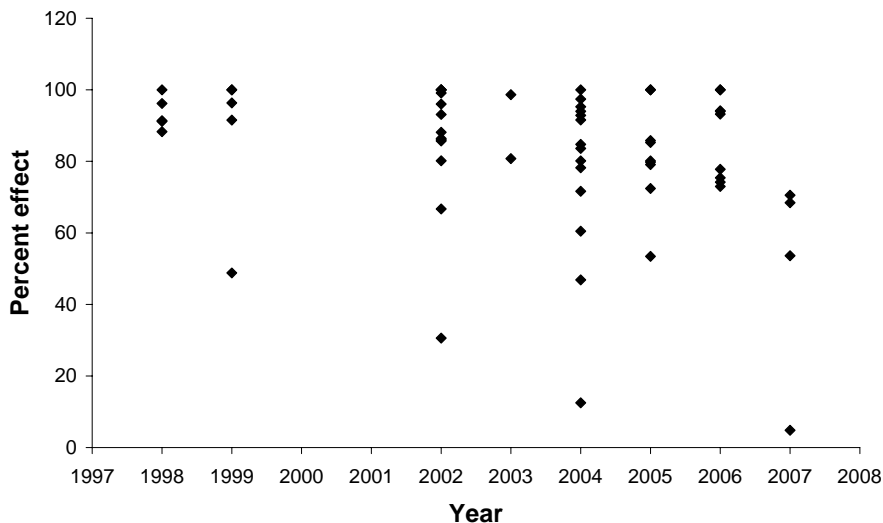
Figure 7.7 Effect of reduced herbicide doses on *Apera spica-venti* in winter wheat herbicide trials carried out by the Danish Agricultural Advisory Service from 1998 to 2007. Efficacy was assessed in April.

When plotting weed density at spraying versus weed coverage at harvest a positive correlation was found for control plots, whereas no correlation was seen for plots treated with the recommended dose. For plots treated with reduced herbicide doses a weak correlation was observed, supporting the conclusion that the effect of reduced doses in some experiments was insufficient to prevent residual weeds at harvest.

Conclusion: In recent years a decreasing effect of reduced herbicide dosages was observed, but no clear evidence was found supporting the hypothesis that grass weed coverage at harvest has increased during the last 10 years.

7.5 Conclusions

The analysis of the DAAS data set and previous research supported our first hypothesis, that early sowing leads to increasing problems with grass weeds. We could, however, not confirm that *Apera spica-venti* densities have increased in recent years, but our analysis confirmed that *Apera spica-venti* is a very competitive weed species and an increase in density could lead to higher yield losses if not controlled satisfactorily. Similarly, we could not confirm that *Apera spica-venti* coverage at harvest has increased in recent years, but we did find indications that the effect of reduced doses has diminished within the last years, suggesting that residual weeds at harvest and the associated seed production could become a problem in the future.

In conclusion, although grass weeds cause significant yield losses, our analyses of the DAAS dataset do not suggest that the observed stagnation in winter wheat yields can be attributed to increasing problems with grass weeds.

7.6 References

Amann A, Zwerger P. & Hurle K. (1992) Einfluss von Saattermin und Grundboden bearbeitung auf die Populationsdynamik von *Alopecurus myosuroides* Huds. in verschiedenen Kulturen. Zeitschrift für Pflanzenkrankheiten und Pflanzenschutz, Sonderheft XIII, 269-276.

Andreasen, C., Stryhn H. & Streibig J.C. (1996) Decline of the flora in Danish arable fields. Journal of Applied Biology 33, 619-626.

Andreasen, C. & Stryhn H. (2008) Increasing weed flora in Danish arable fields and its importance for biodiversity. Weed Research 48, 1-9.

Christensen, S. (1993) Herbicide dose adjustment and crop weed competition. Brighton Crop Protection Conference-Weeds, 1217-1222.

Christensen, S., Rasmussen, G., Olesen, J.E. & Jørgensen L.N. (1996) Weed management for integrated wheat production. Proceedings Second International Weed Control Congress, Copenhagen, Denmark, 1003-1008.

Jensen, J.E. & Petersen, P.H. (2006) Økonomi ved efterårsbehandling af ukrudt i vintersæd. Præsentation ved Efterårsmøde 2006 i Middelfart.

Olsen, C.C., Jørgensen, L.N., Rasmussen, G. & Pedersen, J.B. (1997) Integreret vinterhvede-dyrkning-såtider og udsædsmængder. Danmarks JordbrugsForskning, Grøn Viden Markbrug nr. 184.

Melander, B. (1995) Impact on drilling date on *Apera spica-venti* L. and *Alopecurus myosuroides* Huds. in winter wheat. Weed Research 35, 157-166.

Moss, S.R. (1985) The effect of drilling date, pre-drilling cultivations and herbicides on *Alopecurus myosuroides* (blackgrass) populations in winter wheat. Aspect of Applied Biology 9, 31-39.

8 Soil tillage effects on the development of winter wheat yields in Denmark

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8.1 Introduction

Soil tillage is a key operation in arable farming and fulfils several purposes, which may be integrated in three main characteristics:

- Crop residues and applied organic manures are incorporated into the soil, enhancing decomposition of organic matter and removing pest sources from the very surface
- Traffic-induced hardpans in the top soil layers are loosened, which facilitates root growth, water infiltration and soil aeration
- Weeds are suppressed

Tillage for establishing a new crop is most often a two-step procedure with a <u>primary</u> tillage operation for obtaining the benefits described above, and a <u>secondary</u> tillage operation for creating a seedbed optimizing seed germination and early plant growth. The primary tillage operation in Denmark has traditionally included moldboard ploughing to a depth of 20-25 cm (Rasmussen, 1999). However, recent experience has shown that plough-less tillage (often labelled reduced tillage) is possible prior to many crops (Olesen et al., 2002). A major driver towards reduced tillage systems is the reduction in costs and the ability to till a larger area with the same man-power. The same holds for the trend towards power-take-off (pto) harrows that are very efficient in creating a seedbed nearly irrespective of the soil water content.

This chapter reviews the knowledge of tillage effects on winter wheat yield for Danish soil and climatic conditions. An initial text section highlights some key soil characteristics that should be kept in mind when addressing soil tillage from a soil functional perspective and not an efficiency approach. Next, one section deals with ploughless tillage, while a final section addresses tillage for seedbed preparation.

8.2 Soil structure, self-organization, soil organic matter and principles in tillage

Soil mineral particles interact with organic matter and hence reorganize the material. Self-organization is a process where the organization of a system spontaneously increases, <u>i.e.</u> without this increase being controlled by the environment or an encompassing or otherwise external system (Heylighen, 2001). Young and Crawford (2004) suggested that the soil-microbe system should be regarded as self-organized. This means that the interaction between the mineral and organic particles increases organization. When a self-organized system is disturbed, its resistance to change from the equilibrium state as well as its resilience to return to this equilibrium state is challenged (Holling, 1973). These classical concepts from ecosystem research extend our framework for interpretation of soil behaviour and help identify thresh-

olds of soil disturbance that may be critical to a continued soil function. The concept of self-organization also emphasizes that tillage is far from being the sole process creating soil structure. Tillage should rather be regarded as a way of fractionating a soil along the planes of weakness, which is created as part of the self-organization of soil particles.

Recent research has indicated that critically low levels of organic matter for sustaining soil self-organization (soil structure) have been reached for some Danish soils (Munkholm et al., 2001; Schjønning et al., 2002a; Elmholt et al., 2008). Attempts have been made to identify a 'universal' lower critical threshold of organic matter for sustaining self-organization and hence healthy soils (Loveland and Webb, 2003). However, climate and soil type are key regulators and hence preclude a fixed target value of soil organic matter (SOM) across soils and regions. For Danish conditions, several soils have soil organic C contents as low as 1.0-1.3 g C $100g^{-1}$ soil corresponding to 1.7-2.2 % SOM (e.g. Schjønning et al., 1994, 2002a, 2007). Results from the long-term fertilization experiment at Askov Experimental Station indicate that for that particular soil type (~11 % clay, ~11% 2-20 μm silt, and ~74 % >20 μm sand; Danish classification: JB5) satisfactory tilth conditions were found for the animal manure treated plots at SOM contents as low as ~2.2 %, while tilth problems were recorded for the unfertilized plots with a SOM content of ~1.8 % (Schjønning et al., 1994; Munkholm et al. 2002). Results from Sjælland on loamy soils (clay contents >15 %; Danish classification: JB7) have, in contrast, revealed severe tilth problems for soils with SOM contents as high as 2.4 % (Munkholm et al., 2001; Schjønning et al., 2002a; Elmholt et al., 2008). Recent research indicates that the ratio between soil organic C and soil clay may serve as an indicator of soil 'saturation' with organic matter across soil types (Dexter et al., 2008). More studies are, however, needed to verify the suggested concept.

Heidmann et al. (2001ab) used data from the nation-wide Danish grid for monitoring soil quality attributes to evaluate the trends in SOM. Based on 336 grid intersection points (soils), they concluded that the number of years with ley, the frequency of manure application, and the level of fertilizer application correlated negatively with observed reductions in SOM. This relatively short-term study (10-12 years of monitoring) is in accordance with other Scandinavian studies on trends in SOM contents (Riley and Bakkegaard, 2006, and references therein). Based on the above, it is obvious that long-term continued growing of small grain cereal crops like winter wheat with application of only mineral fertilizers and perhaps with removal of the straw is a strong driver towards low SOM contents. The consequences may turn out to be extremely low SOM contents and critical tilth conditions as quantified for the experimental field used for studies in organic crop rotations at Flakkebjerg Experimental Station (Djurhuus and Olesen, 2000; Schjønning et al., 2007) and as also observed in modern arable cropping (Leif Knudsen, personal information).

Figure 8.1 shows selected results of Danish studies of soil friability, which is an expression of ease of fragmentation. A high friability is desirable for the creation of a suitable seedbed. One study quantified soil friability following more than a century of contrasting fertilization

(Munkholm et al., 2002). There is a clear trend of increase in friability with increase in soil organic C as induced by the different fertilization (Figure 8.1). Dexter (2004) showed that a value of 0.25 for the index displayed in Figure 8.1 may be regarded as a lower limit for soil friability across soil types (consult the reference for details). This threshold corresponds approximately to the level of friability found for the mineral-fertilized plot (NPK) in the Askov experiment (Figure 8.1), which is in accordance with agronomic observations: the UNF treatment is problematic to till, while the NPK and especially the AM plots are friable, yielding no problems in seedbed preparation. The two additional observations in Figure 8.1 were measured at two soils at Sjælland grown continually with small grain cereals for decades (Munkholm et al., 2001; Schjønning et al., 2007). It appears that *i*) both soils had friabilities well below the critical threshold, and *ii*) there seems to be no soil type independent relation between soil organic C and its friability. The Sjælland JB7 soils would need higher levels of organic C to arrive at sustainable conditions for friability than the JB5 soil at Askov.
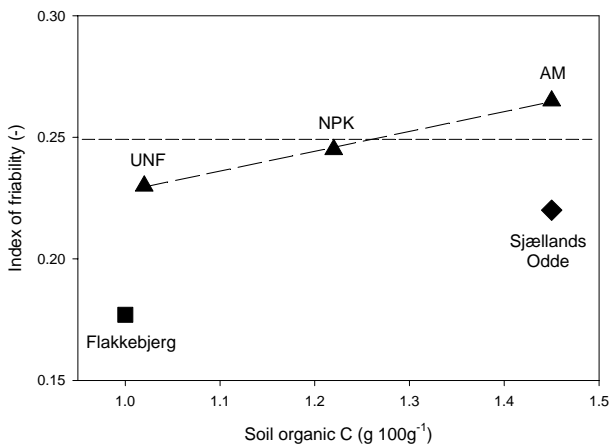
Figure 8.1. Index of friability calculated from tensile strength of dry aggregates as related to the soil content of organic C. A high friability is desirable for creation of a suitable seedbed. The data displayed as triangles shows the conditions measured after ~100 years of repeated contrasting fertilization in the Askov long-term experiment (UNF=unfertilized, NPK=mineral fertilizers, AM= animal manure; Munkholm et al., 2002). The square and diamond show the condition measured in two loamy soils (clay content ~18%) grown with continuous small grain cereals for decades (Sjællands Odde: Munkholm et al., 2001; Flakkebjerg: Schjønning et al., 2007).

Soils low in organic matter are undesirably weak in wet conditions and too mechanically strong in dry conditions (e.g. Munkholm et al., 2001, 2002). One consequence is a narrowing of the water contents at which the soil is friable (Schjønning et al., 1994; Munkholm et al., 2002). This means that the soil is suitable for tillage in a shorter period in the spring. It also implies that more energy is needed to crumble the soil to fragments required for the seedbed. Finally, the weak structure in wet conditions increases the risk of dispersion of clay (colloids)

that may carry e.g. phosphorus and pesticides to the deeper soil layers by by-pass flow. Dispersed clay may also cause cementation of the soil surface, which on clay-holding soils may be detrimental to crop emergence and soil aeration.

The implications of the above for crop growth and yield are multiple. The interaction between SOM and mineral particles and the 'history' of the soil in terms of former tillage operations at non-optimal water conditions etc, form the precondition for the tillage operation. Tillage should be regarded as the tool to fragment the soil along plains of weakness in the soil matrix. Optimal tillage should not influence the inner part of the soil fragments, only the degree of fragmentation. Crop growth and hence yield may be influenced in several ways. One is the quality of the seedbed, where a non-optimal soil structure may cause difficulties in arriving at the correct size distribution of aggregates for best germination of the seeds. Another is soil aeration. Harrowing with rotary cultivators at non-optimal water contents may induce kneading of soil aggregates, which later may turn out to have reduced the aeration potential of the inner of aggregates. This in turn may affect nutrient dynamics- e.g. loss of nitrogen in the form of N_2O rather than diffusion of NO_3 to the roots.

8.3 Primary tillage

Due to the structure in modern agriculture, the number of farms has decreased from 148000 in 1970 to 47000 in 2006. The number of farms with more than 100 ha has increased from 1611 in 1970 to 8255 in 2006 (Danmarks Statistik, 2006). The large area at each farm creates a demand for a high efficiency in field operations. Conventional moldboard ploughing is still used for the major part of the arable land in Denmark (Rasmussen, 1999; Olesen et al., 2002). Moldboard ploughing is a time-consuming operation, which implies a long period for preparing all fields. This in turn increases the risk of bad conditions for the tillage operation. The declining prices of cereals during the 1990s and early 2000s gave additional motivation to phase out the moldboard plough: reduced tillage (non-inverting tillage systems) has a high capacity, which may reduce the time needed for preparing a large area.

8.3.1 Conventional moldboard ploughing

The plough is used on approximately 90% of the arable land as basic equipment for soil tillage (Oversigt over Landsforsøgene, 2007). One of the reasons for the popularity of the plough is that it is less dependent on the weather than other systems. During the last 50 years a lot of research was done in different countries to identify the optimal ploughing depth (e.g. Børresen & Njøs, 1990; Maillard & Vez, 1992; Rasmussen et al., 1996, 1998; Høy, 2000; Schjønning et al., 2002b). Generally, the results of all these trials showed no significant difference in the yield as long as the weeds were kept under control. The Danish tests showed that several ploughs were not able to use skimmers because the legs of the skimmers were too short to reach the ground. It was necessary to plough at least 15 cm to ensure that the plant residues were buried (Høy, 2001). Deep ploughing has during all years shown to be a reliable

method to ensure good conditions for the following crops, but in certain conditions – for example heavy clay soils – it is important that the ploughing is done at the right time. Ploughing heavy clay soil in the spring before drilling a spring crop can be a disaster because quick drying may decrease the friability of clods to a level making it very problematic to create a seedbed by subsequent tillage.

8.3.2 Reduced tillage – non-inverting systems

Since 1970 it has become increasingly popular to save the time it takes to plough the fields. Approximately 10% of the Danish arable land is estimated to be grown without moldboard ploughing (Oversigt over Landsforsøgene, 2007). A dense pan created in the topsoil layers during a period with shallow tillage may be removed by chiseling to the appropriate depth. The advantage is a large capacity and the disadvantage is high fuel consumption compared to other methods.

The most common form of reduced tillage is the use of a shallow stubble cultivator with wing shares. The working depth at the first pass is 5 – 8 cm and is done just after harvest and the second cultivation is 8 – 12 cm close to drilling. Drilling can be done with a drill with disc coulters or with rigid tines.

Direct drilling and shallow tillage (0-5 cm) is rarely used in Denmark due to problems concerning residue management, infestation of grassy weeds and excessive compaction of the topsoil layer (Rasmussen, 1999; Olesen et al., 2002). Many studies have shown that the texturally graded Danish soils derived from morainic deposits are very prone to topsoil compaction. This is in accordance with other studies on similar soils (Ehlers & Claupain, 1994). The degree of compaction depends to some extent on the implement used for direct drilling. Disk direct drills produce in general denser soil below seeding depth than chisel direct drills. Munkholm et al. (2003) compared a single disk drill with a chisel direct drill and found a high frequency of critically high penetration resistances below seeding depth for especially the disk drilled treatment (Table 8.1). Dexter (1986) showed that the proportion of roots penetrating a compacted soil layer is decreasing with increasing soil strength and halved (compared with optimal conditions) when meeting strengths of 1.2 – 2.2 MPa, depending on the 'anchorage' of the root before penetrating the hard soil layer. This has led to the 'rule-of-thumb' of 1.5 MPa as a critical high level of mechanical strength for root growth.

A screening across 10 Danish soils and one Swedish soil with continued shallow tillage showed the same problem for nearly all soils, as exemplified for four soils in Figure 8.2 (Schjønning & Thomsen, 2006). Especially the soil at Bramstrup displayed high stresses for shallow tilled soil. This may be due to a high content of coarse sand for this soil (JB5), reflecting a particularly distinct graduation in texture for that soil.

Table 8.1 Percent of median penetration resistance values exceeding the critical high level of 1.5 MPa averaged for four replicate soil cores per treatment. Based on micropenetration measurements recorded in soil columns within the 40 to c. 150 mm depth. Average water content at measurement: 13, 11 and 13 g 100 g^{-1} for PL, DD-D and DD-C, respectively, where PL is ploughed, DD-D is direct-drilled with a disk drill, and DD-C is direct-drilled with a chisel drill (Munkholm et al., 2003).

Tillage treatment	Percentage median penetration resistance >1.5 MPa	
	Mean	Standard error (n=4)
Ploughed (PL)	30a	13
Disc Direct-drilled (DD-D)	79c	8
Chisel Direct-drilled (DD-C)	64b	9
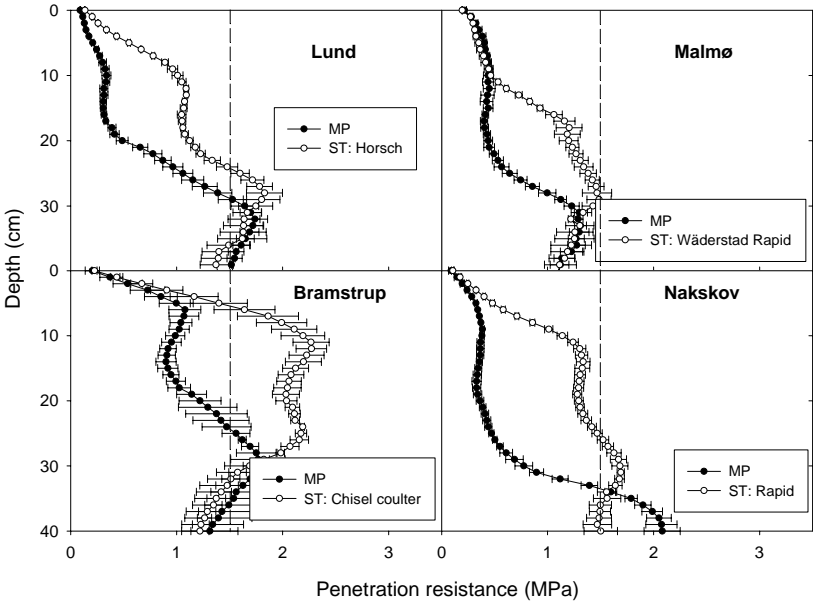
Figure 8.2 Cone penetration resistance for three Danish soils and one Swedish soil (Malmø) under moldboard ploughing (MP) and shallow tillage (ST). The ST working depth was 3-5, 10-15, 10-15 and 10 cm for the Lund, Bramstrup, Malmø and Nakskov sites, respectively. Measurements were carried out at field capacity in the spring. Bars indicate ±1 SE. All soils are morainic deposits with clay contents ranging from 9-18% (Schjønning & Thomsen, 2006).

The effect of reduced tillage is currently investigated in a crop rotation-tillage experiment (CENTS) conducted at Foulum (JB 4; 9% clay, 3.1 % organic matter) and Flakkebjerg (JB 6; 13% clay, 2,0% organic matter). The tillage treatments include Ploughing (P), Harrowing 8-10 cm (H$_{8-10}$) and direct drilling (D). The treatments have been applied to the same plots since 2002. A single disc drill was used in the H$_{8-10}$ and D treatments for the years 2003-2006. From 2007 and onwards a chisel drill has been used for the H$_{8-10}$ and D treatments. A traditional

seed drill has been used in the P treatments except in 2007 when a chisel drill was used. Five different crop rotations are compared.

Figure 8.3 shows that growth of winter wheat roots was delayed and reduced for the harrowed and especially the direct-drilled soil as compared to the ploughed treatment (Munkholm et al., 2008). This may be interpreted as an effect of excessive compaction of the topsoil layer, cf. Table 8.1.
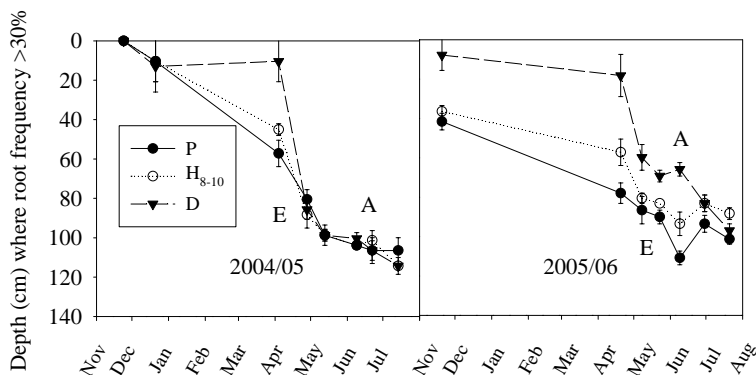
Figure 8.3 Root growth dynamics for winter wheat at Foulum during the 2004-05 and 2005-06 growing seasons. Depth (cm) to which root frequencies were >30%. E: Stem elongation, A: Anthesis. Bars indicate standard error of the mean (Munkholm et al., 2008).

The results from the 2003-2008 period of the CENTS trial show variable effect of reduced tillage on winter wheat yields. In some cases, the H_{8-10} resulted in substantial – although insignificant – yield losses (8-12 hkg ha^{-1}) in comparison with P for several of the tested crop rotations (data not shown). This was particularly prominent when winter wheat was grown after winter wheat. The yield losses could be explained by problems with grassy weeds and fungal diseases (e.g. tan spot). In 2007, D outyielded H_{8-10} and P at both locations. This was due to lower infestation of take-all (*Gaumanomyces graminis*) (relative to both H_{8-10} and P) and grassy weeds (relative to H_{8-10}) (Melander et al., 2008).

The results from the crop rotation with continuous winter wheat are shown in Table 8.2. The poor yields recorded for D in 2004 were related to poor crop establishment under dry conditions in the autumn 2003. Direct drilling resulted generally in poor crop establishment at Flakkebjerg when a disk drill was used under dry conditions. The change to a chisel drill in 2007 solved the problem. The chisel drill causes more soil loosening and results in better soil/seed contact under dry conditions.

In average, ploughing yielded best and gave the smallest variation in yield across the years (Table 8.2). The effect of reduced tillage was more variable for the other crop rotations. Gen-

erally, direct drilling seems to be the most jeopardizing system. A disk drill will work poorly in dry and poorly structured loamy soils and hence result in a poor establishment of the crop. Non-inversion tillage accelerates problems with grassy weeds and fungal diseases such as tan spot in rotations dominated by winter cereals. Shallow tillage often increases yields when take-all is a significant problem.

Table 8.2 Yield of winter wheat, hkg ha^{-1}, for three different tillage systems at the Flakkebjerg location (data from Munkholm et al. (2008) and unpublished results).

Tillage treatment	2003	2004	2005	2006	2007	2008	Mean	SD[1]
Moldboard plough	86.1	94.7	91.7	75.3	65.7	100.6	85.7	11.9
Harrowing 8-10 cm	85.5	92.5	82.8	65.8	68.6	99.3	82.4	13.1
Direct drilling	79.9	51.5	89.0	56.2	79.5	72.8	71.5	14.7
LSD	ns	19.3	ns	sign[2]	10	20.9	nd	-

[1]SD: standard deviation

[2]The tillage effect is significant but an LSD cannot be calculated due to a missing value

ns: not significant

nd: not determined

Results from nine years of continued experimentation on three loamy soils near Horsens indicate that non-inversion tillage is possible with no effect on crop yields if the non-ploughing system includes a harrowing operation to 5-7 cm depth and grass weeds are controlled by herbicides (Table 8.3). This is in accordance with previous experiments (Oversigten over Landsforsøgene, 1986; Høy, 2000).

Table 8.3 Yield results, hkg ha^{-1}, in plots with continuous ploughing or non-inversion shallow tillage on three loamy soils (clay content ranging from 9-15%). Reproduced from Oversigten over Landsforsøgene (2008).

Tillage treatment	2000 s.barley	2001 w.wheat	2002 s.barley	2003 w.wheat	2004 w.wheat	2005 s.barley	2006 w.barley	2007 w.rape	2008 w.wheat	Relative mean, w.wheat
Number of trials	1	3	3	3	3	3	3	2	3	12
Ploughed	68.1	88.4	52.1	72.4	80.9	68.8	72.1	43.0	92.6	100
Reduced tillage[1]	70.3	88.3	46.9	78.6	82.1	66.8	69.6	42.8	90.0	101
LSD	ns	ns	ns	ns	ns	ns	ns	ns	ns	nd

[1]Stubble tillage to 5-7 cm; drilled with a Horsch Flachgrubber followed with a Horsch Airseeder; sprayed with glyphosate after harvest since 2005

ns: not significant

nd: not determined

8.4 Secondary tillage

Before 1980 it was normal to cultivate the soil two times with a light cultivator. On heavy soil it could be necessary to cultivate the soil several times to create a good seedbed. After a day with dry weather the crop was sown. After sowing a spring crop the field was rolled to create a good contact between soil and seed. This method was very time-consuming and was in the 1980s changed to a method where different machines were combined. It was in this period the power harrow began to be used together with a drill. The power harrow is able to create a good seedbed in heavy soil but it can also crumble the soil to such fine particles that heavy rain after sowing can close the soil surface because of dispersion of fine particles. Lighter soil could be prepared with a cheaper combination of cultivator and drill. The cultivator was normally equipped with a scrubber board in front, 2-3 rows of tines and a press roller. The drill could be mounted directly on the cultivator or it could be coupled to a three point linkage on the cultivator. This type of machines became very popular. It made a good job in most conditions and it saved time. It made it possible to sow a crop in almost all situations. The problem compared to the traditional way of seedbed preparation is, that the new methods can work also in bad situations such as wet soil and bad weather.

During the 1990s the former Danish Institute of Plant and Soil Science (Statens Planteavlsforsøg) performed a huge project on winter wheat growing in Denmark (Olesen et al., 1992). In this context, a survey of tilth conditions and plant growth in Danish winter wheat fields was conducted (Schjønning & Thomsen, 1996; Schjønning et al., 1997). The investigation took place during two growing seasons (1993-94 and 1994-95) and included a total of 80 fields at private farms across Denmark. In short, the fields with winter wheat were selected in order to cover the range in Danish soil types although most fields were on morainic deposits from the Weichsel glaciations. All fields selected for study were moldboard ploughed before sowing. The post-ploughing tillage procedures were categorized into three groups:

T^+ The soil was allowed to rest for a few days following ploughing in order to let the upper soil layer dry a little. An S-tined harrow was then used to prepare the seedbed and the seeds sown by a traditional drill.

R^+ The soil was also here allowed to rest for a few days after ploughing. Then a rotary harrow was used to prepare the seedbed and the seeds sown by a traditional drill.

R^- This system consisted of a ploughing operation immediately followed by a combined rotary harrow/drill machine, which means that the topsoil was not allowed to dry.

The measurement programme included a total of five 'visits' at each field. Visit 1 was immediately after sowing and visit 2 at emergence (all plants emerged) a few weeks later. Visit 3 was before start of growth in early spring, while visit 4 was at the beginning of stem elongation. Finally, the fields were visited just after heading (visit 5). Penetration resistance as measured according to the ASAE recommendation (NN, 1978) was determined to a depth of 40 cm at visit 1. A mobile, automated penetrometer (Olsen, 1988) was used for taking a total of 15 replicate measurements across the field. Aggregate (particle) size distribution of the seedbed was determined at visit 1 by means of a nest of sieves shaken by hand to fractionate a

sample of soil collected from the layer above sowing depth. Four replicate measurements were carried out for each field. Wet aggregate stability was determined by a Yoder-like technique (Hartge, 1971) in the laboratory using samples of the seedbed aggregates sampled at visit 1 and air-dried until analysis. Surface roughness was estimated at visit 1 and 3 by means of determining the end-to-end direct distance of a 2 meter long flexible string following the surface elevations of the seedbed.

The direction of the measuring line compared to the tillage and sowing directions was random. Markers were put into the soil at visit 1 in order to allow exactly the same lines to be measured at the spring visit. Six replicate measurements were carried out at each field. At visits 2 and 3, crust penetration resistance was measured by pressing a specially constructed circular plate (area: 2.835 cm^2) into the soil, recording the force needed to break the surface crust (a 'pocket penetrometer'). Sixteen replicate measurements were taken. Sowing depth was measured at visit 2 by digging up a total of 12 plants and measuring the distance from the seed to the above-ground part of the stem (change in colour). Plant density was estimated by counting the number of plants in a quarter square meter bordered by a metal frame randomly located in the field. Six replicate measurements were taken at visit 2 and again in the spring at visit 3. Also here, markers placed in the soil allowed the counting of exactly the same plants at the latter visit as in the autumn. The light reflectance from the crop (Christensen & Goudriaan, 1993) was measured at visits 3, 4 and 5 (n=30).

The results from the survey are shown in Table 8.4 and may be summarized as follows:
- Rotary harrowing of soil immediately after mouldboard ploughing tended to produce a higher number of large clods than was the case when the same implement was used following a period of weathering of the soil or when a tine cultivator was used.
- There was a clear and significant decrease in wet stability of the seedbed aggregates after use of a rotary harrow compared to the application of a tine cultivator. Weathering of the soil prior to the use of the rotary harrow did not affect the stability.
- Rotary harrowed soil tended to form surface crusts following rain.
- Seedbeds prepared by a tine cultivator resulted in shallower sowing depths than soil treated with rotary harrows.
- No significant effects of the soil characteristics on the germination and growth of the winter wheat crop could be detected.

The comprehensive survey thus clearly showed that pto-powered harrows reduce the stability of soil structural units, which increases the risk of creating a surface crust as a potential direct constraint for the germinating plants. The reduced structural stability may also imply changes in the exchange of gases to the interior of aggregates. As mentioned previously in this report, this may in turn influence SOM turnover and nutrient dynamics. However, the results did not give a clear picture regarding the effects on crop growth.

Table 8.4 Soil and crop characteristics as influenced by different secondary soil tillage strategies following mouldboard ploughing. Number of observations for the T[+], R[+] and R[-] treatments were 13, 19 and 12, respectively, for the 1993/94 season and 11, 7 and 18, respectively, for the 1994/95 season. Figures followed by the same letter are not significantly different (t-tests, within one season) (Schjønning et al., 1997).

	Calibrated for[2]	1993/94 Tillage strategy[1]			1994/95 Tillage strategy[1]		
Soil characteristics		T[+]	R[+]	R[-]	T[+]	R[+]	R[-]
Seedbed aggregates							
aggregates > 6 mm, %	C	47[a]	48[a]	56[b]	52[a]	46[a]	50[a]
WAD[3], mm	C	4.1[a]	5.1[a]	5.4[a]	5.5[a]	4.4[a]	5.1[a]
wet stability[4], %	C	79.2[a]	73.0[a]	73.9[ab]	78.9[a]	66.9[b]	68.5[b]
Surface roughness index, R[5]							
autumn value	C	0.17[ab]	0.15[a]	0.20[b]	0.18[a]	0.15[ab]	0.14[b]
loss during winter	C	0.12[ab]	0.10[a]	0.14[b]	0.11[a]	0.08[bc]	0.07[c]
Top layer soil strength							
autumn > 50 kPa, %[6]	-	23	47	67	27	29	44
spring > 150 kPa, %[6]	-	46	79	83	27	29	33
Soil strength at 4 cm depth							
average ASAE CI, kPa	C&T	227[a]	203[a]	223[a]	433[a]	336[a]	393[a]
std. dev. ASAE CI, kPa	C	104[a]	102[a]	148[a]	232[a]	197[a]	199[a]
Crop characteristic							
Depth of sowing, mm	C	31[a]	36[b]	37[b]	33[a]	38[ab]	38[b]
Plant density, m[-2]							
autumn	C&T	355[a]	338[a]	348[a]	370[a]	374[a]	336[a]
loss during winter	C&T	9.1[a]	6.3[a]	7.7[a]	6.7[a]	6.5[a]	6.9[a]
Relative Vegetation Index							
Averages							
- early spring	C&T	1.9[a]	1.9[a]	2.0[a]	2.9[a]	3.1[a]	3.1[a]
- stem elongation stage	C&T	8.0[a]	7.2[a]	8.7[a]	9.2[a]	8.8[a]	11.4[a]
- heading stage	C&T	20.1[ab]	17.5[a]	22.3[b]	20.9[a]	20.9[a]	20.1[a]
Coeff. of variation, %[7]							
- early spring	C&T	1.2[a]	0.7[a]	0.8[a]	2.9[a]	1.3[a]	2.7[a]
- stem elongation stage	C&T	35.9[a]	17.0[b]	19.3[ab]	11.9[ab]	5.1[a]	16.4[b]
- heading stage	C&T	7.5[a]	21.1[b]	12.8[ab]	2.5[ab]	1.5[a]	3.9[b]

[1]Tillage strategies: see text for explanation.
[2]Calibrated to identical values of clay content (C) and/or sowing time (T).
[3]Weighted Average Diameter, WAD = $3(n_i*d_i)$, where n_i denotes the fraction of particles with the mean diameter d_i
[4]Aggregates 2-8 mm not dispersing to diameters below 1 mm during wet sieving.
[5]R = 1/L - 1, where L is the quotient of the measured end to end distance and the real length of a flexible string used in the field.
[6]Frequency of pocket penetrometer strength values exceeding specific values, see text for details.
[7]Coefficient of variation of RVI measurements taken across each field.

The effect of pto-powered harrows on soil characteristics and crop growth was also studied in a field experiment on a sandy loam soil (JB6) in 1994-95 (Thomsen & Schjønning, 1996). In short, secondary tillage by a rotary harrow was performed immediately after or four days after ploughing for winter wheat. For each of these main treatments, three different intensities of energy application were included in terms of the rotor periphery speed. The measurements in this experiment were the same as summarised for the survey above. The main effect on soil of different tillage strategies was a more cloddy seedbed when tilling directly after ploughing compared to tillage carried out after a few days of weathering of the soil surface. Also the speed of the rotary tiller affected the soil, high speeds leading to finer seedbeds and lower wet stability of seedbed aggregates. High rotor speeds furthermore gave rise to increased sowing depth. The crop response to the treatments investigated was a tendency of a lower amount of plants emerged in soil tilled after weathering compared to soil tilled immediately after ploughing. Furthermore, a higher loss of plants during winter was observed for the soil treated after weathering. The Relative Vegetation Index derived from the spectral reflectance measurements also pointed to the soil tilled immediately after ploughing providing the best conditions for plant growth. The field trial thus confirmed the survey at private farms that intensive tillage by rotary harrows can decrease the stability of soil aggregates. On the other hand, the trial did not confirm the findings of the other investigation that tillage just after ploughing will yield a denser and a crusting topsoil.

A range of field experiments has investigated the net effect on crop yield of secondary tillage in establishing a winter wheat crop. Rasmussen (1995) summarized the experiments carried out by the former Danish Institute of Plant and Soil Science in the period ~1985-1994. A total of twelve trial years in winter wheat at three locations (two morainic soils [JB6-7] and one marine deposit soil [JB7]) showed no significant differences in crop yields after the use of rotary harrows compared with tine harrows. The result was confirmed in four trial years for winter barley.

8.5 Summary and conclusions

The main trend in tillage for winter wheat growing the past 3-4 decades has been the introduction and increased use of pto-powered harrows for secondary tillage. A comprehensive survey of soil characteristics in Danish winter wheat fields showed that the use of rotary harrows significantly affects soil structure. The stability of soil aggregates is weakened which increases the risk of clay dispersion and slaking at the soil surface. An increased mobilization of clay colloids may also have significant influence on the potential translocation of clay particles to lower horizons and the aquatic environment. However, this environmental aspect is beyond the scope of this report. The net effect on crop yield of the increased energy application to soil through the rotary harrow seems to be negligible. This is the conclusion from the above-mentioned survey as well as from a range of field experiments.

Non-inversion tillage systems have been introduced and are covering an increasing area especially for the last decade. Field experiments have shown that the yield of winter wheat is not significantly affected by the lack of ploughing when wheat follows a "healthy" crop in the rotation (e.g. pea or winter rape). The most common practice in reduced tillage is some kind of stubble harrowing to 5-15 cm depth prior to sowing of the seeds. This seems to loosen the soil enough to reduce the negative impact of the densification of morainic soils when they are not ploughed. If grass weeds are controlled by herbicides, the yield of winter wheat is about the same as for ploughed soil. The area with no-ploughing tillage is less than 10%. It is therefore concluded that the net effect of tillage on the yield of winter wheat yields in Denmark during the last 3-4 decades only to a small extent has been affected by tillage system.

8.6 References

Børresen, T. & Njøs, A. (1990) The effect on soil properties and crop yield of ploughing depth and seedbed preparation from 1940 to 1990 on loam soil in south-eastern Norway. Proceedings of the 13th International Conference of the International Soil Tillage Research Organization, July 24-29, Aalborg, Denmark, pp. 717-722.

Christensen, S. & Goudriaan, J. (1993) Deriving light interception and biomass from spectral reflectance ratio. Remote Sensing of Environment 43, 87-95.

Danmarks Statistik, 2006.

Dexter, A.R. (1986) Model experiments on the behaviour of roots at the interface between a tilled seed-bed and a compacted sub-soil. I. Effects of seed-bed aggregate size and sub-soil strength on wheat roots. Plant Soil 95, 123-133.

Dexter, A.R. (2004) Soil physical quality Part II. Friability, tillage, tilth and hard-setting. Geoderma 120, 215-225.

Dexter, A.R., Richard, G., Arrouays, D., Czyz, E.A., Jolivet, C. & Duval, O. (2008) Complexed organic matter controls soil physical properties. Geoderma 144, 620-627.

Djurhuus, J. & Olesen, J.E. (2000) Characterization of four sites in Denmark for long-term experiments on crop rotations for organic farming. DIAS Report, Plant Production, No. 33, Danish Institute of Agricultural Sciences, Tjele, Denmark, 74 pp.

Ehlers, W. & Claupein, W. (1994) Approaches toward conservation tillage in Germany. In: Carter, M.R. (Ed.) Conservation Tillage in Temperate Agroecosystems. Lewis Publishers, pp. 141-165.

Elmholt, S., Schjønning, P., Munkholm, L.J. & Debosz, K. (2008) Soil management effects on aggregate stability and biological binding. Geoderma 144, 455-467.

Hartge, K.H. (1971) Die physikalische Untersuchung von Böden. Eine Labor- und Praktikumanweisung. F. Enke Verlag, Stuttgart, 168pp.

Heidmann, T., Nielsen, J., Olesen, S.E., Christensen, B.T. & Østergaard, H.S.(2001a) Ændringer i indhold af kulstof of kvælstof i dyrket jord: Resultater fra Kvadratnettet 1987-1998 (in Danish). DIAS Report 54-Markbrug. Danish Institute of Agricultural Sciences, Tjele, Denmark, 73pp.

Heidmann, T., Østergaard, H.S., Olesen, S.E. & Christensen, B.T. (2001b) Changes in soil content of C and N between different cropping systems and soil types. In: Proceedings of the 11th Nitrogen Workshop, 9-12th September. National Institute for Agricultural Research, Reims, France, pp. 301-302.

Heylighen, F.(2001) The Science of self-organization and adaptivity. In: L.D. Kiel, (ed.) Knowledge Management, Organizational Intelligence and Learning, and Complexity, in: *The Encyclopedia of Life Support Systems* ((EOLSS), (Eolss Publishers, Oxford).

Holling, C.S. (1973) Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4, 1-23.

Høy, J.J. (2000) Behovsbestemt jordbearbejdning, Forsøg 1997-1999. Rapport fra Landbrugets Rådgivningscenter, Skejby, Danmark.

Høy, J.J. (2001) Pløjefri dyrkning med nye typer tandsåmaskiner. Farmtest – Planteavl nr. 1. Rapport fra Landbrugets Rådgivningscenter, Skejby, Danmark.

Loveland, P. & Webb, J. (2003) Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. Soil & Tillage Research 70, 1-18.

Maillard, A. & Vez, A. (1992) Long term effects of ploughless tillage on soil chemical properties and crop yields. Proceedings of the 13th International Conference of the International Soil Tillage Research Organization, July 24-29, Aalborg, Denmark, pp. 723-728.

Melander, B., Holst, N., Jensen, P.K., Hansen, E.M. & Olesen, J.E. (2008) Apera spica-venti population dynamics and impact on crop yield as affected by tillage, crop rotation, location and herbicide programmes. Weed Research 48**,** 48-57.

Munkholm, L.J., Hansen, E.M. & Olesen, J.E. (2008) The effect of tillage intensity on soil structure and winter wheat root/shoot growth. Soil Use and Management 24, 392-400.

Munkholm, L.J., Schjønning, P., Debosz, K., Jensen, H.E. & Christensen, B.T. (2002) Aggregate strength and mechanical behaviour of a sandy loam under long-term fertilization treatments. European Journal of Soil Science 53, 129-137.

Munkholm, L.J., Schjønning, P. & Petersen, C.T.(2001) Soil mechanical behaviour of sandy loams in a temperate climate: case-studies on long-term effects of fertilization and crop rotation. Soil Use and Management 17, 269-277.

Munkholm, L.J., Schjønning, P., Rasmussen, K.J. & Tanderup, K. (2003) Spatial and temporal effects of direct drilling on soil structure in the seedling environment. Soil & Tillage Research 71**,** 163-173.

NN (1978) ASAE Agricultural Yearbook, 296-297.

Olesen, J.E., Olsen, C.C., Petersen, J., Rasmussen, K.J., Secher, B.J.M., Jørgensen, L.N., Kryger, P., Vester, J. & Ersbøll, A. (1992) Udvikling af et dyrkningsprogram for vinterhvede: Grundlag for forskning og modeludvikling. Tidsskrift Planteavl, Beretning S2204.

Olesen, J.E., Schjønning, P., Hansen, E.M., Melander, B., Felding, G., Sandal, E., Fomsgaard, I., Heckrath, G., Axelsen, J.A., Nielsen, V., Jacobsen, O.H., Petersen, S.O., Christensen, B.T., Jørgensen, L.N., Hansen, L.M. & Jørgensen, M.H. (2002) Miljøeffekter af pløjefri dyrkning. DJF-rapport 65, Markbrug, 106 pp.

Olsen, H.J. (1988) Electronic penetrometer for field tests. J. Terramech. 25, 287-293.

Oversigt over Landsforsøgene (1986) Dansk Landbrugsrådgivning, Skejby, Denmark.

Oversigt over Landsforsøgene (2007) Dansk Landbrugsrådgivning, Skejby, Denmark.

Oversigt over Landsforsøgene (2008) Dansk Landbrugsrådgivning, Skejby, Denmark.

Rasmussen, K.J. (1995) Jordbearbejdnings- og såmetoder til vintersæd. Grøn Viden Landbrug-150. Danish Institute of Plant and Soil Sciences, Tjele, Denmark, 6pp.

Rasmussen, K.J. (1999) Impact of ploughless soil tillage on yield and soil quality: A Scandinavian review. Soil & Tillage Research 53, 3-14.

Rasmussen, K.J., Hansen, E.M. & Schjønning, P. (1996) Grønne marker og pløjedybde i et integreret sædskifte med vårsæd på sandjord. Grøn Viden Landbrug-172.

Rasmussen, K.J., Hansen, E.M. & Schjønning, P. (1998) Halm, gylle og pløjedybde til vintersæd på lerjord. Grøn Viden Markbrug-189.

Riley, H. & Bakkegard, M. (2006) Declines in soil organic matter content under arable cropping in southeast Norway. Acta Agr. Scand. B – S. P. 56, 217-223.

Schjønning, P. & Thomsen, H. (1996) Seedbed quality and growth of winter wheat as influenced by soil type, farming system and tillage. Part 1. An investigation of a selection of agricultural fields. Danish Institute of Plant and Soil Science, Department of Soil Science, Winter Wheat Project, Internal report, 27pp.

Schjønning, P. & Thomsen, I.K. (2006) Screening of reduced tillage effects on soil properties for a range of Danish soils. NJF-seminar 378: Tillage systems for the benefit of agriculture and the environment, Odense, maj 2006. Extended abstracts, CD, 227-232.

Schjønning, P., Christensen, B.T. & Carstensen, B. (1994) Physical and chemical properties of a sandy loam receiving animal manure, mineral fertilizer or no fertilizer for 90 years. European Journal of Soil Science 45, 257-268.

Schjønning, P., Thomsen, H. & Olesen, J.E. (1997) Effects of secondary tillage strategy on soil and crop characteristics. Proceedings of the 14th Conference of the International Soil Tillage Research Organization. Fragmenta Agronomica, 2B/97, 579-582.

Schjønning, P., Elmholt, S., Munkholm, L.J. & Debosz, K. (2002a) Soil quality aspects of humid sandy loams as influenced by organic and conventional long-term management. Agriculture, Ecosystems & Environment 88, 195-214.

Schjønning, P., Rasmussen, K.J., Munkholm, L.J. & Nielsen, P.S. (2002b) Jordbearbejdning i økologisk jordbrug - pløjedybde og ikke-vendende jordløsning. DJF rapport - Markbrug, 82, 45 pp.

Schjønning, P., Munkholm, L.J., Elmholt, S.E. & Olesen, J.E. (2007) Organic matter and soil tilth in arable farming: Management makes a difference within 5-6 years. Agriculture, Ecosystems and Environment 122, 157-172.

Thomsen, H. & Schjønning, P. (1996) Seedbed quality and growth of winter wheat as influenced by soil type, farming system and tillage. Part 2. Field trial 1994/95 at Ødum Experimental Station. Danish Institute of Plant and Soil Science, Department of Soil Science, Winter Wheat Project, Internal report, 9pp.

Young, I.M. & Crawford, J.W. (2004) Soils – The final frontier. Review paper: Interactions and self-organization in the soil-microbe complex. Science 304, 1634-1637.

9 Soil compaction effects on the development of winter wheat yields in Denmark

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9.1 Introduction

Soil resources are under increasing pressure due to population growth and intensified agricultural use (Kutzbach, 2000). The total weight of tractor and trailer in slurry application may be as high as 50-55 tonnes (Green & Nielsen, 2006; Oversigt over Landsforsøgene, 2008). Although trailers may be equipped with three axles, the load on these may reach 13-15 tonnes; the load on the rear tractor axle will be even higher. No commercially available slurry trailers on the Danish market have axle loads below 10 tonnes (Green & Nielsen, 2006). Very high axle loads are also affecting soils in harvesting operations (cereals, potatoes, sugar beets, grass). Several investigations have shown that loads even smaller than those mentioned will induce high stresses in the subsoil, exceeding the strength of the soil and hence causing persistent compaction (e.g., Arvidsson et al., 2001).

Subsoil compaction is a stealthy evil because it is not readily visible and because it is cumulative (Horn et al., 1995). Comparisons of virgin soil never trafficked with arable fields have shown marked effects of traffic (Håkansson et al., 1996; Schjønning et al., 2000). Several investigations have shown that compaction of soil horizons deeper than approximately 40 cm is effectively permanent, and that mechanical amelioration is problematic (e.g. Håkansson & Reeder, 1994).

The Danish climate is characterised by wet conditions in the autumn, winter and spring. Soils are most susceptible to compaction in wet conditions. Most traffic situations in arable agriculture therefore imply a high risk of soil compaction. Arvidsson et al. (2000) showed that the risk/probability of subsoil compaction with commonly used machinery in southern Sweden is 100% for spring slurry application and higher than 60% after the 1st of October in sugar beet harvesting. The anthropogenic climate changes are expected to worsen the problem; the winter precipitation for Danish conditions has been estimated to increase 20-40% in a 100-year scenario (Olesen et al., 2006). The anticipated milder winters will also reduce the capability of especially clay soils to recover from soil degradation.

9.2 The soil profile

The farmer is most often thinking of soil in terms of areas rather than volumes. This is obviously because he/she has command of a specific area of land for growing crops. However, an

optimal agricultural use of soil should be based on an understanding of the basic processes taking place in the upper 1-2 meter. So, a one-hectare field should rather be labelled e.g. a 10,000 m^3 field, reflecting that a volume of that size is influencing a crop with a 1 meter rooting depth (e.g.: many grasses). Most crops go deeper; Vetter & Scharafat (1964) performed a comprehensive study of the rooting depth of agricultural crops and found for example a maximum rooting depth of 190, 200 and 250 cm for winter wheat, sugar beets and maize, respectively. Although some Danish soils will limit the root growth to much shallower depths (e.g. the coarse sandy JB1 soils), all soils include more than just the tilled surface layer.

Most Danish soils are derived from glacial deposits of the Weichsel (~12,000 years ago) or the Saale (~200,000 years ago) glaciations. Natural physical, chemical and biological processes have then later on developed the soil profile to the characteristics we find in natural habitats like virgin forests. One basic characteristic of developed soil profiles is the continuous network of pores, which is crucial for most soil functions and services: e.g., roots may proliferate the soil profile and hence utilize water and nutrients distributed in the soil; excess water may drain from the soil; and gases may move to and from the atmosphere. The latter is crucial for maintaining oxic conditions in the soil and hence for aeration of roots and soil microspots with potential production of greenhouse gases like N_2O. The filter function of soils is dependent on a high near-saturated hydraulic conductivity relative to that in the macropores larger than approximately 0.6 mm (Iversen et al., 2007). Water flow in the macropores (like earthworm channels) is not desirable because it will lead to by-pass flow in which water is quickly translocated from the soil surface to deeper soil layers. This in turn has the potential of transporting colloids and dissolved contaminants and nutrients to the groundwater and streams. Farming activities have been shown to influence these important aspects of the subsoil. On the positive side, Schjønning et al. (2005) found that long-term fertilization increased the near-saturated hydraulic conductivity and hence minimized the risk of water flow in macropores. On the negative side, it has been shown that traffic-induced subsoil compaction may increase the frequency of by-pass flow at high precipitations (e.g. Kulli et al., 2003). It is therefore essential that all agricultural practices are regarded not only in the context of the influence on the tilled soil layer but also with the subsoil in mind.

9.3 The compaction process

9.3.1 Stresses in the soil-wheel contact area
Surprisingly few detailed measurements exist addressing the stress acting in the soil-wheel contact area. One reason for this are the technical problems with measurements in the actual contact area as transducers have to be attached directly onto the rubber surface of the tyre. Such measurements exist but only with a poor resolution of the distribution across the contact area. Keller (2005) and Schjønning et al. (2006), in contrast, used an approach, where stress transducers were buried in the soil in a line across the wheel travel direction and at a depth of 10 cm. Topsoil was re-established on top before the test wheel activated the stress transduc-

ers. With this approach, the loose top 10 cm soil put back on top of the stress transducers should be regarded a part of the measuring system, levelling out the very high stochastic variation between readings at the tyre-soil interface. Using very rapid acquisition of data, this produced detailed descriptions of the stress distribution across the contact area. Both investigations showed that the stress distribution across the contact area was uneven for all tyres tested. One implication of this is that the mean ground pressure (wheel load divided by the area in contact with the soil) is a theoretical parameter with poor information on the stresses acting on the soil. For some tyres and some inflation pressures, the maximum stress was found in the middle of the contact area, while for other a double-peak stress distribution was observed, i.e. with stress peaks close to each edge of the tyre. The results of Keller (2005) as well as Schjønning et al. (2006) indicated that – independent on tyre type – the level of the maximum stress was approximately 50 kPa higher than the inflation pressure. This means that the maximum stress transferred to the topsoil – and hence the compaction of that layer – may be predicted directly from the tyre inflation pressure.

9.3.2 Stresses in the soil profile

When a soil is loaded, stresses are transferred from the surface to deeper horizons. Söhne (1953, 1958) suggested that the stress distribution may be described by a modification of the model predicting stress transmission in an elastic medium. In essence, this implies that the stresses in the topsoil close to the load (the wheel) are determined by the specific stress (mean ground pressure: load divided by loaded area), and that the stresses in deeper layers are determined by the (wheel) load. Soils are not ideally elastic and this is one reason why the Söhne model has been questioned (e.g. Trautner, 2003). However, recent research indicates that the basic principle is correct (Lamandé et al., 2007; Lamandé & Schjønning, 2009; also see presentations from "Plantekongres" 2007 and 2008: Lamandé & Schjønning, 2007 and Schjønning, 2008).

Schjønning et al. (2006) measured the stress distribution in the wheel-soil contact area for 20 combinations of tyre type, inflation pressure and wheel load. They further took these precise stress distributions as input to a Söhne modelling of stresses in the soil profile. The results revealed that the soil depth, d_{50}, that experienced a stress level of 50 kPa or larger could be described by the wheel load and the inflation pressure as follows:

$$d_{50} = 32.3 + 7.5 \times F_{wheel} + 7.7 \times \log_2(p_{tyre}), \quad R^2 = 0.960, \quad RMSE = 4.07, \quad (1)$$

where F_{wheel} is wheel load in tonnes, and p_{tyre} is tyre inflation pressure in bars. Approximated, Eq. (1) may be written:

$$d_{50} = 30 + 8 \times F_{wheel} + 8 \times \log_2(p_{tyre}) \qquad (2)$$

This "*8-8 rule*" is a simple and rather accurate rule of thumb: *The depth of the 50 kPa isobar will increase with 8 cm for each 1 tonne increase in wheel load and with 8 cm for each doubling of the tyre inflation pressure.*

9.3.3 What is the strength of the soil?

Any discussion on stress transmission in soil is rather academic if the soil reacts purely elastic. I.e., like rubber bounces back to the original position after the loading event. The quantitative knowledge of the mechanical strength of different soils and at varying water contents is limited. One reason for this are the difficulties in finding the most suitable method of measuring this strength. For the present purpose, therefore, we will rely on observations in the field rather than on disputable laboratory measurements. In Sweden, quite a number of field measurements of stresses and strains (vertical deformation) have been performed in the recent decade. Keller (2004) evaluated the combined data and noted that persistent (non-elastic) deformation was seldom observed when subsoils were subjected to stresses less than 50 kPa. The data similarly indicated an increasing deformation with increase in stress above this limit.

Tijink (1998) reviewed a number of recommendations for allowable stresses in soil (Table 9.1). The recommendations are all based on a general judgement after field measurements and observations. Söhne (1953) suggested that soil at field capacity should not suffer tyres with > 80 kPa inflation pressure. This was supported by Vermeulen et al. (1988) except that they recommended tyre pressures of less than 40 kPa for traffic in early spring. Petelkau (1984) suggested that traffic on spring-wet soil should not take place with mean ground pressures exceeding 50-80 kPa dependent on soil type. Finally, Rusanov (1994) recommended that the stress at 50 cm depth should not exceed 50 kPa, even in dry conditions. The latter is in accor-

Table 9.1 Suggested guidelines to prevent soil compaction, expressed in limits for inflation pressure (p_i), average ground pressure (p_c) and vertical soil stresses at 50 cm depth (p_{50}) in spring or in summer/autumn (after Tijink, 1998).

Reference	p_i (kPa)	p_c (kPa)		p_{50} (kPa)		Remarks
		spring	summer autumn	spring	summer autumn	
Söhne (1953)	80					Normal moisture conditions
Perdok and Terpstra (1983)	100					
Petelkau (1984)		50	80 [a]			Sand
		80	150 [a]			Loam
		80	200 [a]			Clay
USSR (1986) [b]		80	100	25	30	w.c. (0-30) > 90 % f.c. [c]
Rusanov (1994)		100	120	25	30	w.c. (0-30) > 70-90 % f.c. [c]
		120	140	30	35	w.c. (0-30) > 60-70 % f.c. [c]
		150	180	35	45	w.c. (0-30) > 50-60 % f.c. [c]
		180	210	35	50	w.c. (0-30) < 50 % f.c. [c]
Vermeulen et al. (1988)	40	50				early spring, arable land
	80		100			arable land

[a] Moisture content < 70 % of field capacity

[b] Official standard for fine-grained soils, for the whole former Soviet Union. For undriven wheels values are 10 % higher. For two passes in the same rut the values are 10 % lower; for three and more passes values are 20 % lower.

[c] w.c. (0-30) = water content (0-30 cm depth); f.c. = field capacity.

dance with the Swedish observations of Keller (2004) referenced above. Until exact strength values for different soils at varying water contents become available, we will here formulate the "*50-50 requirement*": *Traffic on soil should not induce stress levels higher than 50 kPa for soil layers deeper than 50 cm depth.*

9.4 Compaction effects on crop yields

A range of studies has quantified the effect of soil compaction on crop yields (see e.g. Lipiec et al., 2003). The most comprehensive data sets – and fortunately also the most relevant data for Danish conditions – are (i) a number of Swedish field experiments in the period ~1960-1990 (summarized by Håkansson, 2000; 2005), and (ii) an international series of field experiments in Northern USA, Canada, Scotland, Denmark, Sweden and Finland (Håkansson, 1994).

The Swedish data were compiled in a model for prediction of yield reduction by Arvidsson & Håkansson (1991). For ploughed soils, they identified four categories of compaction effects: (1) Direct effects of compaction of the plough layer, (2) Effects of plough layer compaction persisting after a new ploughing event, (3) Effects of compaction of the soil below the plough layer, and (4) Effects of traffic in ley crops.

9.4.1 The direct compaction effect on plough layer soil

The Arvidsson & Håkansson (1991) model is not directly applicable to Danish conditions anno 2010 because (i) the Swedish soils were generally more clayey than Danish soils, (ii) higher wheel loads are generally used today, and (iii) other (radial ply) tyres are used today. However, the general trends are interesting. The degree of compactness is a parameter giving the density of the soil relative to a reference value obtained by compressing a moist soil sample at 200 kPa. For any crop, an optimum degree of compactness exists for best growing conditions (e.g. Håkansson, 2005; Figure 9.1), and the optimum is generally higher (more dense) than the degree of compactness found in a newly ploughed soil. This means that some compaction (e.g. by a furrow press) of the topsoil should take place in order to optimize the yield. Arvidsson & Håkansson (1991) predicted the degree of compactness from soil water content, wheel load, and tyre characteristics and compared it to otherwise established relations between the degree of compactness and the crop yield (Figure 9.1). In that way they were able to predict the relative reduction in yield derived from the direct compaction effect in the plough layer (effect (1) above). It should be kept in mind that the optimal degree of compactness for a given crop seems to be independent of soil type (Håkansson, 2005), but that it is higher for dry than for wet growing conditions. Thus, Rasmussen (1976) for a clay soil in a wet year found the highest yield of spring barley in soil not compacted after ploughing, while a wheel-by-wheel compaction event gave the best yield in a dry year. This complicates the prediction of the best conditions of the plough layer for optimum yield.
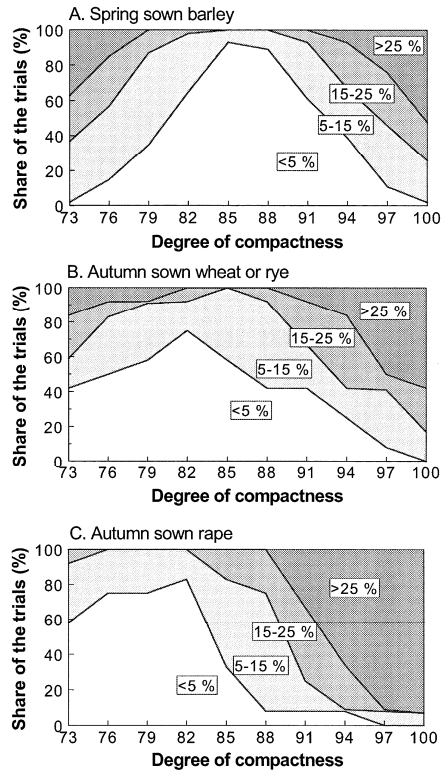
Figure 9.1 Identification of the optimal degree of compactness for three crops from a large number of Swedish field trials. The relative number trials with estimated yield reductions varying from <5% to >25% (relative to yield maximum in the individual trial) when the degree of compactness of the plough layer varied between 73 and 100 (Håkansson, 2005).

9.4.2 The residual compaction effect on plough layer soil after additional ploughing

The results discussed above relate to the direct effect of compaction-induced density for the specific growing year. I.e., the compaction that has taken place in the same growing season as the harvest. The Swedish results indicate that soil 'remembers' previous compaction of the plough layer even if it has been ploughed. These 'residual' effects of a compaction event after a new ploughing operation <u>without</u> further compaction were surprisingly high for the Swedish test conditions (Arvidsson & Håkansson, 1991). E.g., for normal moisture conditions, a 10% reduction in yield was recorded if the soil had been trafficked with an intensity corresponding to 300 tonnes×km ha^{-1} the year before (prior to ploughing) (tonnes×km = the product of the weight of the vehicle (tonnes) and the distance driven (km)). The results indicated that this effect was highest for clay soils. This finding should be considered when evaluating the bene-fits of controlled traffic systems (CTF), because the non-trafficked soil will not display any 'residual' compaction effect.

9.4.3 Compaction effect on the subsoil

A series of 24 long-term field trials with subsoil compaction caused by heavy vehicles was carried out in an international cooperation in seven countries in Northern Europe and North America (USA and Canada) (Håkansson, 1994). Similar experimental traffic treatments were applied in all trials at a soil water content close to field capacity and on one occasion only. The treatments were 0, 1 and 4 passes track by track by vehicles with loads of 10 tonnes on single axes or 16 tonnes on tandem axle units. Tyre inflation pressure was 250-300 kPa. After the experimental traffic, all plots in each individual trial were treated uniformly using vehicles with axle loads <5 tonnes. Annual ploughing to a depth of 20-25 cm was performed in order to alleviate the compaction effects in the plough layer as quickly as possible.
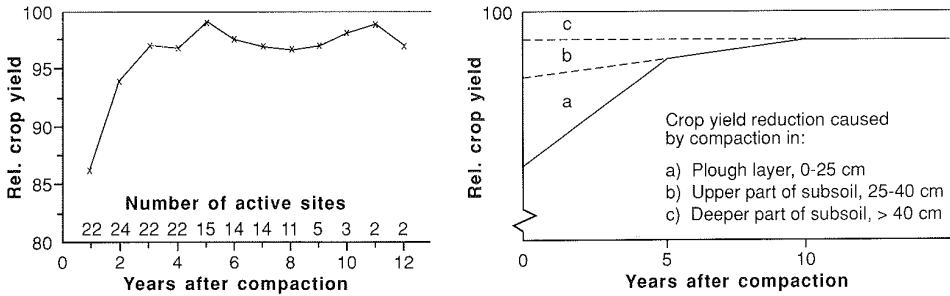

Figure 9.2 The results from a comprehensive international series of field trials with one initial soil compaction event (10 tonnes axle load [5 tonnes wheel load]). The Figures show the development in time of the relative crop yield in exact figures (left) and interpreted in relation to the compaction effect of different soil layers (right) (Håkansson & Reeder, 1994).

Figure 9.2 (left) shows the mean crop response in the whole series of trials in plots with four passes track by track by the vehicles. During the first two years, crop yields were substantially reduced, presumably mainly because of compaction effects in the plough layer. In Figure 9.2 (right), the trend in yield response is predicted as being due to this plough layer effect (a), an effect from compaction of the 25-40 cm layer (b) and finally an effect attributed to compaction of the soil at >40 cm depth (Håkansson & Reeder, 1994). This interpretation of data implies that the plough layer effect lasts for five years, the 25-40 cm layer compaction effect is alleviated within a 10-year period, and that the compaction effect on layers deeper than 40 cm is persistent. The interpretation is based on the yield data of the international series but supported by a range of other experiments. Averaged for all experiments in the international collaboration, the persistent yield loss amounted to 2.5% (Håkansson & Reeder, 1994). The idea of a persistent yield effect is also based on compaction-induced increases in density of deep soil layers > 20 years after the compaction event as reviewed by Håkansson & Reeder (1994).

The international series of trials included two Danish experiments. One trial was located on a JB1 soil at Lundgård, and another on a JB6 soil at Roskilde. Both experiments were run for

nine years after the initial compaction event. The crop was spring barley for nearly all years. At Lundgård, the trend in data resembled the general picture found in Figure 9.2 although single year effects were statistically significant only the first year after compaction (Schjønning & Rasmussen, 1994). At Roskilde, no significant compaction effects were found in any year. Averaged for all years, the four-time-replicated compaction treatment reduced the yield with 0.34 tonnes (3.4 hkg) and 0.05 tonnes (0.5 hkg) per hectare at Lundgård and Roskilde, respectively. The same figures for the last four years of experimentation (inter-preted as subsoil compaction effects only) were 0.25 and 0.06 tonnes per hectare, respectively (Schjønning & Rasmussen, 1994).

9.4.4 The direct traffic damage to the crop

Traffic in a growing crop may introduce a direct damage to the plants and hence a likely re-duction in yield. Rasmussen & Møller (1981) showed that yield reduction from traffic in a ley may be considerable. The increased trend towards injection of slurry in the growing crop ac-centuates the problem for winter wheat. To our knowledge, no investigations have quantified the yield loss deriving from direct damage to a winter wheat crop. Generally, it is known that tyres with low inflation pressures and small lugs minimize the damage to the crop. The dam-age from traffic related to spraying of pesticides may be considerable because it takes place at a late growth stage. In consequence, controlled traffic is used in narrow lanes with no plants.

9.4.5 The combined effect of traffic in crop production, example 1

Table 9.3 shows an example of traffic that causes both plough layer and subsoil compaction and affects the crops both in the short term and in the long term. The example was given by Håkansson (2005), and the calculations are based on the previously mentioned model for soil compaction effects (Arvidsson & Håkansson, 1991). Two systems for spreading of slurry ma-nure are compared. System 1 is optimized with regard to prevention of soil compaction, while system 2 induces much soil compaction. Characteristics for the two systems are given in Ta-ble 9.2.

Table 9.2 Characteristics of the two slurry spreading systems compared in Table 9.3.

System 1 (optimized)	System 2 (non-optimized)
- tractor front axle: 2 tonnes	- tractor front axle: 2 tonnes
- tractor rear axle: 7 tonnes	- tractor rear axle: 7 tonnes
- wagon tandem axle: 9 tonnes	- wagon single axle: 9 tonnes
- mean ground pressure, all: 80 kPa	- mean ground pressure: 140/200 kPa
- spreading width: 12 m	- spreading width: 6 m
- medium dry soil	- wet soil
- well-planned traffic (total driving distance 1.8 times spreading distance)	- poorly planned traffic (total driving dis-tance 4.0 times spreading distance)

The model soil is a sandy loam with ~10% clay. It is assumed that moldboard ploughing is carried out each autumn. The spreading is made some days before sowing of a spring-sown crop, and the manure is incorporated only by shallow harrowing. In both cases, an 8 m^3 spreader is used. This weighs 4 tonnes when empty and is pulled by a 6-tonne tractor. The two systems differ with respect to the wheel loads, the mean ground pressure, the width of spreading, the water content when traffic takes place, and the planning of traffic to and from the part of the field receiving slurry at each field visit (Table 9.2).

Table 9.3 Predicted crop yield losses and increased tillage costs caused by soil compaction in the plough layer and in the subsoil when spreading slurry before spring sowing for a sandy loam soil (clay content 10%). The spreading of slurry is carried out either in an optimized way (system 1) or in a non-optimized way (system 2) - consult text for description. Reproduced from Håkansson (2005).

Type of effect	System	
	1	2
1. Effects in the plough layer in the same year (%)[a]	2.8	8.9
2. Residual effects in the plough layer (%)[b]	0.2	1.5
3. Effects in the 25-40 cm layer (%)[c]	0.1	0.9
4. Effects in the >40 cm layer (%)[d]	-	0.3
Total yield loss (%, sum of 1-4)	3.1	11.6
Total yield loss (€ha^{-1})		
at an annual crop value of 500 €ha^{-1}	15	58
at an annual crop value of 1000 €ha^{-1}	31	116
Increase tillage costs (€ha^{-1})[e]	2	5
Total loss (yield loss + increased tillage costs, €ha^{-1})		
at an annual crop value of 500 €ha^{-1}	17	63
at an annual crop value of 1000 €ha^{-1}	33	121

[a]This effect may vary considerably depending on the methods of seedbed preparation and sowing
[b]Total loss during a five-year period (% of one year's yield)
[c]Total loss during a ten-year period (% of one year's yield)
[d]Total loss during a fifteen-year period (% of one year's yield)
[e]Only roughly estimated, possibly too conservatively

The effects in the same year as the spreading dominate (Table 9.3). Håkansson (2005) also simulated the effects for soils higher in clay content, where the residual effects (Table 9.3: effects 2, 3 and 4) are higher. The compaction effects in the subsoil mainly depend on the wheel loads (cf. the *8-8 rule*, Eq. (2)), which in this case are affected by the use of a tandem axle in system 1. The example given here is not realistic for most Danish conditions in 2009, where the total weight of tractor/trailer systems in slurry application may be as high as 50-55 tonnes and with axle loads of 13-15 tonnes. The persistent effect from subsoil compaction will therefore be much higher than the 0.3% given in this case.

It is difficult to make exact calculations on the economic consequences of soil compaction effects. Nevertheless, Håkansson (2005) estimated that for the non-optimized system in this example, the compaction costs may be higher than the spreading costs or the value of the nutrients in the manure.

9.4.6 The combined effect of traffic in crop production, example 2

Campbell et al. (1986) studied compaction effects in continuous winter barley on a loamy soil with ~22% clay in Scotland. Four years of repeated traffic was applied to soil that was either tilled to ~20 cm depth each year or direct drilled. The tilled soil plots were moldboard ploughed the first year and loosened by a chisel plough the rest of the 4-year trial period. The traffic was applied just before sowing the winter barley crop in the autumn. The traffic treatments comprised zero, one, two, four and six passes of an unladen tractor applied over the whole experimental plots. No more traffic was allowed during the growing season. The tractors weighed 3.4 – 3.8 tonnes corresponding to wheel loads on the rear wheels of maximum 1.03 tonnes. The tyre inflation pressures were 220 – 280 kPa for the front wheels and 80 – 90 kPa for the rear wheels. An additional compaction treatment consisted of one tractor passage at tyre inflation pressures of only 100 and 40 kPa for the front and rear wheels, respectively.

With no or few traffic events, the ploughed soil gives slightly higher yields than the direct-drilled soil (Figure 9.3), although tillage effects were only statistically significant one of the trial years (not shown). It is noteworthy that the reduction of tyre inflation pressure has increased yield, especially for the ploughed soil. The yield is even higher than observed for no-trafficked soil, which reflects a degree of compactness (Figure 9.1) below the optimal in the untrafficked soil. The Scottish results emphasize that the structural conditions in the plough layer are crucial for obtaining a high yield. Wide, low-pressure tyres should be used in all traffic events, and – given that precondition – the traffic should be distributed across the area rather than concentrated in traffic lanes. If very low inflation pressures cannot be achieved, an alternative is the use of permanent traffic lanes, which will be discussed in the following section.

By use of the *8-8 rule* (Eq. (2)), the maximum depth of the 50 kPa isobar below the rear tractor tyres for the experiments in Figure 9.3 can be calculated as:

$$d_{50} = 30 + 8 \times 1 + 8 \times \log_2(0.9) = \sim 37 \text{ cm}$$
and
$$d_{50} = 30 + 8 \times 1 + 8 \times \log_2(0.4) = \sim 27 \text{ cm}$$

for the traffic with rated and the reduced inflation pressures, respectively. This means that the compaction effects in Figure 9.3 for all treatments derive nearly entirely from effects on the plough layer (effects 1 and 2 in the Swedish compaction model, Table 9.3).
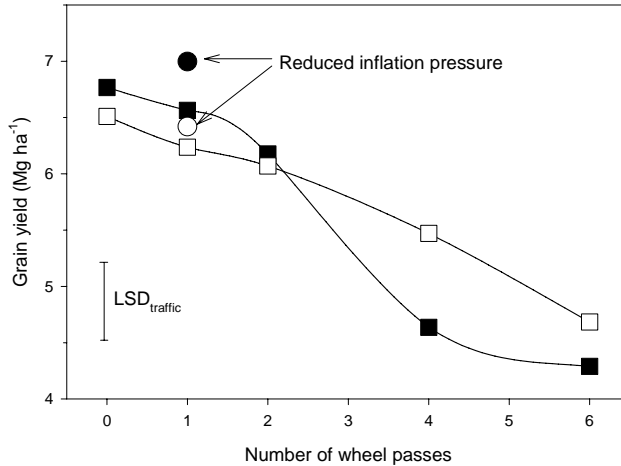
Figure 9.3 Compaction effects on the yield of winter barley for a loamy soil in Scotland as averaged across trial years 2, 3 and 4 after start of annual compaction prior to sowing. Open symbols are direct drilled soil, while closed symbols relate to ploughed soil. The LSD-bar is an approximate indication of variation related to the compaction effect (average of the values obtained for years 3 and 4, no significant effect in year 2). Calculated from Campbell et al. (1986).

The ploughed soil is more vulnerable to repeated wheelings than the direct-drilled soil (Figure 9.3). The interaction between tillage system and compaction was, however, only significant for trial year 4 as an indication that the direct-drilled soil seems to improve its structure and strength during the years.

9.4.7 The combined effect of traffic in crop production, example 3

A recent Danish study of traffic effects on grass yield differentiates the effects of wheel load and tyre inflation pressure (Table 9.4). The study was performed on a 14-hectare field with wide variation in textural composition across the field. The compaction treatments were applied by a Claas Axion tractor mounted with a 15 m^3 slurry tanker equipped with a tandem axle with four 700 mm wide cross-ply tyres. Six to twelve replicate plots randomly located over the field were split into two, one half left unpacked and the other treated with one of four different combinations of wheel load (2.865 kg or 4.745 kg) and tyre inflation pressure (1.0 bar or 2.5 bar).

A range of studies has addressed the effect of traffic and compaction in grass production. The results of the previously mentioned Danish study (Rasmussen & Møller, 1981) emphasize the direct damage to the growing grass crop and the effect on the topsoil. This is because rather small tractors and trailers were used in the investigation. Also most international studies have used wheel loads smaller than those used for modern agriculture in Denmark today (e.g.

Douglas & Crawford, 1991). In contrast, the recent Danish study (Table 9.4) includes treatments, where the d_{50}-values (Eqs. 1 and 2) range from 53 cm (low wheel load, low inflation pressure) to 78 cm (high wheel load, high inflation pressure). This means that the compaction effects most probably include damage to the top part of the B-horizon (~20-50 cm) as well as – at least for the high wheel load treatments – the soil horizons below 50 cm depth. This is reflected in the yield results. Averaged for all four treatments, the grass yield was only 91.7% of uncompacted (Table 9.4) (simulating a 6 m working width). However, we note from the results in Table 9.4 that averaged across tyre inflation pressures, the increase in wheel load from about 2.9 tonnes to 4.7 tonnes decreased the yield with additional 4.2 %-point compared to uncompacted. Increase in tyre inflation pressure also induced a further reduction in yield compared to the non-compacted reference, but this additional effect was only 1.3 %-point as averaged across the two wheel loads.

Table 9.4 Soil compaction effects on yield (% of non-compacted) in grass production with four combinations of wheel load and tyre inflation pressure when applying slurry. Calculated from grass yields measured in compacted and non-compacted plots, simulating a working width of 6 m. All four combinations yielded significantly lower than non-compacted. Statistical tests have not yet been performed for comparison between systems. Preliminary results from Aarhus University (Ole Green).

Inflation pressure	Wheel load		Averages,
	2.9 tonnes	4.7 tonnes	infl. pressures
1.0 bar	94.0	90.7	92.4
2.5 bar	93.6	88.5	91.1
Averages, wheel loads	93.8	89.6	**91.7**

Although the results in Table 9.4 were obtained in experimentation with traffic in grass, they are to a large extent relevant also for other crops. In modern-day Danish growing of winter wheat, at least the two field operations – slurry application and combine harvesting – may induce very high wheel loads. As the compaction damage to soil deeper than approximately 40-50 cm is effectively persistent (Håkansson & Reeder, 1994), the accumulated effect of random traffic effects on the subsoil in winter wheat may be anticipated to have affected yields negatively.

9.5 Controlled traffic farming
Controlled traffic farming (CTF) is increasing in popularity as a means of avoiding soil compaction for the major part of the agricultural fields. In CTF most traffic in field operations takes place in permanent traffic lanes, which is often facilitated by GPS systems. The idea is to allocate all traffic to these lanes, hence optimizing the growing conditions for plants in the area between these lanes. The benefits of this growing system may include reduced energy requirements in tillage (McPhee et al., 1995) and good machine mobility, high tractive efficiency, and timeliness of field operations (Taylor, 1983; Monroe et al., 1989).

9.5.1 Crop yields in CTF systems

Though the trafficked area may occupy up to 20% of the land, the increased yield in the cropped zone may compensate for this loss (Hamza & Anderson, 2005). The results in Figure 9.4 show how the working width (corresponding to the distance between traffic lanes) affects the compaction effect on grass yield in the recent Danish experiment with grass presented in Table 9.4. An increase in working width from ~7 to 22 meter approximately halves the compaction-induced yield reduction. Tullberg et al. (2001) found a yield increase of 16% in CTF systems for cereal production in Australia, while others have reported increases in yield up to 25% in the non-trafficked zones (Chamen et al., 1994). Some experiments on sandy soils have shown a decrease in yield when shifting to CTF (Chamen et al., 1992). This was attributed to manganese deficiency in the loose soil.
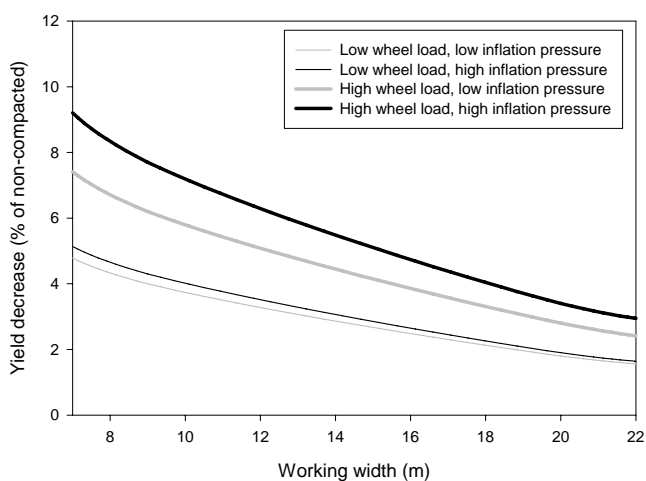

Figure 9.4 The effect of working width for slurry application in grass fields on the effect of compaction on the yield for four different combinations of wheel load and tyre inflation pressure. Calculated from the same data as shown in Table 9.4. Preliminary results from Aarhus University (Ole Green).

9.5.2 Potentials and limitations in the CTF concept

There is no doubt that the CTF concept has potentials for optimizing the growing conditions for plants in the field. We also note, however, that the untrafficked zone of soil will most often need some densification provided by other means (e.g. use of furrow press) in order to arrive at the optimum in degree of compactness (Figure 9.1). It is also noteworthy that winter barley in the Scottish experiment presented in Figure 9.3 yielded best when trafficked by a moderately-sized tractor equipped with real low-pressure tyres. This accentuates the potential of using low-weight machinery not inducing critical stresses below the tilled soil layer and leaving the topsoil with densities close to the optimum degree of compactness.

However, the CTF concept is receiving much interest exactly because the machinery used in the field today is very heavy. Confining traffic to permanent traffic lanes then seems as a

logical way of dealing with the problem. As wheel loads higher than approximately 3.5 tonnes are likely to induce permanent compaction of wet soil below 0.5 m depth (Schjønning et al., 2006), the compaction damage to the subsoil will be limited to the permanent traffic lanes. It is well known from the headlands of agricultural fields that much traffic will create very poor growing conditions. Years of repeated traffic on the same traffic lanes in the field with wheel loads often exceeding 5 tonnes will inevitably lead to an accumulated compaction to a degree that the soil in the lanes is effectively unfit for plant growth for many years ahead. This part of the soil in the field is sacrificed for the sake of increased productivity in the untrafficked zones. This may turn out to be a serious problem, however, if future development in agricultural engineering may allow greater distances between the traffic lanes. Old traffic lanes not fitting into the new system will then manifest themselves as lines of 'deserts' in the field with severe reductions in crop yield.

Another aspect that should be kept in mind when considering the CTF concept is that the traffic lanes may not be used for all field operations. One example in winter wheat growing is the harvest operation. Modern combine harvesters may reach wheel loads up to 9 tonnes, which induces detrimental stresses to deep soil layers. This means that CTF systems in winter wheat may allow for concentration of the traffic when applying slurry, lime, mineral fertilizers, and pesticides. The secondary tillage operation may perhaps also be performed with equipment fitting the same tramlines. However, the ploughing operation, the seeding, and – as mentioned – the harvest will involve traffic in between the traffic lanes.

9.6 Summary and conclusions

The trend in mechanization in agriculture for the past 3-4 decades is characterized by a steady increase in weight of field machinery. This has necessarily been accompanied by development of still better and bigger tyres for carrying the loads. Recalling the general principles for mechanical stress distribution in the soil profile below a running wheel, this means that the plough layer soil probably has not experienced an increase in applied stresses during the recent decades. The present day tyre situation even includes the potential of reducing the stresses to plough layer soil if using rated inflation pressures at moderate wheel loads. All too often (read: nearly always) tyres are inflated for taking the highest loads to the highest speeds on a highway rather than for slow-speed traffic in the field with the actual wheel loads. As an example, the Nokian 800/50R34 flotation tyre often used on big slurry tankers requires an inflation pressure of 160 kPa (1.6 bars) if taken to the highway (rated speed 50 km h^{-1}) with 5.3 tonnes. However, in the field (rated speed 10 km h^{-1}) the same load may be carried at 80 kPa (NDI, 2006). If using the high-speed inflation pressure also in the field, the plough layer soil will experience a maximum stress of approximately 210 kPa, while the low-speed rated inflation pressure would give rise to only ~130 kPa (inflation pressure + 50 kPa: Schjønning et al., 2006; Lamandé & Schjønning, 2008). The 80 kPa difference in stresses will certainly create significantly different conditions for crop growth. Furthermore, a flotation tyre like the one mentioned here has the potential of carrying loads as high as 3 tonnes at 50 kPa inflation

pressure. This means that for many operations, the maximum stresses to the topsoil may be reduced to approximately 100 kPa, which would probably hardly induce densities detrimental to crop growth.

Considering the subsoil, the situation has dramatically changed during the period in question. Today, wheel loads of 5-6 tonnes are more the rule than the exception for many field operations. Some machinery loads the wheels up to 12 tonnes (e.g. self-propelled sugar beet and grass harvesters). The recent research on stress transmission in the soil profile in Sweden and Denmark has documented that such loads – irrespective of the tyres used – will induce very high stresses to deep soil horizons. The documentation of the plastic (persistent) deformation caused by these stresses in the subsoil layers is unfortunately still weak. Until further studies have been conducted, the best data available are the Swedish studies indicating that subsoil layers will be deformed if subjected to vertical stresses higher than ~50 kPa. Compaction of subsoil layers deeper than ~40-50 cm has been shown to be effectively permanent and to induce permanent reduction also in crop yields. This means that the damage is cumulative: if not using CTF, an increasing part of the area has been compacted in the subsoil layers. We do not find it possible to give an exact quantification for Danish soils but we find it most likely that (part of) the decrease in winter wheat yields in Denmark in recent years is due to the compaction of the subsoil.

There is an increasing interest in CTF, which concentrates the traffic in permanent traffic lanes. This is appealing because most of the soil area can be cropped without traffic-induced compaction. However, not all traffic can be allocated to wide-distance traffic lanes used in e.g. slurry application. Modern-day combine harvesters often have high wheel loads that should also only be allowed in traffic lanes (because of the residual plough layer compaction effects and the subsoil compaction discussed above). The harvesting operation can make use of the CTF concept, but then with rather narrow lanes, meaning that more of the area will experience the harmful compaction. Another aspect in CTF is the permanent compaction of >50 cm subsoil layers if using wheel loads higher than approximately 3½ tonnes (as can be derived from a combination of the 8-8-rule and the 50-50 requirement). The technical development may well allow larger distances between the traffic lanes in the future. If lanes at one distance are established today, repeated traffic with high wheel loads in wet conditions may create permanent damage to subsoil layers so pronounced that the soil will never again be available for crop production.

There is an urgent need to reduce the wheel loads to a maximum of approximately 3½ tonnes for traffic in the field in wet conditions. And this requirement is true for CTF as well as traditional field traffic. This aim can be achieved by increasing the number of axles on trailers and/or to reduce the weight of machinery. It will protect the subsoil from serious and permanent compaction and automatically yield a benefit to the plough layer soil because the full potential of modern flotation tyres can then be utilized.

9.7 References

Arvidsson, J. & Håkansson, I., (1991) A model for estimating crop yield losses caused by soil compaction. Soil & Tillage Research 20, 319-332.

Arvidsson, J., Trautner, A. & van den Akker, J.J.H. (2000) Subsoil compaction – Risk assessment, and economic consequences. Advances in GeoEcology 32, 3-12.

Arvidsson, J., Trautner, A., van den Akker, J.J.H. & Schjønning, P. (2001) Subsoil compaction caused by heavy sugarbeet harvesters in southern Sweden. II. Soil displacement during wheeling and model computations of compaction. Soil & Tillage Research 60, 79-89.

Campbell, D.J., Dickson, J.W., Ball, B.C. & Hunter, R. (1986) Controlled seedbed traffic after ploughing or direct drilling under winter barley in Scotland, 1980-1984. Soil & Tillage Rsesearch 8, 3-28.

Chamen, W.C.T., Dowler, D., Leede, P.R. & Longstaff, D.J. (1994) Design, operation and performance of a gantry system: Experience in arable cropping. Journal of Agricultural Engineering Research 59, 45-60.

Chamen, W.C.T., Vermeulen, G.D., Campbell, D.J. & Sommer, C. (1992) Reduction of traffic-induced soil compaction: a synthesis. Soil & Tillage Research 24, 303-318.

Douglas, J.T. & Crawford, C.E. (1991) Wheel-induced soil compaction effects on ryegrass production and nitrogen uptake. Grass and Forage Science 46, 405-416.

Green, O. & Nielsen, K.V. (2006) Trykpåvirkninger i jorden ved gylleudbringning. Farmtest – Maskiner og planteavl, Nr. 74, Dansk Landbrugsrådgivning, Skejby, Denmark.

Hamza, M.A. & Anderson, W.K. (2005) Soil compaction in cropping systems. A review of the nature, cause and possible solutions. Soil & Tillage Research 82, 121-145.

Horn, R., Domzal, H., Slowinska-Jurkiewicz, A. & van Ouverkerk, C. (1995) Soil compaction processes and their effects on the structure of arable soils and the environment. Soil & Tillage Research 35, 23-36.

Håkansson, I. (1994) (ed.). Special Issue: Subsoil Compaction by High Axle Load Traffic. Soil & Tillage Research 29, 105-306.

Håkansson, I. (2000) Packning av åkermark vid maskindrift. Omfattning – effekter – motåtgärder. Sveriges Lantbruksuniversitet, Institutionen för Markvetenskap, Rapporter från Jordbearbetningsavdelningen 99 (ISSN 0348-0976), 123 pp.

Håkansson, I. (2005) Machinery-induced compaction of arable soils. Incidence – consequences – counter-measures. Swedish University of Agricultural Sciences, Department of Soil Sciences, Reports from the Division of Soil Management 109 (ISSN 0348-0976), 153 pp.

Håkansson, I. & Reeder, R.C. (1994) Subsoil compaction by vehicles with high axle load – extent, persistence and crop response. Soil & Tillage Research 29, 277-304.

Håkansson, I., Grath, T. & Olsen, H.J. (1996) Influence of machinery traffic in Swedish farm fields on penetration resistance in the subsoil. Swedish Journal of Agricultural Research 26, 181-187.

Iversen, B.V., Børgesen, C.D., Lægdsmand, M., Greve, M.H. & Heckrath, G. (2007) Mapping the risk of P loss through soil macropores. *In*: Diffuse Phosphorus Loss: Risk assessment, mitigation options and ecological effects in river basins. The 5th International Phosphorus Workshop (IPW5). 3-7 September 2007 in Silkeborg, Denmark. Heckrath,

G., Rubæk, G.H., Kronvang (eds.). DJF Plant Science No. 130. Faculty of Agricultural Sciences, University of Aarhus. pp. 449-451.

Keller, T. (2004) Soil Compaction and Soil Tillage – Studies in Agricultural Soil Mechanics. Acta Universitatis Agriculturae Sueciae, Agraria 489. Ph.D.-thesis. 75 pp.

Keller, T. (2005) A model for the prediction of the contact area and the distribution of vertical stress below agricultural tyres from readily available tyre parameters. Biosystems Engineering 92, 85-96.

Kulli, B., Gysi, M. & Flühler, H. (2003) Visualizing soil compaction based on flow pattern analysis. Soil & Tillage Res. 70, 29-40.

Kutzbach, H.D. (2000) Trends in power and machinery. J. Agric. Eng. Res. 76, 237-247.

Lamandé M. & Schjønning P. (2007) Trykkets forplantning i jorden: effekt af bl.a. dækstørrelse og hjullast. I Sammendrag af indlæg: Plantekongres 2007, s. 138-139. PP-show: http://www.lr.dk/planteavl/informationsserier/info-planter/plk07_d1_2_m_lamande_net.ppt

Lamandé, M., Schjønning, P. & Tøgersen, F.A. (2007) Mechanical behaviour of an undisturbed soil subjected to loadings: Effects of load and contact area. Soil & Tillage Research 97, 91-106.

Lamandé M., Schjønning P. (2009) Wheeling-induced stress transmission in soil. Part II: Effect of tyre dimension and wheel load. Soil & Tillage Research (*in preparation*).

Lamandé, M. & Schjønning, P. (2008) The ability of agricultural tyres to distribute the wheel load at the soil-tyre interface. Journal of Terramechanics 45, 109-120.

Lipiec, J., Arvidsson, J. & Murer, E. (2003) Review of modelling crop growth, movement of water and chemicals in relation to topsoil and subsoil compaction. Soil & Tillage Research 73, 15-29.

McPhee, J.E., Braunack, M.V., Garside, A.L., Reid, D.J. & Hilton, D.J. (1995) Controlled Traffic for Irrigated Double Cropping in a Semi-arid Tropical Environment: Part 2, Tillage Operations and Energy Use. Journal of Agricultural Engineering Research 60, 183-189.

Monroe, G.E., Burt, E.C., Wood, R.K. & Taylor, J.H. (1989) Building and testing traffic lanes for controlled-traffic farming. Transactions of the ASAE 32, 355-360.

NDI (2006) Databog dæk. Traktor – landbrug – industri. Nordisk Dæk Import A-S, Brørup.

Olesen, J.E., Jacobsen, B.H., Thorup-Kristensen, K., Andersson, N., Kudsk, P., Jørgensen, L.N., Hansen, L.M., Nielsen, B.L. & Boelt, B. (2006) Tilpasninger til klimaændringer i landbrug og havebrug. DJF-Rapport, Markbrug, No. 128. The Danish Institute of Agricultural Sciences, Tjele, Denmark.

Oversigt over Landsforsøgene (2008) Dansk Landbrugsrådgivning, Skejby, Denmark.

Perdok, U.D. & Terpstra, J. (1983) Berijdbaarheid van landbouwgrond: Bandspanning en bodemverdichting. Landbouwmechanisatie 34, 363-366.

Petelkau, H. (1984) Auswirkungen von Schadverdichtungen auf Bodeneigenschaften und Pflanzenertrag sowie Massnahmen zu ihrer Minderung. Tagungsbericht Akademie der Landwirtschaftswissenschaften der Deutschen Demokratischen Republik 227, 25-34.

Rasmussen, K.J. (1976) Jordpakning ved færdsel om foråret. II. Jordfysiske målinger. Tidsskrift for Planteavl 80, 835-856.

Rasmussen, K.J. & Møller, E. (1981) Genvækst efter fortørring af græsmarksafgrøder. II. Jordpakning i forbindelse med høst og transport. Tidsskrift for Planteavl 85, 59-71.

Rusanov, V.A. (1994) USSR standards for agricultural mobile machinery: permissible influences on soils and methods to estimate contact pressure and stress at a depth of 0.5 m. Soil & Tillage Research 29, 249-252.

Schjønning, P. (2008) Strukturskader – hvordan og hvorfor er det vigtigt? Kan vi selv klare det, eller skal vi vente på EUs Jordrammedirektiv? I Sammendrag af indlæg: Plantekongres 2008, s. 296-298. PP-show: http://www.lr.dk/planteavl/informationsserier/info-planter/plk08_s1_1_p_schjoenning.ppt

Schjønning, P. & Rasmussen, K.J. (1994) Danish experiments on subsoil compaction by vehicles with high axle load. Soil & Tillage Research 29, 215-227.

Schjønning, P., Iversen, B.V., Munkholm, L.J., Labouriau, R. & Jacobsen, O.H. (2005) Pore characteristics and hydraulic properties of a sandy loam supplied for a century with either animal manure or mineral fertilizers. Soil Use and Management 21, 265-275.

Schjønning, P., Lamandé, M., Tøgersen, F.A., Pedersen, J. & Hansen, P.O.M. (2006) Minimering af jordpakning. Størrelse og fordeling af stress i trædefladen mellem hjul og jord. DJF-Rapport Markbrug 127, Danmarks JordbrugsForskning, Tjele.

Schjønning, P., Munkholm, L.J., Elmholt, S., Debosz, K., Mikkelsen, G.H. & Trautner, A. (2000) Den danske dyrkningsjords tilstand og kvalitet – konsekvenser af trafik og jordbearbejdning. Tidsskrift for Landøkonomi 4/00, 293-300.

Söhne, W. (1953) Druckverteilung im Boden und Bodenformung unter Schleppereiffen. Grundlagen der Landtechnik 5, 49-63.

Söhne, W. (1958) Fundamentals of pressure distribution and soil compaction under tractor tires. Agricultural Engineering, May 1958, 276-281 + 290.

Taylor, J.H. (1983) Benefits of permanent traffic lanes in a controlled traffic crop production system. Soil & Tillage Research 3, 385-395.

Tijink, F.G.J. (1998) Mechanisation strategies to reduce traffic-induced soil compaction. Advances in Sugar Beet Research IIRB, Vol. 1, 57-66.

Trautner, A. (2003) On soil behaviour during field traffic. Acta Universitatis Agriculturae Sueciae, Agraria 372. Ph.D.-thesis. 55 pp.

Tullberg, J.N., Ziebarth, P.J. & Li, Y. (2001) Tillage and traffic effects on runoff. Australian Journal of Soil Research 39, 249-257.

USSR State Committee for Standards (1986) Standard 26955: Agricultural Mobil Machinery; Rates of Force by Propelling Agents on Soil. Moscow, USSR, 7 pp.

Vermeulen, G.D., Arts, W.B.M. & Klooster, J.J. (1988) Perspectives of reducing soil compaction by using a low ground pressure farming system: selection of wheel equipment. Proceedings 11th Conference International Soil Tillage Research Organisation (ISTRO), Edinburgh, UK. Scottish Centre Agricultural Engineering, Penicuik, UK, Vol. 1, pp. 329-334.

Vetter, H. & Scharafat, S. (1964) Die Wurzelverbreitung landwirtschaftlicher Kulturpflanzen im Unterboden. Zeitschrift für Acker und Pflanzenbau 120, 275-297.

10 Farm management

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10.1 Introduction

The considerable variations in yields between farms indicate that a significant part of the explanation of the yield ratios may be related to farm management. However, there is only to a small extent data available that provide a means of a more detailed analysis of the relation between farm management and yield level, as such an analysis calls for a number of valid data even at farm level.

Therefore, the present chapter contains a qualitative analysis of the management conditions that have changed during the last 10-20 years, and how these expectations have affected the yield level in a positive and negative manner. Where possible, data are presented as support for this qualitative analysis.

Farm management covers a complex number of factors that may have both positive and negative effects on yields. Simplified, farm management may be divided into three domains:

- the overall/general production system
- organisation of the day-to-day tasks
- values and thinking.

The premise of this analysis is that good farm management consists of creating a balance between these three domains and in optimizing the overall production results. Thus, there is not necessarily a confined accordance between high yields in wheat and optimized farm management (Noe, 1999; Noe & Alroe, 2003, 2006). Thus, farm management is about what efforts are put into the production as well as how they are managed.

The analysis examines five farm management factors (Knowledge/knowhow, Technology, Structural development, Price relations, and Management thinking) that, in our opinion, are of principal importance for the yield ratio, and we have examined how these factors have changed during the study period. Based on these tendencies, we have drawn up expectations of how the factors have affected the yield ratios (Table 10.1).

Table 10.1 Summary of five farm management effects concerning yield of winter wheat. (next page).

Factors	Development	Expected effect
Knowledge		**Positive**
Education	Educational level of owners and farm managers increased	+
	Education among employees – increased spreading (foreign, cheap)	+/-
	Recruitment procedures, difficult due to fading image and minor year groups	-
Decision support	Planning tools	+
	Monitoring and forecast	+
	Available information improved	+
	Overload of information may reduce the benefit of information and decision support systems	?
Advisory service	From crop advice to administrative tasks	-
	Adviser subsidy reduced and discontinued – advisory service has become more expensive	-
	Knowledge exchange groups – reduced number of field trips, but more focus through knowledge exchange groups	+
	More goal-oriented advice	-
	Number of field trials reduced	
Technology		**Neutral**
Machinery	Machine capacity for establishing reduced	-
	Larger machines, more texture damages	-
	Rationalization (more machine operations in one)	+
	Capacity, higher utilization	+
	Demand increased (more winter wheat – and higher peak load at harvest, and with sowing taking place at the same time	-
	Technology improved	+
	Less punctuality	-
Structural development		**Minus**
Farm size	Farm units larger (more uniform treatment)	+
	Fields larger (fields cover larger variation)	-
	Standard treatment	-
	Differentiated treatment	+
Specialization	Larger area with the same crop (wheat)	+
	Livestock or special crops result in poorer focus on groups	-
Cultivation systems	More mono culture	-
	More wheat on poorer soils	-
Price relations		**Minus**
Wheat	Yield prices fallen, incl. subsidy	-
	EU subsidy crop 1973	+
	EU subsidy production related 1993	-
	EU subsidy, decoupled 2003	0
Approach/action factors	Price on input factors increasing	-
Work	Hourly wages increased	-
Management thinking		**Minus**
Environment	Perception of the environment changed	-
	Major variations in the use of pesticides	
	More organic farms	
	Good agricultural practices	
Focus on yield to focus on costs	It is not that important to obtain high yields in dt/ha – but more important (more focus on) high earnings	-

10.2 Knowledge

The general expectation is that the level of knowledge has increased. In general, the farm managers and the owners have an improved and longer professional education, indicating that knowledge about production factors have increased. Furthermore, new possibilities of knowledge dissemination through new communication technologies have been introduced, i.e. mobile phones, Internet, and advanced decision support systems.

However, there are conditions that point in the opposite direction, for example employment of non-professional foreign workers. Apart from the lack of professional skills, the communication problems in many cases require production standardization and simplification of specific production routines and, in addition, to adapt the production strategies accordingly. All things being equal, this will result in a negative shift in the optimal yield level.

In terms of plant production advisers, the advisory service has changed significantly. Discontinuation of the national subsidies in the advisory service in combination with the many application-related tasks has moved the focus within the plant production advisory service. Focus has changed from production advice to a higher degree of fulfilling the administrational demands in terms of single payment applications, fertilizer accounts, and environmental approvals. Advice on specific plant production issues is increasingly disseminated through newsletters and experience exchange groups.

The overall assessment is that the development in the range of knowledge has had a moderately positive influence on the development of the yields in winter wheat.

10.3 Technology

It must be expected, that changes in composition and use of machinery combined with a change in crop rotation may affect the winter wheat yields.

10.3.1 Combine harvester capacity

The capacity of combine harvesters will have less influence on yields. According to Danmarks Statistik (Statistics Denmark), an assessment of the capacity of combine harvesters from 1982 to 2005 has been made. Assuming 200 hours of use and using a cautious estimate of size and capacity, the capacity was about 2 million ha per year in 1982. The area to be harvested was approx. 2 million hectares. The same assumption in 2005 shows a capacity of approx. 2.4 million ha with a harvest area of 1.8 million ha. Thus, the combine harvester capacity has increased by approx. 33 pct. through the last 25 years, and therefore it cannot be the reason for lower yields.

10.3.2 Machine capacity for soil tillage and sowing

With an increased amount of winter wheat / winter crops a peak load must be expected around the harvesting time of grain and straw of the preceding crop, soil tillage (ploughing and seedbed preparation) and sowing in August-September. If the machine capacity is unchanged, some of the above-mentioned tasks must be carried out under sub-optimal conditions. This will result in yield loss, as correct and timely soil tillage and sowing are important factors in relation to yield increase.

There are no statistics available on existing machine capacity in use for soil tillage. Therefore changes in capacity are estimated based on sold machine capacity (Landbrugsinfo) and some very uncertain assumptions.
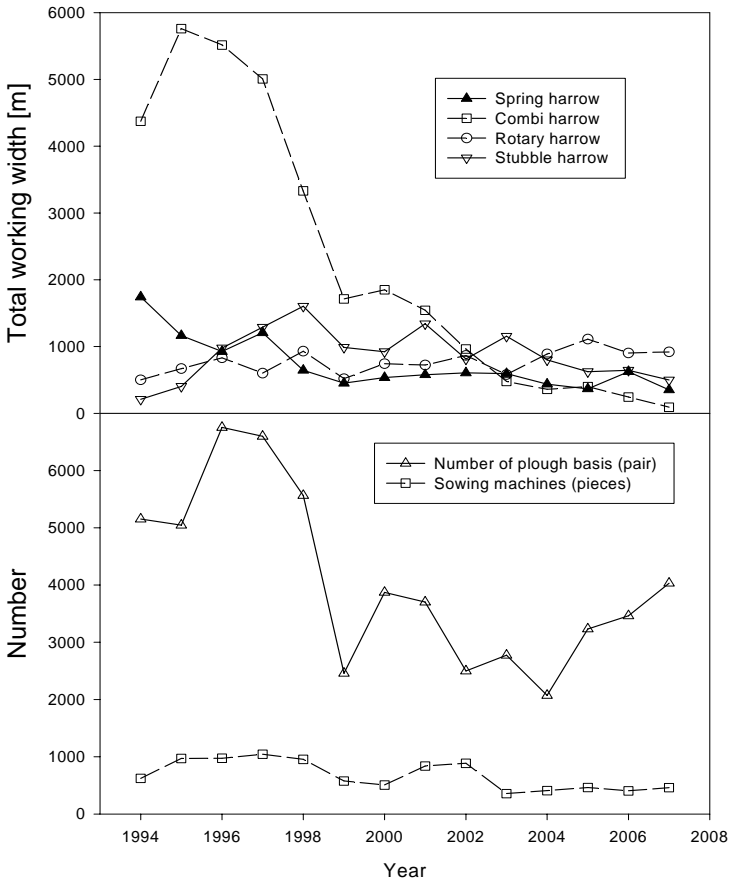

Figure 10.1 Machinery sold and equipment capacity 1994-2007) (Landbrugsinfo)

For most tillage and sowing machines, except rotating harrows, the sale of total work width of machines for soil preparation and sowing has fallen to approx. half or a little less (Figure 10.1) from 1994 to 2007. Even though the machines get bigger, the total work width

(capacity) sold is less, because of fewer machines sold. The figure says nothing about the amount in use, but rather about the increase of new machines. The number of existing machines in use must be added, and machines scrapped, not in use and exported, must be deducted.

Assuming that the existing machine equipment is sold or outphased at the same rate as before, it must mean a reduction in the total machine capacity available for seed bed preparation and sowing. However, if the machines are used longer and more efficiently at the right time, correct and timely operations may still be carried out without affecting the yield.

From 1995 to 2003, the sale of new tractors fell from approx 4,000 to approx. 2,000 per year (Figure 10.2). The total amount of horsepower sold fell not quite as much, from approx. 500,000 hp per year in 1995 to approx. 300,000 hp in 2003. This indicates that the number of tractors is declining and that the tractors are getting bigger.
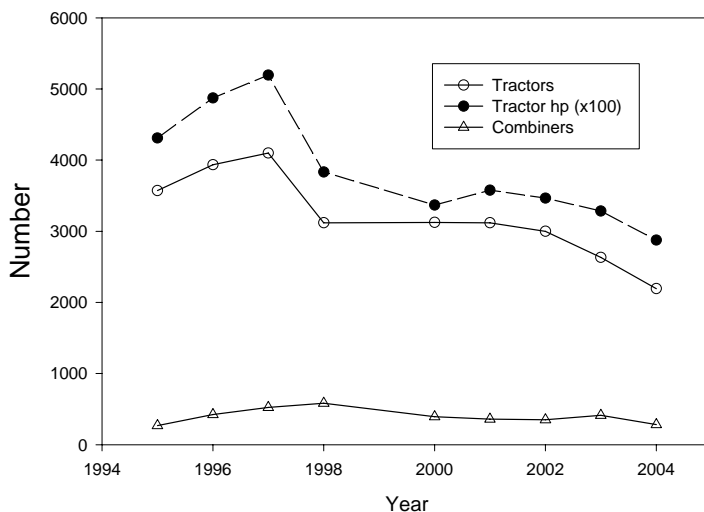

Figure 10.2 Number of combine harvesters and tractors sold, 1995-2003 (Statistics Denmark).

The total investments in agriculture was almost constant during the period. Thus the sales of new machines for soil tillage and sowing show an actual decrease in capacity and not an expression of a general fall in investments.

An argument might be that machines today have a longer operational life than 20 years ago, therefore the reduction is not as high as before – which means that the old machines contribute in maintaining a higher total capacity than the sales statistics of new machines indicate. But seen over a longer time span ,data indicate that the total machine capacity has been reduced.

10.4 Structural development

Over the last 15-20 years, more and more regulations have been introduced in agriculture, i.e. fertilizer accounts, single payment, etc., factors that have moved focus from the day-to-day farm management, monitoring in the field, etc. and have resulted in an increased need for administration.

10.4.1 Farm size

Throughout the period a major specialization has occurred towards farms with only cattle or pigs along with the crop production. At the same time land managed by the farms has increased considerably. The result has been that crop production is of relatively minor importance to the production economics.

Presumably, there are differences in farm management on smaller and larger farms. On small farms the farm manager is able to have the complete overview of the production, thus having control of all production factors. Large-sized farms often have a "professional" farm manager, who also has the full overview, while leaving much of the daily routines, such as soil tillage, plant protection, etc., to other employees, who may not have the same focus on field observations and production as the farm manager on a small farm.

On medium-sized farms, the farm manager may loose the general overview and may not have the possibility of delegating the tasks to employees. If these assumptions are correct, differences in yield should be dependent on the arable area of the farm. Figure 10.3 shows yields in dt/ha on approx. 3,000 farms, where the main production is plant production, included in the DAAS account database in 2006.
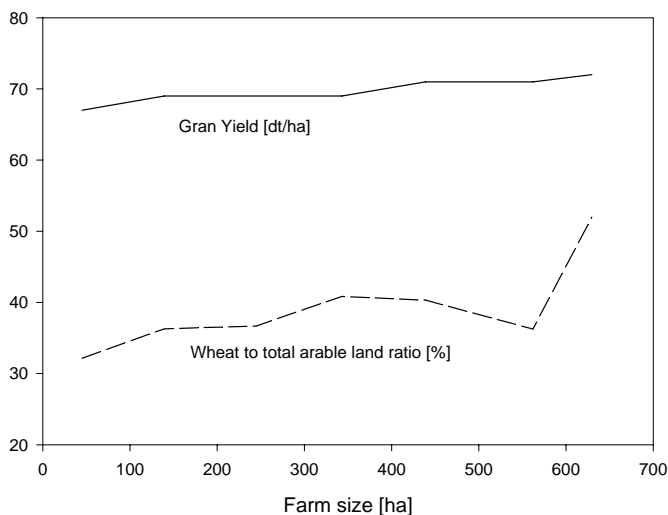

Figure 10.3 Yield and proportion of wheat as a function of farm size in 2006 (DAAS account database).

Most of the farms have 1-100 ha land. Only six farms are 500-600 ha, and three larger than 600 ha. Therefore, this assessment must be applied with some caution. However, there is no indication that farms with more land produce lower yields than farms with less land.

The different soil types behind the figures have been taken into consideration. The share of "good soil" is the same in the different groups. Therefore, there are probably no indications, that wheat on the larger farms is cultivated on "poorer soil" than on smaller farms. Thus, the analysis shows a wheat yield that is more or less the same on small farms as on large farms. An unused potential should be present on the large farms, as more focus can be made on farm management.

10.4.2 Crop rotation and wheat yield

Crop rotation has a clear effect on yields. For instance, a yield reduction of up to 10 % in winter wheat after cereal crops must be expected, in comparison to winter wheat after a good pre-crop like winter oilseed rape.

Figure 10.4 shows the area distribution from 1982 to 2007. The farms are divided into sizes in order to be able to examine if there is a change in wheat area within the different farm sizes.
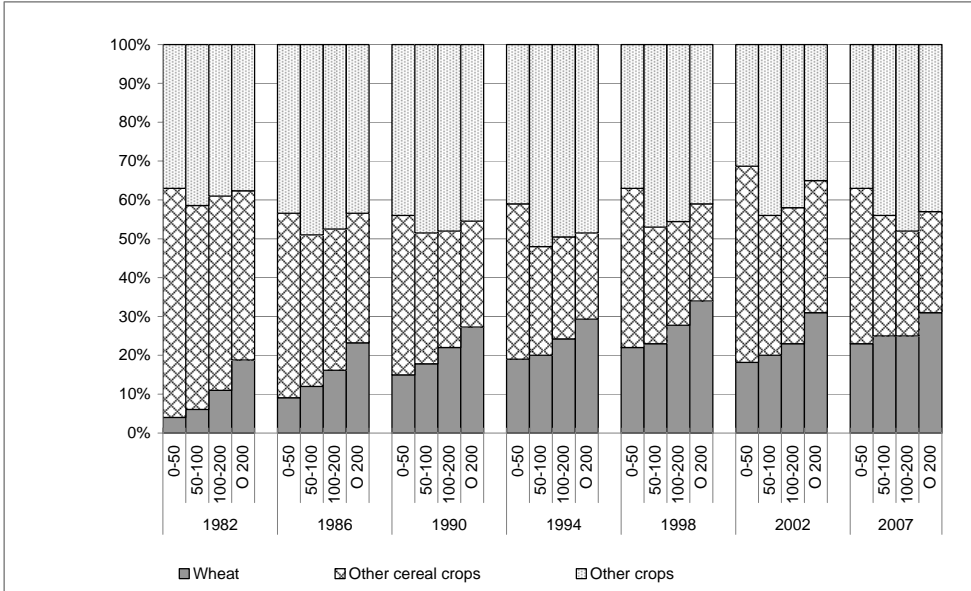

Figure 10.4 Crop distribution area, grouped by farm sizes, 1992-2007 (Statistics Denmark).

The figure shows a significant increase in the wheat area throughout the period for all farms. At the same time the largest farms have had the biggest share of winter wheat. As wheat has given the highest earnings, indications are that the largest properties have increased the winter wheat areas faster than the smaller ones. It also appears that the area with grain (wheat plus

other cereal crops) is approximately the same, accounting for 55-65% of the land. This means, that the crops that have a pre-crop value, have approx. the same share of the arable area, but cereals are more often used as a pre-crop to winter wheat causing some reduction of the yield potential. The area distribution applies to the country as a whole, but there may be significant differences between couties and farms.

On a national level, the area of non-cereal crops that may be grown as pre-crops to winter wheat, is also almost stable. Winter wheat has displaced spring barley, and therefore it is hypothesised that some wheat today is grown on 'poorer' land than in the beginning of the 1980s. Unforunately, this hypothesis may not be examined due to the lack of data. Growing wheat on soils with a lower yield potential, a reduction in the average national yield may be expected.

The structural development has resulted in a higher degree of specialization on the individual farm, which might imply an increase in the roughage area on cattle farms, and an increase in forage grain on farms with pig and crop production. This development will increase the area of winter wheat after cereal crops and contribute to a decrease in the yield potential. The change in crop rotation, and lack of a pre-crop to winter wheat will lead to a decrease in the yield.

10.5 Price relations
The price of the product will be of major importance to the production economics. Furthermore, it must be assumed that higher prices will result in increased focus on productivity and high yields, in this case the wheat yield. On the other hand, increasing costs will result in focus being directed to cost reductions.

Figur 10.5 shows the index for the price of fodder wheat, wage costs (salary) and fertilizer prices. As to the price level, the reference has been taken from the average price of small grain cereals for the assessment of tithe rent charge, which is a weighted average of the prices obtained by the farmers from purchase of wheat from 1st August to 31st December in the current calendar year. Index for wages and for fertilizer are from Statistics Denmark.

This price development weakens the farmer's economic net yield obtained from a higher crop yield. It is of minor importance for the farmer whether the crop yield is 60 or 70 dt. In 1985, the 10 dt was equal to 1,430 DKK in 1985-prices. However, in 2005, the 10 dt was only 430 DKK in 1985-prices. Therefore, a development may have taken place which has led the farmer to reduce his costs and thereby to grow his crop faster/cheaper in order to obtain a high gross yield, at the expense of time and quality. The wages has incresed linearly since 1985, and expressed relative to the wheat price the wages incresed from 40 kg wheat/man-hour to 140 in 2006. The relative fertilizer prices increased slightly in the 1990s, but has increased more significantly since 2000.
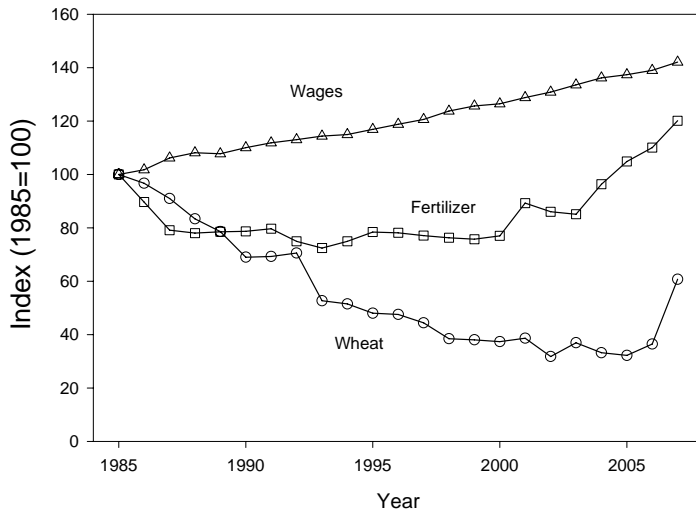
Figur 10.5 Index for wheat prices, fertilizer and wages (Statistics Denmark).

In 1972-73 an intervention price was introduced on wheat, which guaranteed a minimum price. In 1993 an EU area subsidy was introduced, and the intervention price was taken away. The subsidy of approx. 2,300 DKK per ha is equivalent to a yield of 75 dt per ha at a price of just about 30 DKK/dt, equivalent to the price drop between 1992 and 1993. Thus, the income did not drop proportionally. However, the incentive to produce a high gross yield fell drastically, as the area subsidy is independent of the yield. Therefore, there is no economic incentive to increase yields. At the same time the change in subsidies resulted in the price of wheat getting closer to the world market prices.

The considerations about price development may help explain why wheat yields have not increased over the years. However, the problem has been the same in all neighbouring countries in the EU, thus giving no explanation for the development in the individual countries.

10.6 Management thinking

Changes have occurred especially in three areas during the analysis period: 1) Thinking in terms of environment and nature. 2) Professionalism and values. 3) Specialization and differentiation.

10.6.1 Thinking in terms of environment and nature

Throughout the analysis period, a major change has occurred in the way the environmental and nature considerations are handled in the public debate, as well as rules and regulations in

agriculture. Even though there is a high degree of heterogeneity in agriculture, a number of qualitative and quantitative studies support the fact that this debate has contributed to moving the farmers' attitudes in a more environmental direction (Bager & Soegaard, 1994; Noe & Halberg, 2002; Noe et al., 2005; Hansen et al., 2006; Højring et al., 2005; Madsen & Noe 2008; Noe, 2008).

10.6.2 Professional expertise and values

In general, it is expected that the professionalism has moved away from being yield-level fixated to being concerned with the overall profit/earnings on the farm, i.e. from cultivation thinking to business thinking. A number of the above factors must be expected to have affected the professional expertise in that direction, as a result of the structural development, rationalization and owner conditions. New production systems are expected increasingly to put demands on comprehension and organisation as in other types of enterprises. Thereby, the professionalism is no longer connected to the agronomy skills and the production result from a specific field or crop, but rather to the management of a company focusing on the overall context and economy of the farm. This development is, among other things, connected to the size of the farm, as well as employment of non-professional manpower in recent years.

10.6.3 Specialization and differentiation

A third important factor is the increasing specialization and the internal differentiation of tasks. In a large-scale survey about the use of decision support tools, three different ideal typical ways of decision-making in crop production were identified (Langvad & Noe, 2006; Jørgensen et al., 2007a/b):

- Good workmanship, for example more dedicated plant producers
- Management-oriented with more focus on planning and organization of procedures (resource utilization); and finally
- Outsourcing, typically with the farm manager's focus on livestock production as well as occasionally in a very challenging crop. In this case, the focus of the plant production was to find a reasonable balance between effort/action and yield.

The three strategies support the indication that a specialization is happening, in terms of the products that the company is handling as well as a specialization in the area that the specific company focuses on. As the company grows larger, the possibility of outsourcing arises again, with employment of dedicated farm managers in the specific production, where the production thinking will be similar to the two previous strategies. An analysis on the basis of action factors showed a significant difference between the different strategies in, for example, treatment index (Jørgensen et al., 2007b), and it may be expected that there is also a difference in the general yield levels between the three strategies under specialization and outsourcing.

Therefore, a major spread in yield levels must be observed, given the different production strategies. A development that is not necessarily unambiguously related to size or other specific factors. But seen as a whole, this development must indicate that more farms, in their production strategy, focus on conditions other than wheat yields, and therefore with an overall negative effect on the development in the yield of winter wheat.

10.7 Conclusion

Farm management on the individual farm is of major importance to the yields that can be obtained in winter wheat. It is not possible to determine if the actual farm management during the examined time span has changed in a way that would lead to stagnation in the yield increase in winter wheat. However, a number of factors that affect the development of the yield increase, have changed:

- The price of winter wheat has developed unfavourably, and this has resulted in the fact that high yields have had relatively minor importance on the total economy of the farm
- The structural development towards larger farms has not resulted in lower yields on large farms in comparison to small farms - but an increase in the winter wheat area has "moved" the areas out on "poorer" soils, which, all things considered, is assumed to lead to declining yields.
- Presumably, the specialization on the farms has resulted in a more restrained rotation on the individual farms, including permanent wheat with a lower yield potential than first-year wheat with a good preceding crop.
- The study of the development in mechanization – especially with focus on crop establishment – has shown a decrease in capacity of these machines, but on the other hand the machines can be used for more hours
- Seen as a whole, the management thinking must indicate that more farms, in their production strategy, focus on conditions other than wheat yields and therefore can have a negative effect on the development in the yield of winter wheat.
- The major increase in the number of decision support tools and the increase in availability of information should have increased the possibility of increasing yields.

All in all, the conclusion is that a number of factors related to farm management have changed, affecting yields in a negative direction. However, the shortage of farm management data does not allow us to further analyse.

10.8 References and sources

Bager, T. & Søgaard, V. (1994) Landmanden og miljøet. Syddansk universitetsforlag. Esbjerg

Hansen, L., Noe, E. & Højring, K. (2006) 'Nature and nature values in organic agriculture: An analysis of contested concepts and values among different actors in organic farming', *Journal of Agricultural and Environmental Ethics* 19, 147-168.

Højring, K., Noe, E., Busck, A.G., & Erichsen, E.H. (2005) *Landbrugslandet - skabelse og iagttagelse*, Syddansk Universitetsforlag, Odense.

Jørgensen, L.N., Noe, E., Langvad, A.M., Jensen, J.E., Ørum, J.E. & Rydahl, P. (2007a) 'Decision support systems: barriers and farmers' need for support', *OEPP/EPPO Bulletin* 37 (2), 374-377.

Jørgensen, L.N., Rydahl, P., Noe. E., Lanagvad, A.M., Ørum, J.E., Jensen, J.E., Pinnschmidt, H. & Bøjer, O.Q. (2007b) Vurdering af Planteværn Onlines økonomiske og miljømæssige effekt Bekæmpelsesmiddelforskning fra Miljøstyrelsennr. 115 2007 http://www.mst.dk/Udgivelser/publikationer/2007/09/978-87-7052-590-9.htm

Langvad, A. & Noe, E. (2006) '(Re)-innovating tools for decision-support in the light of farmers' various strategies', In: Langeveld, H & Röling, N (eds.), *Changing European farming systems for a better future. New visions for rural areas,* Wageningen Academic Publishers, The Netherlands, p. 335-339.

Madsen, L. M. & Noe, E. (2008) Evaluering af den integrerede rådgivning i AGWAPLAN. Slutrapport i Projekt AGWAPLAN. [www.Agwaplan.dk]

Noe, E. (2008) Drivkræfter og barrierer for omlægning til økologisk jordbrug set ud fra et sociologisk perspektiv. In: H. Alrøe & N. Halberg (eds.) Udvikling, vækst og intergritet i den danske økologisektor- Vidensyntese. ICROFS (1) p 273 – 290.

Noe, E. & Alrøe, H. (2003) 'Farm enterprises as self-organizing systems: A new transdisciplinary framework for studying farm enterprises?', *International Journal of Sociology of Agriculture and Food,* 11 (1), 3-14.

Noe, E. & Alrøe, H. (2006) 'Combining Luhmann and Actor-Network Theory to see farm enterprises as self-organizing systems', *Cybernetics & Human Knowing* 13 (1), 34-48.

Internet sources:
- Statistics Denamek (www.statistikbanken.dk), various tables.
- DAAS Account Database (Landbrugets regnskabsdatabase) Internal database at DAAS.
- Landbrugsinfo (www.landbrugsinfo.dk), various tables concerning machine capacity and economic key figures.

SUMMARY

The Danish national yields of winter wheat are lagging behind and have since the turn of the millennium been surpassed by yields in other north-west European countries. The stagnating yields are a cause of concern for both farmers and farmer's organizations in Denmark.

This project aimed to identify changes in Danish agricultural practice that may explain the stagnating yields. The analyses include effects of soil type, climate and external factors, breeding and genetics, fertilization, plant protection, technology and farm management. Technology was in this context taken as changes in soil tillage and soil compaction, but also considered in relation to farm management.

With focus on the changes since the 1990s we conclude that stagnating yields have not only been observed in Denmark, but also in other north-west European countries. There are several likely contributing factors, and some of these will not persist over time so that yield increases in future may be higher than during the period from 1990 to 2007.