MTT REPORT 109

The management of fungicide resistance in cereals in Finland

Ulla Heinonen, Marja Jalli, Sanni Junnila, Taina Mäkinen (ed.)

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Fungisidiresistenssin hallinta viljoilla Suomessa

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Tiivistelmä

Kasvitaudinaiheuttajat voivat muuntua kestäviksi kasvitautien torjunta-aineita vastaan. Tätä kutsutaan fungisidiresistenssiksi. Tilanne kehittyy yksittäisen tai samalla tavalla taudinaiheuttajaan vaikuttavan usean fungisidin pitkäaikaisesta ja jatkuvasta käytöstä. Fungisidiresistenssin aiheuttavat yksi tai useammat geneettiset muutokset taudinaiheuttajapopulaatiossa. Muutokset periytyvät ja ovat osa taudinaiheuttajan evoluutiota.

Toistaiseksi Suomessa ei ole viljoilla raportoitu markkinoilla olevien fungisidien tehon heikkenemistä. Kuitenkin yksittäisten taudinaiheuttajakantojen testaus on osoittanut, että Suomessa esiintyy kestäviä kantoja ohran verkkolaikusta sekä vehnän piste-, rusko- ja harmaalaikusta.

Tehokkaimmat keinot estää fungisidiresistenssiä ovat fungisidien tarpeenmukainen käyttö sekä taudinaiheuttajapopulaatiossa tapahtuvan valikoitumisen estäminen. Fungisidien käytön vähentäminen on IPM-viljelyn ja fungisidiresistenssihallinnan yhteinen tavoite. Fungisidin valinnassa tulee huomioida useat resistenssin kehittymiseen vaikuttavat tekijät. Viljelijöiden, neuvontajärjestön, kasvinsuojelualan yritysten sekä tutkimuksen tiivis yhteistyö mahdollistaa fungisidiresistenssin ehkäisemiseksi tarvittavan tiedon hankinnan ja jakamisen.

Fungisidiresistenssin hallinta turvaa fungisidien pitkäaikaisen tehon. Resistenssin ehkäisymenetelmät vaihtelevat fungisidiryhmien, taudinaiheuttajien ja kasvilajien välillä. Kaikki ennakoivat toimet, jotka vähentävät fungisidien käyttöä, ovat osa resistenssin hallintaa. Resistenssin muodostumisen ehkäisyssä yhdistyvät monipuoliset kasvinsuojelumenetelmät sekä tarpeenmukainen, useaan tehoaineeseen perustuva kemiallinen torjunta.

Avainsanat:
integroitu kasvinsuojelu, IPM, kasvitaudit, kasvinsuojeluaineet, torjunta-aineresistenssi, viljakasvit

The management of fungicide resistance in cereals in Finland

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Abstract

Fungicide resistance means that the fungicide loses its efficacy on the target pathogen. This situation develops as a response to the continuous use of the same fungicide or continuous use of another fungicide which is related to it through a common mechanism of antifungal action. Fungicide resistance is a result from one or many changes in the genetic construction of the target pathogen population. Mutations are heritable and one part of the pathogens' evolution.

So far, all fungicides are efficient at targeting diseases and there are no reported efficacy losses in Finland. However, the testing of single isolates has shown resistant mutations against net blotch in barley and glume blotch, tan spot and septoria leaf spot in wheat.

The most efficient way to avoid the development of fungicide resistance is to use fungicides only for need and to avoid the selection in pathogen populations. Reducing the use of the fungicides is a joint target for IPM and fungicide resistance management. When selecting the fungicide product, several factors should be taken into account to avoid fungicide resistance. Good co-operation with farmers and research, the advisory service and the pesticide companies is the base to increase and distribute the knowledge on the fungicide resistance management tools.

The target of resistance management strategies is the long-term conservation of fungicide effectiveness. Strategies vary for the different fungicide groups, pathogens and the crop. Every action which leads to avoidance of the fungicide spray is part of fungicide resistance management. Resistance management should integrate preventative cultural practices and optimum fungicide use.

Keywords:
integrated pest management, IPM, plant diseases, pesticides, fungicide resistance, cereals

Hantering av fungicidresistens hos spannmål i Finland

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Abstrakt

Sjukdomsalstrare hos växter kan bli resistenta mot växtskyddsmedel. Detta kallas fungicidresistens. Denna situation uppstår genom långvarig och fortlöpande användning av en enskild fungicid eller flera fungicider som påverkar sjukdomsalstraren på samma sätt. Fungicidresistens orsakas av en eller flera genetiska förändringar i sjukdomsalstrarpopulationen. Förändringarna nedärvs och är en del av sjukdomsalstrarens evolution.

Tills vidare har man inte rapporterat att effekten av fungicider som finns på marknaden skulle ha försvagats i Finland. Tester av enstaka sjukdomsalstrarstammar har visat att det i Finland förekommer resistenta stammar av kornets bladfläcksjuka och vetets blad-, brun- och gråfläcksjuka.

De effektivaste sätten att förebygga fungicidresistens är att använda fungicider endast vid behov samt att förhindra att det sker urval i sjukdomsalstrarpopulationen. Minskad användning av fungicider är ett gemensamt mål för IPM-odling och hantering av fungicidresistens. Vid val av fungicid ska flera olika faktorer som påverkar utvecklingen av resistens beaktas. Ett intensivt samarbete mellan odlarna, rådgivningsorganisationen, företagen inom växtskyddsbranschen och forskningen gör det möjligt att skaffa och distribuera information som behövs för att förebygga fungicidresistens.

Hantering av fungicidresistens tryggar att fungiciderna har en långvarig effekt. Metoderna för förebyggande av resistens varierar beroende på fungicidgrupp, sjukdomsalstrare och växtart. Alla förebyggande åtgärder som minskar användningen av fungicider är en del av hanteringen av resistens. I arbetet för att förebygga uppkomsten av resistens kombineras mångsidiga växtskyddsmetoder samt kemisk bekämpning som bygger på behov och på flera effektiva ämnen.

Nyckelord:

integrerad växtskydd, IPM, växtsjukdomar, växtskyddsmedel, fungicidresistens, sädesväxter

Contents

1 Introduction

Finland is the most northerly country with cereal production. Because of its northern location, Finland has a short growing season but a lot of daylight in summertime. Half of the Finnish agricultural land area is in cereal production and the most common cereal crops are barley and oats. The cereal yield levels are lower than in southern Europe.

The use of the fungicides in cereal production is quite common in Finland: three-quarters of all active farmers uses fungicides at least in some fields every year. Barley and spring wheat are the usual targets for the fungicide sprays. It is rather common to spray the fungicides together with herbicide sprayings and again later in the growing season. In terms of fungicide resistance management, this kind of strategy makes it more challenging.

In fungicides, there are five different modes of action in the Finnish market. It is very important to ensure the effectiveness of the products in the market by using them wisely. This is only possible through good co-operation with farmers and research, the advisory service and the pesticide companies. The main target is to increase farmers' knowledge of fungicide resistance and help them to handle diverse plant protection tools.

So far, all fungicides are efficient at targeting diseases and there are no reported efficacy losses in Finland. However, the testing of single isolates has shown resistant mutations against net blotch, glume blotch, tan spot and septoria leaf spot. Even if the fungicides are effective at the field level, the incidence of resistant isolates may increase if farmers do not take fungicide resistance management into account.

The Finnish integrated pest management approach is based on balanced plant protection guidelines: prevention, monitoring and identification, determination of control requirement, and actual control using an appropriate control method. The general principles of IPM must be taken into practice from 1.1.2014. From the fungicide resistance management point of view, it is positive because IPM is the best way to prevent fungicide resistance.

Photo 1. Barley is the most cultivated cereal crop in Finland. Photo: Marja Jalli.

2 Cereal cultivation in Finland

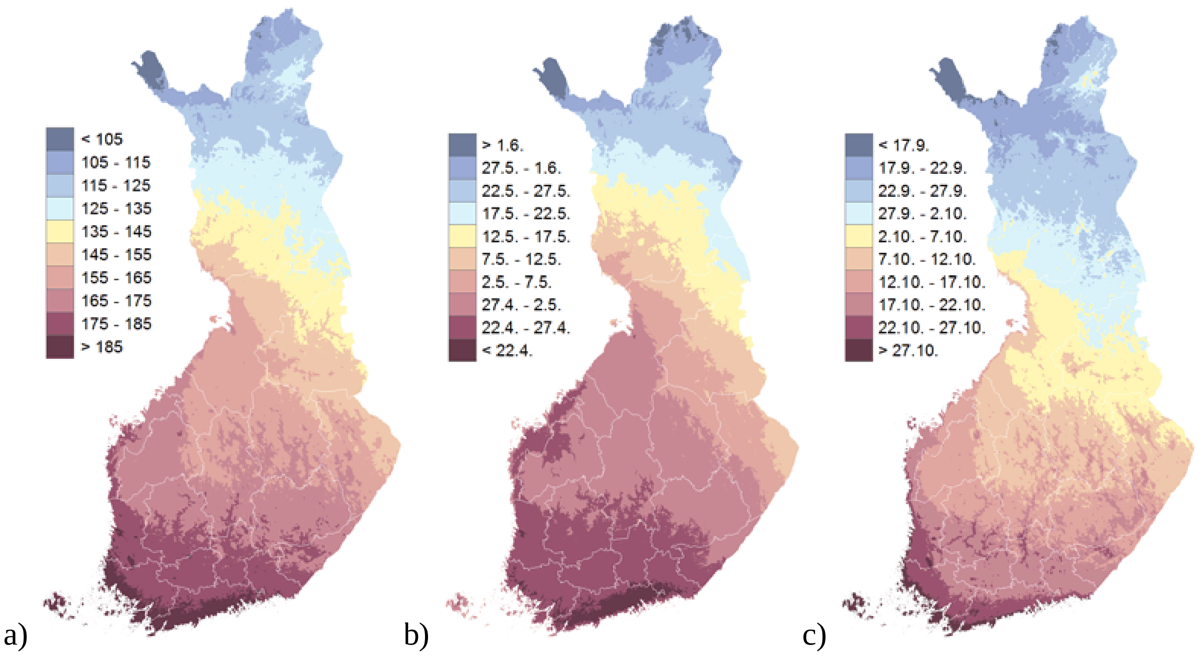
2.1 Climatic conditions

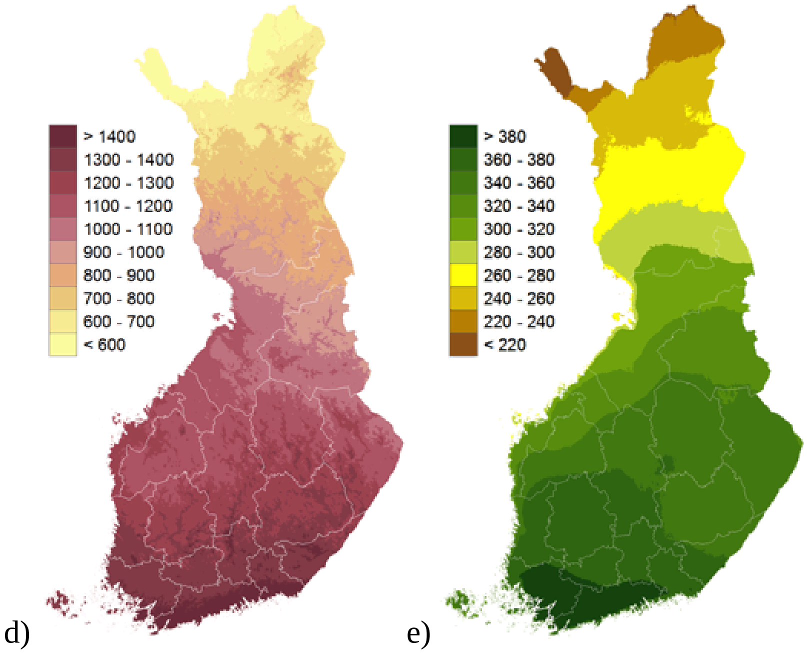
Finland is the most northerly country with cereal production. Most of the cereal production in the other Nordic countries is concentrated in more southern areas than it is in Finland. The Gulf Stream has an influence on the Finnish climate but it is not as strong as in north-west Europe. The climate is more temperate in Finland than in other parts of the world on the same latitude.

The growing season in Southern Finland is about 180 days and in the North it is less than 120 days (Picture 1 a). The growing season normally starts in the south at the end of April and ends before the end of October (Picture 1 b, 1 c). There is more rain than evaporation in Finland. Annual precipitation varies between 550-700 mm in the main cereal production area. Precipitation during the growing season is 300-400 mm in the same area (Picture 1 e).

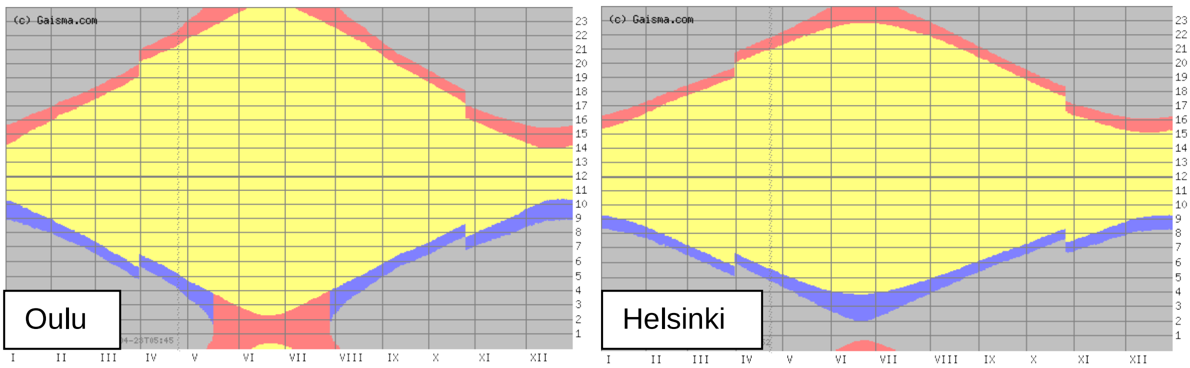
The day length during the growing season is long (Picture 2). In Southern Finland the days are shorter than in the North. In Finland, the cereals develop rapidly because of the significant amount of sunshine and the short growing season. The normal sowing time of spring cereals in Southern Finland starts at the beginning of May and ends at the end of May. The sowing time of winter cereals is from the middle of August to the end of September. Harvesting starts at the beginning of August and normally ends in September, relating to the growing time of the cultivars.

Winter in Finland is long (Picture 3). A continuous frozen winter is very rare in Finland and it is normal that there are mild periods with cloudy weather, rain and brisk wind in wintertime.

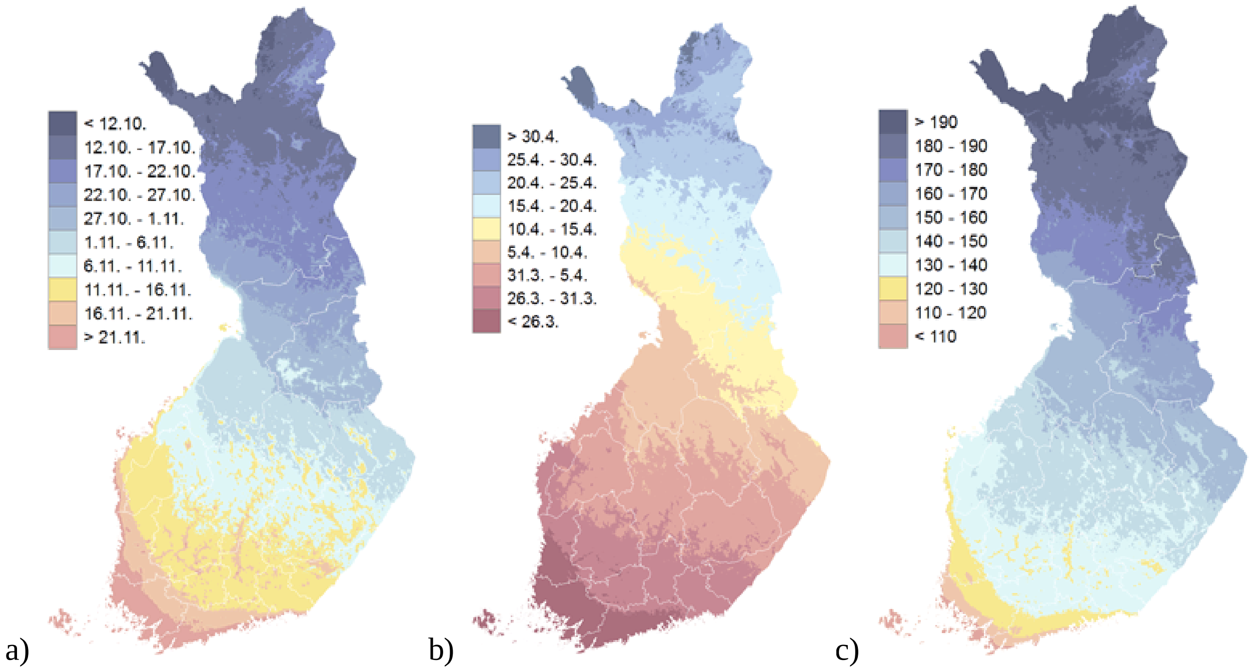




Picture 1. a) The length (days) of the growing seasons (the average temperatures over 24 hours are over +5 °C), b) the beginning of the growing season, c) the end of the growing season, d) the effective temperature sum (Celsius) over the growing season (the sum of the degrees above +5 °C) and e) the average precipitation (mm) over the growing season. The pictures are long-term 1981-2010 averages. Source: Ilmatieteenlaitos, http://ilmatieteenlaitos.fi/terminen-kasvukausi.



Picture 2. The day length graphs from Oulu (65.017°N, 25.467°E) and Helsinki (60.17°N, 24.931°E). The X-axis shows months and the Y-axis the time of the day using the 24-hour clock. Yellow means sunshine, red dusk, blue dawn and grey darkness. The displacement in the graphs represent the start and end of Daylight Saving Time. Source: www.gaisma.com



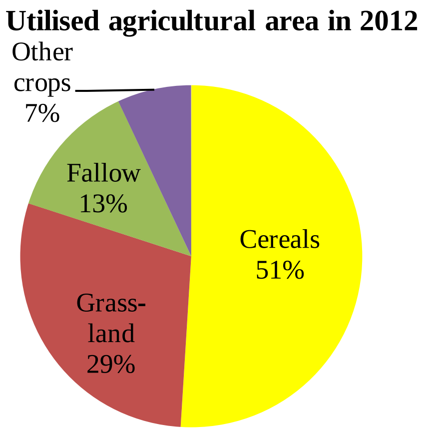
Picture 3. a) The beginning of winter (the average day temperature is less than zero Celsius), b) the beginning of spring, c) the length (days) of the winter. The pictures are long-term 1981-2010 averages. Source: Ilmatieteenlaitos, http://ilmatieteenlaitos.fi/talvitilastot

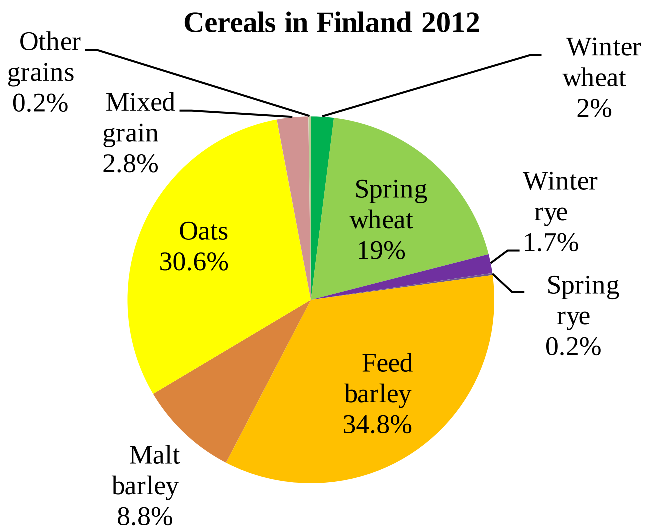
2.2 Cereal production

In Finland, the area used for agriculture is about 6% (2.3 million hectare) of the total area. The average size of the farms was 38.9 ha in 2012. Two-thirds of the farms are used for plant production and close to one-third for livestock production. More than half of the agricultural area is under cereal production (Picture 4). Milk production is the biggest livestock sector in Finland. Most of the cereals are sown in spring, only 3.7% of the cereals are winter types (winter wheat and winter rye).

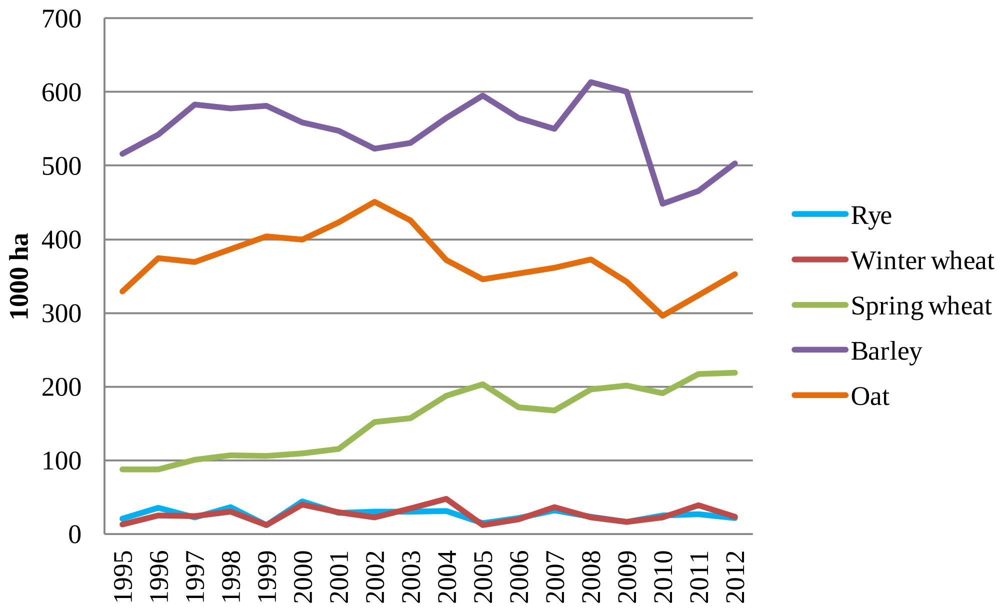
Spring barley has been the most common cereal in Finland (Picture 5) since the end of the 1970s. Earlier, the most common cereal was spring oats, which is now the second largest cereal crop in Finland. In recent years the highest increase in growing area has been for spring wheat. The growing areas for rye and oil seed crops have slightly decreased in recent years.

The Finnish official variety list is published annually in the Finnish Plant Variety Journal. The highest amounts of cultivars are released in spring barley (Table 1). In Finland, there is one plant breeding company, Boreal Plant Breeding Ltd, which is the market leader in their sector.





Picture 4. Cereals are the most common field crops in Finland. The cultivated area of cereals was 1153.6 thousand hectares in 2012. See also Appendix A. Source: OSF, Utilised Agricultural Area



Picture 5. The cultivated area of cereals in Finland in 1995–2012. Source: OSF, Utilised Agricultural Area, 1910 and 1920-2012

Table 1. The number of the cereal varieties on the Finnish seed market in 2011. Source: Evira, Finnish Plant Variety Journal

	Number of varieties 2012, total	***Variety applicant: Boreal Plant Breeding Ltd.***	***Variety applicant: other***
Oats	37	18	19
Hulled oats	2	1	1
Barley, total	75	24	51
Multi-rowed	28	17	11
Two-rowed	47	7	40
Malting barley	13	4	9
Winter rye	14	6	8
Spring rye	3	0	3
Spring wheat	23	10	13
Winter wheat	12	4	8
Triticale	3	0	3

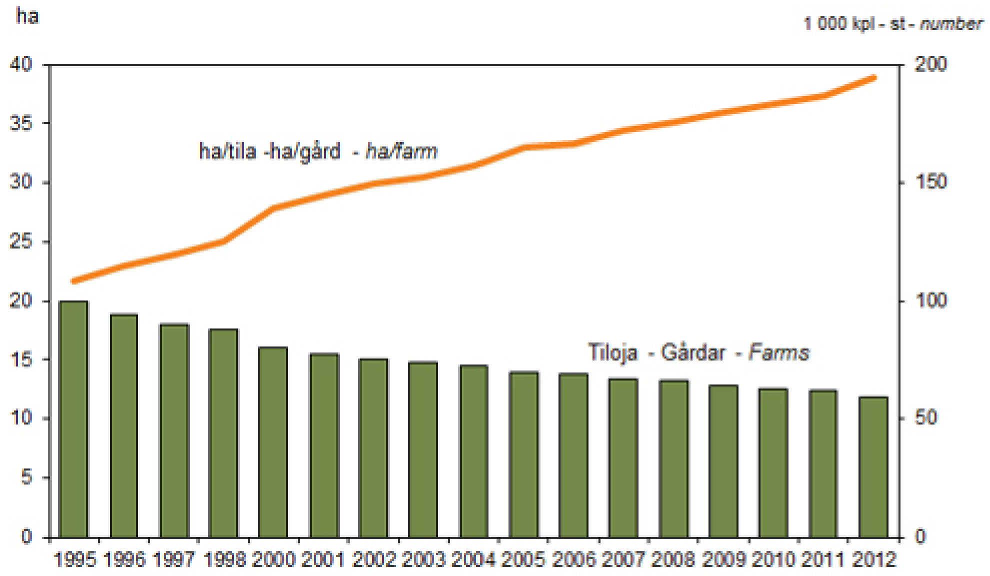
2.3 Cultivation systems

Farms are quite small in Finland (Picture 6). In addition, the plots are relatively small and the shape of the fields is often scrappy.

Ploughing is the most common cultivation method in Finland (covering 50% of the cereal growing area). About 10% of the total area is under no-tillage and the rest is under minimum tillage. The tillage is generally carried out in autumn (Table 2).

The average yield of winter wheat in Finland is 3,750 kg/ha, spring wheat 3,600 kg/ha, rye 2,500 kg/ha, feed barley 3,400 kg/ha, malting barley 3,600 kg/ha and oat 3,200 kg/ha (Appendix B). The fertilizer levels are related to the crop, soil type, locality, yield level and environmental limits. For example, for winter wheat 120 kg/ha nitrogen can be used if the expected yield level is 4,000 kg/ha and 140 kg /ha nitrogen can be used for 5,000 kg/ha expected yield.

Even though the benefits of crop rotation are well known, the practical use of crop rotation is relatively low (Table 3). There are some visible changes in good crop rotation practice within those farms that produce wheat or rye (Table 4). Feed cereals, barley and oats are most often cultivated in monoculture (Table 3 and 4).



Picture 6. The number of farms and the average field area per farm in 1995-2012 in Finland. Source: OSF, Number of farms and average arable land area 1995-2012

Table 2. Basic cultivation by production sector 1 July 2009 – 30 June 2010. Source: OSF: Tike, Farm Structure Survey, Agricultural Census 2010. Source: OSF: Tike, Farm Structure Survey, Agricultural Census 2010

Production sector	***Utilised agricultural area*** *1000 ha*	***Tilled and/or sown arable area*** *1000 ha*	*%*	***Method of cultivation, % of the arable area*** *Autumn ploughing*	*Spring ploughing*	*Conservation tillage[1)]*	*Sowing in untilled soil[2)]*
Pig husbandry	144	118	82	40	9	41	10
Poultry husbandry	44	36	81	39	9	40	13
Cereals production	950	629	66	43	12	29	17
together	1 137	784	230	40	10	37	13
All production sectors	**2 292**	**1 228**	**54**	**46**	**14**	**28**	**13**

1) Cultivation performed with a cultivator, disk cultivator, harrow, rotary hoe, etc. If the arable area was both conservation tilled and ploughed, it is only included in the ploughed area.
2) Does not include supplementary sown grassland area.

Table 3. Arable land cultivated with the same crop[1)] in the years 2008-2010, by production sector. Source: OSF

Production sector	***1000 ha***	***% of the utilised agricultural area***
Pig husbandry	48.2	34
Poultry husbandry	8.8	20
Cereals production	190.2	20
All production sectors	**450.6**	**20**

1) Does not include area that was used for permanent grassland, berry bushes or fruit trees, or greenhouse area.

Table 4. The percentage of field hectares with the same crop over two continuous growing seasons. The percentage values are counted per three periods.
Source: Jauhiainen, L. and Keskitalo, M. Viljelykäytännöt peltolohkotilastojen näkökulmasta, http://www.smts.fi/Viljelykierrosta_vihreaa/Jauhiainen_Viljelykierto.pdf

	Period		
Crop	**1995–1999**	**2001–2005**	**2007–2011**
Feed barley	57	57	60
Oat	51	57	60
Spring wheat	50	44	38
Malting barley	40	48	43
Winter wheat	32	23	17
Winter rye	15	17	13

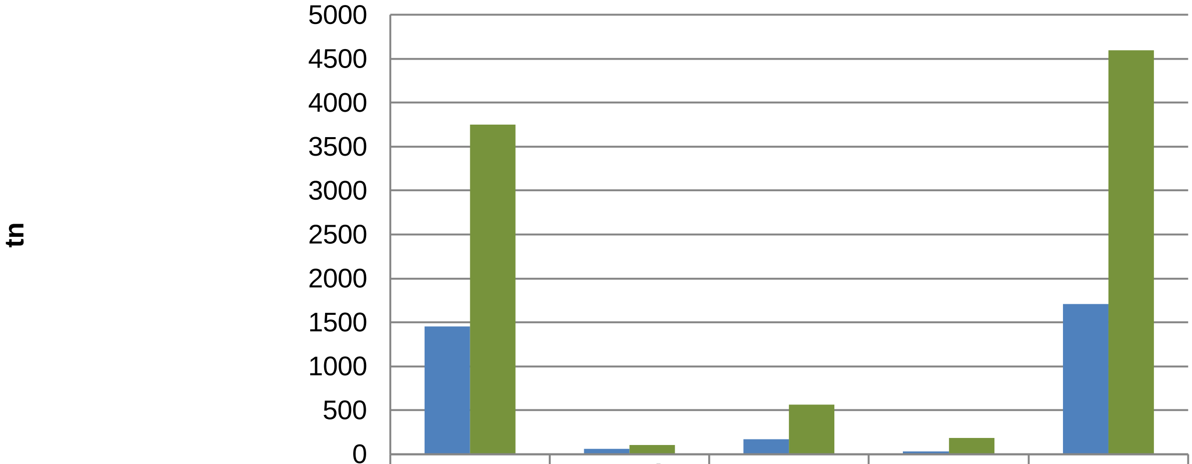
2.4 Use of plant protection products

In agriculture, herbicides are the largest pesticide group, accounting for 85% of the total volume of active substances sold in 2011 (Picture 7). The use of the plant protection products in Finland per hectare remains clearly below the rates used in Central and Southern Europe. In Finland, fungicides cover 10% of the total volume of the active substances sold in 2011.

The rhythm of cereal growth is very fast in Finland (Picture 8). The growth of spring barley is particularly rapid between the beginning of stem elongation stage (the first fungicide spraying time) and the flag leaf stage (the second fungicide spraying time) – there is normally only one week between these growth stages.

According to Aleksi Mäenpää's survey of Finnish farmers, three-quarters of all active farmers use fungicides in at least some fields every year. Fungicide use is more frequent on bigger farms. 80% of the farms with 50-110 hectares use fungicides every year and in farms more than 110 ha fungicides are used annually. Barley in particular is sprayed routinely every year. Farmers have listed several factors, like observations made in the field and the price of the cereal yield, which have influenced the decision of fungicide use. There is variation in the timing and dosage of the fungicide sprayings. The primary fungicide spray together with herbicides is either half (50% of farmers) or full (16% of farmers) doses. The primary fungicide spraying together with growth regulators is done by 31% of farmers with half dose and 24% of farmers with full dose. The primary fungicide spray alone at the time of the flag leaf is done by 21% of the farmers with half dose and 30% of the farmers with full dose.

There are five different mode of action groups in fungicides for spraying and four different mode of action groups in seed treatment fungicides on the Finnish market (Tables 5 and 6). There is only one biological product for cereal seed treatments on the Finnish market. The most common active substance in the spraying products is propiconazole, which is a common partner in the mixtures. Among the seed treatment products, the most common active substance is imazalil.



	Herbicides	Growth regulators	Fungicides	Insecticides	Total
Active substance sales 2011 (tn)	1452	59	169	27	1708
Product sales 2011 (tn)	3749	105	562	184	4600

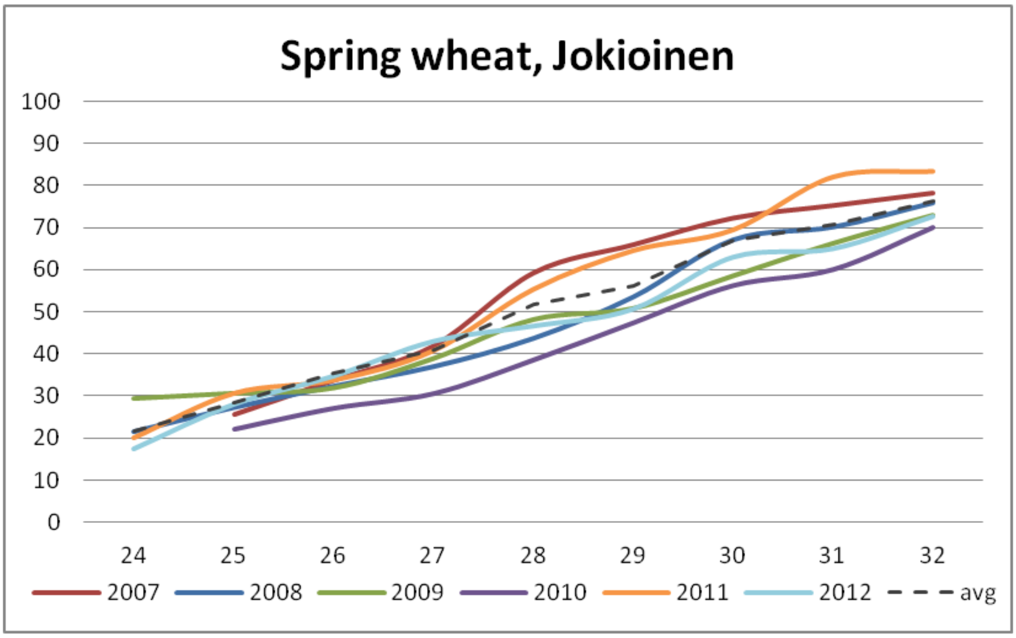
Picture 7. Summary of the volume of agricultural plant protection product sales in Finland in 2011. Source: www.tukes.fi > Plant protection products > Sales statistics

Table 5. Fungicide spraying products for cereals in Finland in 2013. Source: Tukes kasvinsuojeluainerekisteri and www.frac.info

MOA code	*Group name*	*Common name*	*Products: alone and mixtures*		*FRAC code, comments*
Respiration C3	QoI fungicides (strobilurine)	Azoxystrobin	Amistar, Mirador 250 EC		11 *High risk for resistance*
		Picoxystrobin	Acanto	Acanto Prima	
		Pyraclostrobin	Comet Pro	Comet Plus, Jenton	
		Trifloxystrobin		Delaro SC 325, Stratego EC 250	
Sterol biosynthesis in membranes (G1)	DMI (DeMethylation Inhibitors)	Difenoconazole		Armure	3 *Medium risk for resistance*
		Metconazole	Juventus 90	Delaro, Prosaro	
		Propiconazole	Bumper 25 EC, Tilt 250 EC	Akopro 490 EC, Armure, Basso, Bravo Premium, Menara, Stereo 312.5 EC, Stratego EC 250, Tilt Top 500 EC, Zenit 575 EC	
		Syprokonatsoli		Menara	
		Tebukonatsoli		Prosaro EC 250	
		Prothioconazole	Proline 250 EC	Delaro SC 325, Prosaro EC 250	
		Prochloraz	Sportak EW	Akopro 490 EC, Basso	
Sterol biosynthesis in membranes (G2)	Amines ("Morpholines")	Fenpropidin	Tern 750 EC	Zenit 575 EC	5 *Low to medium risk of resistance*
		Fenpropimorph		Comet Plus, Tilt Top 500 EC, Jenton	
Amino acids and protein synthesis (D1)	AP - fungicides (Anilino-pyrimidines)	Cyprodinil		Acanto Prima, Stereo 312.5 EC	9 *Medium risk of resistance*
Multi-site contact activity	Chloronitriles	Chlorothalonil		Bravo Premium	M5 *Low risk of resistance*

Table 6. Seed treatment fungicides for cereals in Finland in 2013. Source: Tukes kasvinsuojeluainerekisteri and www.frac.info

MOA code	***Group name***	***Common name***	***Products: alone and mixtures***		***FRAC code, comments***
Signal transduction (E2)	PP-fungicides	Fludioxonil	Celest Formula M		12 *Low to medium risk of resistance*
Mitosis and cell division (B1)	MBC-fungicides	Fuberidazole		Baytan Universal	1 *High risk of resistance*
Sterol biosynthesis in membranes (G1)	DMI fungicides (DeMethylation Inhibitors)	Cyproconazole		Zardex G	3 *Medium risk of resistance*
		Imazalil	Fungazil A 25, Fungazil E	Baytan I-peittausjauhe, Baytan Universal, Viljan Täyssato -jauhe, Viljan Täyssato -neste, Zardex G	
		Prothioconazole	Redigo FS 100	Lamador FS 400	
		Tebuconazole		Lamador FS 400	
		Triadimenol		Baytan I-peittausjauhe, Baytan Universal	
Respiration (C2)	SDHI	Carboxin		Viljan täyssato -jauhe, Viljan täyssato -neste	7 *Medium to high risk of resistance*
		Pseudomonas chlororaphis MA 342	Cedomon, Cerall		*Biological*



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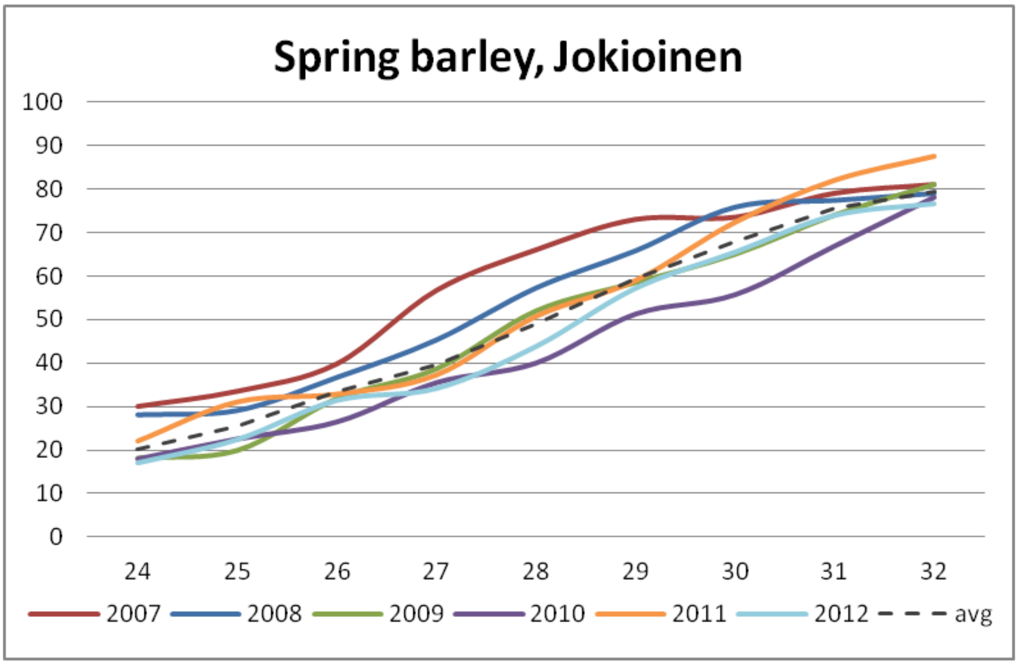


b)

Picture 8. The growth rhythm of spring wheat and spring barley in Jokioinen in 2007-2012 and on average. The growth stages (BBCH scale) are represented on the Y-axis and the time in calendar weeks on the X-axis. Source: Päivi Koski, MTT Agrifood Research Finland, fungicide spraying trials in 2007-2012

3 Integrated pest management, IPM

The FAO definition: Integrated Pest Management (IPM) means the careful consideration of all available pest control techniques and the subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions at levels that are economically justified and reduce or minimise risk to human health and the environment. IPM emphasises the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms.

IPM underlines the preventative methods in crop protection instead of chemical plant protection. Preventative methods and the chemical plant protection are not contradictory methods in IPM: chemical plant protection is a part of IPM and is used only when needed.

The Finnish Ministry of Agriculture and Forestry has issued a decree outlining the general principles of IPM, which professional users of plant protection products must follow from 1 January 2014. Many farmers are familiar with the principles of integrated pest management and follow them already.

The Finnish IPM approach is based on balanced plant protection guidelines. Integrated pest management is based on a four-tiered approach: prevention, monitoring and identification (observation), determination of control requirement (level of threat), and actual control using an appropriate control method.

IPM is a decision-making process. The process involves the following key considerations:

1. The selection and combination of compatible plant protection methods.
2. The choice of control measures is based, for example, on the use of qualified advisors, field observations, forecasting methods and threshold values.
3. IPM takes the benefits arising from plant protection with respect to the farmer, society and the environment into consideration. These include economic benefits as well as benefits that are not easily measurable in monetary terms, such as reduced plant protection product pollution, improved working conditions, and enhanced end product quality due to reduced resistance to plant protection products.
4. IPM considers the crop to be protected with respect to the biotic community as a whole, including beneficial organisms.

In the law regulation of the Ministry of Agriculture and Forestry, the general principles of IPM are listed:

Preventative methods
Crop rotation
Cultivation of soil
The crop variety choice
Well-balanced fertilization

The methods within the growing season
Threshold values
The forecast models of the plant disease
The forecast methods of the bird cherry-oat aphid
The use of the crop protection windows
Prevention of resistance
The bookkeeping of the observations and the effects

4 Fungicide resistance

Fungicide resistance means that the fungicide loses its efficacy on the target pathogen which is no longer sufficiently sensitive to the fungicide. Generally, this situation develops as a response to the continuous use of the same fungicide or continuous use of another fungicide which is related to it chemically and/or biochemically through a common mechanism of antifungal action. The speed of the fungicide resistance development depends on both fungicides and target pathogen qualities.

If the fungicide spray has no effect against the disease, one reason can be fungicide resistance. However, there are also other possible reasons for poor efficacy, like challenging spraying conditions, deteriorated or wrong product, rain soon after application, misidentification of the pathogen, or unusually heavy disease pressure.

4.1 Resistance as part of evolution

Fungicide resistance is a result from one or many changes in the genetic construction of the target pathogen population. Resistance is heritable. Spontaneous mutations are continuously occurring in all living organisms, also in pathogen populations. Mutations are natural and are one part of the pathogens' evolution.

A mutant gene that causes the development of a particular resistance mechanism pre-exists in tiny amounts in the pathogen population. Without natural selection, such a mutation would confer no advantage to the growth or survival of the organism and it would not become general in the pathogen population. Through continuous selection, the mutant gene will benefit and become more common within the population.

In a situation without fungicides, the resistant mutant might exist at a frequency of 1 in 1,000 million spores or other propagules of the pathogen. Amongst the survivors of a fungicide treatment, the resistant forms will be in a much higher proportion according to natural selection. When the resistant form is in 1% or even 10% of the population, chemical control has lost its efficacy and the presence of resistant individuals has become detectable. Even though the obvious onset of resistance is often sudden, resistance may have been building up insidiously at undetectable levels. The speed of development of fungicide resistance is often related to the efficacy of the product. If the fungicide is only 80% effective, the number of variants will be concentrated less after each treatment and the build-up will be slower.

4.2 Different types of resistance

The 'qualitative' or '**single-step'** resistance appears by sudden as a marked loss of effectiveness. It is the simplest form of resistance, and is known as major gene resistance, based on one-point mutation in the genetics of the target disease population. One-point mutation causes a single amino acid change in the target protein and the fungicide cannot work anymore. Once developed, it tends to be stable. If the concern is withdrawn, pathogen populations can remain resistant for many years. The single-step resistance is characteristic of several major fungicides groups including benzimidazoles, phenylamides, dicarboximides and QoIs.

'Quantitative' or **'multi-step'** resistance appears less suddenly than single-step resistance. The role of one-point mutation is not so big in multi-step resistance as in single-step resistance. Multi-step resistance develops gradually and is partial and variable in degree. In multi-step resistance, the strength of the resistance is stronger when several genes are mutated into the resistant form. It reverts rapidly to a more sensitive condition under circumstances where the fungicide is less intensively used and alternative fungicides are applied. Multi-step resistance is characteristic of resistance within DMI fungicides.

'Cross-resistance': Pathogen populations that are developed resistant to one fungicide simultaneously and automatically become resistant to other fungicides that are affected by the same gene mutation and the same resistance mechanism. Generally, they are fungicides that bear an obvious chemical relationship to the other fungicide, or which have a similar mechanism of fungitoxicity.

Some pathogen strains are found to have developed separate mechanisms of resistance to two or more unrelated fungicides: **‘multiple resistance’**. These arise from independent mutations that are selected by exposure to each of the fungicides concerned.

Photo 2. Net blotch is the most common barley disease in Finland. Photo: Marja Jalli.

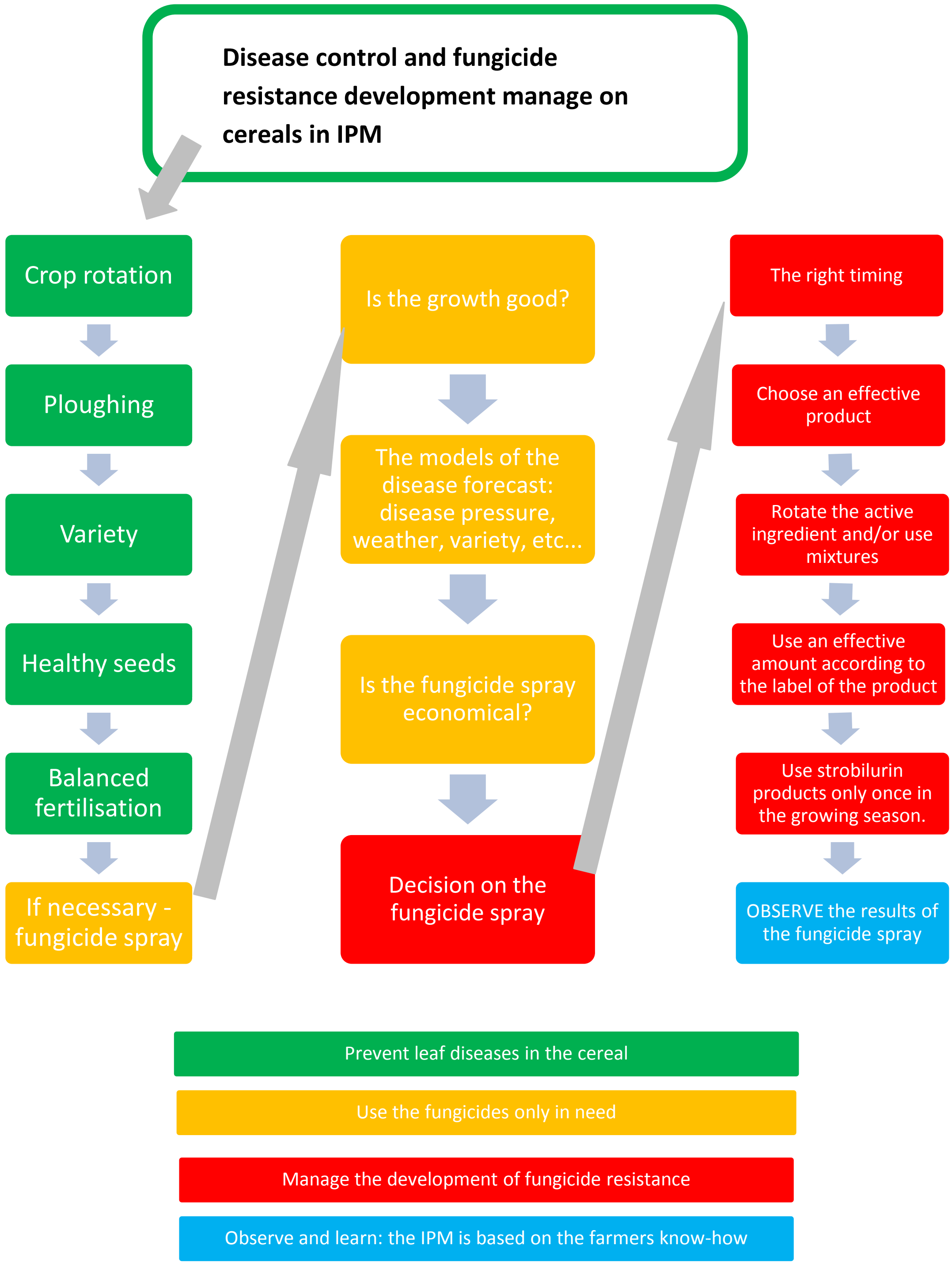
5 Management of fungicide resistance in Finland

The most efficient way to avoid the development of fungicide resistance is to avoid the use of fungicides. If there is no natural selection, the amount of the naturally formed resistant mutations stays low. However, fungicides are part of present-day farming because farmers can use them to rehabilitate the other cultivation inputs like fertilizer from the field.

It is important to decrease the use of the fungicides over a short and long time frame. This is a joint target for IPM and fungicide resistance management. The decision chain of IPM production and fungicide resistance development management is shown in Picture 9. When a farmer is investing in the prevention of cereal diseases, the use of fungicides can be decreased. When selecting the fungicide product, several factors should be taken into account to avoid fungicide resistance. It is important to observe how the product works and learn from the observations: the IPM is based on the farmers know-how.

So far, all fungicides are efficient at targeting diseases and there are no reported efficacy losses in Finland. However, the testing of single isolates has shown resistant mutations against net blotch, glume blotch, tan spot and septoria leaf spot (Table 7). Even if the fungicides are still effective at the field level, there are mutations which can become general if the farmers do not take fungicide resistance management into account.

Photo 3. Importance of rusts has been increasing especially in wheat cultivation in Finland. Photo: Marja Jalli.



Picture 9. IPM and fungicide resistance management go hand in hand

5.1 Preventing cereal leaf diseases

In avoiding the development of fungicide resistance, the main effort is decreasing the amount of pathogen propagules in the field and minimising the risks for selection. Diverse plant protection methods are available and their efficacy is related to pathogen species and the environment.

Crop rotation is the basis of IPM and fungicide resistance management, because it is a natural and economical way of controlling the amount of pests and it has several other benefits for plant production. Crop rotation has a positive effect on the soil structure and helps with nutrition uptake. When several plant species are grown on a farm, the risks brought about by the weather or the markets are reduced.

Crop rotation is most efficient on diseases with one host. Most leaf spot diseases are host-specific, like net blotch in barley and Stagonospra blotch in wheat. In a no-tillage system, crop rotation is even more important. Stem and ear diseases caused by *Fusarium* fungi cannot be handled exclusively with cereal-based rotation. Therefore, oil seed crops are recommended in the rotation in order to decrease the *Fusarium* risk. Airborne diseases such as mildew and rusts cannot be controlled by field-based crop rotation.

The **tillage** system has an influence on the amount of the plant residues above the soil, the soil structure and the occurrence of weeds and some insects. Leaf spot diseases in cereals overwinter in plant residues. Tillage decreases the amount of plant residues above the soil and thus decreases the amount of the primary infection of leaf spot diseases. In addition, environmental conditions in autumn, winter and spring have an influence on both the amount of crop residue and the overwintering of pathogens. All methods that have a positive effect on the decomposition of plant debris decrease the amount of straw-borne pathogens in a field. On the other hand, microbial activity is higher in the no-tillage system and can have an antagonistic effect on pathogens.

Decisions on **crop variety** are relevant to the use of the yield and the feature of the field and also the disease tolerance of the varieties. The disease tolerance of the variety has to be taken into account when the farmer plans the necessity or redundancy of the use of fungicides.

A **healthy and quality seed** is the basis of good cereal growth. Several cereal diseases overwinter and spread with the seeds. Smut diseases, leaf stripe in barley and mould which reduces the germination of seeds can only be controlled with the correct seed staining products. Many cereal leaf diseases, like net blotch, scald, common root rot (*Cochliobolus sativus*), oat leaf spot, stagonospora nodorum blotch and to some extent also tan spot, overwinter in the seeds as well as in the plant residues. If the farmer is using seed from his or her own yield, it is very important to find out the health of the seed in the lab. It is vital to know whether there is a need to use a seed staining product.

Balanced fertilisation is important for the crop, the environment and the economy. If the cereal has a lack of some nutrients, growth suffers and it cannot take the other nutrients in as normal. In such cases, the yield will be lower and the farmer will lose money because there are untapped nutrients in the field or in the worst case they enter the water system. When the fertilisation is based on the fertility report, it is possible to fertilise the cereals according their needs and at the right time of the year. It is very important to recognise the symptoms of the nutrient deficiency from the symptoms of the plant disease. For example, the symptoms of leaf stripe in barley and the lack of manganese symptoms are similar.

5.2 Fungicide use patterns

The target of resistance management strategies is the long-term conservation of fungicide effectiveness. It should be implemented before resistance becomes a problem. Strategies vary for the different fungicide groups, pathogens and the crop. Resistance management should integrate cultural practices and optimum fungicide use. Probably the most important aspect is the use of tank mixtures and alternating fungicides with a different mode of actions.

Fungicide resistance does not develop without the use of the fungicides. Every action which leads to avoidance of the fungicide spray is part of fungicide resistance management. The idea of IPM is to work alongside fungicide resistance management. Every step mentioned earlier in the chapter ‘Preventing the cereal leaf diseases’ creates the basis for fungicide resistance management.

There are several tools that use fungicides to reduce disease pressure and selection for fungicide resistance: use only when justified (avoids unnecessary selection), use protectively (hits small populations), achieve good spray coverage (reduces populations exposed to selection), use tank mixes (reduces populations exposed to selection), and alternate fungicides from different fungicide groups (reduces selection time).

Before fungicide spraying, the need for spraying should be estimated either based on symptoms or forecast models. Different thresholds for different diseases are determined and two Internet-based disease forecast programs are available (WisuEnnuste and ProPlant) in Finland. However, the final decision is always the farmer's and is based on observations and the information available.

Timing. Treatment timings are reflected and decided according to disease development. Due to the rapid growth rhythm and the short growing season, single spraying is in most cases the best strategy. Split application is only recommended in monoculture and reduced tillage systems or in cases of heavy seed-borne disease infection.

Effective product. The target is to keep disease levels at an acceptable level. Advisory company ProAgria publishes a booklet each year with information on the efficacy of different products on different diseases as well as the costs of the treatments.

Rotation of the active ingredient and/or use of mixtures. Alternation or the use of mixtures with different modes of action minimise the risk of resistance development. The availability of a number of different types of fungicides is highly beneficial, both environmentally and in order to overcome resistance problems. The partner compounds applied will dilute the selection pressure exerted by the at-risk fungicide and inhibit the growth of any resistant biotypes that arise. The partner compound can be a multi-site compound known to have a low risk of inducing resistance. Alternatively, it can be a single-site fungicide that is known not to be related to its partner by cross-resistance or by similar mode of action. There is a risk of selecting dual-resistant strains when using a mixture of two single-site fungicides, but the changes of two mutations occurring simultaneously will still be very small compared to that of a single mutation. According to the research, the use of both mixtures and rotations can delay, but not prevent, the build-up of resistant variants.

The temptation to reduce the **rate of application** of fungicides is mainly to reduce costs, but for environmental reasons, especially in conditions where disease pressures are usually low or the risk of financial loss from reduced performance is not great. In point of view of fungicide resistance development, reducing the dose could enhance the development of resistance. When a farmer is using a product according to the manufacturer's instructions, the products will retain the built-in safety factor and secure the claimed levels of performance under a wide range of conditions.

The relationship between fungicide dose and the risk of resistance are not yet fully established. According to some models, a lower dose of the at-risk fungicide can delay the build-up of major gene resistance by decreasing the overall effectiveness, increasing the number of sensitive survivors and hence slow down the selection of resistant forms that can survive the full dose. With regard to multi-step resistance, it has been argued that lowering dose can enhance resistance development by favouring the survival of low-level resistant forms, which would be inhibited by the full dose. The low-level resistant forms could then mutate further and recombine sexually to give higher levels of resistance.

Experimental data regarding the effects of different doses are still rather limited and confusing. However, instead of reducing the amounts used, it is smarter to use the products according to the instructions when spraying the fungicide and turning the fungicide sprays off if they are not absolutely necessary. The decision to turn the fungicide spray off requires the farmer to have faith in his or her own knowledge.

Use strobilurins only once in the growing season. The number of seasonal applications of active ingredients from the same chemical mode of action should be limited. That reduces the total number of applications of the at-risk fungicide and slows down selection to some extent. It can also favour the decline of resistant strains that have a fitness deficit. In addition, the other class of fungicides cannot resist continued and intensive use without there being an impact on the development of the fungicide resistance.

In Finland there are no strict recommendations on the use of strobilurin against wheat diseases as there are in Central Europe, but it is important to use strobilurins only in mixtures with products characterised by other modes of action and just once in the growing season. There is an indication that strobilurins are less effective on glume blotch in Sweden and Norway. Widespread resistance to *M. nivale/majus* is now found also in the Nordic region. QoIs remain effective against rust diseases in wheat. Strobilurins are efficient against *Rhynchosporium secalis* and rust in barley. Their efficacy on net blotch is reduced for some strobilurins compared to previous years in some areas in the Nordic region.

Reduced efficacy has been observed with some DMIs on Septoria leaf blotch and net blotch in the Nordic region. In situations of high risk, it is recommended to choose the most efficient DMI products. Their performance will be improved if they are mixed with compounds with different modes of actions.

It is important to **estimate the success of the fungicide treatment afterwards**. Small areas that are not treated with fungicides, known as windows, help in the evaluation of the effectiveness of the fungicide spray. Documentation is an essential part of the strategy work.

5.3 Role of research in the management of fungicide resistance

NORBARAG (Nordic Baltic Resistance Action Group) was formed in 2008 as a group of representatives from research institutes and chemical companies from Denmark, Estonia, Finland, Latvia, Lithuania, Norway and Sweden. The group includes representatives from pesticide resistance research, pesticide efficacy evaluation, and representatives of the agrochemical companies operating in the Nordic-Baltic region. There are three sub-groups in the NORBARAG: fungicides, herbicides and insecticides. NORBARAG is registered as an NJF (Nordic Association of Agricultural Scientists) working group. NORBARAG is independent but maintains contacts with HRAC, FRAC and IRAC, which have representation only from the agrochemical industry.

The NORBARAG fungicide sub-group monitors the resistance situations in cereals by collecting and analysing the disease samples from participating countries. MTT Agrifood Research Finland collects the samples from Finland and sends them for analysis. In addition, the knowledge shared by the other NORBARAG countries is crucial information. The current situation of fungicide resistance in cereals is presented in Table 7.

The open communication between the researchers, chemical companies, advisory systems, authorities and farmers ensures continued access to reliable and up-to-date information.

Table 7. The main foliar cereal diseases in Finland and their resistance situations. Source: www.mtt.fi/norbarag

The disease	Epidemiology in brief	Importance in Finland	Resistance situation
Glume blotch (*Stagonospora nodorum*)	Hosts: spring and winter wheat (and barley) Live in plant residues and in seeds	Very common, especially in rainy and rather cool summers.	From Sweden. QoI resistance has been confirmed in five fields (2003-2005) where G143A mutation has dominated the population. Samples from the whole Nordic/Baltic region in 2011 showed resistance in several samples throughout the region.
Septoria leaf spot (*Mycosphaerella graminicola*)	Hosts: more common in winter wheat, but also in spring wheat	Importance is increasing in Finland. Previously found only in winter wheat, nowadays also in spring wheat.	Resistance to QoIs (strobilurins) nowadays affects all regions producing cereals. QoI resistance has been verified in Denmark, Sweden, Finland, Estonia, Latvia and Lithuania. So far only Norway has not been tested. Concerning triazoles, the current *M. gramincola* strains show a low or moderate resistance to these compounds. The moderate resistant isolates have been found to be present to a different degree in the Nordic/Baltic region.
Tan spot (*Pyrenophora tritici-repentis*)	Hosts: spring and winter wheat (and barley and rye) Overwinter in the plant residues (and seeds)	Very common, especially in the moist and warm summers in minimum tillage fields.	Observations carried out in the Nordic region show the presence of three different mutations, either in position F129L, G137R or in position G143A for strobilurins. Approximately 50% of the isolates in Sweden and Denmark have so far been seen to have mutations. Samples from Lithuania and Latvia have also shown occurrences of the mutation G143A, and low levels have also been found in Finland. Efficacy of strobilurins can be significantly affected by mutations. Clear signs of cross-resistance between DMIs were measured, but no sign of mutations in the CYP51 gene was found when analysed. In 2012 trials, triazoles are still found only to provide moderate levels of tan spot control.
Powdery mildew (*Blumeria graminis*)	Hosts: mainly wheat and barley but also rye and oats Needs a live plant to survey	Depends on the year. Overwinters in winter wheat in Finland but barley powdery mildew comes from the southern countries.	Because powdery mildew in the south can be resistant to the strobilurin products and most of our powdery mildew comes from there within the growing season, in Finland strobilurin fungicides are not recommended in the cereal growth where there is powdery mildew. In Europe resistance to DMIs has been found, but several of these molecules are still quite effective. Fenpropimorph has been found to be less effective today compared to the past. Among the triazoles, tebuconazole is still found to give reliable field control. Cyprodinil is used less for the control of mildew and it is unknown if changes in sensitivity have taken place.
Rusts (*Puccinia* spp.)	Hosts: all cereals	Depends on the year. Most of epidemic comes from southern countries, Importance is increasing.	No cases of QoI resistance or DMI resistance to these diseases have been confirmed.

Ear blight/snow mould (*Microdochium nivale / majus*)	Host: snow mould: winter wheat and winter rye, ear blight: wheat	Snow mould is common in Finland because of snow-rich winters Leaf symptoms on spring cereals were found for the first time in southern parts of Finland in 2012 from spring wheat.	This disease has previously been found to be resistant to benzimidazoles. QoI resistance has been widely found in France and the UK. Screening from 2009 and 2010 in the Nordic/Baltic region for sensitivity to QoIs showed high levels of resistance. Data from 2011 shows high resistance levels in both Sweden and Denmark. Resistance seen in both wheat and barley. Impact from the use of strobilurins on this disease can no longer be counted on.
Net blotch (*Pyrenophora teres*)	Hosts: spring barley Lives in plant residues and in seeds	Most common barley disease in Finland.	In some regions of Europe, the resistance of *Pyrenophora teres* to QoI fungicides is well established. For this disease, it is the mutation F129L which leads to low to moderate resistance. In the Nordic region, occurrences of F129L have been verified in Denmark, Sweden and Finland. The presence of F129L affects the efficacies of strobilurins in the field to differing degrees. Field efficacy has been found to be influenced in Denmark but not specifically elsewhere in the region. Data from 2010 - 2012 showed no presence of F129L in the Baltic region, Norway or Finland. Different sensitivity to DMI is also known and reduced effectiveness has previously been found in several DMIs (in Finland mainly propiconazole, but also metconazole and propiconazole+cyproconazole).
Spot blotch (*Bipolaris sorokiniana*)	Host: barley (and other cereals) Causes stem and leaf symptoms Overwinter in seeds, soil, and plant residues	Very common in Finland mainly in the barley.	No information
Ramularia leaf spot (*Ramularia collo-cygni*)	Host: barley	Rare in Finland. No epidemics reported.	Few isolates have been screened for sensitivity to QoI and resistance has been confirmed in the Danish and Swedish populations. Experience from France, UK, Sweden and Denmark show widespread resistance in field populations. It is recommended to use triazoles alone or mixed with carboxamides for control.
Rhynchosporium (*Rhynchosporium secalis*)	Host: barley and rye (triticale)	Common in Finland in barley fields, especially in barley monoculture.	This disease is known to shift in sensitivity to DMIs. Studies from the UK have shown that treatments with solo use prothioconazole shift the sensitivity more than mixtures. Sensitivity to DMIs in the Nordic/Baltic region has not been investigated. Only one case of QoI resistance to this disease has been confirmed in France in 2008. Extensive monitoring in Northern Europe in 2009-2012 including investigations in Denmark, Sweden, Finland, Norway and Latvia showed no signs of resistance. It is generally recommended to use mixtures of strobilurins and triazoles (or cyprodinil) for control.

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Appendices

Appendix A. Crops cultivated in Finland 2012

Appendix B. The yield of the main crops in 2011-2012 and the average yield 2001-2011

CROPS, 2012	*1000 ha*	*%*
Cereals	**1153.6**	**50.5**
Winter wheat	23.2	1.0
Spring wheat	219.1	9.6
Winter rye	19.3	0.8
Spring rye	2.0	0.1
Feed barley	401.5	17.6
Malt barley	101.4	4.4
Oats	352.7	15.4
Mixed grain	32.0	1.4
Other grains	2.4	0.1
Grasslands under 5 years	**659.9**	**28.9**
Hay[1])	95.3	4.2
Silage[1])	471.1	20.6
Green fodder[1])	10.2	0.4
Pasture	73.3	3.2
Seed production	10.0	0.4
Other crops	**167.0**	**7.3**
Potatoes	22.7	1.0
Sugar beet	11.6	0.5
Peas	4.7	0.2
Broad bean	8.9	0.4
Turnip rape	53.4	2.3
Rape	15.4	0.7
Linseed and flax	1.3	0.1
Caraway	18.8	0.8
Reed canary grass	10.4	0.5
Whole crop cereal	5.7	0.2
Horticultural crops[2])	12.1	0.5
Other crops	1.9	0.1
Cultivated area, total	**1980.5**	**86.7**
Fallow area	**267.3**	**11.7**
Fallows[3])	75.9	3.3
Nature management fields[4])	145.8	6.4
Green manure	45.5	2.0
Cultivated area and fallow, total	**2247.8**	**98.4**
Other utilised agricultural area	**37.4**	**1.6**
Grasslands at least 5 years[5])	31.9	1.4
Permanent crops[6])	4.0	0.2
Cultivation in greenhouses[7])	0.4	0.0
Kitchen garden	1.1	0.1
Utilised agricultural area, total	**2285.2**	**100.0**

1) Estimated by the first use of the grassland based on the crop production statistics, 2) Incudes. e.g. vegetables, strawberries and ornamental plants (under 5 years) on open cultivation, 3) Includes green, stubble and bare fallow 4) Includes all nature management fields, 5) At least 5-year-old meadows including natural meadows, pastures and grazing grounds, 6) Includes e.g. apple trees, berry plants and nurseries on open cultivation, 7) Includes area under greenhouse production; source Horticultural Enterprise Register. Source: OSF, Utilised agricultural area

Crop	2012 Area 1 000 ha	2012 Yield kg/ha	2012 Yield *million kg*	2011 Area 1 000 ha	2011 Yield kg/ha	2011 Yield *million kg*	2012 - 2011 Difference *million kg*	2012 - 2011 Difference %	Average yield 2001 - 2011 kg/ha
Wheat [1)]	227.3	3900	887.1	253.4	3850	974.8	-87.7	-9	3630
Winter wheat	23.1	4560	105.3	39.4	4400	173.4	-68.1	-39	3760
Spring wheat [1)]	204.2	3830	781.6	214.0	3740	801.4	-19.8	-2	3610
Rye [2)]	20.7	3090	64.1	26.9	2910	78.4	-14.3	-18	2490
Bread grain [1)]	**248.0**	**3830**	**951.1**	**280.3**	**3760**	**1053.2**	-102.1	-10	3510
Barley	451.2	3500	1581	432.0	3510	1514.3	66.7	4	3460
Feed barley [1)]	352.0	3450	1214.7	344.7	3470	1195.1	19.8	2	3390
Malt Barley	99.2	3700	366.6	87.3	3660	319.2	47.4	15	3640
Oats [1)]	313.8	3420	1073.1	308.2	3390	1043.1	30	3	3210
Mixed crops [1)]	20.9	2540	53.2	19.4	2950	57.2	-4	-7	2820
Feed grain [1), 3)]	**786.0**	**3440**	**2707.4**	**759.5**	**3440**	**2614.6**	92.8	4	3350
Other grain	2.4			2.5					
Grain total [1),4)]	**1036.4**	**3530**	**3658.7**	**1042.3**	**3520**	**3667.8**	-9.1	0	3370
Turnip rape	43.0	1140	49.2	76.4	1180	90.4	-41.2	-46	1330
Rape	14.4	1670	24	14.5	1700	24.7	-0.7	-3	1650
Linseed	0.6	630	0,4	1.7	920	1.6	-1.2	-75	..
Caraway [5)]	14.0	570	8,2	16.8	620	10.4	-2.2	-21	..
Potatoes	20.7	23650	489,6	24.4	27580	673.3	-183.7	-27	25030
Sugar beet	11.5	34790	398.7	14.0	48010	675.7	-277	-41	37630
Peas	4.0	2320	9.4	4.8	2500	12	-2.6	-22	2300
Broad bean	8.9	2520	22.5	9.7	2060	20	2.5	13	..
Timothy seed	5.6	520	3.1	6.8	480	3.2	-0.1	-3	430
Hay	95.3	3570	339.7	102.7	3670	3767	-37	-10	3570
Silage	471.0	15700	7396.7	472.0	15590	7351.3	45.4	1	17410
Fresh	59.3	14170	840.6	62.4	14500	905.4	-64.8	-7	..
Prewilted	411.8	15920	6556.1	409.2	15750	6445.9	110.2	2	..
Green fodder [6)]	6.7	11440	77.2	6.7	11480	77.4	-0.2	0	9770
Cereals harvested green [7)]	68.0	3890	265	57.2	4190	240.0	25.1	10	..
Reed canary grass [8)]	14.1	2930	38.8	15.5	2930	45.3	-6.5	-14	..

1) Excl. cereals harvested green
2) Incl. winter- and spring rye
3) Incl. malting barley
4) Excl. other grains
5) The area sown during the harvest year has been deducted
6) ncl. 1st harvest
7) Incl. cereals harvested green
8) Area that yielded harvest in 2011 (harvested in spring 2012)
Source: OSF: Tike, Crop production statistics

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