REPORT

Static yields and quality issues: Is the agri-environment program the primary driver?

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Abstract The Finnish agri-environmental program (AEP) has been in operation for 20 years with >90 % farmer commitment. This study aimed to establish whether reduced nitrogen (N) and phosphorus (P) use has impacted spring cereal yields and quality based on comprehensive follow-up studies and long-term experiments. We found that the gap between genetic yield potential and attained yield has increased after the AEP was imposed. However, many contemporary changes in agricultural practices, driven by changes in prices and farm subsidies, also including the AEP, were likely reasons, together with reduced N, but not phosphorus use. Such overall changes in crop management coincided with stagnation or decline in yields and adverse changes in quality, but yield-removed N increased and residual N decreased. Further studies are needed to assess whether all the changes are environmentally, economically, and socially sustainable, and acceptable, in the long run. The concept of sustainable intensification is worth considering as a means to develop northern European agricultural systems to combine environmental benefits with productivity.

Keywords Genetic gain · Incentive · Nitrogen · Phosphorus · Socio-economics · Yield decline

INTRODUCTION

Crop yields in Finland, one of the world's northernmost agricultural regions, are low compared to those attained at lower latitudes. For example, in Finland barley (*Hordeum*

vulgare L.) grain yields are 80–90 % and 60–70 % of those in Sweden and Denmark, respectively, and less than 60 % of those in France (Fig. 1). The difference is even more striking for wheat (*Triticum aestivum* L.). Such differences in yields among countries are attributable to various causes, but in this case particularly to differences in the length of the growing season and climate-dependent possibilities to replace spring types with higher yielding autumn-sown cultivars.

In contrast to indications of increasing yield trends in many regions (Green et al. 2012; Xiao and Tao 2014), there are alarming signs of a reduced pace in yield increases, static yields, and/or even yield declines (Ray et al. 2012). Thus, yield trends indicate insufficiency in meeting the global demand for increases in food production (Ray et al. 2013). Crop-dependent yield stagnation and decline also apply to Finland (Peltonen-Sainio et al. 2007, 2009), as is the general case in northwest Europe (Grassini et al. 2013). It has been debated whether such changes in yield trends are due to potential limitations for progress in breeding for higher yielding cultivars. Some recent studies, however, highlighted the overwhelming importance of plant breeding in increasing crop yields (Peltonen-Sainio et al. 2009; Mackay et al. 2011; Xiao and Tao 2014). However, changes in crop management and input use in a changed economic-environmental framework (Muukkonen et al. 2007; Salo et al. 2007; Känkänen et al. 2011) may have impacted yield trends and realization of genetic yield potentials, further complicated by changes in climatic conditions (Peltonen-Sainio et al. 2011a), which are often overlooked in yield trend assessments (Osborne and Wheeler 2013).

When Finland joined the European Union (EU) in 1995, crop prices decreased by 40–60 % and fertilizer prices by ca. 10 %. According to a profit-maximization point of

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Fig. 1 Grain yields of barley and wheat in Finland relative to those in Sweden, Denmark, and France during 1961–2012 (5-year moving averages). Data from FAO (2013)

view, fertilizer application rate is determined according to the point where the marginal value of additional yield is equal to the additional fertilizer cost. Experienced changes in relative prices since EU membership resulted in an 11 % reduction in nitrogen (N) use for wheat when a quadratic response function was used, while there was a 22 % reduction using the Mitscherlich function. Such changes in N use associated with yield declines correspond to 2.5 and 4.8 %, respectively (Ylälä 1996). Lehtonen et al. (2007) applied the same functions after calibrating them with more recent data and got similar results for all cereals. It was concluded that the major price changes experienced in Finland after 1995 resulted in no greater than 5 % total reduction in cereal yields, according to short-term, farm-level profit-maximization variable costs and returns. Hence, yields declined less relative to reduction in N use, and thereby an N surplus could be cut off by lower N use *ceteris paribus*. Such an argument evidently represented the rationale for a shift toward more extensive cereal production.

The large-scale Finnish Agri-Environment Program (AEP) was launched in 1995. This was an essential step to make major changes in excess fertilizer use reported for the late 1980s and the 1990s (Antikainen et al. 2008), which resulted in increasing agricultural loadings, eventually comprising 43 % of the total anthropogenic N and 63 % of the phosphorus (P) load (Valpasvuo-Jaatinen et al. 1997). Consequently, upper limits for N and P use were set (Electronic Supplementary Material, Table S1). Since then, national N- and P-fertilizer use rates gradually declined by some 20 kg ha⁻¹ compared to those at the beginning of the AEP period (Electronic Supplementary Material, Fig. S1). Consequently, soil P content has declined slightly, especially during the 2000s (Aakkula and Leppänen 2014). The AEP has been very powerful in terms of commitments made: AEP covered 95 % of field area and was participated in by 90 % of the farmers during the implementation period of 2007–2013. High commitment has been rational since AEP provided a stable €93 ha⁻¹ support payment on top of

the Common Agricultural Policy (CAP) pillar 1 (€150–240 ha⁻¹, depending on region) and least favourable area (LFA) payments (averaging €250 ha⁻¹) for those farmers who committed to comply with the N-fertilizer limits and other conditions of the AEP. The AEP is also rational from a risk aversion point of view when, for example, considering the volatile crop and fertilizer prices since 2007 and the cost-minimization tendency of small and inefficient farms, implicitly incentivized by CAP area payments and high production costs.

Launching the AEP in 1995 pushed forward the development and implementation of environmentally friendly production systems. It is not only important to document *per se* such ramifications for agriculture, but also to learn from the experience and to utilize the information gained to develop AEPs further. Currently, as comprehensive data are available, it is essential to assess the potential causal effects of the AEP on crop productivity and environmental benefits. The Finnish AEP is a valuable source for retrospective assessment due to the extensive commitment by farmers for almost two decades. In this study, we aimed to identify whether the reduction in N- and P-fertilizer uses has impacted on yields of primary cereal crops, spring barley, oat (*Avena sativa* L.), and wheat, and whether the most important quality characteristics that determine their market acceptability have changed.

MATERIALS AND METHODS

Characterization of study periods

The period studied was divided into various subperiods. 1970–1980 was the period when agriculture was strongly mechanized and pre-modern agricultural practices were developed and largely implemented. Compared with the 1960s, during this period, the number of tractors per unit land area more than doubled, and the number of combine

harvesters increased fivefold (FAO 2013). Also use of industrial fertilizers increased by 45 kg N ha⁻¹ and by 12 kg P ha⁻¹ corresponding with 100 kg N and 30 kg P ha⁻¹, respectively (Antikainen et al. 2008), and the method of fertilizer placement was implemented (Esala and Larpes 1986). On the other hand, 1981–1994 was a period characterized by introduction of modern crop-management practices, chemical control of pests and diseases, introduction of plant growth regulators, etc., all of which intensified production. However, use of agro-chemicals has been modest in Finland due to lower pressure for pest and disease outbreaks and because the market and policy incentives have not favoured their use. The latest phase of 1995–2013 was again characterized as the period of Finland being a member of European Union (EU) implementing the CAP, launching the AEP and thereby creating large changes in the socioeconomic environment for practising agriculture.

Data and analyses on changes in yield trends

Data on national yields of cereals was provided by the Information Centre of the Ministry of Agriculture and Forestry (Tike) to measure changes in national yields of barley, oat, and wheat. In addition, multilocation MTT Official Variety Trials were used to analyze changes in genetic yield potentials. Field trials were conducted for barley, oat, and wheat during 1970–2013 in Finland. The total number of locations was 28, but the sites depended on year and crop. Each crop was grown in its most typical region. The trials were managed according to the best practices (see more on Supplementary material SM1). Measurements and analyses followed the procedures specified in Laine et al. (2014). Fertilizer use depended on cropping history, soil type, and fertility. N-fertilizer application rate did not change over time. For all crops, P-fertilizer application rate declined to correspond with the reductions in national P use.

Grain yield (kg ha⁻¹ adjusted to 15 % grain moisture content) and the main quality traits [protein concentration (%), single grain weight (mg), hectoliter weight (kg)] were measured (Laine et al. 2014). Additional traits were measured to characterize changes in yield trends. Changes in national grain yields (±kg ha⁻¹ year⁻¹) were estimated by measuring the change from each single preceding year to the next, transforming the data to the 5-year moving averages and thereafter calculating the average change in national grain yield as a mean across all the years of each study period. Changes in genetic yield potential (±kg ha⁻¹ year⁻¹) were estimated in a similar way, but by comparing the genetic yield improvements in yielding capacity of new cultivars to their predecessors. Cultivars were classified as new cultivars in the first year of

introduction into MTT Official Variety Trials. The degree of realization of the genetic yield potential (±% unit year⁻¹) was based on comparison of national yields from Tike statistics with the genetic yield potential estimated from MTT Official Variety Trials.

A mixed model technique was used to analyze changes in genetic yield potentials and harvested yields according to MTT data using the following statistical model (1):

$$y_{ijkl} = \mu + \alpha_j + \beta_k + \gamma_{jkl} + \eta_i + \varepsilon_{ijkl} \quad (1)$$

where y_{ijkl} is the observed seed yield of the i th cultivar cultivated in the j th location, the k th year ($k = 1970, \dots, 2013$), and the l th trial; μ is the intercept; α_j is the random effect of the j th experimental site; β_k is the fixed effect of the k th year; γ_{jkl} is the random effect of the jkl th trial; η_i is the fixed effect of the i th cultivar; and ε_{ijkl} is the residual error. The assumptions for the random effects were $\alpha_j \sim iid N(0, \sigma_{\text{location}}^2)$, $\gamma_{jkl} \sim iid N(0, \sigma_{\text{trial}}^2)$, $\varepsilon_{ijkl} \sim iid N(0, \sigma^2)$, and all the effects are independent of one other. Annual breeding improvements were calculated comparing the estimated grain yields of different cultivars, $\hat{\eta}_i$, to the year in which each cultivar was entered in the trials. The parameters of the models were estimated using the restricted maximum likelihood (REML) method with the SAS system and MIXED procedure. The same statistical model was used to analyze trends in quality traits.

Grain quality survey: Analyses on impacts of reduced fertilizer rates on cereal quality

The survey data available for analyzing the quality effects of reduced N and P use were from 1988 to 2012 and grain protein concentrations from 1988 to 2010. The data were provided by the Grain Section of the Plant Analysis Unit of the Finnish Food Safety Authority (Evira) and included grain protein concentration (%), single grain weight (mg), and hectoliter weight (kg), which were analyzed by using Nir- and Nit-methods, grain counter, and Dickey John apparatus. The quality survey was based on the grain samples sent to Evira by farmers and on the background information that they supplied. Participating farms were randomly sampled from the data Farm Register of Tike to represent each region. Farms with less than five hectares of cultivated land were excluded from survey. Background information included N- and P-fertilizer uses, crop species, cultivar, and soil type. The number of samples tested varied annually. The total numbers of samples for barley, oat, and wheat were 18 460, 12 124, and 6993, respectively. In total, 65 % of samples were from clay soils, 19 % from sandy soils, and 16 % from organic soils.

Some sources of bias always exist when samples from farms are analyzed. The degree of bias can vary from one

Table 1 The average N- and P-fertilizer application rates for different soil types and time periods. Total number of fields analyzed was 37 577. Data from Evira

Cereal	Period	N-fertilizer use (kg ha ^{−1})				<i>P</i> value		P-fertilizer use (kg ha ^{−1})		<i>P</i> value	
		Clay	Sand	Organic	Mean						
Malting barley	1988–1994	100.2	95.8	84.6	93.6	Period	<0.001	23.7	Period	<0.001	
	1995–2005	91.8	88.5	76.5	85.6	Soil	<0.001	15.4	Soil	>0.5	
	2006–2012	85.7	82.5	75.0	81.1	<i>P</i> × <i>S</i>	>0.9	11.9	<i>P</i> × <i>S</i>	>0.4	
	Change 1	−8.4	−7.3	−8.1	−8.0	Change 1	<0.001	−8.3	Change 1	<0.001	
	Change 2	−14.5	−13.3	−9.6	−12.5	Change 2	<0.001	−11.8	Change 2	<0.001	
Feed barley	1988–1994	93.9	87.4	77.6	86.3	Period	<0.001	23.9	Period	<0.001	
	1995–2005	86.4	86.9	76.4	83.2	Soil	<0.001	16.2	Soil	<0.001	
	2006–2012	81.0	82.1	64.6	75.9	<i>P</i> × <i>S</i>	<0.001	13.1	<i>P</i> × <i>S</i>	>0.05	
	Change 1	−7.5	−0.5	−1.2	−3.1	Change 1	<0.01	−7.7	Change 1	<0.001	
	Change 2	−12.9	−5.3	−13.0	−10.4	Change 2	<0.001	−10.8	Change 2	<0.001	
Oat	1988–1994	90.9	89.2	74.9	85.0	Period	<0.001	24.1	Period	<0.001	
	1995–2005	85.2	85.1	75.5	81.9	Soil	<0.001	14.7	Soil	>0.05	
	2006–2012	82.3	76.6	67.6	75.5	<i>P</i> × <i>S</i>	<0.001	11.5	<i>P</i> × <i>S</i>	0.04	
	Change 1	−5.6	−4.0	0.6	−3.0	Change 1	<0.001	−9.4	Change 1	<0.001	
	Change 2	−8.5	−12.6	−7.3	−9.5	Change 2	<0.001	−12.6	Change 2	<0.001	
Wheat	1988–1994	113.8	106.6	98.6	106.31	Period	<0.001	23.7	Period	<0.001	
	1995–2005	101.4	96.7	91.4	96.5	Soil	<0.001	15.4	Soil	0.04	
	2006–2012	98.7	93.7	79.6	90.7	<i>P</i> × <i>S</i>	>0.12	12.5	<i>P</i> × <i>S</i>	>0.1	
	Change 1	−12.4	−9.9	−7.2	−9.8	Change 1	<0.001	−8.4	Change 1	<0.001	
	Change 2	−15.1	−12.9	−19.0	−15.6	Change 2	<0.001	−11.3	Change 2	<0.001	

Change 1 indicates change in a trait from 1988–1994 to 1995–2005 period while Change 2 that from 1988–1994 to 2006–2012

farm to another depending on how each farmer sees their yield lots and links the yield sample to the original information related to field conditions. In the case that the sample is from pooled yield lots, it can originate from fields that differ in soil type, fertilizer application rates, disease control procedures, and hence, the sample always represents the average over the prevailing conditions of each farm. Some special concern is relevant when analyzing impacts of changes in P-fertilizer use on quality traits, as soil P values were not available in the background information and could not be linked with P-fertilizer-use rates. Therefore, results on quality responses to P-fertilizer rates remain approximate and do not take into account the available P stored in the soil due to substantial historical P-fertilizer use.

To analyze the changes in N- and P-fertilizer uses for farms surveyed, the data were divided according to soil type and into three study periods (Table 1), representing either time before (one subperiod) or after (two subperiods) launching of the AEP. First N- and P-fertilizer application rates for each cereal species were compared over the three time periods using mixed models with the REML estimation method. Variety and region (rural center) were set as random effects, and year was a fixed effect in the models. As recommendations and upper limits (Electronic

Supplementary Material, Table S1) for N- and P-fertilizer uses were dependent on soil type, soil type, year, and soil type–year interaction were included in the statistical analyses. As the distribution of P-fertilizer application rates was skewed, logarithmic transformations were carried out to normalize the data. All results were subsequently transformed back to the original scale.

As significant differences between study periods were found for N- and P-use rates for all cereal species, the differences in quality traits between time periods were analyzed. Inter-annual and regional variations were high for grain quality traits due to differences in weather conditions. As conditions in a rural center and year combination were, however, quite similar, the effects of different fertilizer application rates were also examined within center–year combinations by using a random coefficient regression model in which effects of fertilizer application rates were assumed to be linear. Fertilizer effects were estimated for each rural center and year combination, and variety was treated as a covariate. Soil type was an additional covariate when analyzing N application rate effect, but soil type had no impact on results of the P-fertilizer effect and was excluded from that analysis. Effects of N- and P-application rates were estimated for each time period. Fertilizer effect was thereafter compared between the recurrent time periods.

Fig. 2 Changes in grain yields at national scale and in MTT Official Variety Trials, as well as in potential yields of barley, oat, and wheat in 1970–2012. National data from Tike

To analyze the changes in the removed and residual N, two additional traits were the measures considered. Yield removed nitrogen (YRN, %) was calculated by dividing total harvested N yield (kg N ha^{-1}) by applied N-fertilizer rate (kg N ha^{-1}). Residual nitrogen (ReN, kg N ha^{-1}) was calculated by subtracting the harvested N yield from the applied N-fertilizer rate. The survey data for all periods and all species were analyzed together. The model used included interaction effect of species–period and main effects of species, cultivar, soil type, and period as fixed effects. Graphical examination showed that other interactions did not have practically important impacts on the results. Random effects were year within period, region (rural center), and their interaction.

All statistical analyses were performed using SAS/MIXED-software (Littell et al. 2006). Scatter plots of residual and fitted values revealed some outliers, but because of their small number, they did not influence the results. Graphical examination of data also revealed some clearly biased records, which were removed before analysis.

RESULTS

Trends in realized yields and genetic yield potential

Although national yields have fluctuated in Finland, the yields of all cereals have in general increased in the long run (Fig. 2). Genetic gains in yields have been very consistent throughout the 40-year study period. On the other

hand, no consistent changes in the proportion of realized yield potential were evident (Fig. 3). In all cereals, the interannual variation in degree of realization of yield potential was reasonably high, but less variation was evident during the 2000s.

When considering changes in national yields, cereals have advanced most during the period 1981–1994 (Table 2). Since 1995, the increases in national yields have been modest for barley and wheat, while they have collapsed for oat.

Genetic yield improvements are evident for all cereals and throughout the studied time periods (Table 2). For barley and oat, genetic improvements in yield potential were at their lowest during the first decade period of 1970–1980. Degree of realization of genetic yield potential has been negative since the AEP was introduced. At other periods, they altered depending on crop species and breeding efforts and targets.

Changes in fertilizer use and quality traits

Comparing with the period before launching the AEP, N-fertilizer application rates declined by up to 19 kg N ha^{-1} for cereals (Table 1). Similarly, use of P fertilizers dropped to often correspond to less than half or even only one third of the rate for late part of 1988–1994. Use of P fertilizers has not differed markedly depending on soil type, in contrast with the case of N-fertilizer use rates (clay > sand > organic soils), with the highest reductions in N use on clay and/or sand soils for feed barley and oat (Table 1).

Fig. 3 Interannual variations in ratio between national yield and genetic yield potential (i.e., realization of yield potential, %) (shown as black circles). Dashed line indicates five-year moving averages of realized yield potential. National data from Tike and genetic yield improvement from MTT Official Variety Trials

Use of N fertilizer had a positive effect on protein concentration for all cereals for the first two time periods: 1988–1994 and 1995–2005 (Table 3). For 2006–2012, N-fertilizer use had significant effect on grain protein concentration for oat (0.002 % unit kg^{-1} N) and wheat (0.005), but not for barley. Decline in response of grain protein concentration to N use was significant only for barley and oat and when the 1988–1994 period was compared with 2006–2012. Single grain weight of barley and wheat responded positively to N-fertilizer use, but not for oat. N use increased hectoliter weight by 0.006–0.020 kg kg^{-1} N, depending on crop and time period (Table 3). Phosphorus-fertilizer use scarcely had an effect on quality traits (Electronic Supplementary Material, Table S2).

Quality traits differed depending on study period and soil type for all cereals (Tables 4, 5). Time period–soil type interaction was significant for protein concentration in feed barley and oat, and single grain weight and hectoliter weight in wheat. A consistent, slight decline with time was recorded for grain protein concentration in oat and wheat,

while there was an increase for malting barley. Regarding single grain weight and hectoliter weight, the 1988–1994 period was often associated with the highest mean values for all crops and soil types (Table 5). Although in general interannual and regional variations in acceptable quality of grain were high (Electronic Supplementary Material, Fig. S2), there was no evidence of any systematic increase or decrease in variability after launching the AEP.

For all cereals, grain protein concentration declined by 0.3–0.5 % unit within each decade due to cultivar changes. Coincidentally, single grain weight improved in cereals by 1.5–3.0 mg and hectoliter weight by 0.3–0.7 kg (Table 6).

The proportion of N available for crops that was removed along with the grain yield ranged from 76 to 84 % depending on crop (Table 7). Oat removed N most efficiently. Variation among cereal cultivars was, however, large—6 to 60 % units. Hence, also differences among cereal species in residual N were significant, ranging from 18 kg to 27 kg N ha^{-1} . The most efficient cultivars of feed barley, oat, and wheat left less than 10 $\text{kg residual N ha}^{-1}$. The range among cultivars was again very small for malting barley.

DISCUSSION

Two decades of yield stagnation and decline

Field use in Finland has changed markedly during the twentieth and twenty-first centuries, along with structural changes in agriculture driven by socioeconomic circumstances and developments. For example, higher pork and poultry consumption and production since the 1960s till today have resulted in expanded cereal areas. Concomitant shifts among species have also taken place, such as the increased importance of barley and wheat at the expense of oat. Along with agricultural mechanization and increased use of external inputs, crop management practices have gone through many developmental steps. As in the early phases of mechanization and external input use (prior to 1980), and when they were developed and applied extensively on a national scale (1981–1994), the main target for development was to increase productivity and benefit from improved yield potential.

The special emphasis, particularly from 1995 to the present time, has been to reduce the environmental footprint of agriculture and find means to implement economically attractive production systems as the real prices of cereals decreased (in 1994–2006) due to EU membership and rapidly increasing input prices. Hence, the AEP has been implemented as agriculture has faced the challenge of declining profitability. Increases in national yields were particularly high prior to 1994, but after 1995, the

Table 2 Changes in national mean yields, in genetic yield improvements, and in degree of realization of yield potentials for spring cereals. National yield improvements are given in kg and % year⁻¹. Figures for the highest yield improvement for any of the subperiods are shown in parentheses

Period	Barley	Oat	Wheat
<i>Change in national yield (kg ha⁻¹ year⁻¹)</i>			
1920–1969	24	27	20
1970–1980	30	26	28
1981–1994	60	50	76
1995–2013	7	–3	15
Whole period (kg ha ⁻¹ year ⁻¹)	27	25	29
Whole period (% year ⁻¹)	1.24 (2.05)	1.13 (1.73)	1.29 (2.52)
<i>Genetic improvement (kg year⁻¹)</i>			
1970–1980	28	5	49
1981–1994	37	25	33
1995–2013	68	29	65
Whole period	50	23	51
<i>Change in realized yield potential (±% unit year⁻¹)</i>			
1970–1980	0.26	0.65	–0.94
1981–1994	0.78	0.72	1.28
1995–2013	–0.68	–0.62	–0.41
Whole period	0.04	0.12	0.09

pace of yield improvements collapsed: increases in national barley and wheat yields were less than those for the period 1920–1969 and even negative in oat (Table 2).

Our method estimated genetic yield potential by assessing yield benefits gained by introducing new lines into long-term variety trials. Hence, yield potentials can be considered as attainable (realistic) at the national level. According to van Wart et al. (2013), grain yields at the farm level could approach 75–85 % of the national yield potentials. The proportion of realized yield potentials approached 80 % only for wheat and was around 60–70 % for barley and oat. The realized yield potential did not, however, increase during the AEP period (Fig. 3).

Yields tend to fluctuate in northern Europe (Fig. 2) due to variable weather conditions and depending on crop species and how far north they are cultivated. National yields for all cereals increased at an increasing pace before launch of the AEP (Table 2). Since the AEP began, the pace of yield improvement has fallen substantially and even become negative. The northernmost European growing regions can be characterized as being a part of the one third or quarter of the cropping areas globally that are considered to have undergone yield stagnation or collapse (Ray et al. 2012).

Changes in agronomic practices contributing to yield trends

Changes in management practices have been successful in terms of environmental footprint, especially by reducing

the N balance (i.e., difference between N inputs and outputs) from 90 to 50 kg ha⁻¹, recorded already during the early phase of the AEP (Salo et al. 2007). However, responses to economic challenges driven by EU CAP and markets (i.e., first real crop prices decreased, then price volatility increased) have not safeguarded national improvements in yield trends since launching the AEP in 1995. After launching the AEP, the profitability of cereal farms has been slightly higher than that of all farms only in the years 1995, 1996, 2000, and 2007. Agricultural input prices, especially for fertilizers, energy, and labor, have increased rapidly since 2000, and thereby profitability of cereals farms in Finland has been relatively low, except in 2007 (Niemi and Ahlstedt 2005, 2014, p. 61). Hence, market developments overall have not favored specialized cereal production.

Furthermore, genetic yield improvements were especially evident during the AEP period (Table 2), but changes in realized yield potential were negative. Many full-time intensive farms have criticized the AEP in the overall CAP and market context for being a program that rewards part-time farmers for extensive cultivation but which provides few viable measures for specialization and farmers who struggle with land price rises created by increased CAP area payments (partly due to CAP reforms after 2000) (Lehtonen, personal communication). Structural changes (like farm size growth and part-time farming) are important means to maintain rural livelihoods. There is, however, a risk that AEP measures are primarily adopted by part-time farmers who own a significant share of the land, but not by

Table 3 Effect of 1 kg N-fertilizer input on grain protein content, grain weight, and hectoliter weight in spring cereals. Data from Evira

Cereal	Period	Protein concentration			Grain weight			Hectoliter weight		
		Effect (% kg ⁻¹ N)	SE (% kg ⁻¹ N)	P value	Effect (mg kg ⁻¹ N)	SE (mg kg ⁻¹ N)	P value	Effect (kg kg ⁻¹ N)	SE (kg kg ⁻¹ N)	P value
Barley	1988–1994	0.004	0.0010	<0.001	0.010	0.0032	<0.01	0.016	0.0033	<0.001
	1995–2005	0.004	0.0008	<0.001	0.011	0.0026	<0.001	0.019	0.0027	<0.001
	2006–2012	0.000	0.0011	>0.9	0.009	0.0041	0.03	0.020	0.0037	<0.001
	Change 2	–0.004	0.0014	<0.01						
Oat	1988–1994	0.005	0.0009	<0.001	0.003	0.0019	>0.1	0.006	0.0025	<0.01
	1995–2005	0.003	0.0007	<0.001	–0.001	0.0015	>0.4	0.007	0.0019	<0.001
	2006–2012	0.002	0.0009	0.02	–0.001	0.0026	>0.6	0.008	0.0027	<0.01
	Change 2	–0.003	0.0013	0.03						
Wheat	1988–1994	0.006	0.0011	<0.001	0.005	0.0024	0.04	0.012	0.0028	<0.001
	1995–2005	0.006	0.0011	<0.001	0.006	0.0024	<0.01	0.008	0.0026	<0.01
	2006–2012	0.005	0.0012	<0.001	0.010	0.0032	<0.01	0.010	0.0030	<0.001

Change 1 indicates change in a trait from 1988–1994 to 1995–2005 period while Change 2 that from 1988–1994 to 2006–2012. Only significant changes are shown

P value, significant of difference between means, SE standard error of the mean

full-time farmers with more intensive farming systems. Hence, one can argue whether such changes, when also associated with yield stagnation and decline, have been socioeconomically sustainable in the long run to, e.g., support wellbeing of farmers, competitiveness of farming, and basic investments needed in agriculture. Basic investments essential for efficient crop production, which have been neglected in particular include liming of low pH soils (Myrrä et al. 2005) and maintaining subsurface drainage systems. Such issues are attributable to increasing frequency of leased fields with the aim to increase farm size to gain more area-based subsidies (Pouta et al. 2012).

Reductions in fertilizer use strongly dominate changes in nutrient availability for cereals. Total volume of manure nutrients has not changed significantly during the AEP period despite a 20 % reduction in the number of cattle. Cattle alone contributes to 80 % of total manure production in Finland (Mattila 2006), but reduction in number of cattle has been compensated for by higher annual amounts of manure N and P per animal following changes in livestock feeds (Aakkula and Leppänen 2014).

In general, yield decline and stagnation coincide with systematic reductions in N- and P-fertilizer use rates: gradually by up to 19 kg N and 13 kg P ha⁻¹, representing at most ca. 19 and 52 % reductions in N and P use, respectively, depending on crop and soil type (Table 1). The role of reduced N use dominates over the effects of reduced P use. Eight decades of metadata did not show any yield decline when P-use rates were reduced compared to those implemented according to the AEP (Valkama et al. 2009). On the other hand, genetic yield improvements in cultivars,

which the metadata analyses integrated to all changes in agricultural practices over the decades, have been the highest for the AEP period, likely owing to the development of breeding techniques and screening methods. Hence, change in sensitivity of crop responses to P fertilizers may also have changed. The yield response to P fertilizers tended to be slightly lower in the last three decades compared with previous decades according to Valkama et al. (2009).

Cassman and Harwood (1995) were concerned that if management, under the pressure of the prevailing economic-environmental framework, focuses on short-run profitability gains rather than long-run sustainability, it may be particularly hazardous for soil conditions that are hard to correct for later. Major agronomic changes, targeted or self-oriented, have included the introduction of no-tillage and reduced-tillage methods (Käñkänen et al. 2011), which depend on high glyphosate use (Helander et al. 2012), and the movement toward cereal-dominated monocultures and insufficient use of fungicides (Jalli et al. 2011). Increased farm size has increased distances to field plots, and timeliness costs, and has thus hampered farmers in carrying out management practices in a timely manner (Niskanen and Lehtonen 2014).

No-tillage or direct drilling gradually replaced traditional autumn tillage, and was encouraged for both economic and environmental reasons (Muukkonen et al. 2007) until 2007, with the no-tillage area stagnating at 13 % of cultivated land. Yield reductions caused by no-tillage were substantial (averaging 36 %), although they varied considerably from 10 to 73 % depending on crop and weather

Table 4 The average grain protein concentrations for different soil types and time periods. Total number of fields analyzed was 31 406. Data from Evira

Cereal	Period	Grain protein concentration (%)				<i>P</i> value	
		Clay	Sand	Organic	Mean		
Malting barley	1988–1994	12.3	11.8	12.4	12.1	Period	0.01
	1995–2005	12.3	12.1	12.6	12.4	Soil	<0.001
	2006–2012	12.4	12.1	12.8	12.4	<i>P</i> × <i>S</i>	>0.1
	Change 1	0.0	0.3	0.2	0.2	Change 1	<0.01
	Change 2	0.1	0.3	0.4	0.3	Change 2	0.02
Feed barley	1988–1994	12.2	11.8	12.3	12.1	Period	<0.001
	1995–2005	12.2	12.1	12.5	12.3	Soil	<0.001
	2006–2012	12.2	12.0	12.4	12.2	<i>P</i> × <i>S</i>	<0.001
	Change 1	0.0	0.3	0.2	0.2	Change 1	<0.001
	Change 2	0.0	0.3	0.2	0.2	Change 2	<0.001
Oat	1988–1994	13.1	12.8	13.1	13.0	Period	<0.001
	1995–2005	12.8	12.8	13.1	12.9	Soil	<0.001
	2006–2012	12.7	12.5	12.9	12.7	<i>P</i> × <i>S</i>	<0.001
	Change 1	−0.3	0.0	0.0	−0.1	Change 1	<0.001
	Change 2	−0.4	−0.3	−0.2	−0.3	Change 2	<0.001
Wheat	1988–1994	13.8	13.8	13.7	13.8	Period	<0.001
	1995–2005	13.3	13.4	13.5	13.4	Soil	>0.4
	2006–2012	13.0	12.9	13.2	13.0	<i>P</i> × <i>S</i>	>0.2
	Change 1	−0.5	−0.4	−0.2	−0.4	Change 1	<0.001
	Change 2	−0.8	−0.9	−0.5	−0.7	Change 2	<0.001

Change 1 indicates change in a trait from 1988–1994 to 1995–2005 period while Change 2 that from 1988–1994 to 2006–2012. Only significant changes are shown

conditions at sowing (Känkänen et al. 2011). This suggests that introduction of direct drilling systems may have reduced national cereal yields in total by up to 5 %, although according to farmers, the yield reduction has not been as great in their fields as on the clay soils of experiment sites.

Compacted soils, attributable to heavy field machinery and possibly further emphasized by lack of proper crop rotations and timing of cropping practices in the prime grain cropping area, have potentially reduced yields. For example, wheat after wheat in rotation was associated with average yield losses of about 10–15 % (Jauhiainen, pers. comm.). Compared with the present paucity of crop rotations, increasing diversity in cropping systems will likely reduce nutrient leaching (Rankinen et al. 2013). Compacted soils have impeded root penetration as demonstrated for rapeseed (Peltonen-Sainio et al. 2011b), which may again partly explain the low YRN (Peltonen-Sainio and Jauhiainen 2010) and yield declines. Additional problems for yield losses on compacted soils may have been exacerbated by more frequent warm spells in the 2000s (Peltonen-Sainio et al. 2011a). In addition to physical constraints like soil compaction, some changes in soil fertility have taken place. Modest decline in soil P content represents an example (Aakkula and Leppänen 2014) as does decline in topsoil carbon contents by 0.4 % per year in

mineral soils—corresponding to a carbon stock loss of 220 kg ha^{−1} year^{−1} (Heikkinen et al. 2013). However, the direct contribution of, e.g., soil carbon content reduction to yield trends has not been estimated.

Finally, the role of organic farming has increased, resulting in yield penalties of up to 42 % recorded in wheat (TIKE 2013). However, due to reasonably low areas under organic farming, yield penalties correspond only to some 1.4 % yield reductions at the national scale compared with the situation in which the entire current cereal area would have been solely under conventional production.

These considerations on likely reasons for static or reduced yields emphasize the complex nature of such assessments because changes in cropping systems and conditions involve large numbers of variables. Negative changes in realized yield potentials, however, suggest that reduced N application rates may have partly contributed to the inability of current farming systems to exploit the improved genetic yield potential of modern cultivars. On the other hand, modern cultivars are able to use N more efficiently and during the AEP period YRN increased and ResN declined (Table 7), which again indicates that farmers' concerns that static yields are associated with higher N losses to the environment are not justified.

Table 5 The average grain weight and hectoliter weight for different soil types and time periods. Total number of fields analyzed was 37 577. Data from Evira

Cereal	Period	Grain weight (mg)				<i>P</i> value	Hectoliter weight (kg)				<i>P</i> value		
		Clay	Sand	Organic	Mean		Clay	Sand	Organic	Mean			
Malting barley	1988–1994	45.1	43.7	43.8	44.2	Period	<0.001	70.3	70.1	69.6	70.0	Period	<0.001
	1995–2005	39.6	39.1	38.1	38.9	Soil	<0.001	67.0	67.0	66.0	66.7	Soil	0.03
	2006–2012	40.1	38.6	39.7	39.5	<i>P</i> × <i>S</i>	>0.05	66.4	66.2	66.1	66.2	<i>P</i> × <i>S</i>	>0.7
	Change 1	−5.5	−4.6	−5.7	−5.3	Change 1	<0.001	−3.3	−3.1	−3.6	−3.3	Change 1	<0.001
	Change 2	−5.0	−5.1	−4.1	−4.8	Change 2	<0.001	−3.9	−3.9	−3.5	−3.8	Change 2	<0.001
Feed barley	1988–1994	40.9	40.0	39.9	40.3	Period	<0.001	66.4	65.9	65.0	65.8	Period	<0.001
	1995–2005	37.5	37.0	36.6	37.0	Soil	<0.001	64.2	64.0	63.4	63.9	Soil	<0.001
	2006–2012	37.6	37.2	37.6	37.5	<i>P</i> × <i>S</i>	>0.1	64.0	63.9	63.1	63.6	<i>P</i> × <i>S</i>	>0.2
	Change 1	−3.4	−3.0	−3.3	−3.3	Change 1	<0.001	−2.2	−1.9	−1.6	−1.9	Change 1	<0.001
	Change 2	−3.3	−2.8	−2.3	−2.8	Change 2	<0.001	−2.4	−2.0	−1.9	−2.1	Change 2	<0.001
Oat	1988–1994	33.4	33.4	32.9	33.2	Period	<0.001	55.9	55.6	55.3	55.6	Period	<0.001
	1995–2005	32.7	32.5	32.3	32.5	Soil	<0.001	55.6	55.2	55.0	55.2	Soil	<0.001
	2006–2012	32.7	32.7	32.4	32.6	<i>P</i> × <i>S</i>	>0.6	56.0	55.5	54.8	55.4	<i>P</i> × <i>S</i>	>0.1
	Change 1	−0.7	−0.9	−0.6	−0.7	Change 1	<0.001	−0.3	−0.4	−0.3	−0.4	Change 1	<0.001
	Change 2	−0.7	−0.7	−0.5	−0.6	Change 2	<0.001						
Wheat	1988–1994	37.1	36.5	36.8	36.8	Period	<0.001	80.1	79.1	78.8	79.3	Period	<0.001
	1995–2005	34.7	34.9	34.4	34.7	Soil	<0.001	78.4	78.6	78.2	78.4	Soil	<0.001
	2006–2012	33.6	33.1	31.6	32.8	<i>P</i> × <i>S</i>	<0.001	78.4	78.3	77.9	78.2	<i>P</i> × <i>S</i>	<0.001
	Change 1	−2.4	−1.6	−2.4	−2.2	Change 1	<0.001	−1.7	−0.5	−0.6	−1.0	Change 1	<0.001
	Change 2	−3.5	−3.4	−5.2	−4.0	Change 2	<0.001	−1.7	−0.8	−0.9	−1.1	Change 2	<0.001

Change 1 indicates change in a trait from 1988–1994 to 1995–2005 period while Change 2 that from 1988–1994 to 2006–2012. Only significant changes are shown

Any trends in AEP-driven quality change over time?

Plant breeding has contributed to changes in grain quality with a long-term average of 0.03–0.05 % unit reduction per year in grain protein concentration (Table 6). During the same period from 1970 till now, genetic gains for grain weight have been evident, as is also true for hectolitre weight. When survey data on farm samples were evaluated, we found that response of grain protein concentration to applied N has declined compared with the period prior to 1995 and the introduction of the AEP (Table 3). This indicates that during the earlier periods, N was sufficient to sustain grain protein formation at grain-filling, while it is likely that N fertilizer was allocated more to growth and yield formation at the expense of grain protein concentration during the AEP period. Genetic drawbacks and changes in N supply coincide and thereby likely contribute to reductions in grain protein concentration established for oat and wheat during the AEP period (Table 4). In contrast with the case for other cereals, protein concentrations increased for malting barley (contrary to need). Adverse changes in quality traits during the AEP period also include reductions in single grain weight and hectoliter weight (Table 5).

Table 6 Genetic improvements in quality traits of spring cereals according to MTT Variety Trials 1970–2013

Cereal species	Grain protein concentration (% unit year ^{−1})	Grain weight (mg year ^{−1})	Hectoliter weight (kg year ^{−1})
Barley	−0.05	0.30	0.07
Oat	−0.03	0.15	0.03
Wheat	−0.03	0.17	0.05

No response of cereal quality traits to P-fertilizer use was found when different time periods were compared. In Finland, due to excessive use of P fertilizers in earlier decades, P storage in soils is comprehensive (Saarela et al. 2004). Hence, despite reducing P-fertilizer use substantially, soil-stored P may be sufficient to maintain crop yields (Valkama et al. 2009, Tóth et al. 2014), although the usability of soil P may decline over the time when the most soluble and easy-to-mobilize P has been used (Blake et al. 2003). To date, reduced P-fertilizer use has not likely contributed to stagnant yields (Valkama et al. 2009), or changed quality traits, which contrasts with the detrimental effects of the reduced N use illustrated in this study.

Table 7 Differences between crops and cultivars in yield-removed nitrogen (YRN) and residual nitrogen (ReN) and changes in time according to data from farmers' fields during 1988–2010 (data from Evira.). Total number of fields analyzed was 31 406. S.E., standard error of the mean

Crop	Mean	SE	<i>P</i> value	Variation between cultivars*			Period**				
				Minimum	Maximum	s.d.	1988–1994	1994–2005	2006–2010	Change 1	Change 2
<i>YRN (%)</i>											
Malting barley	0.76	0.022	<0.001	0.73	0.79	0.02	0.73	0.76	0.80	–	–
Feed barley	0.78	0.027	<0.01	0.54	1.14	0.10	0.76	0.80	0.86	–	0.10
Oat	0.84	0.022	=C	0.76	0.98	0.05	0.79	0.83	0.88	–	0.09
Wheat	0.79	0.025	<0.01	0.63	1.02	0.07	0.74	0.82	0.84	0.09	0.10
<i>ReN (kg ha^{−1})</i>											
Malting barley	25.7	2.14	<0.001	24.4	26.6	0.9	30	24	21	–	−9
Feed barley	23.4	2.63	<0.01	−7.2	43.4	9.5	27	21	17	–	−10
Oat	18.1	2.21	=C	7.2	27.8	4.8	22	18	14	−4	−8
Wheat	27.2	2.47	<0.001	9.5	38.8	7.1	35	22	20	−13	−15

* For YRN between cultivars $F_{3,313} = 24.79$, $P < 0.001$; for ReN $F_{3,313} = 27.51$, $P < 0.001$

** For YRN P values were <0.001 for crops, 0.18 for periods, and 0.01 for crop–period interaction, while for ReN, they all were <0.0001. Change 1 indicates change in a trait from 1988–1994 to 1995–2005 period while Change 2 that from 1988–1994 to 2006–2010. Dot indicates nonsignificant change

In conclusion, a large-scale national survey of Finnish farms committed to the AEP showed that the reduced use of N coincided with and also likely contributed to yield stagnation, collapse in realization rates of genetic yield potential, and adverse changes in quality traits. Decreased use of P fertilizer has not to date had a significant effect on yields due to the history of high P application. However, many coincidental changes in agronomic practices also were implemented in northern European agricultural systems during the EU membership period, not only those driven by the AEP. Large-scale market and policy changes have incentivized farmers for cost-minimization, which again has seemingly occurred at the expense of productivity, i.e., through extensification of the Finnish cropping systems. In addition to LFA and CAP pillar one payments, the AEP has further strengthened the incentive for extensive crop production. Whether all the experienced changes are completely environmentally, economically, and socially sustainable, and acceptable in the long run, needs to be further investigated in light of these findings. Sustainable intensification may offer the future means to combine enhancements in productivity in non-water-scarce regions and provide environmental benefits when field- and farm-scale assessments of yield gaps have provided sufficient guidelines for pilot, and thereafter, large-scale implementation.

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