MTT REPORT 102

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Abstract

Crop yield responses to nitrogen (N) fertilizers and associated changes in field N balances were gathered from fertilizer trials by MTT Agrifood Research Finland, Potato Research Institute and Sugar Beet Research Center, to facilitate renewal of the Nitrate decree in Finland. Moreover, data from practical fields were retrieved from the Finnish Food Safety Authority (Evira) and other sources (starch potato data, yield competition data) for comparison with the research data. In both the experimental and farm data, N balances increased along with increasing N fertilizer rates. Moreover, at a given N fertilizer level, N balances increased in the order: yield competition, experimental field data, farm data. Environmentally acceptable N fertilizer rates were proposed by considering the variability in the different datasets in yield responses and N balances, and by using a simple model to estimate the leaching risk.

Keywords:

Nitrogen fertilization, yield response, nitrogen balance, nitrogen leaching, cereals, grass, potato, sugar beet

Suomen maatalouden typpilannoitustasot, typpitaseiden ylijäämä ja nitraatin huuhtoutumisriski

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Tiivistelmä

Osana kansallista nitraattiasetuksen uudistamista Maa- ja elintarviketalouden tutkimuskeskus (MTT), Perunantutkimuslaitos (PETLA) ja Sokerijuurikkaan tutkimuslaitos (SjT) kokosivat kasvien typpilannoituskokeiden tuloksia yhteen lannoitusvasteiden ja typpitaseiden tarkastelemiseksi. Tässä raportissa esitetään typpilannoituskokeiden tulosaineistojen lisäksi Elintarviketurvallisuusviraston (Evira) viljaotannan ja Käytännön Maamies-lehden satokilpailujen yhteydessä keräämää peltolohkoaineistoa lannoitustasoista ja saavutetuista sadoista sekä verrataan lannoitusvasteita ja typpitaseita näiden kahden aineistotyypin välillä. Molemmissa aineistotyypeissä typpilannoituksen ja typpitaseiden välillä oli selvä yhteys: lannoituksen lisääminen johti suurempiin taseisiin. Lannoituskokeissa saavutettiin keskimäärin pienempiä typpitaseita kuin käytännön viljanviljelyssä, kun taas satokilpailujen taseet olivat kaikkein pienimpiä. Tämä vaihtelu huomioiden nitraattiasetukseen ehdotettiin viljelykasvikohtaisia typpilannoituksen ylärajoja, jotka perustuvat osin havaittuihin typpitaseisiin ja osin typpilannoitusvasteisiin sekä maalajien välisiin eroihin typen huuhtoutumisherkkyydessä. Huuhtouma-arviossa hyödynnettiin yksinkertaista tutkimusaineistoista johdettua mallia.

Avainsanat:
Typpilannoitus, satovaste, typpitase, typen huuhtoutuminen, viljat, nurmi, peruna, sokerijuurikas

Contents

1 Nitrogen leaching risk as affected by N fertilization

Nitrogen (N) uptake from soils is one of the most essential factors affecting crop growth. Depending on the soil organic matter (SOM) content and activity of soil microbes, variable amount of N becomes plant-available from the soil, and cultivation of legumes imports N to soil by biological N fixation. However, N fertilization by animal manures, other N-rich materials or by chemical fertilizers is often the major N input needed to promote high yields of agricultural crops. While increasing crop yields, higher N fertilizer rates lead to higher N surpluses (or field balances, calculated as N input in fertilizers minus N output in the crop yield) (Mattila et al. 2007, Salo et al. 2007b, Saarijärvi 2008, Valkama et al. 2013a), that are associated with increasing risk of N leaching in Finland (Salo and Turtola 2006).

Presently the average national N balance is around 50 kg/ha and regional N balances vary from 30 to 70 kg/ha (Salo et al. 2007b). Reflecting recent decreasing trend in N balances, a nationwide hydrogeochemical mapping indicates that NO_3 concentration in Finnish groundwater has decreased during recent decades (Backman 2004, Nyroos ym. 2006). In contrast, according to N load estimates in larger rivers along the western coast especially, there is a slightly increasing trend in the N load to the Baltic Sea (Ekholm et al. 2008).

In practical farming N balances will usually maintain at a reasonable level since N fertilization is restricted by economic optimum and decreasing yield responses after certain doses. However, these critical doses vary from year to year and site to site according to growth conditions, especially the weather during the growing season, and are therefore difficult to predict at the time of sowing. With some crops, diminishing quality may also motivate farmers to use lower rates of N fertilizer. Therefore, the economic optimum N fertilization is often difficult to predict in practice (Valkama et al. 2013a, 2013b) and there is scarce knowledge whether the economic optimum should be considered acceptable from the environmental point of view. The attempt of this report was to collect data from different sources (published scientific articles, unpublished controlled fertilizer trials, practical farming) which can be used to estimate the effects of increasing N rates on yield responses as well as on the associated N balances in Finnish conditions. The N balances were then used as an indicator of the N leaching risk due to increasing N fertilizer rates of different crops.

The relationship between N balance and N leaching is estimated according to the study of Salo and Turtola (2006) and other research. Accordingly, while annual N balance alone does not usually explain well the observed annual leaching, averages over several years have more predictive power. Leaching and balance also correlate better for farm managements that include very high leaching risk (like high input of animal manure, Lemola and Turtola 2006). Based on these findings, we made the following estimations of N leaching risk associated with different N balances in mineral soils (Figure 1).

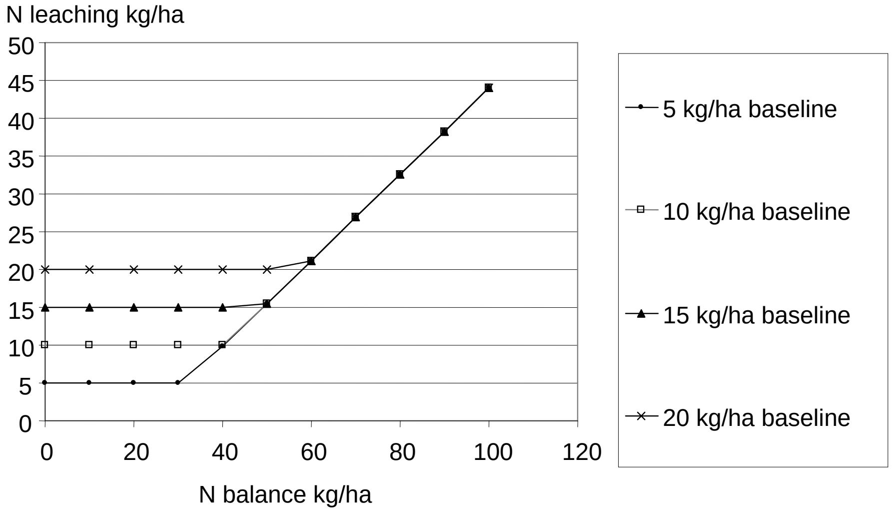

Fig 1. Tentative linear-plateau equation between N balance and N leaching. (N leaching = max baseline; -13+0.57 x N balance; Salo and Turtola 2006).

According to this estimation, N leaching first follows a plateau and then a linear relationship, suggesting that 57% of N balance would be leached. The higher the expected baseline N leaching, the higher N balance is required before it starts to affect N leaching. If the soil has a high amount of N in the internal cycling (N turnover from organic matter) the effect of N balance is not visible at low balance values.

When these equations are scaled according to the average Finnish N balance of 50 kg/ha (Salo et al. 2007b) and estimated average N leaching of 15-18 kg/ha (Vuorenmaa et al. 2002), the baseline N leaching of 15 kg/ha results no increase due to N balance of 50 kg/ha. However, if the baseline leaching is low, then N balance of 50 kg/ha would increase leaching by 10 kg/ha and leaching would again end up close to 15 kg/ha. Thus we can roughly estimate that N balance of 50 kg/ha does not, on the average, increase risk of N leaching considerably whereas in case of N balances of higher than that there would be a tendency of increased N leaching.

The measured amounts of leached N (at a certain N balance) vary considerably between different soil types and weather conditions, as was observed in a lysimeter trial with clay, silt, sand and peat soils (Lemola and Turtola 2006). Very high N leaching was measured for peat soil even at negative N balances while for mineral soils there was a sharp increase in leaching at annual N balances of 30-70 kg/ha. The range of 30-70 kg/ha falls roughly to the breaking point of our linear-plateau model of mineral soils, but it is obvious that the model estimation is not valid for predicting N leaching from individual fields. Rather the model gives general grounds to consider limits for maximum use of fertilizer N in terms of the environmental risks. For organic soils, even with N balances around zero there may be a considerable risk of N leaching, depending on climatic factors favoring SOM breakdown.

2 Experimental data on yield responses to N fertilization and associated N balances

2.1 Cereals

For evaluating the effect of N rates on cereal yields the Finnish data include considerable amount of experiments and other sources. These data vary from detailed and sophisticated field experiments to surveys where farmers have reported their N fertilizer rates and estimated yield levels. Unfortunately the traditional field experiments have become rare in the two last decades, therefore the newest cultivars and most recent management methods, such as direct drill, are not widely, if at all, tested against N rates.

Most of the N fertilizer experiments of cereals are summarized by Valkama et al. (2013a), who collected all available N rate experiments of spring cereals and compared them with statistical meta-analysis. The effect of N rate on yield quality parameters was also evaluated from the same dataset (Valkama et al. 2013b). In this report, the results from one of the latest N rate experiment (Pietola et al. 1999) conducted in 1993–1996 are discussed also separately although this experiment was also included in the meta-analysis of Valkama et al. (2013a).

The largest and most long-term dataset concerning cereal production in practical farms is collected annually by the Finnish Food Safety Authority (Evira), which analyses close to 1500 grain samples for grain quality and records the farmer's fertilizer use and estimated yield level. This dataset has been used also earlier to estimate changes in fertilizer N rates and grain quality (Salo et al. 2007a).

Other sources for evaluating the effect of N rates on yield and N balances were collected from the yield competitions reported by the professional journal, Käytännön Maamies. The data of yield competitions demonstrate cases, fields and managements with very high yield potential.

For evaluating the risk of N leaching, we calculated simple field N balances (N input in fertilizers – N output in harvested yield). Although the correlation of N balance or surplus with N leaching is not as direct as could be expected (Salo and Turtola 2006), there is a tendency towards higher leaching risk with higher N balances. According to Finnish results from lysimeter trials, there is a sharp increase in the leaching after certain N balance, which is depending on soil texture and SOM (Lemola and Turtola 2006).

2.1.1 Barley

Spring barley is the most widely cultivated cereal crop in Finland with 500 000 ha (25% of total cultivated area) and it has been the most popular plant in the N fertilizer trials as well. In the meta-analysis of N fertilization by Valkama et al. (2013a), the response of barley yield on N rate was largely depending on productivity of the soil without N fertilizer (Fig. 2). When yield without N fertilizer was 1000–2000 kg/ha, N rates above 150 kg/ha still slightly increased yield. On soils with medium yields without N fertilizer (2000-3000 kg/ha), N rates up to 150 kg/ha increased barley grain yield. In turn, if barley yields without N were as high as 3000–4000 kg/ha, N rate of 50 kg/ha was sufficient for the maximum yield increase of 30%.

In the four-year experiment in Jokioinen (southern Finland) on mineral soil reported by Pietola et al. (1999), barley grain yields increased up to the used maximum N rate of 180 kg/ha (Fig. 3). According to the regression equation between N rate and yield over the four years, 160 kg/ha N rate was sufficient to produce 95% of the maximum yield. Barley was the most sensitive crop in unfavorable climatic conditions, however. In the rainy growth season of 1995 the grain yield of barley was 1400–2000 kg/ha lower than in the three other experimental years.

The Evira grain quality dataset from the practical farms showed an average barley grain yield of 3620 kg/ha in 1990–2007. N rate averaged on mineral soils at 89 kg/ha and on organic soils at 77 kg/ha. There was, however, no trend between N rate and yield (Fig 4). Although farmers try to optimize N rate according to their earlier experience from the field parcel, poor growing conditions can lead to small yields irrespective of N rate. It might well be, however, that grouping the data set according to yield levels without added N as was done by Valkama et al. (2013a), would result in correlations between N rates and yields, but this is impossible due to lack of the knowledge in this respect.

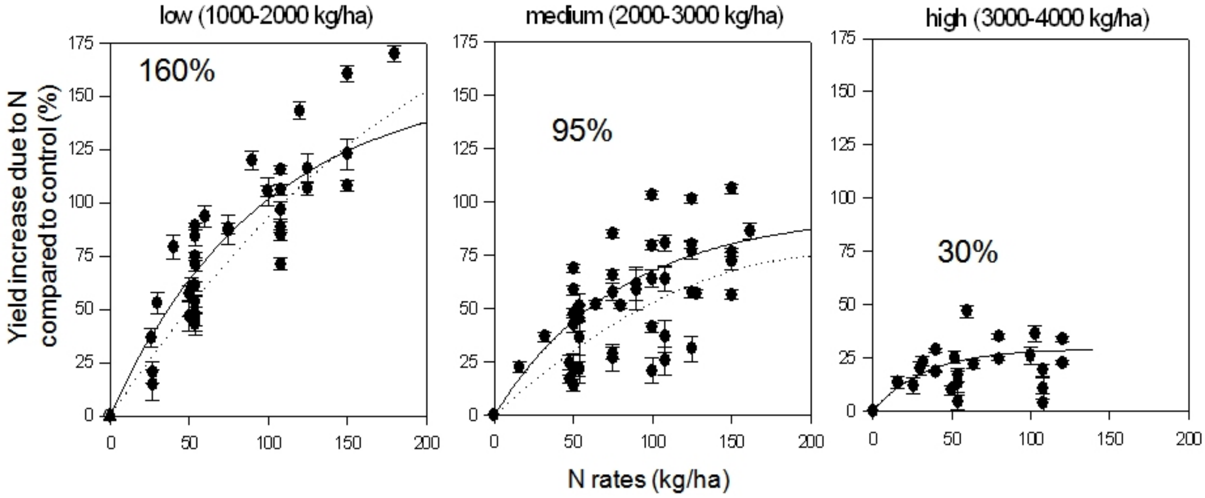

Figure 2. The effect of N rate on barley yield increase compared to control without N fertilizer in Finnish N fertilizer experiments in 1960–2004. There are three classes of yield levels without N fertilizer, low, medium and high. (Figure by Elena Valkama, Valkama et al. 2013a).

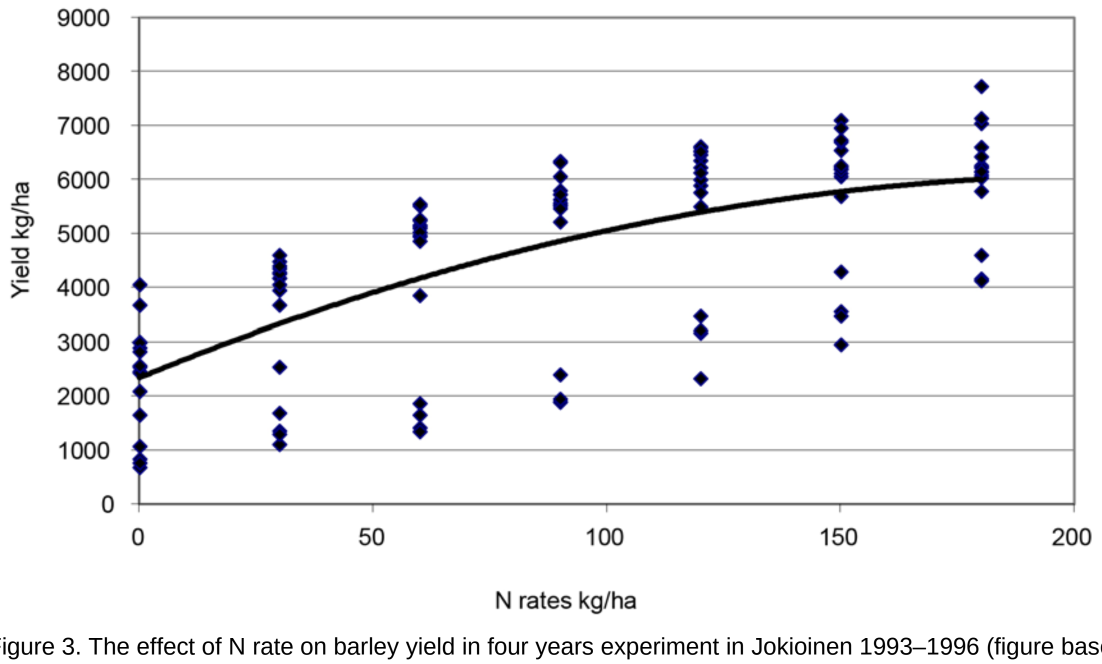

Figure 3. The effect of N rate on barley yield in four years experiment in Jokioinen 1993–1996 (figure based on data of Pietola et al. 1999). The lower response of year 1995 can be seen from the respective markers clearly below the regression line.

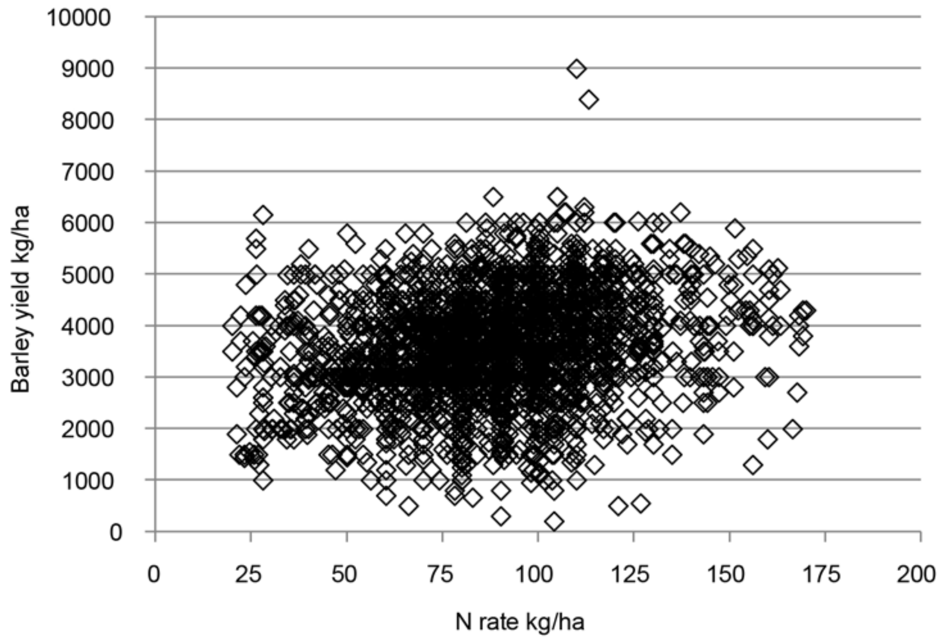

Figure 4. Nitrogen fertilizer rate and the respective barley yield as recorded at practical farms in Evira's grain quality data of mineral soils in 1990–2007.

In the data set covering all Finnish N fertilizer experiments with spring barley, N balances increased according to linear equation (Valkama et al. 2013a, Fig. 5a). For barley, N rate of 150 kg/ha in the experimental plots resulted in N balance of 60 kg/ha. Taking all spring cereals together, for every 10 kg increase in N fertilization there was an increase of 5.0-7.4 kg in N balance.

In the field experiment in Jokioinen in 1990s (Pietola et al. 1999), N balance of barley was very variable due to the growing conditions. For example, at the N rate of 90 kg/ha, N balance varied from -20 to 60 kg/ha and at the N rate of 150 kg/ha from 20 to 100 kg/ha. In three years out of four, N balance was below 50 kg/ha even with the N rate of 180 kg/ha but in the year of poor growing conditions, N balance increased to 110 kg/ha (Figure 6). Fertilizer N rate of 150 kg/ha resulted in N balance of 40 kg/ha (average of four years), which is 20 kg/ha lower than the one including all experiments (Valkama et al. 2013a).

In the Evira's grain quality data set a linear relationship between N rate and N balance was obvious both in mineral and organic soils (Fig. 7). In this data representing situation at practical fields, N balance reached 60 kg/ha with N rate of 130 kg/ha on both soils.

In the barley data of the yield competitions, where soil conditions and field management are likely to be optimal, the highest N rate of 130 kg/ha averaged to only 10 kg/ha of N balance (Fig. 8). Extrapolating the regression equation beyond the reported N rates would estimate N balance of 60 kg/ha to be reached at N rate as high as 200 kg/ha.

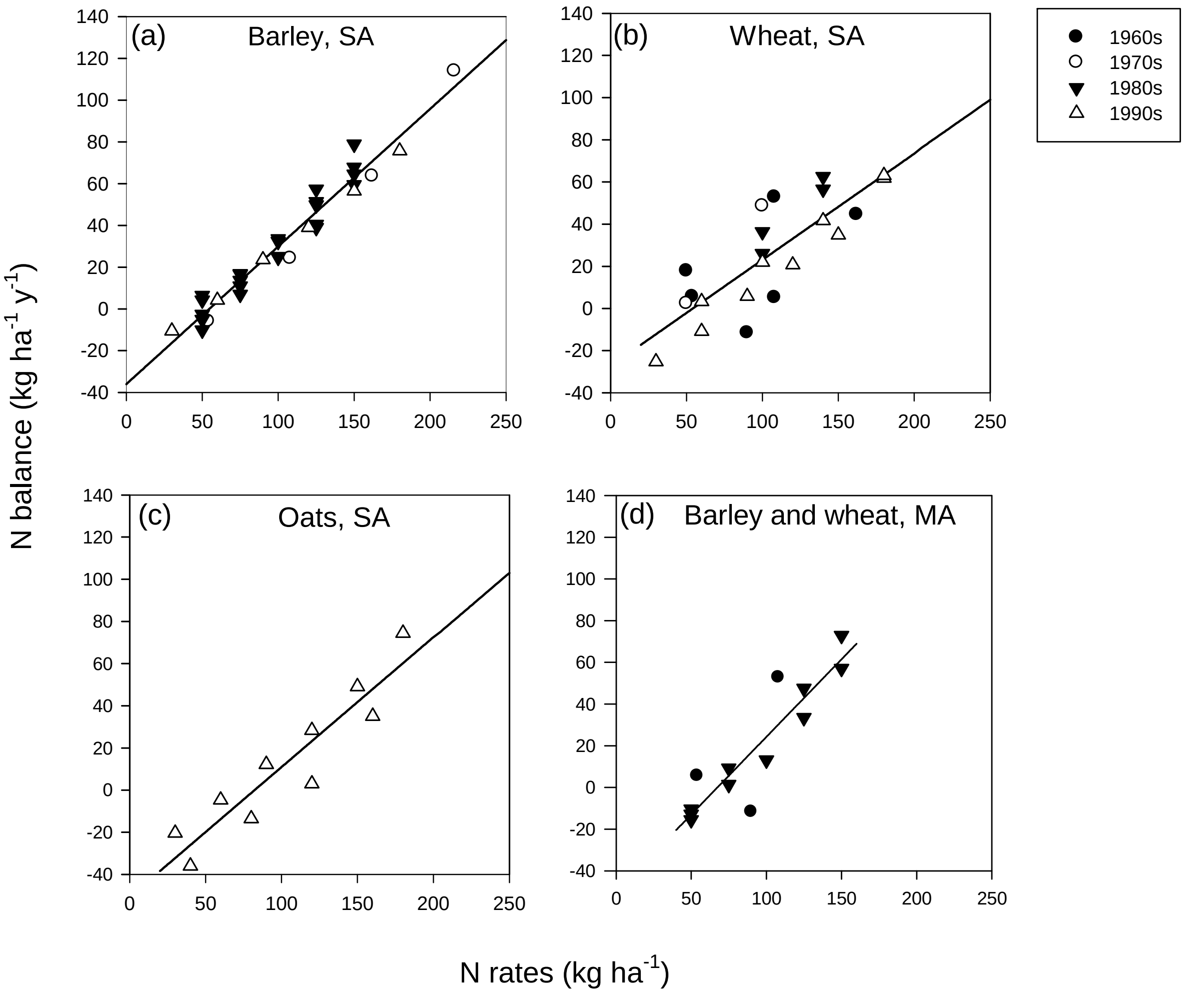

Figure 5. Relationships between increasing N rates and N balances for spring cereals cultivated on (a–c) slightly acidic (SA, pH 5.8-6.9) and (d) moderately acidic (MA, pH 4.9-5.7) soils, in 1960s–1990s. Each symbol represents average annual N balance for the duration of an experiment (Valkama et al. 2013a).

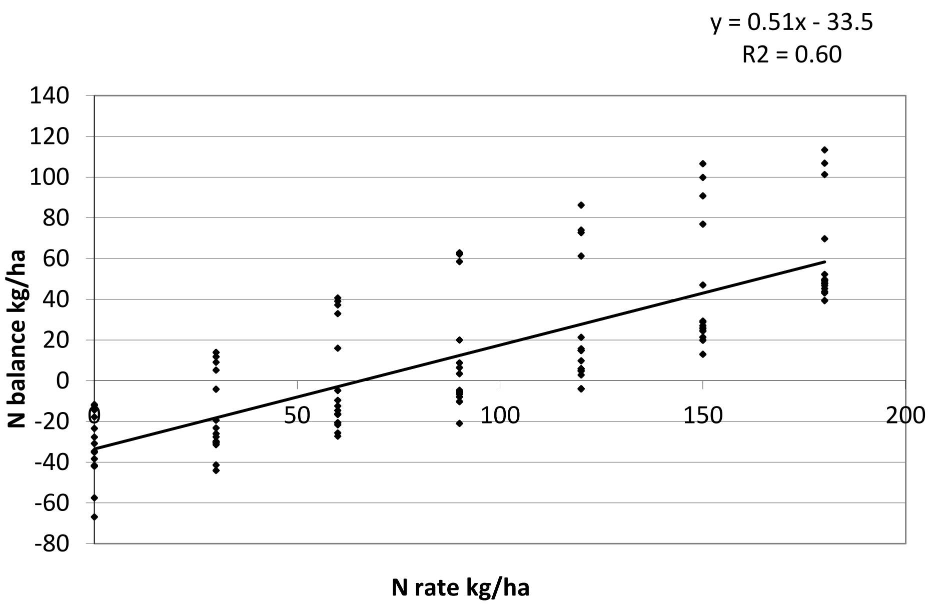

Figure 6. Relationship between increasing N rates and N balances of barley in one experiment on mineral soil in 1993-1996 (Figure based on data of Pietola et al., 1999). The year 1995 with lower N fertilizer response is demonstrated by markers that are clearly above the regression line.

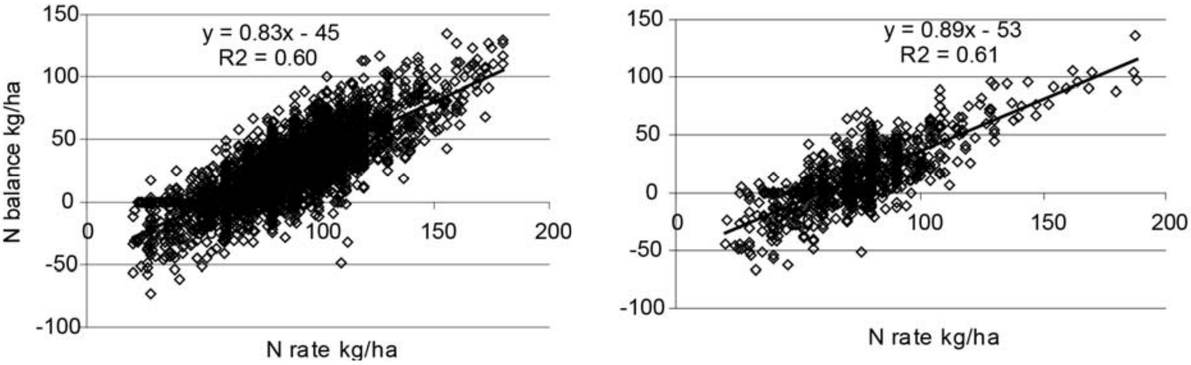

Figure 7. Relationships between increasing N rates and N balances for barley in Evira's grain quality data on mineral soils (left) and on organic soils (right).

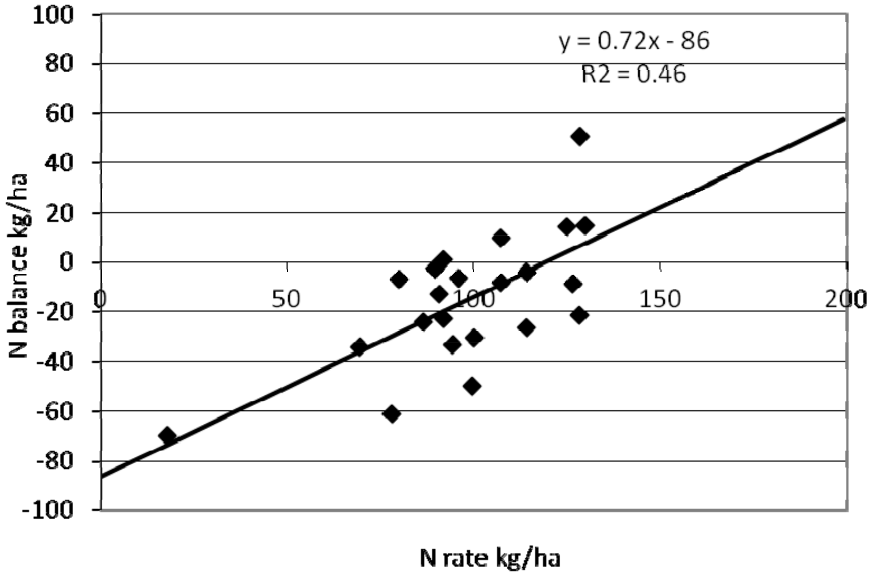

Figure 8. Relationship between increasing N rates and N balances of barley in yield competition data published in Käytännön Maamies -journal.

2.1.2 Oats

Oats is the second most widely cultivated cereal crop in Finland, with 325 000 ha and 16% of the cultivated field area annually. Experimental data of oats was available from the same sources as barley data although the number of field experiments was much smaller (Valkama et al. 2013a). On those experimental plots, which produced medium yield level without N fertilizer, N rates up to 150 kg/ha increased the yields, whereas on plots producing high yields without N, the respective N rate was 120 kg/ha (Fig. 9). In the experiment of Pietola et al. 1999, the yield response curve was similar to that of the larger data set with low yield without N fertilizer, i.e. N rate higher than 150 kg/ha did not increase oat yield (Fig. 10). Again, in Evira's grain quality data, there was no clear relationship between N rate and oats yield on mineral soils (Fig. 11).

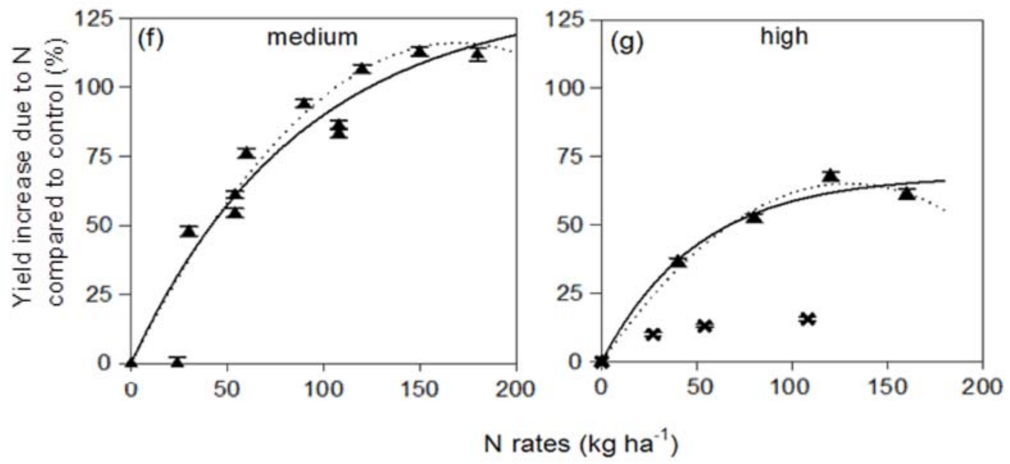

Figure 9. The effect of N rate on oats yield increase compared to control without N fertilizer in Finnish N fertilizer experiments in 1960–1999. There are two classes of yield levels without N fertilizer, medium and high. (Figure by Elena Valkama, Valkama et al. 2013a).

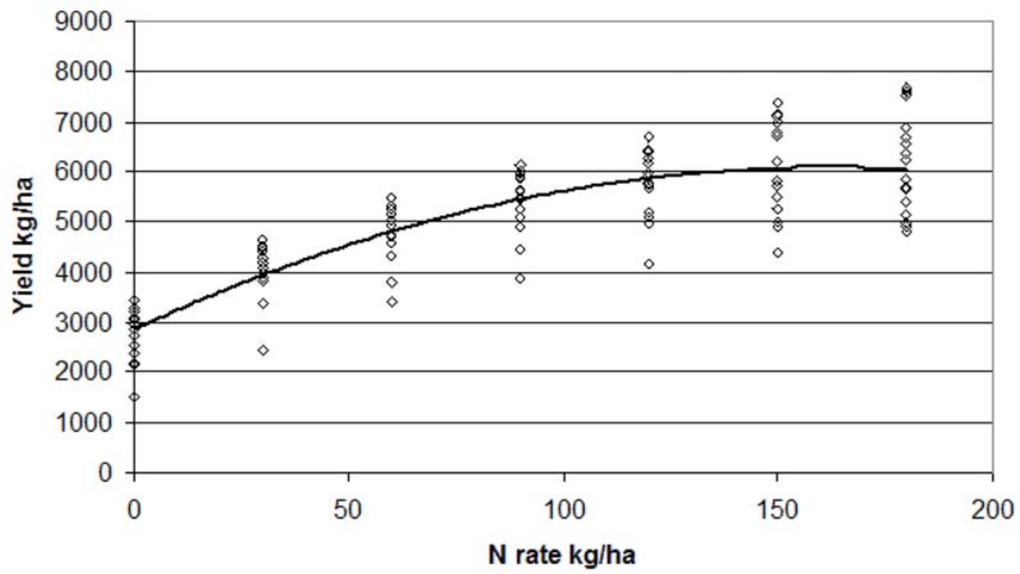

Figure 10. The effect of N rate on oats yield in a four-year experiment in Jokioinen in 1993–1996 (Figure based on the data of Pietola et al., 1999).

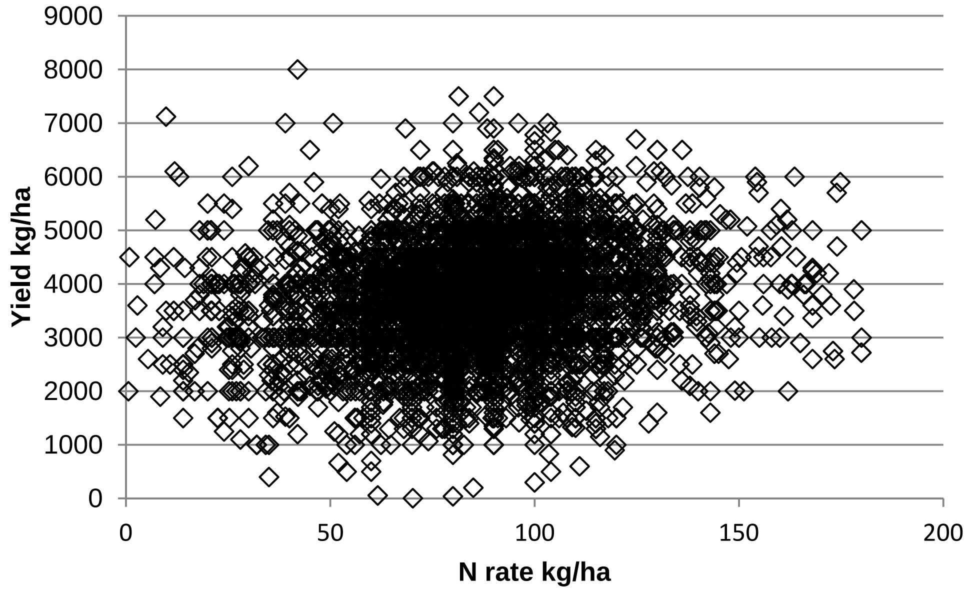

Figure 11. Nitrogen fertilizer rate and the respective oats yield as recorded at practical farms in Evira's grain quality data of mineral soils in 1990–2007.

In the meta-analyzed dataset of all field experiments with oats, the relationship between N rate and N balance was also linear, but resulted in lower N balances compared to barley. N balance of 60 kg/ha was reached by approximately 180 kg/ha N rate (Fig. 5c). In the dataset of Pietola et al. 1999, oats was also more efficient in taking up N and with the highest rate of 180 kg/ha, N balances averaged below 50 kg/ha (Fig 12). In Evira's data from practical farms, N balance for oats reached 60 kg/ha with N rate of 133 kg/ha on both mineral and organic soils (Fig 13). In the yield competition data, there were only few oats examples, but with those fields N balances were always below zero also with the highest N rates of 120 kg/ha.

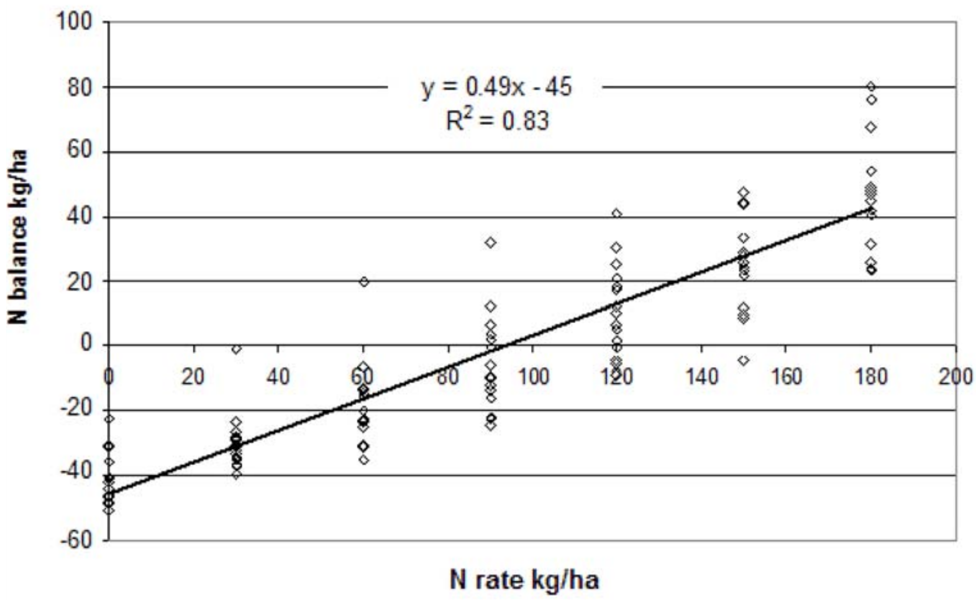

Figure 12. Relationship between increasing N rates and N balance of oats in one experiment on mineral soil (Pietola et al., 1999).

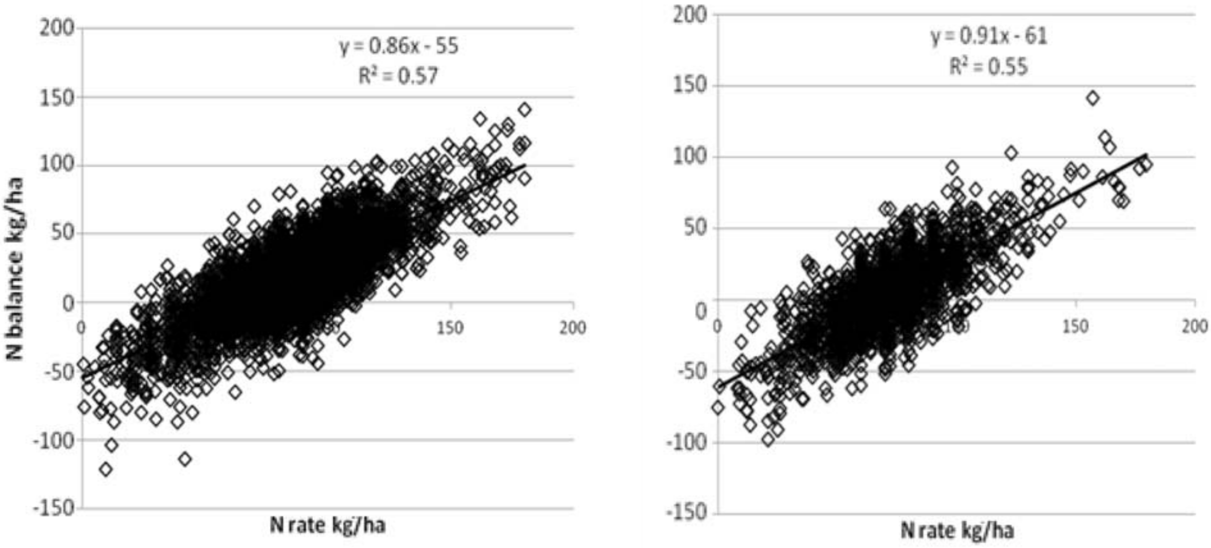

Figure 13. Relationships between increasing N rates and N balances for oats in Evira's grain quality data on mineral soils (left) and on organic soils (right).

2.1.3 Spring wheat

In Finland, spring wheat is cultivated in the southern and western part of the country, covering 190 000 ha and 10% of the cultivated area. Experimental data on N fertilizer responses of spring wheat were available from the same sources as of barley and oats data. Those experimental plots, which produced low yield level without N fertilizer, N rate up to 200 kg/ha increased the yields, whereas on plots producing medium or high yields without N, N rates increased yield by 25–50% and the increase continued slowly up to 150 kg/ha (Fig. 14). In the experiment of Pietola et al. 1999, the highest N rate of 180 kg/ha still increased the yield (Fig. 15). In Evira's grain quality data, in turn, the relationship between N rate and yield could not be observed (Fig. 16). Averaged N rate in Evira data was 110 kg/ha and the average yield was 3660 kg/ha.

A meta-analysis of the effect of increasing N rates on protein content of spring wheat showed that in general spring wheat responded less than barley and oats, but the response was more pronounced if the yield level without fertilizer N was low (Valkama et al. 2013b). In all cases, the models developed from the data predicted that adequate protein content for bread-making purposes would be reached at N fertilizer of 120 kg/ha or less.

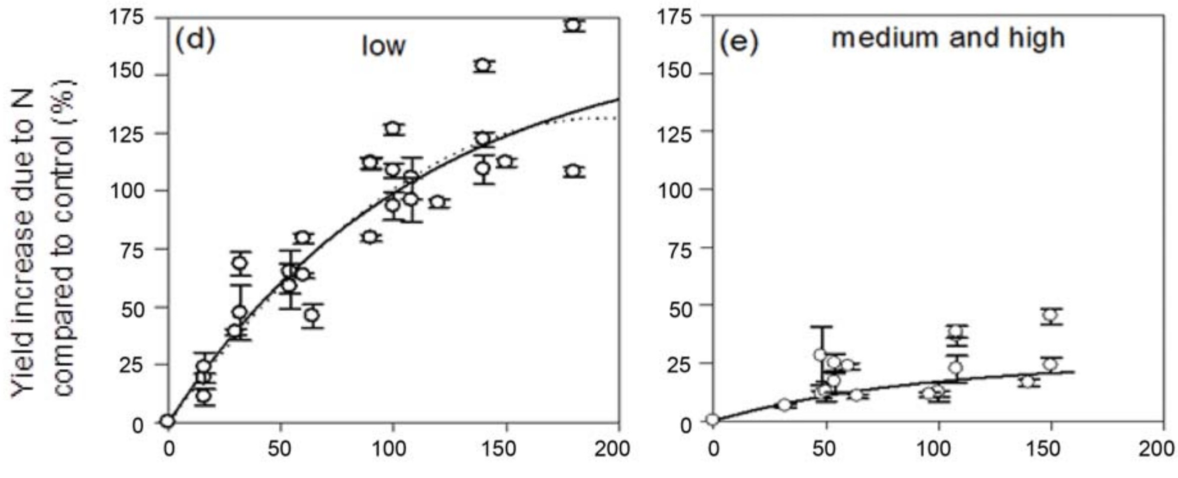

Figure 14. The effect of N rate on spring wheat yield increase compared to control without N fertilizer in Finnish N fertilizer experiments in 1960–1999. There are two classes of yield levels without N fertilizer, low and combined medium/high. (Figure by Elena Valkama, Valkama et al. 2012).

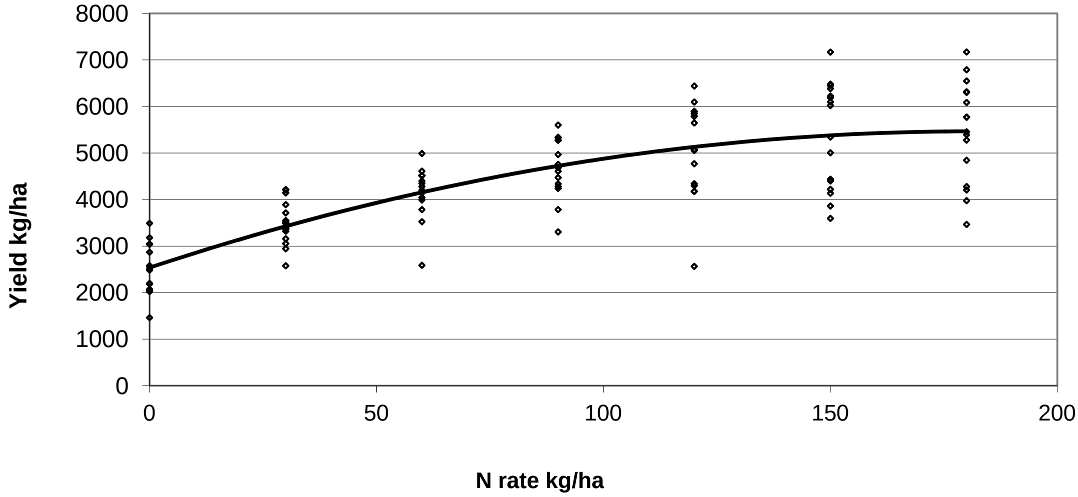

Figure 15. The effect of N rate on spring wheat yield in a four-year experiment in Jokioinen in 1993–1996 (Figure based on the data of Pietola et al., 1999).

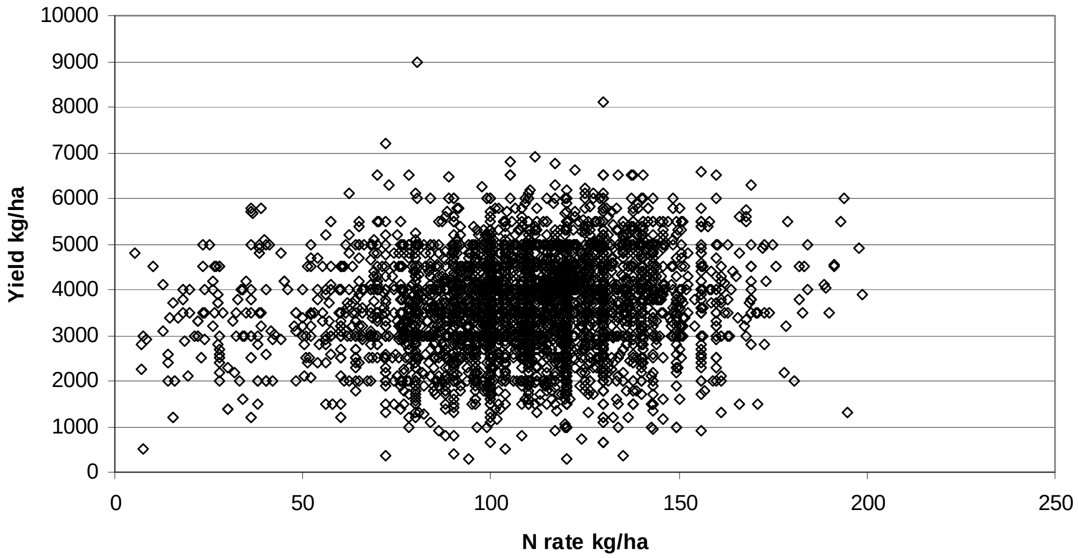

Figure 16. Nitrogen fertilizer rate and the respective spring wheat yield as recorded at practical farms in Evira's grain quality data of mineral soils in 1990–2007.

In the meta-analyzed dataset of all field experiments for spring wheat, the relationship between N rate and N balance was also linear as with barley and oats. Nitrogen balance of 60 kg/ha was reached by approximately 170 kg/ha (Fig. 5b). In the dataset of Pietola et al. (1999), N balances averaged below 50 kg/ha even with the highest N rate of 180 kg/ha (Fig 17). In the Evira's data, N balance of 60 kg/ha was reached with 138 kg/ha N rate (Fig 18). In the yield competition data there were only few examples of spring wheat, and also there N rate of 140 kg/ha was associated with N balance of 60 kg/ha.

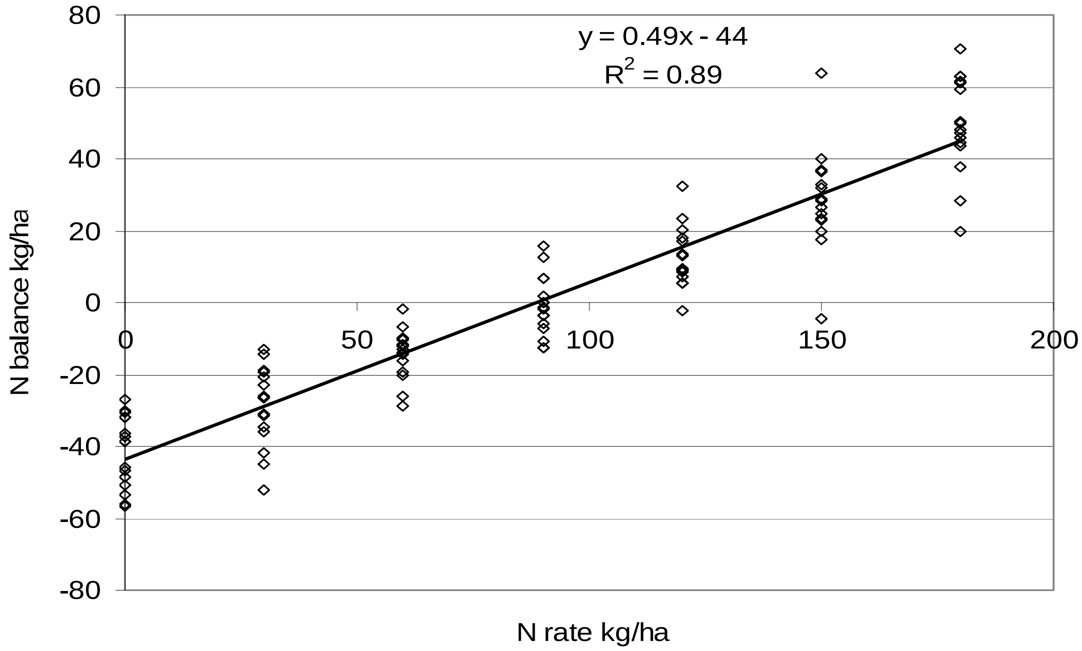

Figure 17. Relationship between increasing N rate and N balance of spring wheat in one experiment on mineral soil (Pietola et al., 1999).

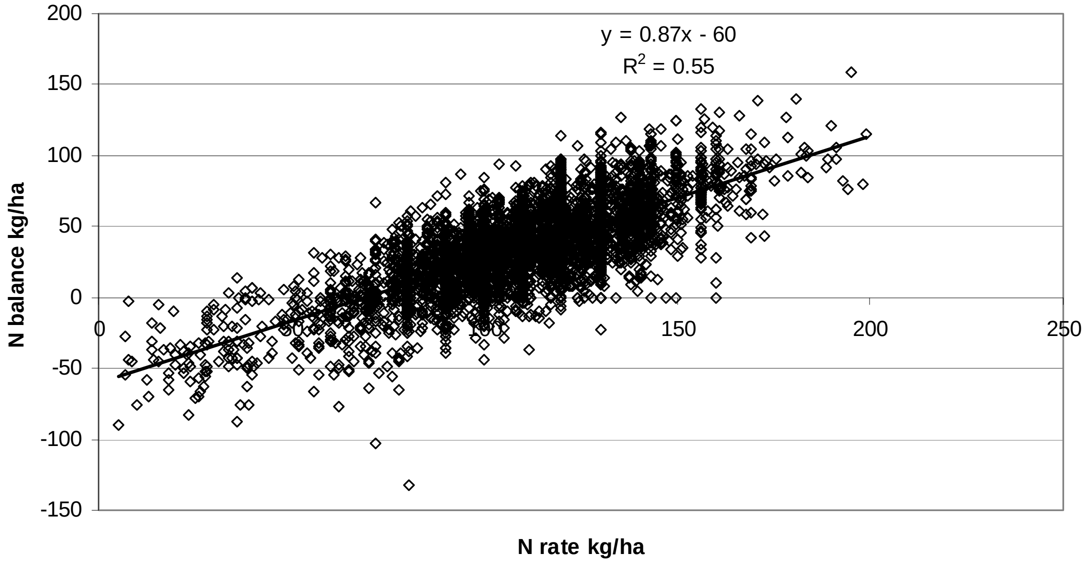

Figure 18. Relationship between increasing N rate and N balance of spring wheat in Evira's grain quality data on mineral soils.

2.1.4 Winter wheat

For winter wheat (27 000 ha and 1% of the cultivated area) there was scarce experimental data concerning the effect of N fertilization. In the Evira's data from practical farms, the average N rate of winter wheat was 140 kg/ha and average yield was 3990 kg/ha. Similarly to other cereals, the reported yields did not correlate with N rates in this data set (Fig. 19). There was, again, a linear relationship between N rate and N balance (N balance = 0.87 x N rate – 54 N kg/ha) in the Evira's data (Fig. 20). According to this equation, N balance of 60 kg/ha is reached by N rate of 131 kg/ha.

In the yield competition data, there were nine observations in which N rate averaged to 163 kg/ha, and yield to 6370 kg/ha. Yield was increased by N rate according to a linear equation (yield = 48 x N rate – 1489 kg/ha, R^2 = 0.41). There was, however, no correlation between N rate and N balance; the mean of N balance was 34 kg/ha, ranging from -13 to 71 kg/ha.

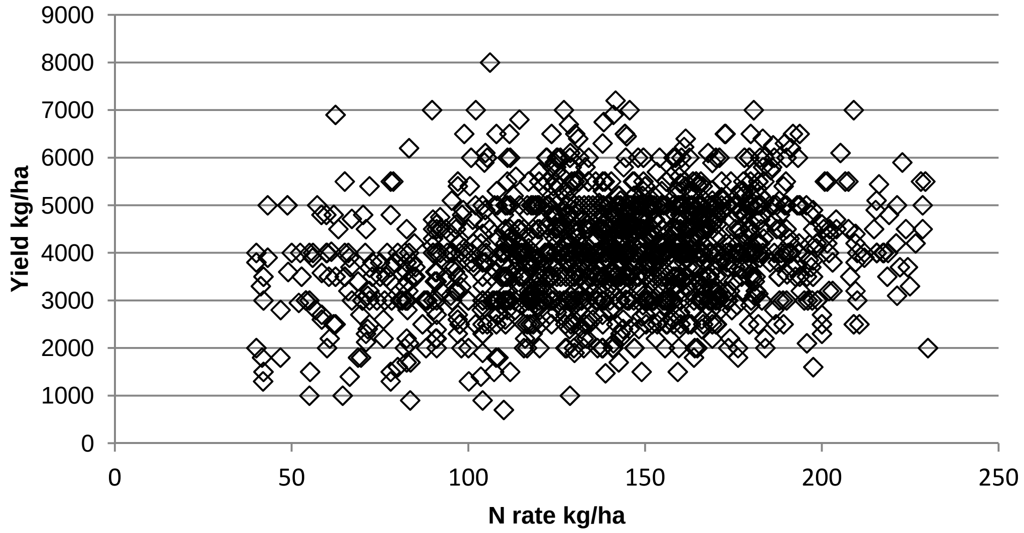

Figure 19. Nitrogen fertilizer rate and winter wheat yield in Evira's grain quality data of mineral soils in 1990–2008.

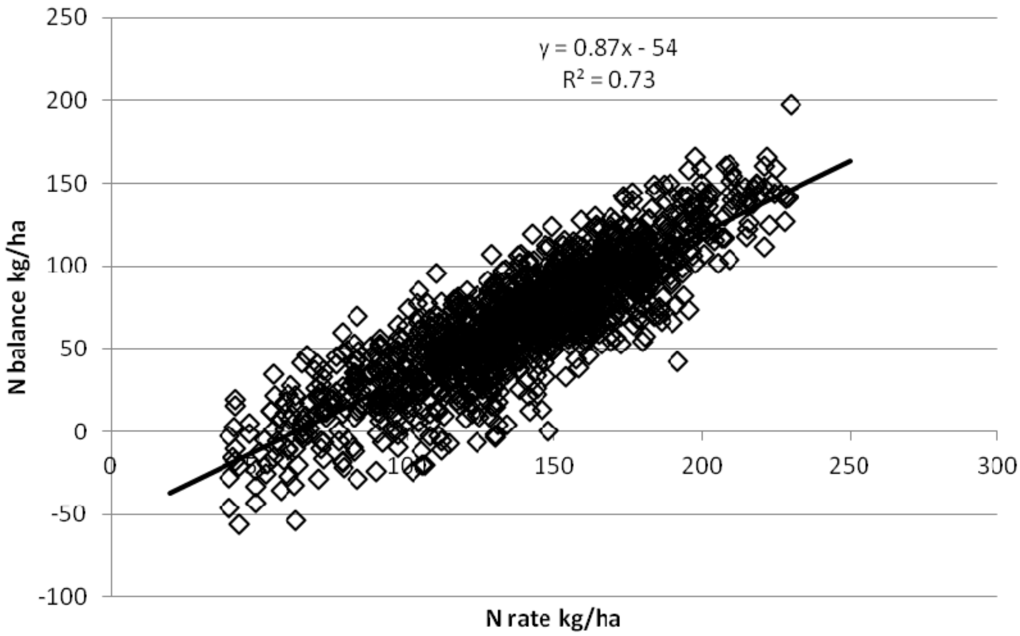

Figure 20. Relationship between increasing N rate and N balance of winter wheat in Evira's grain quality data on mineral soils.

2.1.5 Winter rye

Similarly to winter wheat, for winter rye (25 000 ha and 1% of the cultivated area) there was little experimental data concerning the effect of N fertilization. In the Evira's data from practical farms, the average N rate of winter rye was 105 kg/ha, the average yield was 3010 kg/ha, and the yields did not correlate with N rates (Fig. 21). A linear relationship between N rate and balance was observed (N balance = 0.90 x N rate – 38 N kg/ha) in Evira's data (Fig. 22). By this equation, N balance of 60 kg/ha is reached by N rate of 110 kg/ha.

In yield competition data, there were only four observations available and two of them were from hybrid cultivars. Those cultivars produced 8500 kg/ha yields with N rates of 81 or 158 kg/ha. N balances were respectively -40 and 20 kg/ha. Agrimarket Oy, Boreal Plant Breeding and Yara Finland have launched recent field experiments for hybrid winter rye, and they have informed that autumn fertilization of 30 kg/ha and spring application of 130 kg/ha have resulted in 5600–6100 kg/ha yield levels (http://www.agrimarket.fi/Maatalous_ja_Elaimet/kasvuohjelmat/Viljat/Hybridirukiin_viljelytekniikkaan_lisatietoa/).

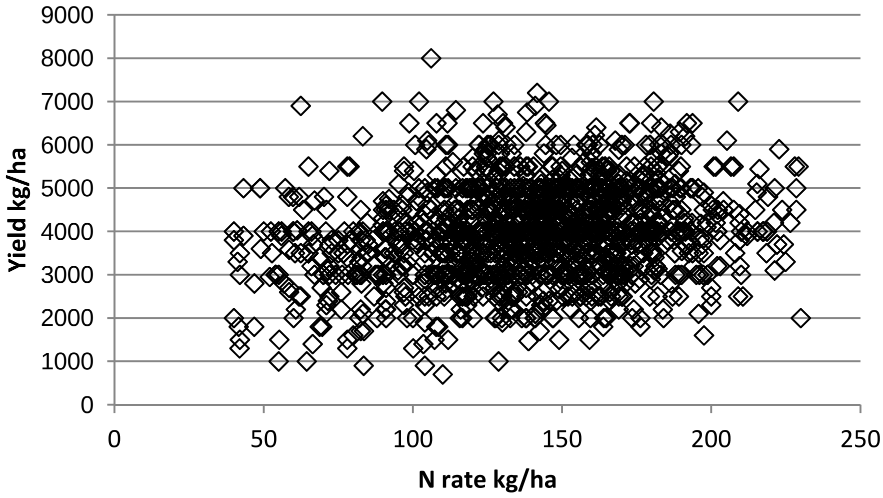

Figure 21. Nitrogen fertilizer rate and winter rye yield in Evira's grain quality data of mineral soils in 1990–2008.

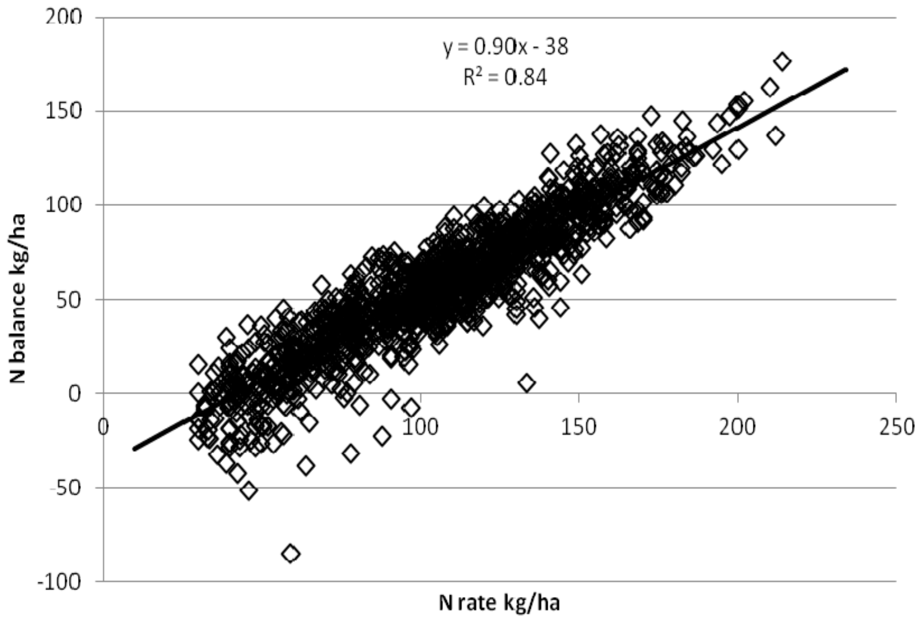

Figure 22. Relationship between increasing N rate and N balance of winter rye in Evira's grain quality data on mineral soils.

2.2 Oilseed crops

2.2.1 Spring turnip and oilseed rape

The cultivation area of spring turnip and oilseed rape covers 100 000 ha and 5% of the total cultivated area in Finland. In the study of Pietola et al. (1999), turnip rape responded well to N rate, and yield increased until 180 kg/ha (Figure 23). Nitrogen balances averaged 60 kg/ha at N rate of 136 kg/ha (Fig 24). While the highest N rates of 180 kg/ha still increased yield, these rates also resulted in N balances as high as 85 kg/ha.

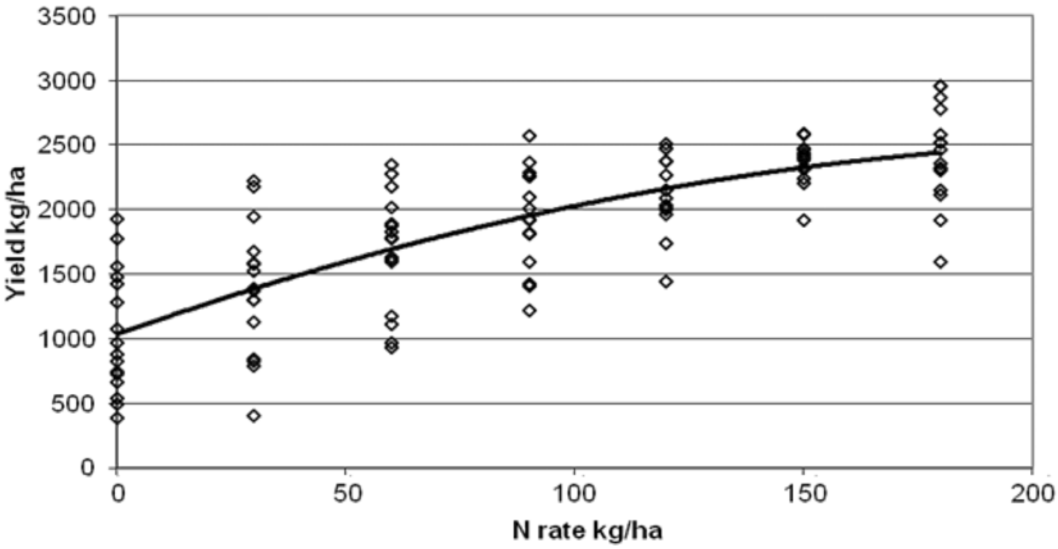

Figure 23. The effect of N rate on turnip rape yield in a four-year experiment in Jokioinen in 1993–1996 (Figure based on data of Pietola et al., 1999).

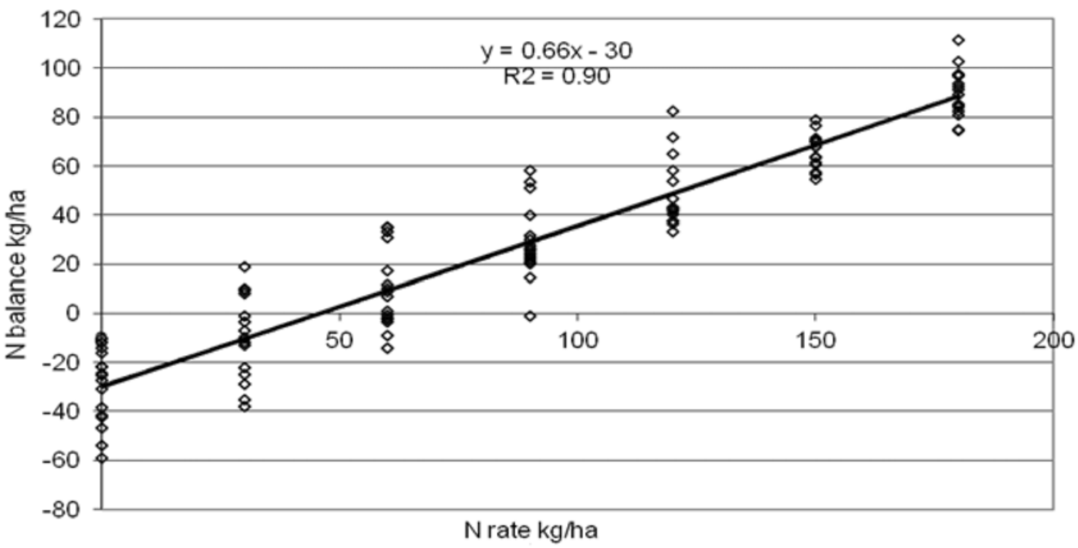

Figure 24. Relationship between increasing N rate and N balance of turnip rape in one experiment on mineral soil (Figure based on data of Pietola et al., 1999).

2.2.2 Winter turnip and oilseed rape

The cultivation area of winter oilseed crops is very small but the interest among farmers is increasing. There are no published experiments available for N fertilisation in Finland. In yield competition data there were two fields with N rates of 155 and 168 kg/ha where the yields were 2600 and 4800 kg/ha, respectively.

Field experiments reported by Yara Finland (http://www.farmit.net/koetulokset/tuloksia-2012) showed that autumn N application of 30 kg/ha together with spring N applications of 110 or 140 kg/ha produced 2600 and 2960 kg/ha yields, respectively. If autumn application was 60 N kg/ha, spring applications of 110 and 140 kg/ha resulted in yields of 3210 and 3440 kg/ha, respectively.

2.3 Grassland

Grassland covers 644 000 ha, i.e. 32% of cultivated field area in Finland. Silage production is by far most important form of grass production (479 000 ha) and it has been the most widely cultivated grass crop in general during the last years (2011 - 2012). Cultivation areas for hay and pasture are 106 000 ha and 77 000 ha, respectively. Grassland forms a higher percentage of farm land in North than in South Finland. So far there are no published reviews available concerning grass responses to N fertilization. We therefore made a synthesis for silage leys based on individual research publications (Raininko 1968, Hiivola et al. 1974, Luostarinen 1974, Tähtinen 1979, Joki-Tokola et al. 2002, Tyynelä et al. 2004). Pastures are discussed in a later section.

The silage experiments that were conducted in 1960's and 1970's included very high N rates, up to 600 kg/ha/year. Both two and three cut systems were used in the experiments and N application was divided accordingly for each cut. Here we report the results for annual DM yield and annual N rates only. The combined data on mineral soils (Fig. 25) shows clearly that yield increase of grasses tends to slow down above N rate of 200 kg/ha/year. After N rate of 300 kg/ha/year there is very little yield increase. The dataset from organic soils is smaller and contains very large variability between the experiments (Fig. 26). Especially in the study of Tähtinen (1979) there seems to be some unknown factor limiting the yield compared to the other experiments. For both soil types the biological optimum of N fertilization is rather high according to these experimental data. On mineral soils the biological optimum is achieved with N rate of 344 kg/ha/year and on organic soils 335 kg/ha/year. On mineral soils the equation DM yield = -0.051 (N rate)^2 + 34.9 x (N rate) + 2715 explains 92% of the variation in DM yield (Fig. 27). It should be noted that one data point from Hiivola et al. (1974, N 600 kg/ha/year) was omitted as an outlier. Variation is much higher on organic soils and the regression equation DM yield = -0.024 (N rate)^2 + 20.4 x (N rate) + 4430 explains only 45% of the variation in DM yield.

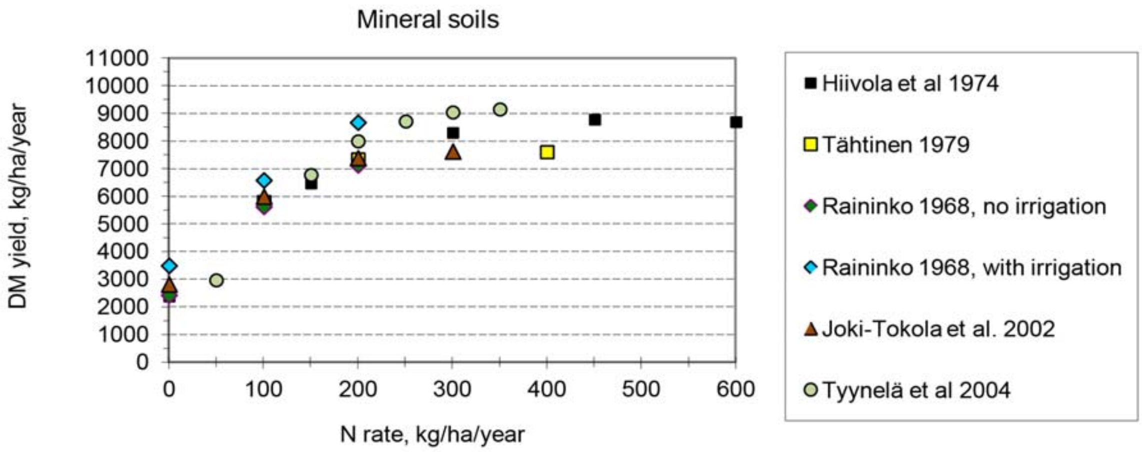

Figure 25. The effect of N rate on grass yield in Finnish field experiments on mineral soils in 1960–2012, see text for the references of the data sets.

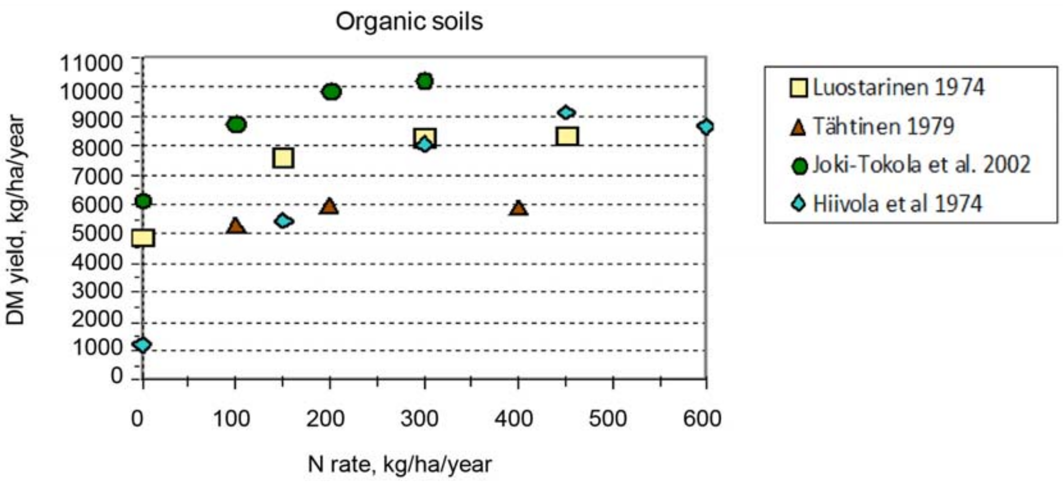

Figure 26. The effect of N rate on grass yield in Finnish field experiments on organic soils in 1970–2002, see text for the references of the data sets.

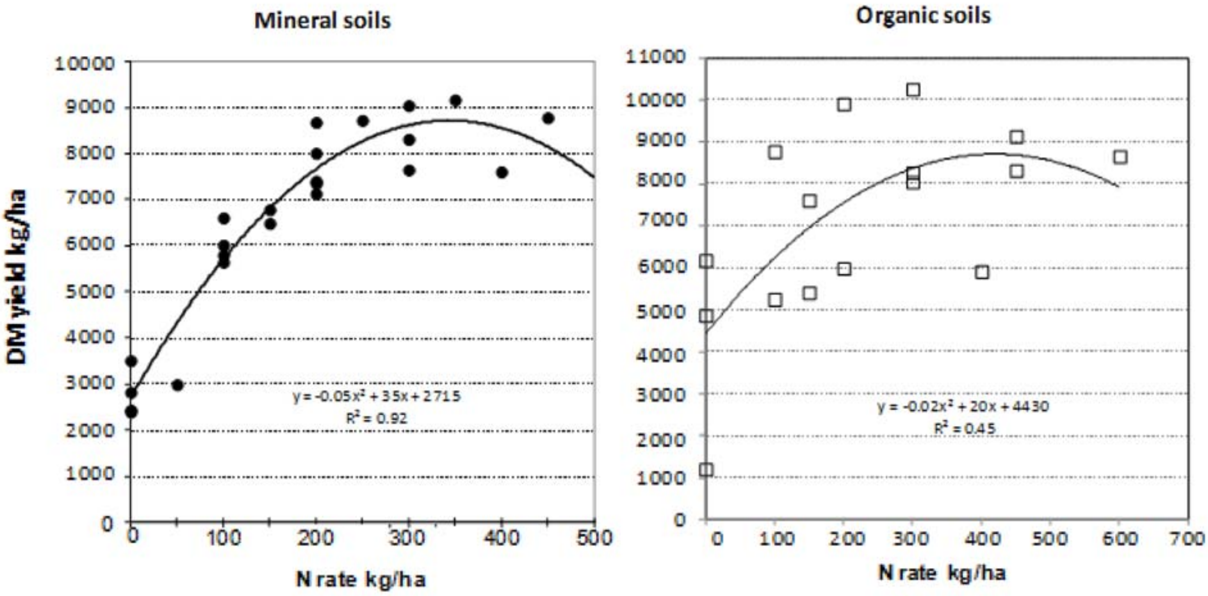

Figure 27. The polynomial equations between N rate and grass yield on mineral and organic soils.

Similarly to cereals, for grasses as well there was a strong connection with applied N amount and calculated N balance. The relationship between N rate and N balance was explained slightly better with polynomial than with linear regression (Fig. 28, Table 8 on p. 31) but even the linear equations explain more than 90% of the variation. N balances tend to be lower than 0 kg/ha/year with N applications of 135 kg/ha/year in mineral soils and with N applications of 238 kg/ha/year in organic soils. N balance of 60 kg/ha/year is reached in mineral soils with N rate of 264 kg/ha/year and in organic soils N balance of 0 kg/ha with N rate of 238 kg/ha/year.

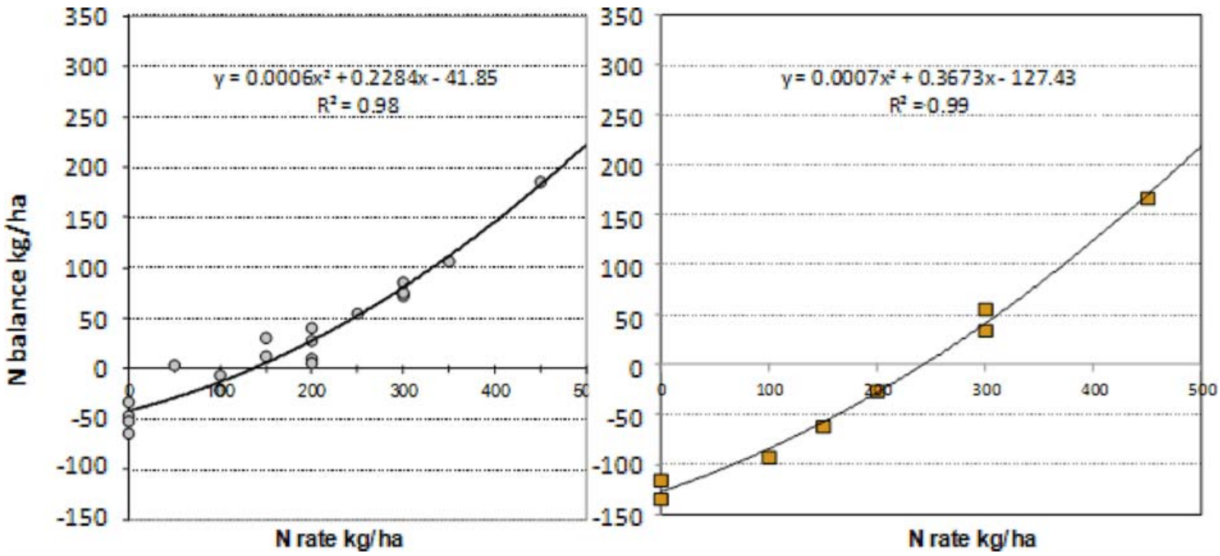

Figure 28. Relationships between increasing N rates and N balances of grassland on mineral soils (left) and on organic soils (right).

The previously presented N fertilization experiments were conducted with mineral N fertilizers only. However, the use of animal manure in grassland farming is a common practice in Finland but there are some farm data sets where nutrient balances are calculated (Kaasinen 2011, Korhonen 2011). In these data the N balances are slightly positive or negative even when animal manure forms part of N fertilization. However, care must be taken when using these values because these calculations include only soluble part of manure N, not total N. When assuming that approximately 50 % of the total N of cow slurry is in soluble form, it can be estimated from Korhonen (2011) that the annual N balance on 11 farms during three years was on average 22 kg N/ha/year with yield level of 6600 kg DM/ha. Classification of the individual paddocks according to three yield categories (low, medium and high) revealed the strong effect of yield level on N balances, because N balance was 55 kg N/ha/year in low yield category (4800 kg DM/ha/year) and -29 kg N/ha/year in high yield level category (8700 kg DM/ha/year). Furthermore, in a recent study where slurry and biogas digestate were compared in combination of mineral N in grassland rotation, the annual balances for total N were in the range of -22 - +37 kg/ha (Virkajärvi et al, manuscript) pointing out that N balance may not be on a very high level in grassland farming even when animal manure is used.

There are a few experiments on N fertilization rate for pasture and most of the studies have been done before the importance of environmental issues were fully understood (Huokuna 1968, Ettala ym. 1971, Rinne & Takala 1971, Rinne 1978). Therefore, between 1998 and 2006 a series of experiments were carried out to quantify yield response, N balance and environmental impacts of grazing (Lemola and Turtola 2006, Saarijärvi 2008, Virkajärvi et al 2010). As expected N cycling on pasture differs fundamentally from that on cut grass (e.g. Saarijärvi 2008). Due to higher positive N balance, lower N efficiency, and higher N leaching compared to cut grass (Table 1), a new experiment with three N levels (120, 170 and 220 kg N/ha/year) was conducted at MTT Maaninka (Virkajärvi et al. 2006, Laitinen 2008).

Table 1. N Balance of the grass and grass-clover pastures (Saarijärvi 2008)

	Grazing years		Renewal	
Nitrogen inputs kg ha^{-1} a^{-1}	Grass	Clover	Grass	Clover
Fertilizer	220	0	0	0
Concentrates	67	62	15	15
Deposition	3	3	4	4
Symbiotic nitrogen fixation	0	216	0	0
Total input	290	281	19	19
Nitrogen outputs kg ha^{-1} a^{-1}				
N yield in grass dry matter	0	0	144	143
Milk	69	66	20	20
Excretion during milking	71	66	19	19
Retention in pregnancy	4	4	1	1
Ammonia volatilization (EXP IV)	16	16	Nd	Nd
N_2O emission	3	5	Nd	Nd
Surface runoff	4	4	3	3
Leaching	17	9	60	40
Total output	184	170	247	226
Balance kg ha^{-1} y^{-1}	106	111	-228	-207

The results of the fertilization experiment showed that metabolizable energy (ME) yield responded much less under grazing than under cutting: on pasture the response was only 40 MJ ME/kg N/ha/year (measured based on animal performance) compared to that of simulated grazing (i.e. cutting with the same frequency) 202 MJ ME/kg N/ha/year (measured based on *in vitro* D value). Furthermore, response on pasture was clearly curvilinear with a substantial yield increase (77 MJ ME/kg N/ha/year) between N rates 120 and 170 kg/ha/year but a minor response (12 MJ ME/kg N/ha/year) between N rates 170 and 220 kg/ha/year (Laitinen 2008). The experiment was conducted on a coarse mineral soil (sandy loam) in Central Finland. Based on these experiments we would suggest for pastures a maximum of 190 kg/year with adjustments according to the length of the grazing season. This is in line with other European recommendations when adjusted with livestock unit grazing days per hectare (Saarijärvi 2008).

2.4 Sugar beet

Sugar beet has a very long growing season compared to other agricultural crops in Finland, from May to late October. During this period the plant constantly takes up N which makes sugar beet one of the most efficient user of N in Finnish agriculture. The cultivation area of sugar beet is roughly 14 500 ha (< 1% of field area) and it will probably stay stable, since this area is needed for fulfilling the Finnish white sugar quota. Cultivation is somewhat concentrated close to the factory (Säkylä) and most of the sugar beet fields are situated in the south-western part of Finland.

Recent sugar beet experiments in 2009–2012 by Sugar Beet Research Centre (SjT) have been conducted with the maximum N rates determined by the Finnish Agri-Environmental Program (140 kg/ha). The results show increasing root yields and sugar yields until the N rate of 140 kg/ha (Fig. 29 and 30). N balances calculated from the experimental data were very low, below 10 kg/ha with the used N rates (Fig. 31). Extrapolation of the linear relationship (N balance = 0.49 x (N rate) - 57 N kg/ha) gives a N balance of 60 kg/ha with N rate of 239 kg/ha.

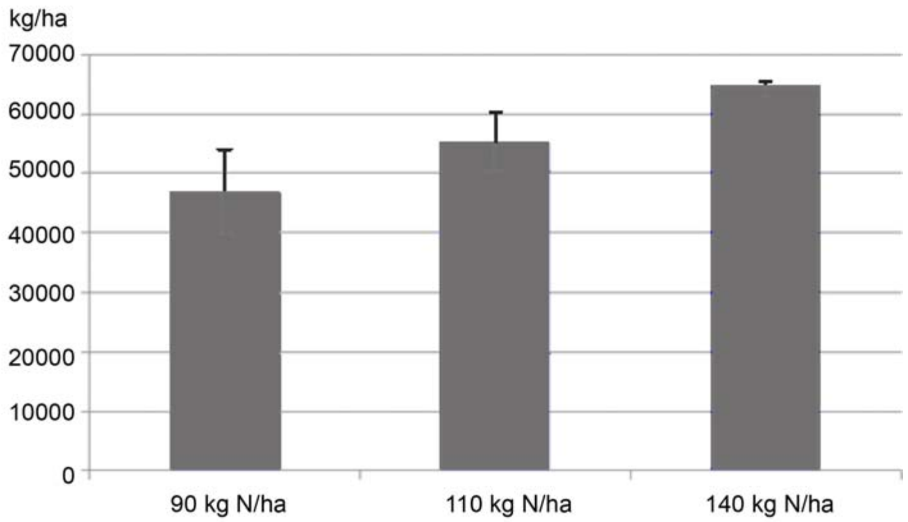

Figure 29. The effect N rates on root yield of sugar beet in the experiment conducted in 2012 by SjT.

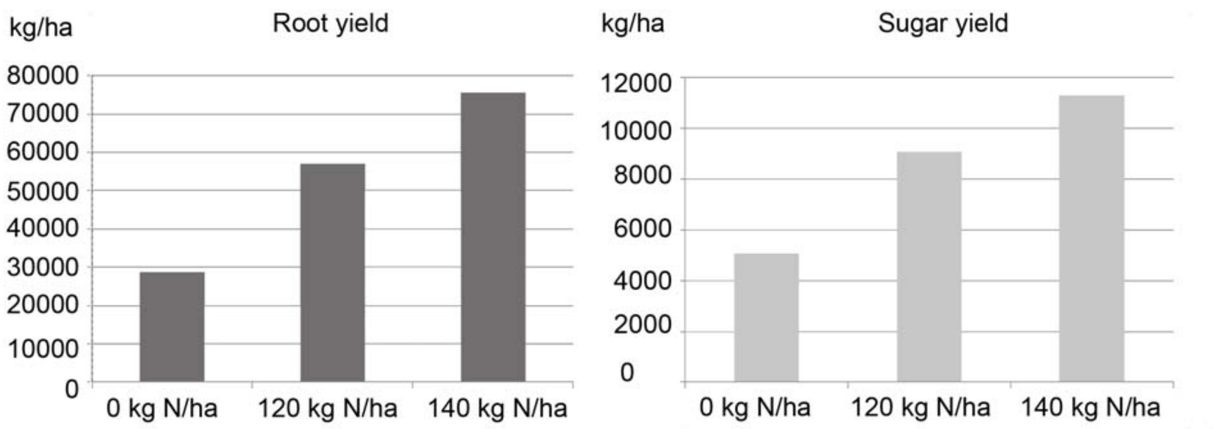

Figure 30. The effect N rates on root yield (left) and sugar yield (right) in the experiment conducted in 2009-2011 by SjT.

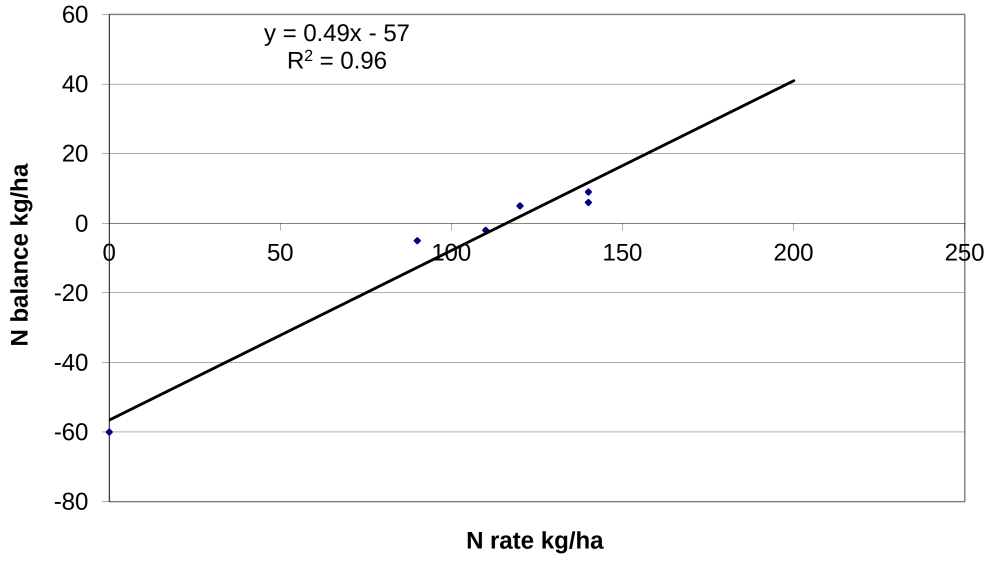

Figure 31. Relationship between increasing N rate and N balance of sugar beet in experiments conducted in years 2009–2012 by SjT.

2.5 Potato

In Finland, potato is cultivated on 26 000 ha (1% of field area). The relatively short growing season restricts the use of fertilizer N since rates above optimum increase the vegetative growth and delay tuber formation, resulting in risks of low yield and quality. The main source of field experiments is the Potato Research Institute (PETLA) with 10-year experimental series of N fertilization in 1994–2003 and three-year irrigation experiments in 2001–2003. Altogether PETLA has made 330 field experiments (in 1994–2010), from which the effect of N rate on yield and N balance can be calculated. In the field experiments, the N rate for maximum tuber yield was 122 kg/ha (Fig. 32) while the starch yield tended to increase with N rates as high as 180 kg/ha (Fig. 33).

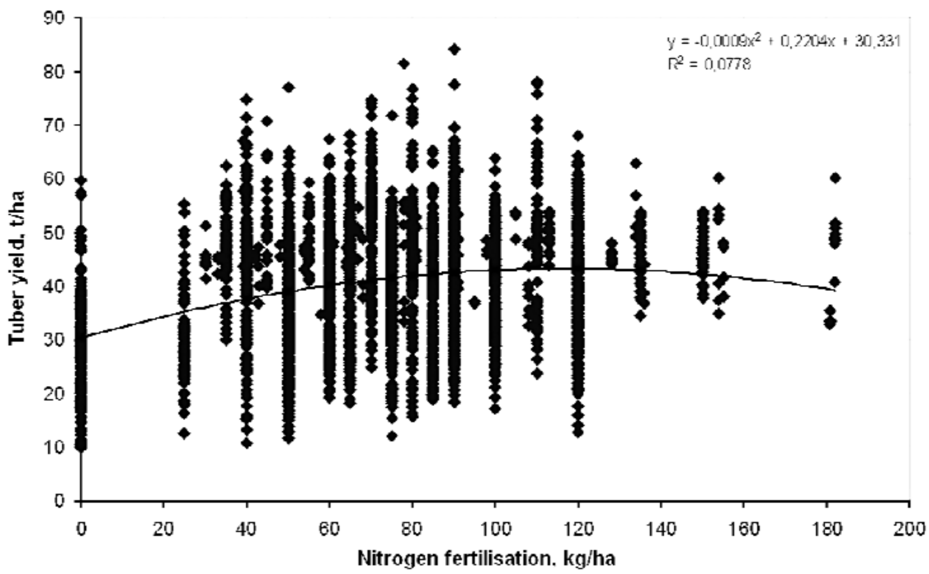

Figure 32. The effect of N rate on potato yield in field experiments of PETLA in 1994–2010 (350 experiments).

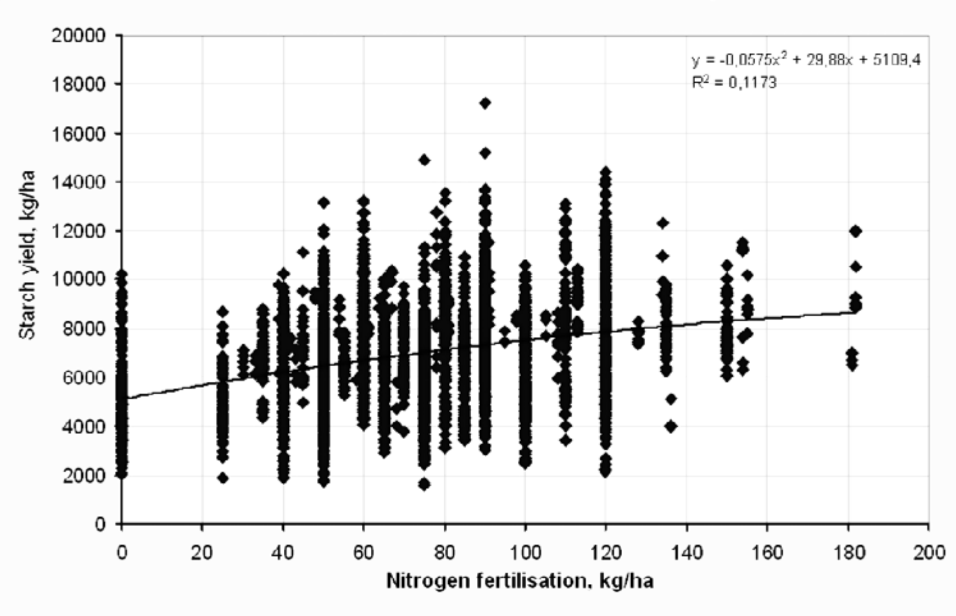

Figure 33. The effect of N rate on starch yield in field experiments of PETLA in 1994–2010 (350 experiments).

In the data of field experiments, the relationship between N rate and N balance depended clearly on the yield level. In the whole dataset of 3940 yield observations, the linear equation was: N balance = 0.57x(N rate) – 74 N kg/ha (with $R^2 = 0.37$). When the data was divided according to the yield levels, linear equations explained 73- 93% of the variation (Fig. 34). With yield below 25 t/ha, N balance of 60 kg/ha was reached with N rate of 130 kg/ha. Statistical tuber yields are usually between 25–35 tn/ha, where N balance of 60 kg/ha was reached with N rate of 161 kg/ha.

Moreover there is a databank covering practical cultivation of starch potatoes from which it is possible to calculate N balances realized on farmers' fields. N fertilization of starch potato resulted in slightly higher N balances (Fig. 35) in practical conditions compared to the field experiments of PETLA. Zero balance was reached with N rate of 40-110 kg/ha while in the data of PETLA the respective rates varied 60-160 kg/ha. On the average, N balance of 60 kg/ha was associated with N rate of 156 kg/ha. With starch yields of 3500–5000 kg/ha and N rate of 135 kg/ha, N balance was 60 kg/ha. In Table 2, N rates leading to N balances of 0 or 30 kg/ha are estimated from starch potato production data according to the content of organic matter in the soils.

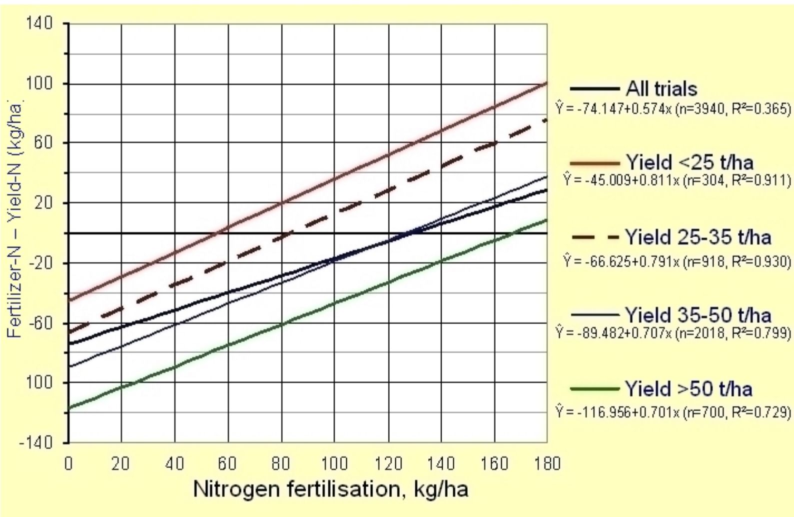

Figure 34. Relationships between N rates and N balances in the potato experiments of PETLA in 1994–2010.

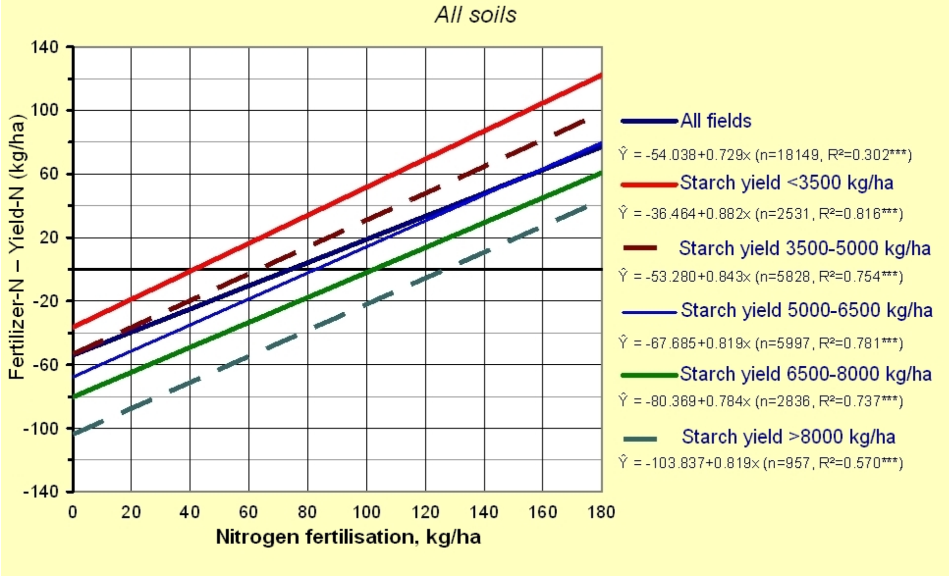

Figure 35. Relationships between N rates and N balances in the databank of starch potato production in 2002–2011.

Table 2. N rates of starch potato related to starch yields and resulting in N balances of 0 or 30 kg/ha in the databank of starch production in 2002–2011.

		Starch yield kg/ha					
		All	<3500	3500-5000	5000-6500	6500-8000	>8000
Soil type	OM %	N rates kg/ha to reach N balance of 0 kg/ha					
All soils		74	41	63	83	102	127
Mineral soil	0-3	74	38	62	82	102	124
Mineral soil	3-6	74	40	63	82	102	126
Mineral soil	6-12	74	42	63	84	102	134
Mineral soil	12-20	75	45	65	84	105	120
Organic soil	>20	72	44	65	85	102	132
		N rates kg/ha to reach N balance of 30 kg/ha					
All soils		115	75	99	119	141	163
Mineral soil	0-3	121	73	98	121	141	164
Mineral soil	3-6	116	75	98	119	142	162
Mineral soil	6-12	115	76	100	121	140	174
Mineral soil	12-20	110	77	101	120	142	151
Organic soil	>20	106	78	98	120	137	172

2.6 Horticultural crops

In Finland the area under horticulture is approximately 15 700 ha (www.maataloustilastot.fi/puutarhatilastot). Horticultural crops are a group of great diversity in their N demand and share of N in different parts of the plants, either harvested or left in the field as crop residues. The most important outdoor vegetables are garden pea (2 860 ha), carrots (1 480 ha) and onions (1 110 ha). The area under berries is 5 974 ha and under fruit 700 ha. For vegetable crops a few field experiments exist, from which data can be obtained to estimate yield response to fertilizer N, and the associated N balance. Usually the tested vegetable crops have been cabbage, carrot and onion while for berries and fruit the number of experiments is smaller. For most of the horticultural crops, only information of the their typical N concentrations, their fertilizer N recommendations and base yields can be used to roughly estimate the N demand and approximate N balances.

In the field experiments of Salo (1999), total N uptake of cabbage both in head and crop residues was over 200 kg/ha with N rates from 160–250 kg/ha. Cabbage yields of 40-70 t/ha need considerable amount of N of which 30–50% is left on the field as crop residues. Also carrot takes up high amounts of N, the total N uptakes of 150-190 kg/ha being reported in Finnish studies (Salo 1999, Salo et al. 2001). Compared to cabbage, carrot is very efficient in its N uptake and it can produce high yields with N fertilizer rates of 50–100 kg/ha. High onion yield can take up more than 150 kg/ha (Salo 1999, Salo et al. 2001). However, onion yield formation is more dependent on the growth conditions than growth of cabbage or carrot and in unfavorable growing season it can be as low as 50 kg/ha. Also high temperatures can enhance bulb development and reduce the yield levels. Thus recommended N fertilizer rates of onion, 80–100 kg/ha, are relatively low compared to the observed maximum uptakes.

Pickling cucumber was tested with N rates of 110–170 kg/ha, leading to N uptakes of 118-159 kg/ha and yields of 60-80 t/ha (Suojala-Ahlfors et al. 2005). Jokinen et al. (1991) tested yield and N uptake of crisphead lettuce with N rates from 0 to 230 kg/ha. Total N uptake in well-yielded lettuce crops was 135 kg/ha and outer leaves contained half of the total uptake.

Data from field experiments (Fig. 36) shows that with high yields of horticultural crops N balances can be low even with high N rates. However, excessive N rates accumulate N balances rapidly, as demonstrated by the values of lettuce. In the reported field experiments N mineralization from soil has been excellent as can be seen from N uptake of unfertilized control treatments. In practical farming, the yield levels are usually smaller and the risk for high N balances will thus be more pronounced.

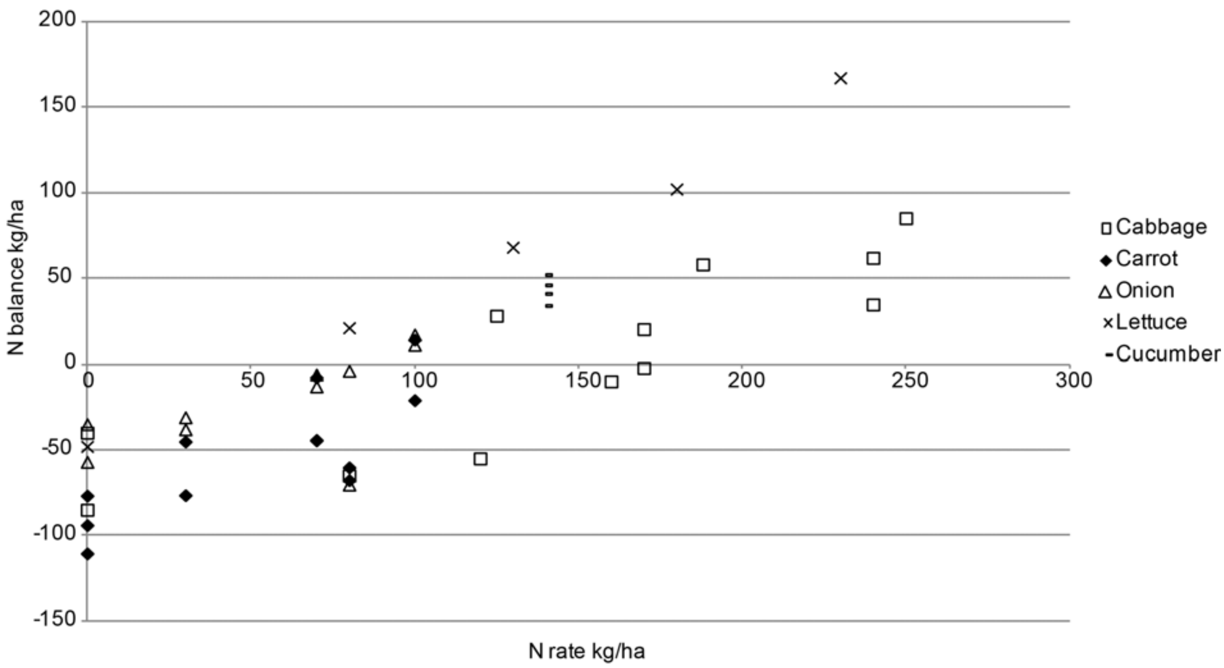

Figure 36. Relationships between N rates and N balances in the experiments of field vegetables at MTT in 1991–2005.

The amount of N in crop residues for typical field vegetable crops is presented in Table 3. Nitrogen content of non-harvested parts can be two-fold (cauliflower), equal (white cabbage) or considerably smaller (onion) than in harvested parts of the crop. Consequently, N balances tend to be high for some of the vegetable crops, and only by adding crop residues to the N uptake, we can reach similar N balances as with other crops. Therefore, if crop residues are left in the field they should be managed carefully and their N content should be taken into account in the fertilizer planning of the next cropping season.

Table 3. Nitrogen balances of different field vegetable crops as calculated from normative yields and N fertilizer recommendations (Viljavuuspalvelu 1997). For N balance on the right, both harvested yield and crop residues are considered.

Crop	Normative yield	N in yield	N in residues	N rec. (1997)	N_balance (harvest)	N balance (harvest+residues)
	t/ha	kg/ha				
White cabbage, winter	50	100	90	200	100	10
Cauliflower	13	31	84	175	144	60
Chinese cabbage	20	40	40	155	115	75
Carrot (storage)	50	85	61	100	15	-46
Red beet	35	88	57	110	23	-34
Onion	30	72	22	100	28	6
Pickling cucumber	40	64	24	140	76	52

N rec. = N recommendation in Viljavuuspalvelu (1997)
N balance (harvest) = N rec. – N in yield
N balance (harvest + residues) = N rec. – (N in yield + N in residues)

There are few data on N balances in practical horticulture. Nitrogen balances of cabbage as reported by Koppelmäki and Marttila (2008) averaged at 134 kg/ha, cauliflower at 147 kg/ha and white cabbage at 135 kg/ha with an average yield level of 31 500 kg/ha. These observed N balances are at the same level as those calculated in Table 3.

2.7 The representativeness of N balances in different datasets

The relationship between N rates, crop yields and respective N balances was very variable between the different datasets as described above. While N rates clearly affected the yields according to the field experiments, in the datasets representing practical farming, there was no correlation in Evira's data and neither in the data of TEHO-project (Kaasinen 2010, TehoPlus 2012). This may be partly due to the fact that the yield level of individual fields is often estimated rather than actually measured. Moreover, it is possible that better correlations would appear if we had the knowledge to group the practical data sets according to yield levels without added N, as was done with the experimental data by Valkama et al. (2013a).

However, similarly to the experimental data there was a clear tendency to higher N balances with higher N rates also in the farm data. Moreover, at a given N rate, the N balances were most often higher in the practical data than in the experimental data, which makes it difficult to predict the actual environmental risks of a certain N fertilizer level. One way out is to compare N balance data from field experiments against the Evira data, to demonstrate the proportion of the better-than-average growth conditions (realized in the field experiments and in the yield competitions) to the variability in practical farms. By this way it is possible to estimate how large proportion of practical fields would follow the outcome of a particular experimental data and end up at a certain N balance at a given N rate.

For spring barley, the relationship between N rate and N balance can vary considerably due to the growing conditions. In good growing conditions (Yield competition data) and in field experiments (Valkama et al. 2013a, Pietola et al. 1999) N balance stays lower than in the farm data as an average (Table 4, Figure 37). In order to evaluate the proportion of good growing conditions in practical farms, we calculated what percentage of observations in Evira's data (Fig. 38) followed the linear equation of yield competition or field experiments. N balances of yield competition equation represented only 7 observations out of 3800 (0.18%). Equation from experimental data of Pietola et al. 1999 represented 619 observations (16.3%). Two equations of Valkama et al. (2013a) from the field experiments represented 800 (21.1%) or 1320 (34.7%) observations, the higher percentage for the equation being valid for slightly acid soils (pH 5.8–6.9).

Table 4. The linear relationships between N rate and N balance for barley; N balance = a x N rate + b.

a	b	R^2	Source
0.74	-50	0.87	Valkama et al. 2013a; pH 4.9-5.7
0.66	-36	0.96	Valkama et al. 2013a; pH 5.8-6.9
0.51	-34	0.60	Pietola et al. 1999
0.83	-45	0.60	Evira (mineral soils)
0.89	-53	0.61	Evira (organic soils)
0.72	-86	0.46	Yield competition fields

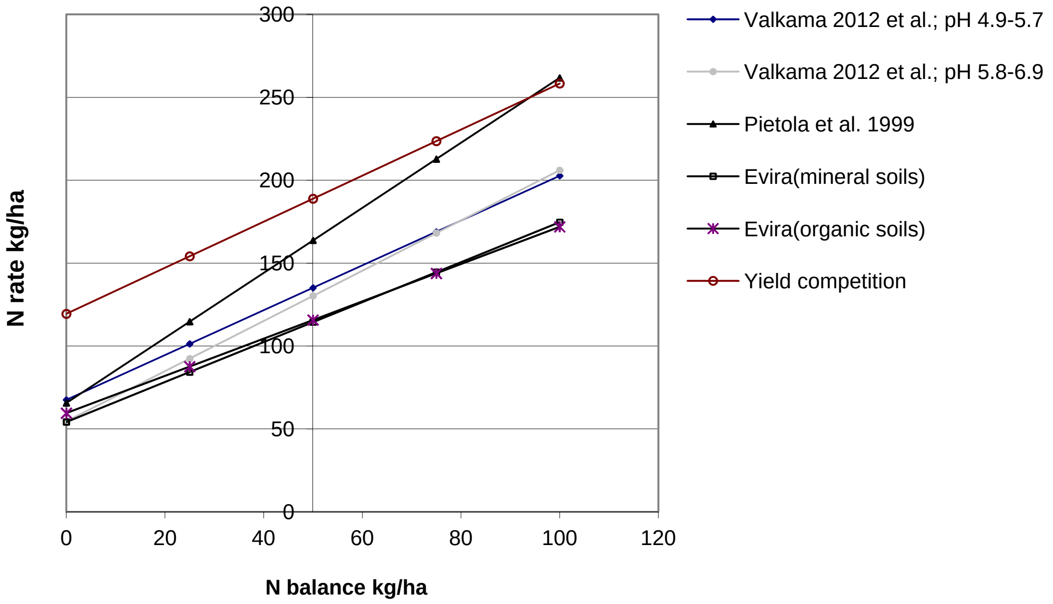

Figure 37. Relationships between N rate and N balance in different barley data.

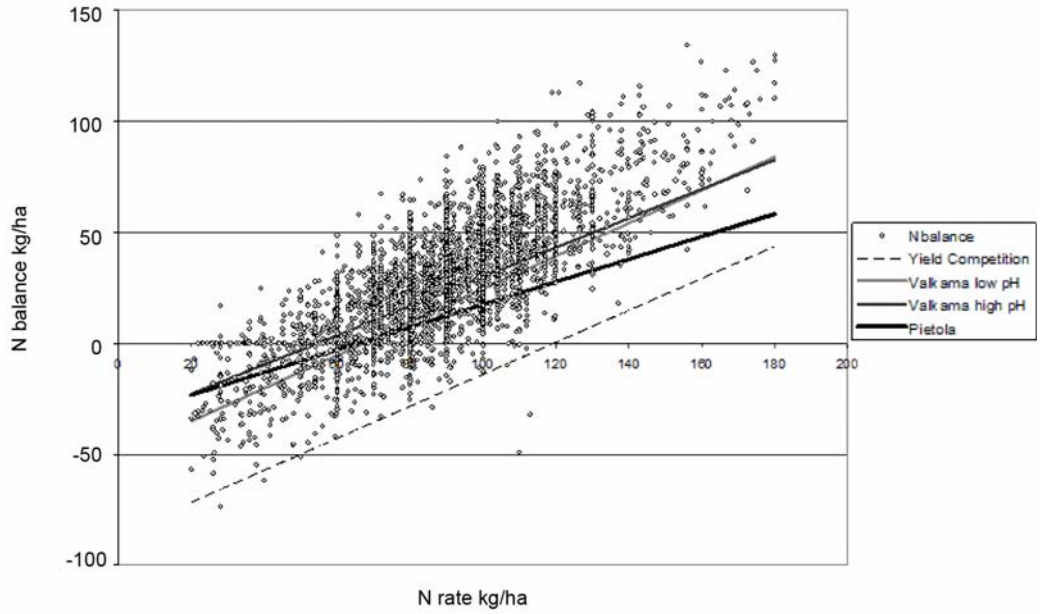

Figure. 38. The distribution of Evira observations and different equations from the field experiments and yield competition.

With similar comparisons for oats, the proportion of N balances in Evira's data falling below the equation by Valkama et al. (2013a, Table 5) was 16% (1053 observations out of 6662) and below equation by Pietola et al. (1999) 11% (744 from 6662).

Table 5. The linear relationships between N rate and N balance for oats; N balance = a x N rate + b.

a	b	R^2	Source
0.62	-51	0.87	Valkama et al. 2013a; pH 5.8-6.9
0.49	-45	0.83	Pietola et al. 1999
0.86	-55	0.57	Evira(mineral soils)
0.91	-61	0.55	Evira(organic soils)

For spring wheat, compared to the equation from the experimental data of Pietola et al. (1999, Table 6) there are 523 cases out of 5304 (10%) with lower N balances in the Evira's data. Two equations of Valkama et al. (2013a) give 1677 (32%) or 2090 (39%) cases with lower N balances in the Evira data, the higher number for the equation for the higher soil pH 5.8–6.9.

Table 6. The linear relationships between N rate and N balance for spring wheat; N balance = a x N rate + b.

a	b	R^2	Source
0.50	-27	0.87	Valkama et al. 2013a; pH 4.9-5.7
0.74	-50	0.87	Valkama et al. 2013a; pH 5.8-6.9
0.49	-44	0.89	Pietola et al. 1999
0.87	-60	0.55	Evira(mineral soils)

For winter cereals and turnip rape we do not unfortunately have such field experiment data as for spring cereals. If we divide Evira's field data of winter wheat into fractions, such as 5%, 16% or 50%, we can have some idea how N rates and N balances behave for these fractions. For 16% of the data, N balance follows an equation: 0.75 x N rate – 55 kg/ha, i.e., 16% of the field data shows lower N balances than predicted with this equation. When the averaged equation (50% fraction, Table 7) from Evira's data results in N balance of 50 kg/ha with a N rate of 120 kg/ha, the equation above (for 16% fraction) ends up to the same N balance with a N rate of 140 kg/ha. For a 5% fraction, an equation: N balance = 0.65 x N rate -60 kg/ha, results in N balance of 50 kg/ha with a N rate of 170 kg/ha.

Table 7. The linear relationships between N rate and N balance for winter wheat, winter rye and turnip rape; N balance = a x N rate + b.

Crop	a	b	R^2	Source
Winter wheat	0.87	-54	0.73	Evira(mineral soils)
Winter rye	0.90	-38	0.84	Evira(mineral soils)
Turnip rape	0.66	-30	0.90	Pietola et al. 1999

For grassland (Table 8) and sugar beet (Table 9), there exist only field experiment data, and thus distribution of N balance in practice is not possible to evaluate. For potato (Table 9), the equations were based on the field experiments run by PETLA or the starch production data collected from the farms. These data are divided according to the yield classes and exact distribution of potato yield levels is not available. Annually potato yields average to 29 t/ha, and yield class 25-35 t/ha shows the equation where half of the fields give higher N balances and the other half lower N balances.

Table 8. The polynomial relationships between N rate and N balance for grassland; N balance = a x $(N\ rate)^2$ + b x N rate + c

Soil type	a	b	c	R^2	Source
Mineral soils	0.0006	0.2284	-42	0.98	Virkajärvi, collected experiments
Organic soils	0.0007	0.3673	-127	0.99	Virkajärvi, collected experiments

Table 9. The linear relationships between N rate and N balance for sugar beet, potato and starch production; N balance = a x N rate + b.

Crop	Yield t/ha	a	b	R^2	
Sugar beet		0.49	-57	0.96	SjT, field experiments
Potato	All classes	0.57	-74	0.37	PETLA, field experiments
	yield<25	0.81	-45	0.91	
	25-35	0.79	-67	0.93	
	35-50	0.71	-89	0.80	
	>50	0.70	-117	0.73	
Potato, starch	All classes	0.73	-54	0.30	Farm data
	yield<3500	0.88	-36	0.82	
	3500-5000	0.84	-53	0.75	
	5000-6500	0.82	-68	0.78	
	6500-8000	0.78	-80	0.74	
	>8000	0.82	-104	0.57	

To show the variation between the different data sets and equations of N balances, we further calculated the N rates that would result in N balances of 0, 20, 40, 60, 80 and 100 kg/ha when using the different equations (Table 10).

Table 10. Nitrogen fertilizer rates that would result in the given N balances (0-100 kg/ha) as estimated according to different equations.

		N balance					
		0	20	40	60	80	100
Barley	Valkama et al. 2013a; pH 4.9-5.7	68	95	122	149	176	203
	Valkama et al. 2013a; pH 5.8-6.9	55	85	115	145	176	206
	Pietola et al. 1999	66	105	144	183	223	262
	Evira(mineral soils) farm data	54	78	102	127	151	175
	Evira(organic soils) farm data	60	82	104	127	149	172
	Yield competition	119	147	175	203	231	258
Oats	Valkama et al. 2013a; pH 5.8-6.9	82	115	147	179	211	244
	Pietola et al. 1999	92	133	173	214	255	296
	Evira(mineral soils) farm data	64	87	110	134	157	180
	Evira(organic soils) farm data	67	89	111	133	155	177
Spring Wheat	Valkama et al. 2013a; pH 4.9-5.7	54	94	134	174	214	254
	Valkama et al. 2013a; pH 5.8-6.9	68	95	122	149	176	203
	Pietola et al. 1999	90	131	171	212	253	294
	Evira(mineral soils) farm data	69	92	115	138	161	184
Winter Wheat	Evira(mineral soils) farm data	62	85	108	131	154	177
Winter rye	Evira(mineral soils) farm data	42	64	87	109	131	153
Turnip rape	Pietola et al. 1999	45	76	106	136	167	197
Grass	Virkajärvi (mineral soils)	135	183	226	264	299	332
	Virkajärvi (organic soils)	238	266	292	317	341	365
Sugar beet	Field experiments	116	157	198	239	280	320
Potato	All	130	165	200	235	270	305
Experiments	yield<25	56	80	105	130	154	179
	25-35	85	110	135	161	186	211
	35-50	125	154	182	210	238	266
	>50	167	196	224	253	281	310
Starch potato	All	74	101	129	156	184	211
Farm data	yield<3500	41	64	86	109	132	155
	3500-5000	63	87	111	135	158	182
	5000-6500	83	107	132	156	180	205
	6500-8000	103	128	154	179	205	231
	>8000	127	151	176	200	224	249

3 Discussion on maximum N fertilizer rates

Which fertilizer levels would be biologically justified without causing unacceptable environmental loading? We do not have enough experimental data to show directly the extent of N leaching for increasing N fertilizer rates even for the most common agricultural crops in Finland. Therefore we used three steps in the present evaluation of N fertilizer rates that would not cause high environmental risks.

First, we gathered available Finnish data of N fertilizer responses on cereal, grasses, potato, sugar beet and vegetable yields, both from field experiments by research institutes and from databanks representing practical farming. From this data it was possible to see the ranges of biological optima beyond which extra N fertilization would definitely cause high environmental risks.

Secondly, to estimate the leaching risk of cereals, we proposed a simple model comprising of two parts, a plateau and a line, the line representing the dependency of N leaching on N balance. Based on the model we set annual N balance of 50-60 kg/ha as a tentative critical balance beyond which we suppose high risk of N leaching.

Our third step in finding environmentally acceptable limits was to calculate the N balances associated with available research and farm data. In both types of data, experimental and farm data, N balances showed a clear, linear dependency on N fertilizer rates: higher N fertilizer rates were associated with higher N balances. However, for a given crop and N fertilizer rate, the balances tended to be lower in the field experiments compared to the farm data, with the exception of the yield competition data of cereals which showed very low N balances. Using this variation we estimated the fraction of the field data that would fall in the same environmentally favorable categories as the field experiments or the yield competition.

For cereal crops in mineral soils, within the variability between different datasets, N fertilizer levels leading to N balances of 50-60 kg/ha were considered the highest acceptable in terms of environmental risk. Following this we ended up to 160-170 kg/ha for the spring cereals and winter rye, and 200 kg/ha for winter wheat (Annex). For the other crops, both the balance values and biologically optimum fertilization were taken into account to propose the acceptable N fertilizer rates.

For grasses the current N fertilizer recommendations are the highest in numbers but they are still clearly lower than the biological optimum for grass yield. Furthermore, for cut grass nitrogen balances are typically low and even negative, indicating lower risk of N leaching compared to annual crops that is also verified by numerous national and international research data. This is due to that perennial grasses are able to utilize nutrients from the very beginning of the growing season to the end of it. Furthermore, the biomass is harvested several times during the season and the proportion of harvested biomass of the total biomass is high. On pastures, the yield responses to fertilizer N are clearly lower than for cut grass and consequently balances are more positive and N leaching risk is higher.

For soils with high amount of SOM very little data was available compared to mineral soils. In organic soils N balances show typically lower values due to larger proportion of N supplied by SOM and therefore the balance values are not comparable to those of the mineral soils. For the same reason, environmentally acceptable N fertilization is lower for organic soils. To allow this justification, we can use the review of Valkama et al. (2013a), where an increase of 1% in SOM increased cereal yields with 321 kg/ha in mineral soils (2.9-7.4% SOM), containing N about 6.5 kg/ha. Using this data, in organic soils (with 20% or more SOM) a reduction of N fertilization by 40 kg/ha compared to mineral soils could be justified (Annex). Based on the same results, it would be justified to apply lower N fertilizer rates for mineral soils rich in SOM (6-12% or 12-20%, ‘rm’ and ‘erm’ according to the Finnish classification, respectively).

Finnish climatic conditions during and outside the growing season vary greatly from years with drought to those of excess wetness as well as from coldness to moderately warm seasons. Consequently the risk of N leaching is hard to predict but will naturally be more pronounced on soils which do not have a large water retention capacity. Therefore, for very coarse mineral soils, with particle size of the dominant fraction > 0.06 mm (KHt in Finnish classification) that are most vulnerable to nitrate leaching, a slightly reduced N fertilization (-10 kg/ha from the values of mineral soils) to all crops would further diminish the N leaching risk.

Finally, it must be noted that besides SOM or water retention capacity the agronomic and environmental outcome of N fertilization is very variable due to other soil properties, such as soil pH. In the study of Valkama et al. (2013a) there was a clear difference between moderately acidic (pH 4.9-5.7) and slightly acidic (pH 5.8-6.9) soils for N balances at a given N rate, with higher N balances for the more acidic soils. In more northern parts of Finland there was a tendency for higher N balances as well. This gives reasons for 10-20 kg/ha lower maximum N amounts in northern part of the country. When SOM content of agricultural soils generally increases towards the north, this is partly accomplished by the above described, lower maximum N rates for soils rich in SOM.

Climatic factors, especially excess wetness or severe drought, may have different power depending on soil's structural properties on a particular field, and they may induce higher than average N balances at a given N rate. On the other hand, in favorable conditions with good soil structure it is possible to achieve very high yields with small N balances. Despite decades of research there is still lack of practical tools to predict field-specific N fertilization, and it is difficult to set up maximum rates that would be evenly justified for all fields. Further models and innovations are needed to promote economically and environmentally optimal N fertilization.

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5 Annex

Maximum N fertilization levels (kg/ha) for different crops in Finland as proposed by MTT, PETLA and SjT. When 150 kg/ha or above, the applied amount has to be divided into two portions with at least two weeks between the applications.

	Mineral soils***			Organic soils
Organic matter, %	**<6**	**6-12**	**12-20**	**>20**
	CEREALS			
Spring barley, oats, cereal mixtures	160	150	140	120
Spring wheat	170	160	150	130
Winter rye *	160	150	140	120
Spring rye	160	150	140	120
Winter wheat*, ryewheat*, spelt*	200	190		140
Other cereals and their mixtures	160	150	140	120
GRASSLAND	250	240	230	210
	OIL AND INDUSTRIAL CROPS			
Winter turnip rape, winter winter oilseed rape **	200	190	180	160
Spring turnip rape, spring oilseed rape	170	160	150	130
Flax, maize, oilhemp, sun-flower	150	140	130	110
LEGUMES	60	50	50	40
SUGAR BEET	170	160	150	130
	POTATO			
Starch potato	120	110	100	80
Early potato	100	90	80	60
Other potato	110	100	90	70
	VEGETABLE CROPS			
Cabbages and leek	250	240	230	210
Other onions	160	150	140	120
Root crops	200	190	180	160
Spices and herbs	120	110	100	80
Other vegetable crops	200	190	180	160
Berries and fruits	140	130	120	100
Nurseries	200	190	180	160

***In autumn in organic soils max 20 kg/ha, in other soils 30 kg/ha**
**** Fertilization before Sept. 1 is not taken as autumn fertilization but is accounted for the maximum 200 kg/ha**
***** For very coarse textured mineral soils, with particle size of the dominant fraction > 0.06 mm (KHt in Finnish classification) maximum nitrogen fertilization is 10 kg/ha less**

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