Crop production in a northern climate

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CONCEPTS AND ABBREVIATIONS USED IN THIS THEMATIC STUDY

In this thematic study *northern growing conditions* represent the northernmost high latitude European countries (also referred to as the northern Baltic Sea region, Fennoscandia and Boreal regions) characterized mainly as the Boreal Environmental Zone (Metzger *et al.*, 2005). Using this classification, Finland, Sweden, Norway and Estonia are well covered. In Norway, the Alpine North is, however, the dominant Environmental Zone, while in Sweden the Nemoral Zone is represented by the south of the country as for the western parts of Estonia (Metzger *et al.*, 2005). According to the Köppen-Trewartha climate classification, these northern regions include the subarctic continental (taiga), subarctic oceanic (needle-leaf forest) and temperate continental (needle-leaf and deciduous tall broadleaf forest) zones and climates (de Castro *et al*., 2007). Northern growing conditions are generally considered to be less favourable areas (LFAs) in the European Union (EU) with regional cropland areas typically ranging from 0 to 25 percent of total land area (Rounsevell *et al*., 2005).

Adaptation is the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities (IPCC, 2012).

Adaptive capacity is shaped by the interaction of environmental and social forces, which determine exposures and sensitivities, and by various social, cultural, political and economic forces. Adaptations are manifestations of adaptive capacity. Adaptive capacity is closely linked or synonymous with, for example, adaptability, coping ability and management capacity (Smit and Wandel, 2006).

Resilience is the ability of a system and its component parts to anticipate, absorb, accommodate or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration or improvement of its essential basic structures and functions (IPCC, 2012).

Vulnerability is the propensity or predisposition to be adversely affected (IPCC, 2012). It is a dynamic concept, varying across temporal and spatial scales and depends on economic, social, geographic, demographic, cultural, institutional, governance and environmental factors.

SRES refers to the Special Report for Emission Scenarios of the Intergovernmental Panel on Climate Change (IPCC).

A2 forcing scenario represents a pessimistic scenario of the SRES, anticipating high greenhouse gas and aerosol emissions.

B1 forcing scenario represents an optimistic scenario of the SRES, anticipating low greenhouse gas and aerosol emissions.

GCM refers to global climate model(s).

RCM refers to regional climate model(s).

1. INTRODUCTION AND BACKGROUND

In the context of global changes, climate change is one of the greatest challenges facing humankind and terrestrial ecosystems. On a global scale, some of the most considerable and direct impacts of climate change over the next few decades will be on agricultural and food systems (Lobell *et al.,* 2008; Battisti and Naylor, 2009). Increasing global population growth, urbanization and an ever-increasing demand for food, together with rising standards of living in the highly populated regions and the concomitant changes in food consumption towards production-inefficient, meat-intensive diets, are placing unprecedented demands on agriculture and natural resources (Foley *et al.,* 2011; Peltonen-Sainio and Niemi, 2012). To meet the world's future demand for food security and sustainable agriculture, substantial growth in food production must be coupled with dramatic reductions in the environmental footprint of agriculture. Foley *et al.* (2011) anticipate that tremendous progress could be made by halting agricultural expansion, closing yield gaps on less productive land, increasing cropping efficiency, shifting diets and reducing waste.

Agriculture is a sector that is closely linked to climate and that is thereby naturally prone to impacts of climate change. Agriculture in the northern European climate – the focus area of this thematic study – is practised at higher latitudes than elsewhere on the planet (Figure 1) and takes account of many special, even exceptional, features and conditions. It is projected that climate warming will progress particularly fast in the high latitude regions of the northern hemisphere. This means that there is only limited time available for development and implementation of adaptation measures that are essential to improve resilience and adaptive capacity of the northern agricultural sector. On the other hand, prolongation of the currently exceptionally short growing season implies opportunities for yield increases

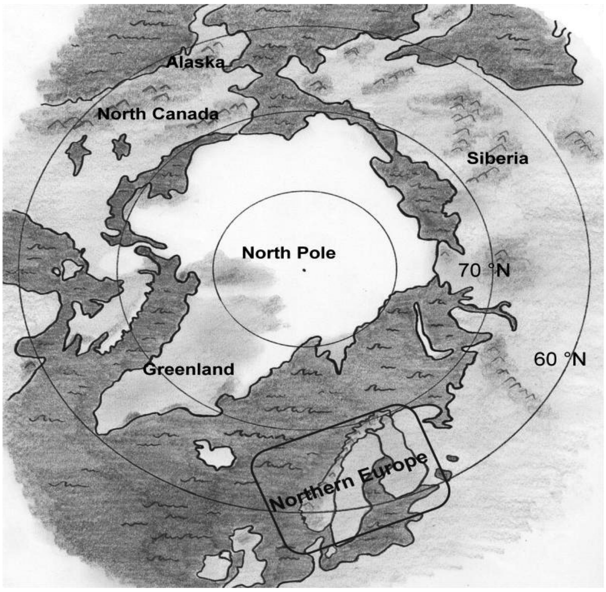

Figure 1. Northern European growing conditions are exceptional at the global scale. At >60 °N not only grass crops but also large-scale, intensive grain and seed crop production is practised, contrary to the case elsewhere at comparable latitudes

Source: Peltonen-Sainio *et al.* (2009b). *Drawing*: Jaana Nissi/MTT.

and sustainable intensification of production systems in the northern regions. One could even say that by these means climate change takes northern European crop production into a new era. However, fluctuating weather conditions, meaning large inter- and intra-annual as well as spatial variation, are typical for high latitude agro-ecosystems. Therefore, variable conditions have required hitherto continuous adaptation and measures by farmers to manage production risks. Because northern European regions are considered to have major obstacles to agriculture, they are mainly regarded in the European Union (EU) as less favourable areas (LFAs). These refer to agricultural areas that are currently characterized as economically marginal, non-optimal production regions (Rounsevell *et al*., 2005). In the future, challenges and constraints for northern cropping systems induced by or associated with climate change, are not likely to ease, even though in general production potentials are anticipated to increase substantially (Peltonen-Sainio *et al.,* 2009a). Therefore, northern agriculture is at an interesting but challenging crossroads.

In Europe and its northernmost regions, land use and crop productivity per unit land area are projected to change substantially in the future. The outcome is, however, especially dependent on the rate of progress of technological development (Rounsevell *et al*., 2005; Ewert *et al.,* 2005). In the case that technology (including plant breeding) continues to progress at current rates, the need for agricultural land in Europe is likely to decline drastically if demand for agricultural commodities does not increase, if agricultural policies do not encourage extensification of vast production areas and/or if overproduction is not accepted, for example, through increasing export of agricultural commodities (Rounsevell *et al*., 2005). Sustainable intensification through agro-technological development in regions with relatively unproductive lands (environmental conditions allow more efficient agricultural production), such as in the Russian Federation and many eastern European countries, would allow, for example, large-scale production of bioenergy in set-aside fields (Hakala, Kontturi and Pahkala, 2009).

Many alternative future prospects for field use are considered for northern growing areas: yield gap closing, sustainable intensification or, in contrast, extensified production systems. One could argue that the present "semi-extensive or semi-intensive" system is less of an attractive alternative when it comes to yield gains, input use efficiencies and environmental impacts if compared with having both sustainably intensified and fully extensified fields. Depending on future conditions for competitiveness of agricultural production, policy, markets and economic incentives for both intensified and extensified systems could result in combined cropping systems incorporating monocultures, diversified rotations favouring protein crops or other currently minor crops, environment-preserving cover-crops, bioenergy crops and/or naturally managed fields. Thereby, the outcome for future field use will actually determine to what extent northern European agriculture takes responsibility or outsources all the multidimensional challenges related to food production and nature preservation. The fundamental questions regard the focus-areas for production of different agricultural commodities in Europe under changing climates, the risks and opportunities, and how northern European agriculture, which is projected to face drastic and progressive changes in production capacities and systems, will function in the context of European and global food and agricultural systems in the future.

This thematic study characterizes the typical features of the northern European agriculture and climate, it evaluates vulnerability of crop production to climate change at high latitudes, and considers the means to adapt to climate change and improve resilience, productivity and sustainability of high latitude cropping systems in the future.

2. NORTHERN EUROPEAN CLIMATE AND CROPPING SYSTEMS

Agriculture in northern European high latitude conditions is possible only due to the Gulf Stream, which, together with its northern extension towards Europe, the North Atlantic Drift, is a powerful, warm and swift Atlantic Ocean current that originates in the Gulf of Mexico and favourably influences the climate of the west coast of Europe (Peltonen-Sainio *et al*., 2009b). Therefore, northern European temperatures during the growing season are typically higher than elsewhere at comparable latitudes, enabling production of many grass and cereal crops as well as some special crops to a limited extent.

Boreal regions represent conditions that combine many special features and constraints for crop production, such as harsh winters, an exceptionally short growing season, long days during the summer months, generally cool mean temperatures during the growing season, high risk of early and late season night frosts, early summer drought and high risk of abundant precipitation close to harvests (Peltonen-Sainio *et al*., 2009b). However, not only the general obstacles for northern growing conditions *per se*, but unpredictability caused by substantial fluctuation in conditions, represent biological and economic challenges and risks for farmers when managing cropping systems at the northern margins of global food production. Extreme climatic events may cause total crop failures, averaging one per decade, as documented since the 1960s for Finland (Peltonen-Sainio and Niemi, 2012). In contrast to present day sophisticated agricultural systems and practices and access to world trade, food security and agricultural production under northern European conditions in the past went firmly hand in hand. During recent centuries, insecurity in crop production caused by harsh climatic conditions plunged the population into food shortage, famine and up to 30 percent mortality, as documented for the Finnish population at the end of the 1600s (Peltonen-Sainio and Niemi, 2012).

2.1 Weather conditions and constraints

The thermal growing season typically starts in mid-April to mid-May and ends by late September to early November, thereby ranging over 125 to 200 days in regions with a significant share of agricultural land in northern Europe (Tveito *et al.,* 2001). Mean degree-days for the growing season (daily mean temperature above 5 °C) range from 800 to 1700 °Cd[1] (Tveito *et al.,* 2001), but only part is utilized for crop production and often less efficiently the further north the region (Peltonen-Sainio, Jauhiainen and Venäläinen, 2009). In addition to spatial differences in mean growing season degree-days, regional differences in probabilities of having growing seasons with different degree-days vary. For example, in Finland, degree-days can range from 800 °Cd to 1300 °Cd within the southeastern region depending on the year (Peltonen-Sainio, Jauhiainen and Venäläinen, 2009).

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[1] Cd = cooling degree.

Temperature. Northern European growing conditions are generally characterized as cool. The northernmost agricultural regions in the Boreal Zone (close to 65 °N) have summer temperatures averaging 12 °C, while in southern Finland and Norway mean temperatures approach 16 °C, which represents the average for Estonia and which is exceeded in southern Sweden.

Precipitation. The number of days with precipitation ≥1.0 mm ranges from 50–100 to 200, being highest in the western coastal regions of Norway (Tveito *et al*., 2001). Typically during the summer months accumulated precipitation is low, averaging 40 mm per month in May–July in the Baltic Sea region and thereafter increasing to a maximum of 70–80 mm per month during late autumn. However, differences in distribution of precipitation between and within seasons are high (Kjellström and Ruosteenoja, 2007). In general, precipitation falls unevenly over time and contrary to the requirements of the major field crops. Droughts typically interfere with plant stand establishment and early plant growth and development, which is especially critical for yield formation of spring sown seed crops. Also regrowth of grass crops after the first cut is often retarded by temporary drought.

Winter conditions. In northern European conditions the period outside the growing season is long (Tveito *et al*., 2001). Number of frost days (daily mean temperature below 0 °C), which indicates length of the thermal winter, ranges from 50–70 in the southernmost regions of Sweden up to 150–200 in the northernmost agricultural regions (Tveito *et al*., 2001; Jylhä *et al*., 2008). Freezing point days (days with a daily minimum air temperature <0 °C and daily maximum temperature >0 °C) are again typically higher in spring (30–40 days) than in autumn and winter (Jylhä *et al*., 2008). Snow cover tends to range from less than 90 days in southern Sweden up to 200 days in the northern parts of the Boreal Zone regions with agricultural land (Jylhä *et al*., 2008). There have been fluctuations in severity of winter conditions when determined according to the extent of Baltic Sea ice. In general some 20 percent of winters were classified as severe or extremely severe in 1902–1990, while some 10 percent were extremely mild (Jylhä *et al*., 2008).

2.2 Special features of northern crop production to cope with

The growing season in northern Europe is characterized by a strikingly low number of effective growing days, i.e. days combining sufficient temperature and water availability with lack of night frosts and snow cover (Table 1) (Trnka *et al*., 2011). The low number of effective growing days is likely to be the major limitation contributing to the modest yields realized in the northernmost European regions such as Finland (Peltonen-Sainio, Jauhiainen and Hannukkala, 2007; Peltonen-Sainio, Jauhiainen and Laurila, 2009; Peltonen-Sainio *et al*., 2009b).

Because of a special combination of agro-climatic conditions, crop development, growth and yield determination have many unique features. These call for special mechanisms and approaches when adapting to northern conditions through plant breeding and through crop management tailored to northern agricultural systems characterized by high production risks and uncertainties (Peltonen-Sainio *et al*., 2009b).

Table 1: The 5th, 50th and 95th percentile values for agro-climatic indices during 1971–2000 and the estimated changes in the median values for 2030 assuming the A2 SRES scenario according to Trnka *et al.* (2011)

Zone	Effective global radiation (MJm^{-2}/ year)			Effective growing days (days/year)			Date of last frost (day of the year)			Proportion of dry days in JJA (%)			Proportion of sowing days in early spring (%)		
	The experienced period of 1971–2000														
	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
BOR	581	1 417	1 824	57	115	154	127	146	169	2	31	83	0	5	16
ATN	1 536	2 187	2 596	133	190	226	91	117	142	3	14	58	13	30	48
CON	1 693	2 296	2 812	123	172	212	92	113	135	4	23	55	23	41	60
MDN	2 161	2 795	3 434	159	201	242	53	61	100	33	51	74	33	50	65

	Estimated time horizon of 2030				
	Change (%)	Change (days)	Change (days)	Change (%)	Change (%)
BOR	3 – 7	11 – 17	–6 – –4	–6 – 1	4 – 5
ATN	0 – 3	3 – 17	–8 – –5	3 – 11	3 – 5
CON	–3 – 1	––2 – 5	–7 – –4	4 – 11	4
MDN	–10 – –2	–11 – –3	–24 – –20	4 – 9	1 – 2

The range for the future estimates is based on three GCMs: ECHAM, HadCM and NCAR. Environmental Zones (Metzger *et al.*, 2005) are: BOR, Boreal; ATN, Atlantic North; CON, continental; MDN, Mediterranean North. JJA refers to June––July–August.
Source: Peltonen-Sainio and Niemi (2012).

Crop and cultivar selection represent a fundamental means for a farmer to cope with prevailing conditions, and especially so in the short northern growing conditions characterized by many special features requiring breeding for strict adaptation. The northern European growing seasons are cool, but in general the average temperatures are favourable for growth and yield formation of cereals, rapeseed (both oilseed rape [*Brassica napus* L.] and turnip rape [*B. rapa* L.]), grain legumes and many other temperate crops. In spite of the fact that crop production is surprisingly diverse in European high latitude conditions when compared with comparable latitudes elsewhere in the northern hemisphere (see Figure 1), cereal and grass crops dominate Boreal agro-ecosystems (Table 2). Typically the proportion of grassland extends from the south to the north, contrary to that of cereals and other crops. Also spring-sown cereals and rapeseed dominate at higher latitudes, as in Finland, while winter types become increasingly common and gradually start to dominate when moving towards the southern parts of Sweden (Peltonen-Sainio *et al.*, 2009a). Owing to a low number of alternative, economically feasible crops and to strong fragmentation of agricultural sectors and the south-north dimension (e.g. field crop production concentrated in southern Finland and dairy production in the north), northern European crop rotations are not currently sufficiently diverse to prevent soil compaction (Alakukku *et al.*, 2003; Peltonen-Sainio *et al.*, 2011) or efficiently prevent or alleviate crop protection risks.

Sowing. The growing conditions in Boreal regions often have very narrow windows for favourable sowing time in spring (Table 1) and autumn. In spring, snow has to melt and the fields need to dry to carry machinery without destructive effects on soil structure – but not too dry so as to maintain a favourable combination of soil moisture and temperature for germination (Peltonen-Sainio *et al.*, 2009b). In the autumn, drought does not typically

Table 2: Total agricultural land as well as area under cereal production (ha), temporary and permanent meadows and pastures in Boreal region countries for 2000–2009

Country	Total agricultural land 1000 ha	Cereals 1000 ha (%)	Grassland 1000 ha (%)	Others %
Estonia	871	287 (33)	425 (49)	18
Finland	2 264	1 164 (51)	668 (30)	19
Norway	1 036	321 (31)	656 (63)	6
Sweden	3 151	1 089 (35)	481 (15)	50

Proportions of areas for pea (*Pisum sativum* L.), rapeseed, potato (*Solanum tuberosum* L.) and sugar beet averaged <1% from total agricultural land for each crop and country.
Source: FAO Statistics (www.faostat.fao.org)

interfere with plant stand establishment of winter sown cereals, but again the window for sowing is small after harvests of a pre-crop to provide seedlings with sufficient capacity for winter hardening and to be thereby better prepared to resist overwintering damage (Peltonen-Sainio *et al*., 2009b). Abundant autumn rainfall can prevent sowing when fields are not able to carry the machinery. Night frosts occur both in early and late summer. In the early season, night frosts may retard growth of cereals but without lethal effects, contrary to the most frost-sensitive species, rapeseed and sugar beet (*Beta vulgaris* var. *altissima*) that need to be resown after severe night frosts. On the other hand, early season potato plant stands are actively sheltered from night frosts.

Water availability. Precipitation is unevenly distributed in northern conditions when compared with requirements of many crops. Early summer drought accompanied by development-enhancing long days often interferes with plant stand establishment and subsequent yield determination (Peltonen-Sainio *et al.,* 2009b; Peltonen-Sainio, Jauhiainen and Hakala, 2011). Early summer drought is particularly damaging for spring-sown crops as overwintered crops can better utilize snow melt water. Furthermore, winter crops have their roots already in the deep soil layers by the start of the growing season, which enables access to water. For example, depending on the region in Finland, only 30–60 percent of the precipitation needed at early summer for undisturbed yield formation of spring barley (*Hordeum vulgare* L.) fell on average over three decades (Peltonen-Sainio, Jauhiainen and Hakala, 2011). Such a water deficit resulted in yield losses averaging 7–17 percent depending on region.

Reduction in yield potential caused by early summer drought cannot be compensated for by higher precipitation later in the growing season, although it generally favours grain filling and results in higher grain weight (Peltonen-Sainio *et al*., 2007; Rajala *et al*., 2011). Lack of compensation capacity in northern conditions is associated with long-day-induced accelerated development and maturity processes of the crops. Because of the uniculm growth habit (i.e. main shoot growth is advanced and favoured at the expense of tiller initiation and growth) of spring cereals induced by long days (Peltonen-Sainio *et al*., 2009c), tillering as a plastic trait cannot compensate for harmful early summer drought effects, which is contrary to the plasticity mechanisms operating at lower latitudes.

Despite water scarcity at critical stages of growth, field crop production is basically rainfed in northern Europe and only horticultural crops are irrigated. Hence, northern European farmers do not currently have the means to cope with water stress other than for conserving soil water content with crop management systems. According to FAO, >1 percent of total agricultural land in Estonia is equipped with irrigation machinery, 4 percent in Finland, 5 percent in Sweden and 12 percent in Norway. Restricted water availability is not only the principal reason for yield losses, but is also associated with low nutrient uptake efficiency. Water deficit has been frequently and severely experienced, for example in Finland in the 2000s. During 2002–2003, 1 400 farms, many with livestock, suffered from water scarcity: over 64 000 m^3 of water was transported to farms at average costs of €5/m^3. Also yields were low and some 20–40 percent of autumn sowings were re-established. Additional costs to agriculture alone in the extreme southwestern areas were nearly €10 million (Silander, 2004).

In addition to yield losses caused by early summer drought, abundant precipitation at grain-filling may reduce quality and challenge harvests. Owing to late summer precipitation, grains and seeds are always dried before storing. When not causing lodging, post-heading rain may favour grain and seed fill, but it interferes with seed set when occurring at flowering in oilseed rape (Peltonen-Sainio *et al.*, 2010). The harmful effects of late summer rains were, however, recorded across many regions of Europe.

Overwintering. Harsh overwintering conditions result in poor winter survival, yield losses or total failures even in the adapted, most resistant crops and cultivars. Severe overwintering damage occurs, and may be lethal when a combination of unfavourable, critical conditions occur together or succeed each other (Hömmö, 1994). Under northern conditions, winter survival is typically dependent on latitude (which is associated with harshness of winters), crop species and winter-hardiness of a particular cultivar.

Low winter temperatures rarely cause crop death as hardened overwintering crops usually tolerate freezing temperatures during winter (Hömmö, 1994; Antikainen, 1996), especially if accompanied by protective snow cover. Abundant snow cover may, however, maintain the temperature range at the plant stand level favourable for infections by low-temperature parasitic fungi (Ylimäki, 1969; Hömmö and Pulli, 1993; Nissinen, 1996; Serenius *et al.,* 2005). Melting of snow, especially in spring when the number of freezing point days is at its highest, can result in formation of hermetic ice cover ("ice encasement") that causes anoxia, i.e. impeded oxygen flow for crop maintenance respiration (Hofgaard *et al.,* 2003). Freezing point days may also cause freezing of the uppermost soil layers, and thereby root breakage. Carbohydrate reserves may be insufficient for long-lasting winters, or if winters are exceptionally warm, which enhance crop metabolism (Niemeläinen, 1990; Antikainen, 1996; Hakala and Pahkala, 2003).

The degree of risk and uncertainties that are associated with growing winter cereals and rapeseed depends on region, being highest in the north. When excluding grasslands, high overwintering risks in general can be seen as negligible or modest growing areas for winter crops, especially in the northernmost Boreal regions when compared with areas in central and southern Europe. Also, large differences are apparent for sown and harvested areas over years. Choosing spring cereals over winter types allows farmers to reduce production risks at high latitudes. Severe winter damage in one year has been demonstrated to result in decline in sown areas of winter cereals in the subsequent year (Peltonen-Sainio, Hakala and

Jauhiainen, 2011), indicating that farmers are risk- averse. Another example of adaptation measures is that winter cereals are often sown on sloping fields to aid surface water run-off from the fields and thereby reduce risks for formation of hermetic ice cover. Late sowing is used to avoid formation of dense canopies before winter, as is use of cultivars resistant to pathogens to avoid winter damage (Serenius *et al.*, 2005). For susceptible winter cereals, especially in the northernmost areas with deep and long-lasting snow cover, plant protection measures against fungal infections are often needed to cope with the overwintering risks represented by fungal pathogens (Serenius *et al.*, 2005).

Crop protection. Risks of pest and disease outbreaks are lower in northern, cool climates with short growing seasons and long winters, when compared with more southern agricultural regions in the northern hemisphere. Cool climates hold back reproduction and the number of generations of pests and diseases per season (Hakala *et al.*, 2011). Therefore, use of agro-chemicals is generally modest. However, there are many examples of how recent changes in farming, farm structures and cropping systems are driven by political, economic and environmental motives, and summers with warm spells, drought and stressed plant stands have highlighted the harm caused to crop production through reduced farmer awareness and insufficiency in their crop protection measures (covering the whole range, from preventative actions to chemical control).

2.3 Production uncertainties and extreme events

Depending on outcome of the climatic constraints and other production risks related to northern climates, as well as farmer capacity for risk avoidance, substantial fluctuations in production quantities and qualities are apparent for northern conditions (Peltonen-Sainio, Jauhiainen and Hakala, 2009; Peltonen-Sainio *et al.*, 2009b; Peltonen-Sainio and Niemi, 2012). Fluctuations in weather conditions affect both economic and environmental sustainability of agricultural production. For example, spatial and temporal differences in frequency and abundance of precipitation may result in inadequate uptake of nitrogen, low removal rate of applied nitrogen and increased risks of nutrient leaching (Rankinen *et al.*, 2007; Peltonen-Sainio and Jauhiainen, 2010). Such a high risk of leaching into natural water systems has been addressed by the Agro-Environment Program through reducing nitrogen fertilizer application rates (Salo, Lemola and Esala, 2007) and by implementing soil-incorporating methods other than conventional autumn tillage (Rankinen *et al.*, 2007). This is an example of a policy-driven means to tackle the adverse effects of climate related to agriculture and the environment.

Extreme events and other climatic constraints causing production uncertainty require continuous adaptation by farmers to cope with risks that cause economic losses. The likelihood for climatic extremes increases towards the northern regions of the Boreal Zone (Table 3). As an example, the risk of early season frost is evident everywhere in Finland, but particularly in the more northern regions. A contrary constraint to frost is represented by heatwaves occurring in May, close to sowing and seedling emergence. Such heatwaves occur at least every ten years and typically result in poor plant stand establishment. Furthermore, during the period of the most intensive growth, severe drought (<10 mm accumulated

Table 3: Likelihood for having some exceptional weather events every 10th, 20th and 50th year, depending on region in Finland according to comprehensive modelling exercise with regional, long-term climatic datasets by Venäläinen *et al*. (2007)

Repeating period (years)	Helsinki (60.1 °N 24.6 °E)		Jyväskylä (62.1 °N 25.4 °E)		Oulu (65.0 °N 25.3 °E)		Sodankylä (67.3 °N 26.4 °E)	
	95%	95%	95%	95%	95%	95%	95%	95%
Minimum temperature in May (°C)								
10	–2.7	–1.4	–8.4	–6.9	–7.8	–6.5	–15.9	–12.8
20	–3.2	–1.8	–9.1	–7.3	–8.9	–7.0	–17.9	–14.0
50	–3.7	–2.1	–9.8	–7.8	–10.2	–7.6	–20.2	–15.5
Maximum temperature in May (°C)								
10	25.2	26.3	27.0	27.7	25.7	26.5	24.7	26.8
20	25.7	27.0	27.3	28.2	26.1	27.3	25.4	27.9
50	26.3	27.7	27.7	28.8	26.6	28.3	26.1	29.2
Duration of drought period in May–August with <10 mm precipitation (days)								
10	39	53	32	39	38	51	33	42
20	44	68	35	44	42	64	37	51
50	50	86	38	53	48	79	41	65
Precipitation per day (mm)								
10	47	66	46	64	38	54	35	45
20	52	76	52	75	42	63	38	50
50	60	92	61	92	50	77	42	57
Duration of period with daily minimum temperatures –20 °C (days)								
10	4.9	7.6	9.2	13.2	10.9	13.9	13.0	18.1
20	6.1	10.4	10.7	16.5	11.9	16.0	14.7	22.9
50	6.9	15.8	12.3	21.1	12.9	18.9	16.9	28.1
Depth of snow cover at most (cm)								
10	67	78	88	95	67	82	100	118
20	73	88	94	103	72	97	106	132
50	79	102	99	113	79	117	114	153

For each case the 95% confidence intervals are shown (the best estimate is often close to the mean of the intervals). Table is published in Peltonen-Sainio and Niemi (2012).

precipitation), lasting 35–55 days, interferes with crop growth at least once in ten years, while heavy rains (39–55 mm per day) that cause lodging and/or flooding occur once every tenth year (Peltonen-Sainio and Niemi, 2012).

As examples in the previous section indicate, farmers in the northern agricultural regions are used to facing and trying to cope with climatic constraints. This is also evident according to a recent study carried out in the northern regions of Norway (Kvalvik *et al*., 2011). However, owing to a limited capacity to cope with climatic constraints, variation in yield and quality is evident (Peltonen-Sainio and Niemi, 2012). Despite high yield variability, farmers consider that coping with agricultural policy is more challenging than coping with changing climate and climatic constraints (Kvalvik *et al*., 2011).

Climatic extremes are most hard to cope with, and can result in total crop failures. For example, during recent decades yields in 20 percent, 45 percent, 22 percent and 18 precent of the agricultural land area in Finland failed totally in 1981, 1987, 1998 and 1999 respectively (Peltonen-Sainio and Niemi, 2012). Of these years, some had exceptionally cool growing seasons, except 1999 when severe drought interfered with crop growth. Also overwintering damage may be a significant source of yield variability (Peltonen-Sainio, Jauhiainen and Hannukkala, 2007; Peltonen-Sainio, Hakala and Jauhiainen, 2011). However, in the case of total or extensive winter damage, resowing with spring crops is practised and therefore the contribution of winter damage to annual crop loss area is often masked. In general, yields of minor crops such as grain legumes and rapeseed are more vulnerable to variable conditions and climatic risks (Peltonen-Sainio and Niemi, 2012).

3. CLIMATE CHANGE, EXTREME EVENTS AND VULNERABILITY OF NORTHERN CROP PRODUCTION

3.1 Future climate forecasts: where do we go from here?

Temperatures are projected to rise most in northern climates and especially so in winter (December–February) and spring (March–May) when compared with other European regions (Ruosteenoja, Tuomenvirta and Jylhä, 2007). By the end of this century (2071–2100), according to the SRES A2 scenario, the probability intervals for temperature increase calculated by the GCMs range from 4.5 to 7.5 °C in winter and 2.8 to 7.2 °C in spring months when compared with the 1961–1990 period. The corresponding figures for the SRES B1 scenario are 2.5 to 5.4 °C and 1.4 to 5.0 °C, respectively. These estimates are in general some 0.5 to 2.0 °C higher than for western, southwestern and southeastern Europe, though closer to those calculated for eastern Europe. Contrary to this, the probability intervals for temperature elevation during summer months (June–August) are substantially lower for northern regions than for elsewhere: 2.0 to 5.4 °C for A2 and 1.0 to 3.8 °C for B1, while being even 2.6 to 8.4 °C for A2 and 1.6 to 5.3 °C in eastern Europe (Ruosteenoja, Tuomenvirta and Jylhä, 2007). Intervals for temperature changes were most alike for autumn months (September–November) in European regions with a ≤1.0 °C difference at most for the A2 scenario and even less for B1. Therefore, in the north winters are expected to get milder and the growing seasons to become warmer and prolonged, by 40–50 days in inland areas of Finland and even more in the southwestern coastal regions of the country (Ruosteenoja, Räisänen and Pirinen, 2011).

Precipitation. In Europe, projections for precipitation differ depending on season, and within a season depending on region (Ruosteenoja, Tuomenvirta and Jylhä, 2007). For winter months, the highest increase in precipitation is projected by GCMs to take place in northern European regions by the end of the century when compared with 1971–1990 (up to 50 percent in A2 and ~30 percent in B1 scenario). However, uncertainty due to the choice of GCM is particularly high for winters, especially for northern climates (Kjellström and Ruosteenoja, 2007). For southwestern and southeastern climates, winter precipitation may increase or fall by about 20 percent at most. For spring months, the probability intervals for northern climates are comparable with estimates for eastern regions and range from no change up to ~40 percent and a 20 percent increase in precipitation according to A2 and B1 scenarios, respectively. For southwestern and southeastern regions, change in spring precipitation is likely to be negative. In general, autumn precipitation is estimated to change according to spring precipitation but the probability intervals will narrow.

Northern Europe represents the only region for which probability intervals for summer precipitation are projected to slightly increase (ranging from ~0 percent to 15 percent regardless of forcing scenario). Elsewhere in Europe summers are projected to get drier (Ruosteenoja, Tuomenvirta and Jylhä, 2007). For example, in Finland summer precipitation is estimated to gradually increase by the end of this century with regard to both the multi-model-mean precipitation and the variation (Ylhäisi *et al*., 2010). Therefore, precipitation is projected to increase in northern European climates throughout the year with differences in seasonal distribution: winters will get wetter, as is also the case, but to a lesser extent, for spring and autumn, than for winters, and again a little less increase in precipitation for summer than for spring and autumn. Also within the growing season precipitation is projected to increase unevenly, the absolute increase estimated to be largest in July (Ylhäisi *et al.,* 2010).

Winter conditions. As a result of higher estimates for future winter temperature and precipitation, major changes are projected to take place in winter conditions, such as fewer days with frost and snow, shorter frost season and a smaller liquid water equivalent of snow (Jylhä *et al.,* 2008). These projected changes were produced by all model simulations irrespective of the forcing scenario and the driving GCM, and they evidently have implications for agriculture based on “the mercies of nature”. Annual number of frost days is predicted to decline from an average of ~120–180 days in the main agricultural regions of the Boreal Zone by 50–70 days by the end of this century according to the A2 forcing scenario (Jylhä *et al*., 2008). Also the number of freezing point days will decline in autumn by 5–10 days and in spring by 10–15 days in the southernmost regions of the Boreal Zone and by 0–5 days in the northernmost regions. Contrary to this, freezing point days will become more frequent in winter months and especially so in the northern parts of the Boreal Zone.

As a result of climate warming the first frost day in autumn will be delayed by about one month and the last frost day in spring advanced by one month by the end of the century (Jylhä *et al*., 2008). The number of days with snow cover over land areas ranges from ~90 to 200 (1961–1990) at the south-north axis in the Boreal Zone, but declines by 30 to 60 days, with the most drastic change occurring in the southern regions. The annual extent of snow cover at high latitudes has already declined in recent decades (Zhang and Walsh, 2006). Decline in days with snow cover is estimated to be most prominent during spring months (Jylhä *et al*., 2008). In general, under the A2 scenario, thermal winters may disappear in southwestern Finland by the end of the century (Ruosteenoja, Räisänen and Pirinen, 2011).

An indication of severity of winter conditions is represented in northern European regions by the extent of Baltic Sea ice. By the end of this century, unprecedentedly mild and extremely mild winter conditions will dominate regardless of the model used for projections (Jylhä *et al.,* 2008). Thereby, all the different weather parameters that characterize winter conditions and that are likely to have evident impacts on overwintering capacity of field crops and expression of winter damage in established plant stands will change in tandem. This challenges anticipation and adaptation of northern cropping systems to changing climate, especially concerning expansion of overwintering crop areas (Peltonen-Sainio, Hakala and Jauhiainen, 2011).

Extreme events are, in general, expected to become more frequent in the future when climate changes. There is evidence from observations gathered since 1950 of change in some climate extremes. Also economic losses from weather-related and climate-related disasters have increased though, with large spatial and interannual variability (IPCC, 2012). Heatwaves, episodes of heavy precipitation and/or severe drought, wind storms and storm surges are projected to change in Europe between 1961–1990 and 2071–2100 according to RCM simulations (Beniston *et al.,* 2007). In northern Europe, frequency, number and intensity, and duration of heatwaves will increase (shown in order from the highest to the lowest change). When the mean annual number of days exceeding 30 °C was 0–5 for the period 1961–1990, for the end of this century in the southernmost regions of the Boreal Zone, such episodes are likely to become more common and may range from five to ten by the end of this century (Beniston *et al.,* 2007). In southern Europe days with >30 °C may then approach 100.

Episodes of heavy winter precipitation are estimated to increase in both northern and central Europe as well as heavy summer precipitation events in northeastern Europe, but both winter and summer precipitation episodes will become more rare in the south (Beniston *et al.,* 2007). For example, at high latitudes (62.5 °N) the number of months in which the highest monthly precipitation is simulated to break the records of the twentieth century is ten by the end of this century in A1B scenario (six in the case of unchanged climate), though the estimate is four months for the Balkan Peninsula (42.5°N) (Ruokolainen and Räisänen, 2009). The corresponding estimates for the number of months with the highest mean temperature are 11 (for 62.5 °N; six in unchanged climate) and 12 (for 42.5 °N), respectively. Furthermore, in Finland the high precipitation records are more likely to be broken than the low precipitation records (Ruokolainen and Räisänen, 2009). Projected changes in precipitation and temperature imply possible changes in flooding patterns (IPCC, 2012).

Shift in environmental zones. Climate change is projected to result in changes of many critical agro-climatic indices (Table 1, Trnka *et al.,* 2011). Eventually also climate subtype distributions may change in such a manner that the subarctic continental climate will disappear northwards beyond the present agricultural land by the end of this century (de Castro *et al.,* 2007). On the other hand, the temperate continental climate will start to dominate in the high latitude countries of Europe and a temperate oceanic climate may reach some of the southern and southwestern coastal parts of Sweden and Norway.

3.2 Impacts of climate change and vulnerability of agro-ecosystems

Prolongation of growing season. The current, extremely short growing season of northern European agricultural regions is projected to become longer in the future. This is likely to occur by benefitting from the advanced start to spring sowing, but not necessarily from delayed maturity and harvest in autumn. Advances in sowing time are estimated to proceed rapidly at latitudes >60 °N (Peltonen-Sainio *et al.,* 2009a; Rötter *et al.,* 2011). Elevated daily mean temperatures during the growing season partly chip away at the crops' capacity to benefit from climate-warming induced higher cumulated degree-days during the growing season. Higher degree day values in the future will be attributable to both elevated daily mean temperatures and greater number of days in the early and late growing season with daily mean temperatures exceeding +5 °C. However, elevated temperatures are harmful for growth and yield determination for a variety of grain and seed crops, as described in more detail below, and call for adaptation through plant breeding (Peltonen-Sainio *et al.,* 2009a; Rötter *et al.,* 2011; Hakala *et al.,* 2012). Growing season accumulated temperature sums that are estimated to be utilized by crops for growth and are agronomically feasible (means earlier sowings, but not delays in harvest period) were anticipated to increase by some 140 °Cd by 2025, 300 °Cd by 2055 and 470 °Cd by 2085 in scenario A2, when averaged over regions with significant arable land in Finland (Peltonen-Sainio *et al.,* 2009a). Thereby, the extent of potential cultivated areas for many crop species is anticipated to expand at high latitudes in Europe.

Improvements in potential for crop diversification. Potential cultivated areas of the commonly grown major and/or minor crops (depending on Boreal region) will increase considerably, especially above their current northern limits for cultivation (Peltonen-Sainio *et al.,* 2009a). By the mid-century some of the contemporary crops, spring cereals, rapeseed and grain legumes will be grown up to 65–66 °N, i.e. as far north as there is arable land available in the Boreal Zone. Already this opens new opportunities for diversified crop rotations (Peltonen-Sainio and Niemi, 2012). Of the current spring-sown minor crops, oilseed rape, pea and faba bean (*Vicia faba* L.) are particularly strong candidates to become major crops in northern European regions. These crops have good potential for industrial processing, they are currently being bred and there is substantial need to substitute imported soybean (*Glycine max* L.) with regionally produced protein crops (Peltonen-Sainio and Niemi, 2012; Peltonen-Sainio *et al.,* 2012).

In addition to opening doors for expansion of areas for present crops, novel or extremely marginal minor crops may be introduced. Owing to the higher base temperature requirement for maize (*Zea mays* L.) growth than for temperate crops, silage maize could become a novel crop for the most favourable growing regions of the Boreal Zone, up to 61–62 °N by the end of this century (Peltonen-Sainio *et al.,* 2009a). Grain maize would only like gain ground across southernmost regions of Sweden (Elsgaard *et al.,* 2012) owing to the requirement for a long growing season and its being frost and chilling sensitive. When bench-marking the current cropping situation in a nearby region, grain maize has in fact only recently been introduced into Denmark due to elevated temperatures during the growing season, while forage maize has been an important crop there for a long time (Olesen *et al.,* 2011). Cultivation of current minor crops that require 1000–1100 °Cd and/or are prone to frost, e.g. buckwheat (*Fagopyrum esculentum* Mill.), flax (*Linum usitatissimum* L.), oil hemp (*Cannabis sativa* L.) and sunflower (*Helianthus annuus* L.), is today limited up to 62 °N and/or only in the most temperature-favoured regions, but their cultivation could expand northwards or increase in the present regions (Peltonen-Sainio *et al.,* 2009a).

As winters become milder, the temperature regimes in the northern regions of the Boreal Zone may gradually start to resemble those typical of southern Sweden and Denmark today. It is possible that expansion of winter-sown crops (cereals and rapeseed) northwards will represent major risks as a result of fluctuating winter conditions, and this could delay their adaptation for expanded production by many decades. Winter wheat (*Triticum aestivum* L.) and triticale (X *Triticosecale* Wittmack) may have the potential for expansion in the first wave, turnip rape thereafter, and winter barley and oat (*Avena sativa* L.) much later (Peltonen-Sainio *et al.,* 2009a). Also potential for introduction of new or neglected perennial grasses and forage legumes or expansion in their production in current regions may be improved along with prolonged, warmer growing seasons with milder winters (Hakala *et al.,* 2011).

Elevated temperatures are harmful to cereal and rapeseed yields throughout Europe (Reidsma and Ewert, 2008; Peltonen-Sainio *et al.,* 2010), and this sensitivity is also expressed in the northernmost European regions (Peltonen-Sainio *et al*., 2010; Peltonen-Sainio, Jauhiainen and Hakala, 2011; Kristensen, Schelde and Olesen, 2011). According to numerous studies carried out in many cropping regions across the globe, it seems evident that the present cultivars are adapted to rather narrow ranges of temperature typical for northern European growing seasons (relatively cool conditions at high latitudes) and even a small and temporary increase in mean and/or maximum temperatures reduces yields.

Heatwaves – elevated temperatures of extended duration – are particularly harmful for crop production under northern conditions as together with long days they accelerate developmental rate if they occur prior to heading or at flowering (for seed producing crops), or they cause premature maturation when occurring at grain-filling (Peltonen-Sainio, Jauhiainen and Hakala, 2011; Hakala *et al*., 2012). For example, rapeseed is particularly sensitive to elevated temperatures at late seed set and during seed fill: years with elevated temperatures often coincided the years with greatest yield losses (Peltonen-Sainio, Jauhiainen and Hannukkala, 2007). Also Frenck *et al.* (2011) showed that elevated temperatures were particularly harmful for yield formation of oilseed rape cultivars, though not their biomass. Episodes of elevated temperatures are often associated with drought, causing more severe yield reductions (Rötter *et al.,* 2011) and challenges for regrowth of cut grass crops. As an example of the impacts of elevated temperatures at national level, Peltonen-Sainio, Jauhiainen and Hannukkala (2007) found that higher temperatures accounted for up to two-thirds of the recorded, marked yield declines in rapeseed in Finland. Temperature elevation may cause yield losses also for winter cereals (Peltonen-Sainio, Jauhiainen and Hakala, 2011), as grain yield of winter wheat responded non-linearly to mean winter temperatures, with the highest yield at 4.4 °C and lower yields both below and above this inflection point (Kristensen, Schelde and Olesen, 2011). Peltonen-Sainio, Jauhiainen and Hakala (2011) did, however, show that elevated temperatures during the growing season were not harmful for winter wheat or rye (*Secale cereale* L.).

The negative effects of +5 °C elevation on yields cannot be compensated for by elevated CO_2 concentration (770 ppm) (Frenck *et al*., 2011). Also the experiments of Hakala (1998) showed that the benefits for growth provided by CO_2 enrichment (700 ppm) for spring wheat tended to compensate partly, but not completely, for the yield losses caused by elevated temperatures (by 3 °C). This was also evident according to a model-based assessment (Rötter *et al.*, 2011), according to which total growth duration decreased and yield losses were apparent at temperature increases exceeding 3 °C. Another exercise used long-term datasets of field crops typical for Finland and compared crop responses with elevated temperatures through grouping experiments according to the temperature range experienced during the growing season. Yield losses were again apparent for years having typical temperatures estimated for 2025 when compared with those typical for 1985 (Peltonen-Sainio, Jauhiainen and Hakala, 2011).

Increases in precipitation. In general, anticipated increases in early summer precipitation would have favourable impacts on crop production, while the projected increase in precipitation in August and September anticipates harmful impacts on crop maturation, harvest and quality (Ylhäisi *et al.*, 2010). Over recent decades, early summer drought has already somewhat eased off in the Boreal Zone, for example in the southwestern regions of Finland, as 5–9 mm more June precipitation was recorded per decade (Ylhäisi *et al.*, 2010). This is likely associated with 140–230 kg/ha higher grain yields in spring cereals and may, thereby contribute 15–20 percent of the cereal mean yield increases, recorded to be 1000–1600 kg/ha during the period from the 1960s to the 2000s (Peltonen-Sainio, Jauhiainen and Laurila, 2009). Such impact on yields results from increases in precipitation at the most critical developmental phase for yield formation of many seed producing crops. However, in the future more dramatic increases in precipitation are likely needed in order to meet the demands of more abundant plant stands supporting improved yield potentials, and to avoid that plant stands suffer from insufficient access to water when temperatures rise in the northern long day conditions (Ylhäisi *et al.*, 2010). If rain showers become more abundant and irregular in the future (as one manifestation of more general extreme events), rains become less efficiently used by crop stands and distribution of precipitation may meet the demands of the crop stands less efficiently. On the other hand, excess rain causes lodging, delayed ripening of plant stands, flooding with anoxia and results in deterioration of quality.

Milder winters. Typically temporal and spatial inter- and intra-annual variation in overwintering damage is high under northern growing conditions, exhibiting drastic regional differences in winter conditions in a south–north dimension. It is likely that in the near future climatic constraints are likely to become too harsh for successful expansion of overwintering crops because the winters may combine mild and severe periods, and fluctuation in winter conditions *per se* challenges overwintering capacity (Hakala *et al.*, 2011; Peltonen-Sainio, Hakala and Jauhiainen, 2011). Fluctuating conditions for winter wheat in particular have typically hampered overwintering, and freezing point days are likely to become more frequent in winter months and especially so in the northern parts of the Boreal Zone (Jylhä *et al.*, 2008). On the other hand, in the future further increasing autumn precipitation challenges winter rye that has presently better overwintering capacity than winter wheat (Peltonen-Sainio, Hakala and Jauhiainen, 2011), while low winter temperatures that have been critical for overwintering success of winter rye are projected to ease off.

Emerging crop protection risks. In general, and concerning the vast majority of cases, the changes in climatic conditions described above are likely to increase risks related to weed, pest and pathogen infestations in the future (Hakala *et al.,* 2011). The impacts of changes in severity of risks and predispositions of crops are not, however, straightforward due to the complex nature of interactions between climatic conditions (microclimates in crop stands), crop performance, incidence of pests and their predators, pathogens and their antagonists, weeds and their competitors, appearance of host plants other than cultivated crops, viruses and their vectors, etc. Another dimension of emerging crop protection risks in the future is introduction of alien species into northern agro-ecosystems (Hyvönen and Jalli, 2011; Vänninen *et al.,* 2011; Hannukkala, 2011). All these issues emphasize the need for region-dependent assessments of crop protection risks on a case-by-case basis.

4. NEEDS AND MEANS FOR ADAPTATION AT THE NORTHERN MARGIN OF AGRICULTURE

Adaptation is the key factor that will shape the future severity of climate change impacts on food production (Lobell *et al.,* 2008). Adaptation can largely reduce the potential harmful impacts of climate change and thereby alleviate variability of crop yields and farmer income (Reidsma *et al.,* 2010). In northern growing conditions, prompt adaptation measures are needed as changes in conditions are projected to be considerable and warming will proceed rapidly. On the other hand, owing to the lag period even after successful, globally followed-through mitigation measures, climate change will shape future agriculture at high latitudes.

As the examples above (section 2.2) indicate, farmers in northern areas are accustomed to adapting to continuously varying conditions. However, foreseen profound changes in regional production capacities and cropping patterns in the northern European conditions call for changes in agricultural policy. Need for policy guidance is particularly emphasized if highly productive fields are going to be sustainably intensified in the future, while poor performing extensified. One can characterize the present common agricultural policy (CAP), LFA and national payments as being rather inflexible. They are about to sustain existing production structures and means without necessarily encouraging towards the radical changes that are essentially required for successful adaptation as described below (sections 4.1 and 4.2). Ideally policy incentives should encourage and reward coupling of improvements in realization of production capacities (i.e., catching up emerging yield gaps; Peltonen-Sainio, Jauhiainen and Laurila, 2009) with environmental benefits and orientation according to market demands. This also means motivating investments for consolidating production and competitiveness as well as improving environmental care when adapting to climate change. Successful adaptation as such is a means to increase resilience of northern crop production, but hedging against yield losses and failures caused by climate variation and extreme events may imply development of, for example, weather index insurance systems (Myyrä, Pietola and Jauhiainen, 2001; Pietola *et al.,* 2011).

Climatic extremes will have significant impacts on agriculture and food security (IPCC, 2012). Developed countries are, in general, better equipped financially and institutionally to adopt specific measures to respond and adapt to projected changes efficiently regarding exposure and vulnerability to climate extremes (IPCC, 2012). In general, reducing exposure, increasing resilience to changing risks and reducing vulnerability of cropping systems are the key management approaches to adapting to a changing climate (IPCC, 2012).

4.1 Aiming at redeeming prospected opportunities

In general, prolonged growing seasons and an elevation in CO_2 concentration would increase yield potentials of major field crops. Estimates for increases in yield potentials are substantial, and suggest even doubling of yields per hectare (Peltonen-Sainio *et al.,* 2009a; Olesen *et al.,* 2011), but their realization in future climates requires many adaptation measures. Benefits in yield potential are gained indirectly if lower-yielding crops are replaced by more productive ones.

Field use in northern Europe may change drastically in the future. There is potential to markedly diversify cropping systems. Cultivation of crops that benefit relatively more from prolonged growing seasons, and are thereby more competitive, may be expanded most if their production uncertainties are managed. As an example, in the near future oilseed rape is likely to replace low-yielding turnip rape, a globally marginal crop that is currently grown and bred within Europe only in Finland (Peltonen-Sainio, Jauhiainen and Venäläinen, 2009; Peltonen-Sainio *et al.,* 2009a, 2009d). This is an example of adaptation means to better utilize the future conditions through enhancing yield potential. The role of other protein crops, faba bean, pea and lupins (*Lupinus* spp.) to substitute partly for imported soymeal may also increase owing to high demands for protein-rich feed sources in the future and when there are better opportunities to produce such crops in northern regions. Also the prospects for expanded production of high-yielding triticale are good as only modest increases in winter temperature enable its production at larger scales than are possible today. It may expand at the expense of spring fodder cereals, barley and oat. Also other overwintering types of presently dominant spring sown cereals, especially wheat, may become more common also in the northernmost regions of the Boreal Zone (Peltonen-Sainio *et al.,* 2009a). Also novel crops such as maize may eventually approach the northern agricultural regions (Peltonen-Sainio *et al.,* 2009a; Elsgaard *et al.,* 2012) though prospects for soybean production remain poor. In fact, farmers in Finland started to gather experience in cultivation of forage and bioenergy maize in the 2000s when heartened by warm summers. Introducing grain legumes, peas and faba bean in particular into crop rotations offers many ecosystem services that directly or indirectly contribute to improved resilience to climate change (Peltonen-Sainio and Niemi, 2012).

The growing season in northern Europe became two to three weeks longer during 1890–1997, and the prolongation took place both at the beginning and at the end of the growing season (Carter, 1998). Since 1965, the thermal growing season has in general started 2.0–2.8 days earlier per decade in Finland, except in the 1980s (Kaukoranta and Hakala, 2008) when a couple of exceptionally cool growing seasons occurred (Peltonen-Sainio and Niemi, 2012). Farmers have already adapted by sowing spring cereals 0.6 to 1.7 days earlier, depending on the region, while sugar beet and potato were sown 2.5 and 3.4 days earlier respectively (Kaukoranta and Hakala, 2008). In the case of potato, technology changes also enabled earlier sowing despite the acute sensitivity of potato to damage from night frosts.

This is an indication of an already occurring adaptation to climate warming and expansion of growing season in northern conditions.

4.2 Coping with challenges

Improvements in the resilience of northern cropping systems require that wide-ranging adaptation measures to changing and fluctuating conditions are taken. Realizing the prospects for increased yield potentials in northern regions, enabling marked diversification in cropping systems and improving resilience of northern crop production require adaptation measures (Table 4). In the future farmers will need to cope with: (i) elevated daily mean temperatures that interfere with crop growth, particularly when occurring under the long day conditions of northern latitudes; (ii) scarcity of water at critical phases of yield determination and harmful effects of abundant precipitation late in the growing season; (iii) greater pest, disease and weed pressure under future climates and cropping systems; (iv) other uncertainties caused in particular by extreme events; and (v) a generally greater need for inputs, especially nitrogen and crop protection agents and measures (Peltonen-Sainio *et al.*, 2009a).

Breeding for high temperature insensitivity or escape. Only plant breeding can provide comprehensive, primary solutions and thereby adaptation means to counter the negative impacts of elevated temperatures in the northern regions (Peltonen-Sainio *et al.*, 2009a; Peltonen-Sainio, Jauhiainen and Hakala, 2011; Rötter *et al.*, 2011). A recent study indicated that modern rapeseed cultivars were especially sensitive to elevated

Table 4: Main climate change adaptation needs and means to improve production capacity and resilience of northern crop production

Constraint	Crops of particular concern	Adaptation measure(s) needed
Long days, elevated temperatures, enhanced development rate	Seed crop plants	Breeding for insensitivity to elevated temperatures
Water availability and distribution	Spring sown crops	Development of year-round water management systems (including irrigation), breeding for improved water use efficiency, expanding cultivation of winter crops that have ability to escape early summer drought
Winter hardiness	Overwintering crops	Breeding for improved overwintering capacity, avoiding introduction of cultivars not well adapted to northern climates
Crop protection risks	All crops	Healthy propagating material, breeding for disease resistance, chemical and biological control systems, alarm systems
Extreme events	All crops	Alarm systems, breeding for improved yield stability, improving resilience through crop diversity
Access to nutrients	All crops	Fertilization practices (including split fertilizer use), crop rotations, increased cultivation of nitrogen-fixing legumes, breeding for improved nitrogen and phosphorus use efficiency

Source: Peltonen-Sainio *et al*. (2009a).

temperatures experienced in northern European conditions (Peltonen-Sainio, Jauhiainen and Hannukkala, 2007). It is possible that with climate warming, breeding lines will be more frequently exposed to elevated temperatures already during the selection programmes, and thereby responsiveness to elevated temperatures will to some extent be spontaneously addressed. However, as climate warming is likely to progress gradually, it means that newly released cultivars will always be better adapted to past rather than future temperature conditions, as might be the case with rapeseed temperature sensitivity recorded for Finnish conditions (Peltonen-Sainio, Jauhiainen and Hannukkala, 2007). Therefore, owing to the long time period needed in breeding new cultivars, prompt actions are called for, together with strategies (Table 4) that have clear sense of direction to counter the harmful and more aggravated impacts of heat in the future (Ortiz *et al.,* 2008).

Adaptation through altering cropping patterns can, in certain cases, ease the exposure of plant stands to the most critical temperature elevations. For example, introducing winter types that benefit from or are less susceptible to elevated temperatures (Kristensen, Schelde and Olesen, 2011; Peltonen-Sainio, Jauhiainen and Hakala, 2011) is a means to adapt to elevated temperatures. In the future, for example, replacing the most early maturing fodder barley with fodder triticale or introducing later maturing barley cultivars may be among the means to avoid or escape the evident risk of yield losses. Also changes in sowing time may be a means of avoiding critical growth phases that occur during times of stress, though for northern conditions the range of shift in sowing time is very limited and applicable only for the fastest maturing cultivars. However, according to a model-based assessment, adjustment of sowing time in spring barley did not alleviate yield losses sufficiently (Rötter *et al.,* 2011). For winter wheat, avoiding harmful temperature effects is also possible through delayed sowing or by growing cultivars with a higher vernalization requirement and/or stronger day length requirement (Kristensen, Schelde and Olesen, 2011).

In addition to shifting time of major phenological events, for example by earlier sowing (Olesen *et al.,* 2012), another means to adapt to changing temperature conditions is through shifting the duration and timing of phenological phases via plant breeding. For example, Patil *et al.* (2010a) suggested that winter wheat would be better adapted to the expected warmer winters if genotypes had a longer vegetative period, without advancing their reproductive stages. By such means, yield levels could be maintained even under shorter growing seasons. Another example of a trade-off between major developmental phases that has occurred in spring oat in Finland is that modern, higher-yielding oat cultivars have a shorter period from sowing to harvest compared with older cultivars owing to their shorter grain-filling period and higher share of the pre-anthesis period compared with the duration of the post-anthesis period (Peltonen-Sainio and Rajala , 2007). This has likely increased yield stability of oat by reducing risks related to delayed harvests. These examples emphasize the potential for trade-offs between developmental phases in order to adapt to changing temperature conditions. And in addition to temperature change, induced shifts in phasing may be a means to escape drought or risks of night frosts.

Developing water management systems. Despite the ability to moderate negative impacts of climate change through rather inexpensive changes in cropping systems, the largest benefits are likely to result from costly water management measures, including irrigation (Lobell *et al.,* 2008). Finland has exceptionally abundant, good-quality freshwater resources, but currently they are utilized for irrigation only in horticulture, and thus the total irrigated area remains small. The present and future major constraint of limited water can be solved through irrigation, but this requires developing systems that not only focus on enhancing productivity through irrigation but also protect the environment. The environmental load from agriculture is, in general, expected to increase in northern European aquatic environments (Jeppesen *et al.,* 2011). On the other hand, projected increases in precipitation outside the growing season challenge overwintering and soil drainage and represent a higher risk for nutrient loads, erosion, poor soil bearing capacity and soil compaction. Therefore, water resource management faces great challenges throughout the year. All these call for adaptation measures that include development of comprehensive water management systems (Table 4). Also, means other than irrigation may improve resilience of cropping systems with respect to water scarcity at critical developmental phases. For example, soil water-holding capacity may be improved in the long run by water conservation methods such as adding crop residues and manure to soils (Smith and Olesen, 2010) and using reduced tillage or direct drilling (Känkänen *et al.,* 2011).

Sustaining expansion of overwintering crops. Milder winters in the future may open up new opportunities for introduction of autumn-sown overwintering crops in the Boreal Zone to a greater extent than they are cultivated today (Peltonen-Sainio *et al.,* 2009a). For example, Finland is among the most virgin temperate areas for winter types of grain and seed crops, as the only currently grown crops, winter rye and wheat, cover only 1 percent of agricultural land. Winter types are attractive because of their higher yield potential, better ability to avoid early summer drought-induced yield losses, and soil cover, reducing risk of erosion and nutrient leaching. According to Patil *et al.* (2010b), projected future increases in drainage and nitrogen leaching are offset by increased water and nitrogen removal by the advanced growth of crops driven by warmer winters. It is, however, likely that, in the near future, climatic constraints are likely to be too harsh for successful overwintering of crops as winter may comprise mild and severe periods and the expected fluctuation in winter conditions will challenge the overwintering capacity of crops (Peltonen-Sainio, Hakala and Jauhiainen, 2011). Therefore, cultivation of winter crops may experience massive expansion by the mid-century (Table 5), as by then winters are likely to be “permanently” milder. An example of farmers’ continuous adaptation in northern conditions is that severity of winter damage in any one year is associated with a smaller area sown in the following year (Peltonen-Sainio, Hakala and Jauhiainen, 2011).

Contrary to the current situation in the northernmost Boreal region, Finland, in Uppland in Sweden, which lies at a comparable latitude to southernmost Finland, winter types of rapeseed have already been successfully adapted for cultivation. For example, in 2008 there were only 1300 hectares of spring turnip rape in Sweden and the crop seemed set to vanish from cultivation in the near future. Under future Finnish conditions, spring turnip rape will probably remain an important crop only in the northernmost growing regions, and it is likely to play an important role as a pioneer crop when new regions are approached. It seems likely that in northern regions as a whole, not only oilseed rape will dominate as an oil crop in the future, but also winter types will gradually approach the northernmost cropping regions of the Boreal Zone (Peltonen-Sainio *et al.,* 2009a).

Providing for increasing pest, disease and weed problems. Agriculture in the Boreal Zone has been favoured by exiguous risks represented by pests and diseases, when compared with the more southern regions of the northern hemisphere. However, changing climatic conditions and the means to adapt to these through changes in cropping patterns and systems may initiate new problems with higher occurrences of weeds, pests and pathogens (Hakala *et al.,* 2011). Major drivers for more challenging crop protection risks in the future are various. Among some examples are introduction of new species favouring prolonged growing seasons and elevated temperatures, expansion of cultivation of winter crops, stresses caused to crops by climatic constraints and increased sensitivity of crops to pest, disease and weed infestations, and a greater number of generations of pests reproduced in a prolonged and warmer growing season (Hakala *et al.*, 2011). Another dimension of further emerging crop protection risks in the future is introduction of alien species into northern agro-ecosystems (Hyvönen and Jalli, 2011; Vänninen *et al.,* 2011; Hannukkala, 2011).

The prospected changes in northern growing conditions call for adaptation measures such as resistance breeding, development of alarm systems, increase in frequencies of control treatments, and introduction of biocontrol opportunities, in addition to chemical control, production of healthy propagation material and increased use of high quality, upgraded or commercial certified seed (instead of farm-saved seed, which is the major current practice, Peltonen-Sainio, Rajala and Jauhiainen, 2011). There has also to be consciousness of potentially associated changes in vulnerability of developed management practices and cropping systems to crop protection risks. Owing to the complex nature of interactions between various factors affecting the success of pest, pathogen and weed infestations in the future (see above) region-dependent, case-by-case assessments of the means to cope with crop protection risks are needed even within the Boreal Zone.

4.3 Match or mismatch of adaptation and mitigation?

Agriculture needs to both reduce greenhouse gas emissions and adapt to a changing and more variable climate, but there is likely potential for synergies between adaptation and mitigation (Smith and Olesen, 2010). Adaptation and mitigation cannot be considered as separate routes to progress and virtually all the mitigation measures have direct or indirect impacts on the carbon and/or nitrogen cycle of agro-ecosystems (Smith and Olesen, 2010). In general, adaptation measures also have positive effects on mitigation, especially concerning measures that reduce soil erosion, increase nutrient use efficiency, reduce nitrogen and phosphorus leaching, conserve soil moisture, increase crop diversity, modify microclimate to reduce temperature extremes, sustain extensification of low productivity fields and avoid clearance of new fields (Smith and Olesen, 2010). However, especially on the dairy farms of the northern parts of Finland, new fields with peat soil (which due to their high carbon content are especially prone to high greenhouse gas emissions when incorporated) have been cleared, not for increased crop production *per se*, but to provide an expanded field area where manure can be applied to avoid excess nutrient loads per hectare.

The question of match or mismatch of adaptation and mitigation is even more relevant in northern Europe owing to the high climatic risks for agricultural production, variable weather conditions during growing seasons and even crop failures caused by extreme climatic events (Peltonen-Sainio and Niemi, 2012). In general, success in adaptation to climate change, i.e. implementing practices, cropping patterns and systems for climate-smart agriculture, not only improves resilience of northern agro-ecosystems, but through higher yielding capacities of crops strengthens the carbon sink at the regional level, though not in the context of contributing to global carbon sequestration or being anyhow comparable to the sink represented by Boreal forests. Nevertheless, in the case of insufficient adaptation, the environmental (also carbon) footprint of northern crop production is likely getting bigger, as vulnerability to climatic constraints in the future may result in yield losses and variability, which again will be associated with insufficient nutrient uptake, reduced nutrient use efficiencies and energy inefficiency, and farmers will hold back other essential management measures because of cautiousness regarding economic risks, etc.

5. TOWARDS RESILIENT CROPPING SYSTEMS WITH IMPROVED ADAPTIVE CAPACITY

Field crop production is universally susceptible to fluctuating weather conditions, irrespective of crop and environment. Though the global food supply is complex in nature, Lobell and Field (2007) showed that simple indicators of growing season temperatures and precipitation explained 30 percent or more of year-to-year variations in global average yields for the six most grown crops. Even though major advances have taken place, when it comes to development of cropping systems, technologies and breeding for phenotypic stability, management of climate-induced fluctuations in yields is often inefficient. It has been amply demonstrated that extreme and/or untimely critical weather events, especially drought, flood, heat and cold, cause major damage to food production systems, resulting in crop losses, and sometimes total failures over vast areas (Kumar *et al.,* 2004; Sivakumar, Das and Brunini, 2005; Battisti and Naylor, 2009). In the future, extreme events are projected to become more frequent as the climate changes (Klein Tank and Können, 2003; Alexander *et al.,* 2006; IPCC, 2007; Battisti and Naylor, 2009). Northern European agriculture is not projected to be in any way immune to such challenges today or in the future.

An essential step to improve resilience of northern cropping systems to changing climates is to develop the necessary activities for implementation of recognized adaptation strategies. They are essential to reduce vulnerability of northern crop production in the future (Table 4). As a part of this process, the National Adaptation Strategy (NAS) was launched in Finland in 2005 as the first NAS in Europe, followed by many others over several successive years (Biesbroek *et al.,* 2010). Strong interaction and dialogue among stakeholders, policy-makers, farmers, extension services, researchers, etc. are needed to implement the challenging list of adaptation requirements within a relatively short

Table 5: Example of anticipated time frames for specific significant changes in Finnish arable crop production required by climate change adaptation and implemented in order to improve resilience of northern cropping systems

Time frame	Anticipated change
2015→	Increased need for crop protection and more diverse control options: anticipation and control increasingly important to avoid production risks and volatility in yields.
2015–2025	Current cultivars give way: new range of cultivars move gradually from southernmost towards northern regions of Boreal Zone. Yield potentials increase, as do also realized yields in case of successful adaptation measures.
2015–2025	Cropping systems are diversified: for example, oilseed rape has replaced turnip rape also in the northern European cropping systems and grain legumes are cultivated more commonly to improve crop-based protein self-sufficiency and benefit from many of the ecosystem services (including nitrogen) that diversified cropping systems provide.
2020–2040	Crop production is sustainably intensified and thereby concentrated in the most favourable production regions in Boreal countries: excess arable land is used e.g. for production of commodity exports, bioenergy production, strongly specialized production and/or as naturally managed fields.
2020–2040	Water management systems for northern agro-ecosystems have been developed and implemented, especially into sustainably intensified production regions of the Boreal Zone. Thereby, nutrient cycles are more "closed".
2055→	Spring sown crops are largely replaced by winter types and cultivars. This concerns many cereals and rapeseed in particular.
21st century	Extreme weather events cause a great deal of uncertainty for production: spatial and temporal success in production is accompanied with failures elsewhere. Adaptation needs to become more and more appreciated as a means to improve resilience of northern agro-ecosystems.

time frame. An example of the requisite time frame for getting results from successful implementation of adaptation measures, in order to improve resilience of northern cropping systems, is shown in Table 5.

Successful implementation of adaptation measures together with climate change-induced opportunities for gaining higher yields in prolonged northern growing seasons are the main drivers for considering future field use alternatives. Namely, increases in future yield potentials may be so significant (Peltonen-Sainio *et al.*, 2009a) that presently available arable land proves to be excessive. Moreover, as production capacities of fields range from highly productive to poor, and parts of them are surrounded or plugged into highly vulnerable environments, seeking for a balance between sustainable intensification and extensification of cropping systems is justified as a future task. Extensified fields with low or hardly any input use may serve as nature preserving areas that also contribute to biodiversity enrichment. On the other hand, presently underperforming fields allowing more efficient agricultural production should be those sustainably intensified in the future decades (Table 5). It is obvious that there are likely to be large regional differences between needs for extensification and sustainable intensification of cropping systems. However, also within each farm there are fields that earn intensification as well as those better to extensify. Sustainable intensification concerns food production in particular, as is also the case with field-produced bioenergy if not otherwise competitive (e.g., sufficient production volumes, well-functioning logistics) and having a sufficiently low environmental footprint.

5.1 Contribution of breeding to more resilient cropping systems

Europe is among the world's largest and most productive suppliers of field products (Olesen and Bindi, 2002). In general, in each country, and often in different regions within a country, various crops are grown that are considered to be sufficiently adapted to the prevailing conditions. This is particularly critical for the Boreal Zone in which climatic conditions and constraints represent a unique combination of conditions to cope with.

Local plant breeding efforts often focus on developing cultivars of major field crops that are especially adapted to meet the typical local growing conditions (Peltonen-Sainio, Jauhiainen and Venäläinen, 2009; Peltonen-Sainio *et al.,* 2009a). Contrary to regionally adapted cultivars, many European "supranational" cultivars are also recognized and are grown over vast areas under a wide range of conditions. This tendency has strengthened in recent decades and may seriously threaten resilience of cropping systems.

A couple of examples are given that characterize cultivar variability in response to northern growing conditions. When cultivars adapted to northern conditions were compared, it was found that two types of associations existed between plasticity of yield and yield under stressful or favourable conditions for cereals: for spring wheat, oat and six-row barley, high yield plasticity was associated with crop responsiveness to favourable conditions rather than yield reductions under stressful conditions, while in winter wheat and rye, high yield plasticity resulted from the combination of high yield under favourable conditions but low in stressful environments. Evidently the former type of plasticity is the preferred one. Furthermore, modern spring wheat cultivars had higher maximum grain yields compared with older ones at the same level of plasticity (Peltonen-Sainio, Jauhiainen and Sadras, 2011). These examples emphasize the role and opportunities that plant breeding has in contributing to more resilient cropping systems through breeding for less-sensitive cultivars. The concept of "less-sensitivity" may comprise many improved characteristics that are advantageous when targeting improvements for resilience of northern agro-ecosystems: sufficient growing time, lodging resistance, disease and pest resistance, nutrient use efficiency, water use efficiency, tolerance to elevated temperatures, capacity to compete against weeds and overwintering capacity in autumn sown crops *inter alia*. Improvements in many of these traits are also central when aiming at sustainably intensifying northern cropping systems.

Sustainable intensification of cropping systems represents a means to narrow yield gaps in the future. In northern growing conditions, yields of cereals and rapeseed have in many cases stagnated or declined, despite evident progress in genetic yield gains (Peltonen-Sainio, Jauhiainen and Hannukkala, 2007; Peltonen-Sainio, Jauhiainen and Laurila, 2009). This means an increase in the gap between attained and potential yields. In addition to plant breeding, developments in technology and crop management are essential when targeting advances in agriculture through coupling improvements in crop production capacity and competitiveness with environmental benefits. In addition to breeding for more efficient cultivars, one of the evidently most challenging but also promising means to progress along this route is to develop sophisticated water management systems for northern growing areas, which generally have abundant supplies of fresh water.

5.2 Increasing diversity of northern cropping systems

Farm diversity. Despite the strong, general linkage between weather conditions and yields (Lobell and Field, 2007; Lobell, Cahill and Field, 2007), changes in weather conditions do not solely determine the extent of yield variability. Technological sophistication and developed farming systems may partly alleviate climate-related risks in Europe (Olesen and Bindi, 2002). Farm characteristics, such as intensity of cropping, farm size and land use, contribute to the capacity to resist climate-induced yield variability (Reidsma *et al.*, 2010).

High levels of farm diversity can be considered a means to adapt to and cope with climate change-induced increase in unfavourable conditions related to elevated temperatures and droughts, and thereby reduce vulnerability of yields and improve resilience to climate change (Reidsma and Ewert, 2008). Farm diversity can be expressed at the farm, region, country or climatic zone level (Reidsma and Ewert, 2008). At the farm level, diversity relates to diversity in farming activities. These can include differences in crops grown, degree and means of fertilizer use, pesticide use, irrigation and other basic management practices. As different crops respond differently to climate constraints and variability, greater crop diversity on farms may improve resilience and adaptation to climate change and thereby decrease vulnerability to climatic constraints (Howden *et al.*, 2007).

There are basically two means to diversify cropping systems: by introducing more diverse crop rotations (i.e. having more crop species for cultivation) and/or diversifying within a crop through introducing cultivars differing as much as possible genetically (though not at the expense of adaptation to prevailing conditions) and thereby in their responsiveness to weather conditions (Howden *et al.*, 2007). The latter is a particularly important approach in the case that economic incentives are limited and do not enhance cultivation of a greater number of different crop species. Northern agro-ecosystems are typically dominated by cereal and grass crops (Table 3). In the future, also for northern growing conditions, increases in diversity at the regional and farm scales are more possible owing to prolongation of growing season and concomitant opportunities to introduce novel crops or expand cultivation of current minor crops at the expense of cereal monocultures. Introduction and/or expansion of minor crops to diversify northern agro-ecosystems need, however, to be balanced in the sense that many minor crops (such as rapeseed and grain legumes) may be less well adapted to northern conditions (farmers may be also less used to managing associated responses and risks), which again may be associated with increased crop responsiveness to fluctuating conditions. This again may cause additional fluctuations in yields and does not necessarily result in the expected degree of improvement in resilience. On the other hand, the essential ecological services that diversified crops could provide to northern crop rotations may, in turn, enhance resilience.

Another means of diversifying future cropping systems at high latitudes is by further developing management of winter-sown crops that offer dual-opportunities: not only through their higher yield potential, reduced predisposition to early summer drought, and diversification of crop rotations, but also due to efficient capture of additional nitrogen that is mineralized during warmer autumns (Patil *et al.*, 2010b; Thomsen, Laegdsmand and Olesen, 2010). Results of Patil *et al.* (2010b) underline the importance of integrating winter, catch or cover crops into cereal-based cropping systems to improve resilience to harmful climate-change effects.

Benefiting from cultivar diversity is based on crop responses differing regarding timing of exceptional weather events, such as drought, heavy rains, low and high temperatures, depending on crop and phenotypic stability of the cultivar grown and management practices. In general, there is genetic variation available among current barley germplasm in response to many weather variables, except to waterlogging, early summer drought and high temperature accumulation rate at pre-heading (Hakala *et al.*, 2012). Thus, barley cultivars adapted to northern growing conditions do not have variation in their responses to some of the most critical risks that are likely to characterize changing climate. Weather conditions are also associated with the risk of pest and disease outbreaks and the magnitude of subsequent crop losses and, therefore, cultivar resistance to major diseases is likely to represent another important means to improve resilience. Rötter *et al.* (2011) also underlined that in addition to breeding adapted cultivars, agronomic practices, including crop protection, could help improve resilience and reduce risks of yield losses.

Another means to increase farm diversity in northern conditions is through extensification of cultivation in some areas and/or fields that have low productive capacity or represent especially high risks for the environment. Extensification may be implemented by using fields for production of bioenergy, if rational, or reserving them as naturally managed fields (see Table 5). Another important aspect of farm diversity is that the northernmost European countries are considered to have valuable croplands of high ecosystem quality (contrary to the most intensively cultivated croplands in Europe) and are therefore worth protecting to preserve their agricultural biodiversity (Reidsma *et al.*, 2006). On the other hand, in the future these northern cropping systems may, however, be sustainably intensified owing to higher potential yields in order not to expand the gap between actual and potential yields. This again may leave land for extensification, nature or to be used as naturally managed fields.

Regional diversity. At the regional level, diversity means differences in farm intensity, farm size, farm management and cropping systems. Integration of animal husbandry into crop production evidently increases regional diversity. During past centuries agriculture was most vulnerable to crop failures and the Finnish population to famine until animal production was launched as an essential component of Finnish agriculture and especially to buffer against food insecurity (Peltonen-Sainio and Niemi, 2012). In addition to farm characteristics, socio-economic conditions affect the adaptive capacity of agriculture (Reidsma, Ewert and Lansink, 2007). For example, input intensity and economic size influence, in addition to climate and land use, spatial variability in yields and income. Farm characteristics influence climate impacts on crop yields and income and are good indicators of adaptive capacity, and therefore different farm types with different management will adapt differently (Reidsma, Ewert and Lansink, 2007). Reidsma *et al.* (2010) demonstrated that greater diversity in farm types reduced impacts of climate variability on a regional scale, though certain farm types may still be vulnerable within a region.

Reidsma and Ewert (2008) assessed different regions in Europe and established that harmful effects of elevated temperatures were more modest in Mediterranean climates compared with central European temperate regions. Such an advantage was attributed to greater diversity of farms (size, intensity) and associated reduced regional vulnerability of wheat yields to climate variability. In light of this assessment, resilience of agriculture may be increased in Mediterranean regions by this means even though the Mediterranean is considered to be the most vulnerable region to climate change in Europe (Reidsma *et al.,* 2009). In the Boreal region, Finland being an example, agriculture is fragmented as production sectors are divided between the south and north (e.g. field crop versus dairy production regions), which again increases diversity in northern areas of the country while reducing it in southern areas owing to lack of diverse grass mixtures grown in south on a large scale.

6. SUMMARY

Northern European crop production may benefit from climate change in the long run, but not without comprehensive and extremely costly adaptation measures. In addition to being expensive, development and implementation of adaptation measures will also take time, which necessitates prompt responses in activating all the processes that target successful adaptation. In the case of northern European agriculture, successful adaptation does not mean that agricultural productivity and food production capacity would be sustained in “business as usual capacities”, but in the case of successful adaptation, northern European agriculture may even increase in productive capacities. On the other hand, there is also more to lose if yield potentials would drastically increase but, owing to more complex, coincident stresses, yields could stagnate or decline from the present levels. The “Stern Review on the Economics of Climate Change” type of analysis is, however, essential to estimate costs and benefits in northern agro-ecosystems. And this can be done today, in the light of recent understanding on anticipated changes in future production potentials as well as requirements for comprehensive adaptation measures.

Implementation of adaptation measures within an adequate time frame represents the avenue to substantially improve resilience of northern cropping systems to future climate. Cropping systems need to be highlighted as a concept because the key issue is not how a single trait or even several essential traits are tailored to a cultivar in order to improve resistance to or tolerance of climatic or other constraints. Such well-adapted cultivars are, however, essential components of larger cropping system, the performance of which must be managed as a whole to provide improved resilience to climate change and variability. Other essential components needed to improve resilience to future northern climates, in addition to well-adapted cultivars, are diversification of crop rotations and alternative crops (including nitrogen-fixing legumes, rapeseed, winter crops), development of water management systems, provision for emerging pests and diseases, planning of regional and farm-scale field use by balancing intensification and extensification, and a halt to further fragmentation of animal and crop farms. Adaptation at the farm scale may have cumulative effects on resilience also at the regional level. All these critical adaptation measures to improve resilience to climate change and variability in northern growing conditions are also essential steps towards sustainably intensified northern agricultural systems.

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