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Establishing long-term nitrogen response of global cereals to assess sustainable fertilizer rates

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Abstract

Insight into the response of cereal yields to nitrogen (N) fertilizer is fundamental to improve nutrient management and policies that can sustain economic crop benefits and food sufficiency with minimum N pollution. Here, we propose a new method to assess long-term (LT) regional sustainable N inputs. The core is a novel scaled response function between normalized yield and total net N input. The function was derived from 25 LT field trials for wheat, maize and barley in Europe, Asia and North America and fitted by a 2nd order polynomial (R^2=0.82). Use of response functions derived from common short-term field trials, with soil N not in steady state, gives risks of soil N depletion and N pollution. The scaled LT curve implies that total N input required to attain the maximum yield is independent of this maximum yield as postulated by Mitscherlich in 1924. The unique curve was incorporated in a simple economic model with valuation of externalities of N surplus as a function of regional per-capita GDP. The resulting LT sustainable N inputs range between 150 and 200 kgN/ha and this interval narrows with increasing yield potential and decreasing *GDP*. The adoption of LT response curves and external costs in cereals may have important implications for policies and application ceilings for N use in regional and global agriculture and ultimately the global distribution of cereal production.

Introduction

Finding a balance between the benefits of nitrogen (N) fertilizer use for food production and the impacts of agricultural N pollution on human health and ecosystems is a challenge from the regional to the global scale[1,2]. Current global anthropogenic addition of new N from the Haber-Bosch process, cultivation of N fixing crops and combustion of fossil fuels more than doubles the natural input of reactive N[3], thereby exceeding the assumed planetary boundary of N[4] and causing high environmental costs[3,5]. The use of synthetic fertilizers and manures across the nearly 40% of earth's ice-free land devoted to agriculture[6] comprises the largest source of ammonia, nitrate and nitrous oxide pollution globally, with severe impacts on ecosystems, human health and climate change[3,7].

A pivotal relationship for improving agronomic and environmental performance of food systems is the response of crop yield to addition of N fertilizer. This relationship sets the yield increase per unit of fertilizer input (the agronomic efficiency AE) and is the basis for estimating N surplus and N use efficiency (NUE, ratio of crop N removal to N input[8]). The N response curve together with prices on crop and N fertilizer, inform farmers about how much N fertilizer they need to apply in a given year to obtain the most profitable crop yield, and informs strategies for developing regions to achieve food security without depleting soil N[9,10]. In today's increasingly globalized agricultural markets, profit margins for most crops are narrow and farmers struggle to achieve a consistent return on investment[11,12]. Proper management of nutrient resources is a relevant factor in this quest, but the societal costs of N pollution are only rarely incorporated into economic decisions for farming. Establishing policies that promote societally optimal N-rates, often substantially lower than optimal rates for private economic returns[13,14], also relies upon accurate characterization of N-yield responses.

Long-term field experiments (LTEs) are essential to quantify N response for assessment of economic and environmental performance of alternative nutrient management practices[15-17], since the time to establish steady state between N input, crop yield, N losses and the soil N pool can exceed decades, depending on soil organic matter fraction and quality (e.g. C/N ratio) and the history of fertilizer use[15]. While numerous short-term trials (single year; STEs) are carried out across the globe to inform extension activities, LTEs represent a substantial investment of research time and resources, and are therefore scanty in areas like Latin America and Africa[18]. STEs can inform yearly management decisions but they cannot correctly characterize the long-term impacts, and associated costs and benefits, of changing N management policies. Improved understanding of LT N response functions across regions is critically needed and here we address this knowledge gap.

Drawing upon the generic principles governing N transformations and uptake when N input, crop yield and soil N pools are in near steady state, here we propose a generic LT N response relationship for cereals that can be used to inform policy decisions. We focus on the three major global staple cereals, wheat (16% of global crop area for 2013-2017[19]), maize (14%), barley (3.4%) and also address lowland rice (12.5%). We collect and analyze a global set of LTEs for Europe, North America and Asia, and use the Broadbalk wheat experiment in the UK (since 1843)[20] to establish a conceptual model describing the differences between short and long-term N responses.

Results

Effects of duration and rotation on N response of wheat from the Broadbalk wheat experiment .

Over the past 175 years the combined effects of different amounts of NPK fertilization, use of manures, improved cultivars, pesticides, liming and fallowing could be demonstrated and explained by analysis of crop and soil characteristics[20]. The LT response of wheat in rotation (Fig. 1) was taken from observations in Broadbalk from 1985 to 2018, where plots were given the same annual N fertilizer rate (N rate) every year[21]. This LT response was compared to the ST (1st year after adjustment of N rate) response at commercial wheat trials in different parts of England between 1994 and 1998 (Supplementary Note 2).

Grain yield at zero N input (*Yo*) for the commercial STEs (5.0 t/ha) is substantially higher than for the LTE in Broadbalk (1.7 t/ha) because more N is available from fertilizer residues and mineralization of the soil organic matter and crop residues originating from previous higher fertilizer inputs. For LTEs like Broadbalk, the mean net supply of N from the soil is low and the dominant N sources for *Yo* are N deposition (*DEP*) and natural biological N fixation (*BNF*) from free-living bacteria. However, The mean maximum attainable yields (*Ymax*) for the LTEs and STEs both converge to 9.1 t/ha. The *Ymax* for LTEs for continuous wheat in Broadbalk is lower (Supplementary Note 2).

***Fig. 1 Long- and short-term N response for winter wheat in rotation in the UK**. Long-term N response as observed in Broadbalk, Rothamsted (N=245, R^2=0.84) and the common first year N response for representative commercial sites in different parts of England (N=105, R^2=0.55; dashed lines, 95% Confidence Intervals, see also Supplementary Note 3).*

With continued application of a certain N-rate to soil-cropping systems, ST N response curves gradually shift to the LT N response (Fig. 2). When the LT N rate is higher than the historic rate, grain yields will gradually increase due to soil N accumulation causing increased soil N delivery through greater returns of mineralized N from N in roots and crop residues to the soil[21,22], and an overall improved soil fertility and quality. When the LT N rate is lower than the historic rate, grain yields will gradually decrease due to soil N depletion causing decreased soil N delivery from mineralization. The first case typically applies to developing regions in Africa and south Asia where N rates are increased to meet the market demand or reduce regional food and feed insecurity, the second case to industrialized regions such as Europe where environmental policies restrict N fertilizer use to reduce N pollution[23,24].

***Fig. 2 Conceptual explanation of the difference between short-term and long-term N response curves.** ST N response of wheat grain yields in the UK in a situation with a history of high N inputs at 150 kgN/ha [25](red line with solid red dot showing response in first year and the red/green dot in near* *steady state), ST N response in a situation with a history of low N inputs at 60 kg N/ha (blue line with solid blue dot showing response in first year and the blue-green dot in near steady state), as compared to the LT generic N response where soil N is in steady state with all N inputs (dashed green line representing Broadbalk). With time passing, the new N application regimes will change soil status and yields, and both the ST blue and red lines will converge to the LT green dashed line, as indicated by the arrows.*

Scaling annual LT N response of wheat in rotation in Broadbalk . Given its long duration, the soil N and carbon status at every rate in the Broadbalk trial is in near steady state with its constant annual N rate. Every observation year between 1985 and 2018 delivers an N response curve with its proper *Ymax*, which ranges between 6 and 12 t/ha, and a *Yo* ranging between 0.23 and 3.62 t/ha (Fig. 3a). Differences in Ymax reflect differences in annual weather conditions and changes in cultivars (new cultivars were introduced in 1991 and 2013), while *Yo* is also affected by annual N mineralization.

We hypothesize that observed long-term N response for can be approximated with a single curve, which describes the relative (normalized) yield (*Yr=Y/Ymax = Yield Index*) in steady state as a function of total available N (*Nav*). *Nav* is defined as the sum of N from fertilizers and soil N supply, including atmospheric deposition (*DEP*) and biological fixation (*BNF*). The amount of available N from soil, *DEP* and *BNF* is referred to as *SN*, which governs crop production in unfertilized plots. This curve in Fig. 3b was derived by first scaling observed annual yields to the annual *Ymax*, and conversion of *Nrate* to *Nav* by addition of *SN* (Supplementary Note 3). For each observation year, both *Ymax* and *SN* were estimated from a 2nd order polynomial fit to the observations, where *SN* is the intercept on the horizontal axis. *SN* ranged between 4 and 64 kgN/ha. Mean *SN* is 30 kgN/ha and shows no trend in time; with a local *DEP* of 20 kgN/ha in 2017, this would suggest a *BNF* of 10 kgN/ha, which is in accordance with averages for the UK[26]. Finally, all scaled observations were fitted again with a 2nd order polynomial with zero intercept (Fig. 3b). The resulting N response relationship for Broadbalk wheat in rotation is expressed by:

$$Yr = -1.354E\text{-}5 \times Nav^2 + 7.291E\text{-}3 \times Nav \qquad (R^2\ 0.954;\ \text{Eq. } 1)$$

***Fig. 3 Effect of scaling on annual N response curves** from 1985 to 2018 for winter wheat in rotation at Broadbalk, Rothamsted. **a**: 2nd order polynomial fits of annual N response curves from unscaled observations and mean curve (red), **b**: yields indexed to maximum annual yield and N rates per year of observation transformed to available N by adding estimates of non-fertilizer sources, and fitted with a 2nd order polynomial with zero intercept (Eq. 1).*

The same procedure was applied to observations for continuous wheat at Broadbalk and gives an almost identical quadratic yield response (R^2 0.903; Supplementary Note 3). One LTE of relatively long duration (since 1961) for maize in Nebraska (USA) was comparable in setup to Broadbalk (6 N and 3 P rates)[27]. As for Broadbalk, scaled annual N response data fit a quadratic function (R^2 0.934, for details see Supplementary Note 4). On average *Yr* at a given *Nav* for maize in the USA is somewhat (11%) higher than for winter wheat in the UK, indicating that maize has a stronger N response than wheat. Maize is a C4 crop with N dilution different from that in C3 crops like wheat[28] causing the grain N contents in maize to be somewhat lower (1.5% versus 1.9%[29]). Further, the harvest index of maize tends to be somewhat higher[30].

Back transformation of the scaled curves to N response curves, as needed to plan regional long-term N requirements for a certain cereal yield target, would require independent estimates of site-specific *SN* and *Ymax*.

A generic LT N response for global wheat, maize and barley. We next seek to examine whether the LT N response established at Broadbalk holds for other cereals in experiments around the globe. The transformations using individual *Ymax* and *SN* values that allowed coalescence of data from the respective years at Broadbalk into a single curve was also applicable for a set of 25 global LTEs for wheat, maize and barley in Europe, North America and Asia. These 25 LTE's cover a wide range of soils, climates and practices, with N rates ranging from 0 to 300 kgN/ha and *Ymax* from 2.8 to 12.8 t/ha (Table 1, Fig. 4a). The 2nd order polynomial fit of pooled scaled N response data for global cereals was:

$$Yr = -1.870E\text{-}5 \times Nav^2 + 8.768E\text{-}3 \times Nav \qquad (R^2\ 0.818;\ \text{Eq. } 2).$$

Maximum *SN* was 88 kgN/ha. N response in Eq. 2 is very similar to Broadbalk wheat in rotation (Eq. 1, Fig. 4b), but somewhat steeper, which could be the effect of maize in the USA (Supplementary Note 4).

Despite their empirical nature, models of the quadratic form "$Yr = a \times (Nav)^2 + b \times Nav$" do satisfy some "general principles of biology":

1. Relative yield, *Yr* = 0 for *Nav*=0; In the long term there cannot be dry matter production (by photosynthesis) without N;
2. The law of diminishing returns; with increasing N inputs the internal N concentration increases and the dry matter production per unit of N input (the agronomic efficiency) decreases; the coefficient "*a*" represents the rate of diminishing returns;
3. The presence of an *Ymax* induced by other negative feedbacks at high biomass or high tissue N concentrations; in cereals examples of such feedbacks are lodging or increased pest incidence.

Fig. 4 Unscaled (a) and scaled (b) long-term N response data for wheat, barley and maize trials in Europe, North America and Asia *and 2nd order polynomial fit with zero intercept, as compared to Broadbalk wheat in rotation.*

The validity of the LT generic N response curve was verified by back calculation of the original unscaled cereal grain yields for every LTE, using 25 alternative 2nd order polynomial fits of the dataset of indexed yield as a function of *Nav*, each time leaving out the observations for the validation site. The high correlation (0.945) between original and back calculated yields (Supplementary Note 6) and the low Root Mean Square Error (*RMSE*) of the prediction (0.52 t/ha) shows that our generic curve indeed represents local N response of cereal yields across a wide range of soils and climates and suggests that it can be used as a first approach for regions where LT curves are not available, like in Africa and Latin America, provided that local *SN* and *Ymax* are known. As we found a similar scaled N response for Broadbalk for the 25 global LTEs, *Ymax* can signify either mean attainable yield over many years, or the attainable yield for a given year, depending on the purpose.

In general fertilizer rates and practices in countries change slowly and hence soils can be expected to be in near-equilibrium with N rates. Therefore we sought confirmation of our generic LT response curve using national data on crop yields and N fertilizer use. Modelled yield responses in Europe corresponded well with national data for rainfed wheat, barley and maize[31] (*Ymax* at 90% of *Yw*; R^2 0.796; Supplementary Fig. 10) and for wheat[32] ($R^2 = 0.579$; Supplementary Fig. 11). In developing countries these national data are often absent or unreliable. As an alternative, we compared maize response in nine countries in Sub Saharan Africa (SSA)[10], using modelled N requirements for target yields according to the Global Yield Gap Atlas[33], with *Ymax* set to 80% of water-limited yield potential (Y*w*). We found a reasonable fit (R^2 0.671, Supplementary Fig. 12), although in this SSA study AE and modelled N requirements were proportional to *Ymax*, which is not the case in our generic response curve. Applicability of the generic curve for Africa was further verified against trial results in Niger and Malawi (Supplementary Fig. 13-15).

Notably, the LT generic N response curve seems not applicable for lowland rice. A first provisional scaled N response curve based on four LT trials for lowland rice in India and Nepal, with wheat as a winter crop as common in South Asia, showed a much weaker increase of yields with *Nav* (Supplementary Note 8) and no *Ymax*, likely because of higher rates of non-symbiotic BNF as compared to wheat and maize[34], high ammonia loss from urea fertilizers and redox conditions promoting denitrification, all factors weakening yield response to N fertilizer addition[35,36].

A generic model for Agronomic Efficiency of global cereals. The tight relation between absolute N rate and relative yield implies that the amount of fertilizer-N required to produce e.g. 70% of *Ymax* is fixed, i.e. irrespective of the value of *Ymax* itself. This might be unexpected and is only possible if the conversion of fertilizer-N into grain biomass becomes more efficient with rising *Ymax*. The agronomic use efficiency of the applied nitrogen ($AE = [Y-Yo]/Nrate$) expresses the efficiency by which applied N is converted to grain yield[37]. The long-term AE is achieved when soil N supply is in steady state with annual input rate[10], and can be estimated from LTEs**.** For the ensemble of 25 LTE's for wheat, maize and barley in Europe, North America and Asia the *AE* was calculated for each Nrate and LTE and could be fitted accurately as a linear function of *Yo*, *Ymax*, *Nrate* and two interaction terms (Eq. 3, Fig. 5).

$$AE = 4.62 - 8.37 \times Yo + 9.84 \times Ymax - 0.0365 \times Nrate + 0.0172 \times Yo \times Nrate - 0.0223\ Ymax \times Nrate$$

(R^2 = 0.924, N=94; Eq. 3)

This expression explicates the positive impact of *Ymax* and negative impact of N rate on N use efficiency, the latter causing diminishing returns from N input (Fig. 1). The positive impact of *Ymax* exemplifies Liebscher's (1895) law[38] that the use efficiency of a yield-constraining factor (here N) increases as the other factors are more optimal (here expressed in *Ymax*, which comprises genotype, weather, soil and crop husbandry factors). De Wit (1992)[39] demonstrated that this Liebscher principle holds for N responses in various crops, and showed that it relies on higher efficiencies in both N uptake and conversion into grain, at higher *Ymax*. Taken to its extreme, this Liebscher principle leads to the assumption by Mitscherlich (1924)[40] that the activity coefficient for any nutrient in the exponent of his response function is independent of other factors. In the words by C.T. De Wit (1992) on Mitscherlich: "*This heroic assumption ... implies that the absolute amount of nutrient needed to reach a certain fraction of the maximum yield is the same whether yields are low or high. Of course, such universal constants do not exist, but this does not exclude the possibility that constant activities manifest themselves in more restricted domains and yield ranges.*" Our present analysis of LTE data points at the existence of this (near) constancy of N requirement. We find that N requirement to reach *Ymax* (or a certain fraction thereof) is uncorrelated with *Ymax* itself.

The AE function in Eq. 3 can be converted to an *Yr* relation with *Nrate*. AE models derived for STEs, also approximate long-term response when using low values of *Yo* (See Supplementary Note 7 and example for STE for maize in Nebraska, USA). Global application of AE models for derivation of long-term sustainable N inputs requires *Yo* data which are increasingly available but not for all regions. Also, *Yo* depends on *DEP* which changes over time. Regional S*N* as needed for Eq. 2 is available from global models[26].

Fig. 5 Agronomic Efficiency (AE) for global cereals. *AE increases with Ymax and decreases with an increasing Nrate (visualized with isolines of applied N fertilizer with Yo set at mean observed value in*

LTEs of 2.9 t/ha). Data points are unscaled observations for the 25 LTEs, with AE at observed Nrate adjusted to nearest Nrate isoline using Eq. 3.

Implications of a generic LT N response. Our finding of a generic N response curve for wheat, maize and barley in Europe, USA, South Asia and China, with *Ymax* ranging between 2 and 13 t/ha, implies that the *Ymax* is attained in a fairly narrow range of *Nav*. This *Nav* at *Ymax* (referred to as *Nmax*) is found by solving Eq. 2 for *dY/dNav*=0. *Nmax* for Eq. 1 was 234 kgN/ha, the mean *Nmax* for the 25 LTEs was 217 kgN/ha (SD 41 kgN/ha). The observed range of *Nmax* across the 25 sites, is 143 to 307 kgN/ha and *Nmax* is uncorrelated with *Ymax* (R^2 0.055). This implies that *AE* (and also *NUE*) at given relative yield Yr increases with *Ymax*. One cause for achieving a high *Ymax* in a specific region or year is a good synchrony between crop N demand and N availability from soil and fertilizer[41]. This leads to high *AE* when N fertilizer rates are not excessive[42] (Fig. 5). One could also reason that a high *Ymax* is the result of a favorable climate, crop physiology and crop-soil system, including a well-functioning root system allowing maximum interception and utilization of available N, in addition to water and other nutrients.

The hypothesis of *NUE* increasing with *Ymax* could only be tested for N trials at Broadbalk, where also N content of grain and straw were measured (Supplementary Note 9). For a N rate range of 144-288 kg N/ha, similar as for attaining *Ymax* for the global cereals, *NUE* increased significantly (R^2 0.166, N=64), and almost proportionally with *Ymax*, with an average *NUE* of 40% for an *Ymax* of 6 t/ha increasing to 80% at 10 t/ha.

Economic optimal N rates for cereals using generic LT N response. Farmers need insight into the marginal response of yield to N rate to determine the economic optimal N rate (EONR[43]) which is lower than *Nmax* due to the cost of N fertilizer. Our EONR applies to the scale of national or regional cereal sectors. Marginal response depends on the time horizon of optimization and the choice of response curve. The net economic return is the gross return from crop sales minus the costs of labor, capital and N fertilizer inputs, and depends on prevailing prices of grain and N fertilizer. The N rate giving maximum financial return is a proxy for the mean optimal N rate for regional or national cereal farming. Taking into account the external cost of N pollution provides a proxy for the optimal N rate for society and provides guidance for fertilizer and nitrogen policies[13,44].

The calculated range of N rates delivering a high net positive financial, decreases from (a) using ST N response, to (b) LT N response, to (c) including external costs. These ranges of N rates for price levels in the Netherlands, using ST and LT N response curves for wheat in rotation at Broadbalk are, (a) 219 kgN/ha (14-233), (b) decreasing to 157 kgN/ha (61-218), to (c) 90 kgN/ha (45-135) (Supplementary Note 10). In other words, including the external costs will reduce the optimal N level by 40% in this case.

For global cereals, we varied *Ymax* from 2-12 t/ha and *GDP* from 2-50 kUSD/cap (Fig. 6). Marginal cost of crop production and N pollution for countries are estimated using an income (*GDP*) elasticity of 0.85 (Supplementary Note 11). The optimum N rate for farming profits increases with the maximum attainable yield. This increase is independent of *GDP* but depends on the prices of grain and fertilizer. In many regions with high market access, world market prices apply, but in some regions of the developing world, production and consumption of cereals are more controlled by local markets; e.g. in Kenya prices for wheat and N fertilizer are up to 1.5 to 2 times as high as in Europe and North America[45]. For economic analysis at society scale we considered that the virtual price per kg of cereal on the “food plate” is higher than at farm gate. For this we ran a scenario with a price ratio of one and three. We did not account for feedback effects of reduced cereal supply on prices or for subsidies on cereal and fertilizer, although these are present in many regions; e.g. N fertilizer subsidies are up to 70% of the world market price in India[46].

The optimal N rate for society (*SONR*) is lower than the optimal rate for farming, and the difference between these values increases strongly with *GDP*. At an *Ymax* of 6 t/ha and a *GDP* of 50 kUSD/cap, optima for farm and society are 207 and 88 kgN/ha, respectively, and for a *GDP* of 2 kUSD/cap the optima are 209 and 197 kgN/ha, respectively. However, *Ymax* also tends to increase with *GDP* because of better access to technology and high yielding cultivars and better farm management. The lower the GDP the lower the difference between optimal N rates for farming and society. The higher the potential yield, the smaller the difference between optimal N rates for countries.

Fig. 6 Increase of societal optimal N rates for global cereals *with increasing yield potential (Ymax; from 2 to 12 t/ha) and with decreasing GDP (from 50 to 2 kUSD/cap) using the generic LT response of yield to N availability (Eq. 2), a "farm gate-food plate" price ratio of 1, and a decrease of the marginal cost of N pollution with GDP. For comparison, the optimal N rate for farming in the EU is shown.*

Assessing the safe operating space for N fertilizer application.

For regional farm nutrient management and national environmental management, knowledge of the safe operating space for N application is more relevant than knowledge of the optimum point values. The concept of "safe space" of N application[47] can be defined as the N range where yields are high, pollution is low and where net economic benefits for both farming and society are in balance[48]. This "safe space" of N rates is illustrated for three *GDP* levels, 50 kUSD/cap (typical for North America and Northwest EU), 25 kUSD/cap (typical for central and southern EU), 10 kUSD/cap (typical for Eastern Europe and South America) and for two food plate to farm gate cereal price ratios.

The minimum *Ymax* allowing "safe" (beneficial) application of N fertilizer decreases with increasing *GDP* (Fig. 7). The safe range of N rates, with robust net benefits for both farming and society, is fairly constant increasing only slightly with *GDP*. However, the optimum range with high benefits for both farming and society strongly decreases with increasing *GDP* and price ratio. With increasing GDP, society is increasingly willing to pay to prevent the impacts of N pollution and the fixed farm costs per hectare increase (for both we use a *GDP* elasticity of 0.85).

When food prices are high people tend to accept more N pollution, e.g. in case of food shortage or food hedonism. Our welfare analysis is simple and ceteris paribus, as we did not consider feedback effects of regional changes in cereal production on prices of grain and land. If *SONR* would be applied globally, global yield supply would not change very much as lower N rates and yields in developed regions would be compensated by increases in developing regions. Furthermore, the farm gate price of raw cereals contributes about 10% to the price of cereal food products in the USA and the EU (Supplementary Note 13). Therefore the LT effects of a modest change in global cereal supply on cereal prices will be modest, in spite of the relative inelasticity of cereal demand[49].

EONR is more sensitive to the shape of the LT N response curve than to the price of cereal. *SONR* is most sensitive to *Ymax* for high *Ymax* (8 t/ha) and *GDP* (50 kUS$/cap), while for mid *Ymax* (4 t/ha) and *GDP* (10 kUS$/cap) also to *GDP*. Uncertainty of *EONR* is also dominated by uncertainty in the shape of LT N response curve, while uncertainty of *Ymax* contributes most to uncertainty in *SONR* (Supplementary Note 12). Uncertainties in *SONR* (6-8%) are higher than for yield (1-2%) and do not affect our welfare analysis which intends to illustrate direction and approximate size of effects of *Ymax* and *Nrate* on *SONR,* focusing on high- and mid- income countries. For low-income countries

(*GDP* < 1kUSD/cap) *SONR* converges to *EONR* (Figures 6 and 7), but our welfare analysis is less applicable here in view of absence of valuation data for N pollution.

For the Netherlands with a *GDP* close to 50 kUSD/cap, current *Ymax* ranges between 8 and 10 t/ha, while current (mineral) fertilizer equivalent N rates range between 150 and 200 kgN/ha (see Supplementary Note 12). This current range overlaps with the safe space, but current N rates exceed the optimal N rates for society by 15-30 kgN/ha. The same conclusion applies to France (*GDP* 35 kUSD/cap), while for Romania with a *GDP* of 9 kUSD/cap, current N rates between 50 and 100 kgN/ha are about 50 kgN/ha below the safe space (Supplementary Note 12). Transposing 30 kg N on a hectare under wheat from the Netherlands to Romania, would increase the societal benefit, without yield loss. For countries with a *GDP* lower than 5 kUSD/cap, optimal N rates for farming and society converge. For China (*GDP* 3.2 kUSD/cap, *Ymax* rainfed wheat 6-9 t/ha), current N rates of 200 to 300 kgN/ha exceed the farming optimum of 200-225 kgN/ha. In India (*GDP* 1.0 kUSD/cap, *Ymax* 3-6 t/ha) current N rates are around 100 kgN/ha which is about half of *EONR* and *SONR*, while urea fertilizer is subsidized. In Kenya (*GDP* 1.2 kUSD/cap, *Ymax* 3-6 t/ha) current rates are around 50 kgN/ha, and about 30% of *EONR* and *SONR*.

Gaps between current N rates and the safe operating space may appear quite modest but will tend to increase in the future for different reasons. In the EU this gap will increase due to stricter environmental N policies and ambitions for extensification and nature inclusiveness, which both will tend to reduce yields per hectare. In Kenya and India, as examples of developing regions, increasing *GDP* will increase willingness to pay to reduce pollution and therefore increase marginal external N costs per kg of N surplus. The shape of the safe range of Ymax-Nrate combinations illustrates that for N rates above 150 kgN/ha development and access to higher yielding cultivars is a better strategy for more sustainable agriculture than strategies to increase application of synthetic N.

Fig. 7 Classification of long-term economic benefits for farming and society of adding N fertilizer to rainfed wheat with increasing attainable yield (Ymax)*, for three levels of Gross Domestic Product (GDP) and two Food plate to Farm gate price ratios of grain. N application as CAN equivalents at a fertilizer price of 1 USD/kgN and assuming no other N inputs than background (SN) of 25 kgN/ha. Grain price is 0.2 USD/kg. Damage cost per kg of N surplus increases with GDP (4, 10 and 20 USD/kg for, respectively, GDP of 10, 25 and 50 kUSD/cap), likewise fixed farm cost (resp. 185, 480 and 980 USD/ha). The “robust” range of N rates is set at 0.25 of the range with net benefits.*

Conclusions. Based on 25 long-term field experiments with maize, wheat or barley we found a generic relationship expressing the responses of cereal yield and agronomic N efficiency, respectively, to N application rate. The relationship is globally applicable and for a wide range of conditions. It is very different from the short-term responses that are commonly used. The generic relationship applies for *Ymax* in the range between 2-16 t/ha as in the underlying observations. A *Ymax* lower than 2 t/ha indicates strong growth limitation by water or other factors, hampering normal crop development and response to N fertilizer, while *Ymax* above 16 t/ha may apply to special cultivars or management practices. LT trials used in this study do not include use of manure, but our generic curve is likely also applicable for organic fertilizers using replacement values, for manure N by assuming an observed LT fertilizer replacement value of one[50].While first results for lowland rice are promising, more LTEs for other regions are needed for global applicability. Global application can be improved by compilation and analysis of observations of *SN* and *Yo*. The mere existence of these curves may point at universal principles of plant metabolism and scalable mass relationships as found by West[51]. Application of our generic response curve has important implications for optimal N rates, for agriculture and society as needed to ensure farm income, food sufficiency and sustainable agro-food systems. As an illustration for agriculture, we recalculated the global maize production by Mueller et al. (2012)[52] using our generic response curve. This reduced the global maize yield by about 120 Mton (20%) for the same global amount of N fertilizer use. This implies that the LT N fertilizer needed to achieve a target maize yield (here for year 2000) is higher by 6 Mton N (40%) than based on ST response. This indicates that current global maize production relies on unsustainable net soil N depletion (Supplementary Note 12). As an illustration for society, we find that the inclusion of external costs of N fertilizer use in intensive, high income countries, reduces optimum N rates for cereals by almost 25%, as compared to current optimum rates for farm economy. Using our generic response function, the N rate that safeguards robust farm returns, regional food sufficiency and more acceptable N pollution levels varies strongly across the world. “Too little” regions need more N fertilizer to jumpstart crop yields and replenish N depleted soils, whereas “too much” regions with high GDP need to reduce N fertilizer input[3,48]. Policies to implement *SONR* globally will both reduce and redistribute global use of synthetic N and may have important consequences for the current food system, e.g. changes of land use (and land prices and rent), choice of cultivars and rotations to increase *NUE*, and possibly higher food prices and farm gate prices to compensate for lower yields per hectare. The route towards *SONR* needs to be evaluated against other options to reconcile N pollution and food sufficiency, both regarding farm N management (not only N rate but also precision N timing and placement and use of fertilizer products with higher N efficiency) and N policies (e.g. N regulation versus N taxation). Our long-term non-linear response of yields to changed input of synthetic fertilizer could be incorporated in Computable General Equilibrium models (CGE), to improve projection on how markets respond to changes in fertilizer regimes or policies. Our calculation of external cost of N pollution could be used to define N pollution taxes as part of policies to offset the regressive distributional effects of internalizing external effects. Implementation of more inclusive N policies that account for environmental costs comes with the risk of increased land demand and will change spatial allocation of cereal production and regional import/export of cereals (for example in Europe[53]). These risks can be mitigated by additional policies to reduce food waste and change food choices[54] to prevent export of N polluting agricultural activities from high to low GDP countries[44]. Dealing with N problems in global agriculture requires a holistic nitrogen[55] and food system approach balancing risks and opportunities for changes in land use and resource security for agriculture, rural livelihoods and dietary choice[56].

Data availability

Summaries of N response data for Broadbalk Winter wheat trials at Rothamsted Research and for global cereals are provided in Supporting Information, details are available upon reasonable request. Selections of original observations for Broadbalk are available via the electronic Rothamsted Archive (http://www.era.rothamsted.ac.uk/).

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Author contributions

HJMG was the initiator and together with HFMB, RH and NDM developed the concept and were lead authors; MG provided and assisted the use and interpretation of the Rothamsted database; RH and HFMB provided and analyzed the LT trial data for SSA and Europe. Others contributed to analysis and manuscript, PE notably data and validation for Africa, BG and SL for China and Asia, FP for Latin America; LL,NM for the *NUE* and *Ymax* analysis, TWB and BHJ for the economic analysis.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper.

Methods

Broadbalk wheat trials at Rothamsted Research

We used results from the Rothamsted experimental site to construct LT N response curves for winter wheat in rotation and continuous wheat[20]. Results apply to trials at the Broadbalk site for the period 1985-2018, where only mineral fertilizer was used and P, K and Mg and pesticides were adequately supplied. Mineral N application levels were 0, 48, 96, 144, 192, 240 and 288 kgN/ha. P fertilizer rates were 0 and 35 kgP/ha, and K rate fixed at 90 kgK/ha. At low N levels, grain yields for 35 kgP/ha were somewhat higher but not significant (CI 95%; Supplementary Fig. 2). Therefore, results for 0 and 35 kgP/ha were pooled for the analysis of N response. The zero fertilization plots further offer insight into effects of changing air pollution and climate on crop yield over the past one and a half century. Interestingly, the yields of winter wheat in the zero fertilizer plots varied considerably over the past 150 years, between 0.5 and 1.5 t/ha but, showed no net increase or decrease. However, yields of optimally fertilized plots in crop rotation showed a yield increase by a factor of five for winter wheat.

Wheat varieties used were Brimstone (1985-1990), Apollo (1991-1995), Hereward (1996-2012), Crusoe (2013-2018) data for 2015 was excluded from the analysis as spring wheat was sown that year, due to very wet autumn weather conditions preventing the usual sowing of winter wheat. For wheat in rotation preceding crops were mostly potato or forage maize.

Data for ST N response of winter wheat in rotation are based on 15 trials for commercial crops in different parts of England representative of the main arable areas In 1994 to 1998[25]. Mineral N application levels were 0, 80, 120, 160, 2000, 240 and 280 kgN/ha and in the same range as in the Broadbalk experiment (and without explicit information on the rotation).

Long-term field trials

The distinction between short-term and long-term is to some extent arbitrary. Most relevant is that soil N should be sufficiently close to steady state that yield response to change of fertilizer input can be quantified, which could also be formulated as that response curves have adequate curvature to determine *SN* and *Ymax*. For Europe we used 11 LTEs for winter wheat and two for barley[57]. We used 8 LTEs for wheat in South Asia and found two for China. For maize we found three LTEs for the USA (Supplementary Note 4), and two for China. This added up to a total of 27 LTEs (see Supplementary Note 1). The 27 LTEs cover a wide range of soils, climates, cultivars, fertilizer types and management regimes. In all trials, other nutrients were not deficient. Two of the 27 trials were discarded, a wheat trial in Bologna (Italy with SN 103 kgN/ha) and one in Punjab (Pakistan, with SN 389 kgN/ha). We considered SN values exceeding 100 kgN/ha as an indication that soil N was too far from steady state.

Soil types were mostly loam and clay soils. Climate: temperate (mean annual 9 ^{o}C; annual precipitation 700 mm), continental (mean monthly minimum -10 ^{o}C, maximum 30 ^{o}C; precipitation 450-800 mm) and tropical (annual precipitation 1500-1800 mm, Maximum temp 35-45 ^{o}C, minimum 7-14 ^{o}C). Fertilizer types in Europe and USA were mostly ammonium nitrate, in Asia mostly urea, with sometimes part of N fertilization from diammonium phosphate. Fertilizers are applied with one to three dressings, but the number of dressings probably had little effect on N response[58].

Experiment	Region	Crop	Type	Start and used Period	Key Reference
Winter wheat					
Broadbalk	United Kingdom	In rotation and continuous	Field, 7 N rates	1843; 1985-2018	Johnston et al., 2018
Müncheberg	Germany	In rotation	Field, 5 N rates	1962; 1984-2002	Hijbeek et al., 2017
Limburgerhof	Germany	In rotation	Field, 5 N rates	1987; 1987-1994	Lang et al., 1995
Oldenburg	Germany	In rotation	Field, 5 N rates	1984; 1985-1993	Klasink and Steffens 1995
Rauischholzhausen	Germany	In rotation	Field, 5 N rates	1984	Von Boguslawski 1995
Speyer	Germany	In rotation	Field, 5 N rates	1984; 1994-1999	Bischoff 1995
Spröda	Germany	In rotation	Field, 5 N rates	1966; 1999-2010	Albert and Grunert 2013; Körschens et al. 2014
Grabow	Poland	In rotation	Field, 4 N rates	1980-current	Rutkowska and Skowron, 2020
India, Pakistan, Bangladesh	South Asia		Nine sites, 16 field trials	1982-2008	Jat et al., 2014
Laiyang, Shandong	China	Maize - wheat rotation	Field, 3 N rates	1978-2013	Personal communication Gu
Winter barley					
Oldenburg	Germany	In rotation	Field, 5 N rates	1984; 1985-1993	Klasink and Steffens 1995
Speyer	Germany	In rotation	Field, 5 N rates	1984; 1994-1999	Bischoff 1995
Maize					
Wisconsin	USA	In rotation and continuous	Field, 4 N rates, 28 rotations, 2 replicates	1968; 1990-2004	Stanger et al., 2006
Kansas	USA	Irrigated continuous	Field, 6N rates	1961; 1997-2006	Schlegel et al., 2017
Iowa	USA	Maize-Soybean	Field + Model, 7 N rates	1996-2005	Thorp et al., 2007
Changping	China	Irrigated continuous	Field, 3 N rates	1984, 2011-2012	Wen et al., 2016
Laiyang, Shandong	China	Maize wheat rotation	Field, 3 N rates	1978-2013	Personal communication
Lossa, Konni	Niger	Maize, millet, sorghum,	Field, 5 N rates, not a LTE	1997-1998	Pandey et al., 2001
Chikwawa	Malawi	Irrigated maize-rice two crop system	Field, 4 N rates, not a LTE	2007	Fandika et al., 2008
Sub Saharan Africa	Nine countries	Continuous	Model supported by field data,	Used for validation	Ten Berge et al., 2019
Rice-wheat double cropping systems					
Parwanipur	Nepal	Irrigated	Field, 4 N rates	1980-2000	Gami et al., 2001
Bhairahawa	Nepal	Irrigated	Field, 3 N rates	1978-2013	Rawal et al., 2017
Ludhiana, Punjab	India	Irrigated	Field, 4 N rates	1984-1997	Bhandari et al., 2002
Bidhan, West Bengal	India	Irrigated	Field, 2 N rates	1986-2004	Majumbar et al., 2008

Table 1 Overview of characteristics of used LT N trials *(for details, full references and data see Supplementary Table SI 1 and 2)*

Scaling procedure for N response

Experimental N response data were scaled and fitted by 2^{nd} order polynomials, assuming scaled observations for multiple sites were uncorrelated. For scaling two transformations were applied,

1. Y-axis: Transformation of observed absolute site yield to yield index by dividing by *Ymax*. The Y index ranges from 0 to 1.
2. X-axis: Transformation of rate of added N in mineral fertilizer to total N input rate, including N inputs from N deposition, biological nitrogen fixation and net soil N mineralization. The sum of N inputs from these other N sources was approximated by the X intercept of the 2^{nd} order polynomial fit (Supplementary Fig. SI 3).

The assumption that the 119 scaled observations for the 25 LTEs are uncorrelated while in fact being stratified was tested by comparing the fitted 2^{nd} order polynomial on the total dataset (Eq. 2) to the 25 fitted polynomials for the individual sites. Eq. 2 proved to be identical to the median regression line, after sorting the 25 regressions by Yr for Nav = 100 kgN/ha.

N use efficiency, N loss for wheat at Broadbalk

While N fertilizer input generally is the main driver for increasing cereal yields, over fertilization and poor timing and placement of fertilizer is a major cause of N pollution[48,59]. Data on N content in grain and straw was only available for Broadbalk and not for the 25 global LTEs. The *NUE* in Broadbalk is expected to be higher than for most global practices in view of better management and assumed near steady state. The N content in grain for wheat in rotation at Broadbalk is about 1.5% up to a total N input of 100 kgN/ha, increasing linearly up to 300 kgN/ha (Supplementary Note 9). A linear model of N% with *Ymax* and *Nav* was fitted to observations between 1985 and 2016, in which *Ymax* for a given year varied between 6.5 and 12.9 t/ha.

$$N\% = 1.873 + 3.26E\text{-}3 \times Nav - 6.20E\text{-}2 \times Ymax \qquad (R^2 = 0.743,\ N{=}224,\ \text{Eq. 4})$$

With N% the N percentage in grain. The N dilution effect with increasing *Ymax* and the N enrichment with *Nav* are both highly significant (>99.9%) and relevant, but the statistical significance of the effect of *Nav* (T value 24.5) is larger than of *Ymax* (T value -5.6). In view of the LT nature of Broadbalk trials and application of N rate scaling, Eq. 4 has global applicability for wheat cultivation. While grain yields level off with N input, the LT N removal in grain increases from a zero intercept almost proportionally with N input up to 250 kgN/ha, which is in line with previous findings for arable systems at country scale[59] (Supplementary Fig. 22b). N surpluses and the subsequent risk of nitrate leaching start at a total N availability of 180 kgN/ha, which for Broadbalk corresponds to a N fertilizer rate of 150 kgN/ha (Supplementary Fig. 22c). Mean *NUE* for the 32 years of observation increase from 40% at 50 kgN/ha to at peak at about 80% at a total N availability of 150 kgN/ha and gradually decrease again to 60%. A *Nav* of 150 kgN/ha at Broadbalk corresponds to a N fertilizer rate of 120 kg N/ha (Supplementary Fig. 22d). The observed initial increase of NUE may be caused by increased tillering and root development with addition of N fertilizer, promoting efficient uptake of available N and internal N allocation (sink strength governed by tiller and grain numbers).

Calculation procedure of optimal N rates

In this paper we combine approaches from microeconomics (production economics, the individual optimizing agent), environmental economics (price on externalities) and macroeconomics (regional to global agriculture, society, welfare). Our basic macroeconomic analysis considers differences in prices and costs around the world, but does not account for multiple interacting markets and their effects on cereal prices when cereal supply changes. We calculate two economic optima for N application: for cereal farming and for society. In both cases, the optima depend on the slope of the N response curves (Supplementary Fig. 23-24). The net benefit function B is:

$$B = Y \times Py - Nrate \times PN - Cfixed - CNpollut \qquad \text{(Eq. 5)}$$

Where *Py is the* crop price (USD/kg), *PN* fertilizer price (USD/kgN), *Cfixed* the cost of seed, tillage, harvest and other inputs and *CNpollut* the external cost of N pollution. For farming, *CNpollut* is not considered. By considering prices for both farming and welfare, Eq. 5 combines production economics and environmental economics as it addresses both producers and consumers. How both agents will respond to these prices to maximize their utility will depend on policy context. The negative externalities can be implemented as a tax on nitrogen and in that case the two optimal N-applications would be the same. Alternative communication of N issues and design of N policies can make farmers beneficiaries of reduced N pollution and consumers virtual payers of improved N fertilizer management (e.g. by food labelling and N foot-printing http://www.n-print.org/).

The economic optimum for farming can be determined from the following equation:

$$dY/dNav \times Py - PN = 0 \qquad \text{(Eq. 6)}$$

Where *dY/dNav* is the first derivative of the unscaled N response function as derived from Eq. 1 or Eq. 2, using case specific values of *Ymax* and *SN*. For the calculation of the optimum N rates the quadratic global relation between cereal yield and *Nav* (Eq. 2) is substituted in Eq. 6. The minimum value of *Nav* is calculated by solving Eq. 5. For B = 0. This minimum N rate depends strongly on *Cfixed*; *Cfixed* increases per unit of yield with decreasing yield and provides the penalty for farmers when decreasing N input too much. The resulting equation for B can also be expressed as a 2nd order polynomial of N rate, and optima and cross points simply follow from standard calculus for solution of quadratic functions.

The calculation of the optimum N rate for society also accounts for the increase of N pollution with increasing N input:

$$dY/dNav \times Py - PN - dPfixed/dNav - dPNpollut_i/dNav = 0 \qquad \text{(Eq. 7)}$$

*P*y is not the farm gate price of cereals per se, but the price equivalent as paid by those who are bearing the cost of N pollution. This virtual “food plate” price of rough grain could be higher than the farm gate price and accounts for value creation in food processing after correction for assignable costs (e.g. labor and energy for milling and baking) and reflects cost of shareholder dividend, risk insurances or market imperfections in the cereal supply chain. As this price is uncertain, we solved Eq. 7 for *Py* equal to the farm gate price and three times this value. A ratio of three is consistent with the relative increase of gross added value of all agricultural commodities in food processing in the EU (ratio of 2) and the US (ratio of 3). A ratio of three is also consistent with a ratio of 1.2-2.6 based on the farm gate price of bread wheat in Northwest Europe (0.25 USD/kg) and in bread (0.3-0.6 USD/kg) for details see Supplementary Note 13. To include the cost of the various impacts of N pollution ($Npollut_i$ where subscript *i* refers to various N pollutants e.g. NO_3, NH_3, N_2O) can be expressed in monetary units by multiplying the pollutant flux by their respective unit damage costs (USD/kgN)[11]. Pollutant fluxes are estimated as fractions of N inputs or N fluxes. Here we approximated *Npollut* by N surplus and a lumped unit damage cost per kg N surplus (Supporting note 10). N surplus was calculated as:

$$Nsurplus = Nav - Nremoval \qquad \text{(Eq. 8)}$$

Where *Nremoval* is N removal by the crop calculated as: Y *x N%/100* (with N% according to Eq. 4). The resulting relations between *B* and *Nav* can be expressed as 3rd order polynomials and optima and cross points were determined using the SOLVER function in Excel.

For calculation of optima and safe ranges of *Ymax* and *Nav* we used a ceteris paribus approach, and did not take into account consequential effects of changes in cereal production on *Py* or *Cfixed,* the latter for example by effects on land prices and rent. This would require application of CGEs to model global supply, demand and trade of cereals and, involving many assumptions for example regarding changes in relative use of cereals for food, feed and fuel. Our simple economic approach is to demonstrate the effect of using long-term instead of short-term response curves and consideration of the social cost of N surplus and the safe operating range of *Nav*.

Calculation of cost of N pollution and optimal N rates for countries

The current N rate for wheat on sandy to loamy soil in the Netherlands is 165 kgN/ha and 60% of N is applied as manure[60]. For the calculation of total allowable N rate, 1 kg of manure N has a Fertilizer Equivalence of 60% of 1 kgN applied as Calcium Ammonium Nitrate (CAN), and manure N input for arable systems is limited to 170 kgN/ha[60]. Current Dutch environmental legislation limits the total, fertilizer equivalent N rate from synthetic fertilizer and manure for winter wheat to 165 kgN/ha for sandy soils and 190 kgN/ha for loess. These rates are economically suboptimal for farming, irrespective of the use of ST or LT curves. However, winter wheat is grown in rotation which provides residual soil N for the following wheat crop. For fixed cost of (contracted) labor for planting, tillage, crop management and harvest for wheat cultivation in the Netherlands we used a value of 680 USD/ha/yr and for other inputs like P, K, pesticides and energy 430 USD/ha/yr (Supplementary note 10).

For quantification of the cost of N pollution for other countries we used a *GDP* dependent cost per unit of N surplus (*UC*), derived from results for 27 EU countries[3,44](Supplementary Note 11):

$$UC = 0.3412 \times GDP^{1.0362} \qquad (R^2 = 0.6673;\ \text{Eq. 9})$$

In the EU27 dataset mean national *GDP* between 2010-2014 ranged from 7 kUSD/cap in Bulgaria to 59 kUSD/cap in Denmark (excluding 108 kUSD/cap in the very small Luxembourg), N surplus in 2008 between 23 kg/ha of used agricultural land in Romania and 176 kgN/ha in the Netherlands, and the UC ranged from 2 (Bulgaria) to 43 USD/kgN (Denmark). The *GDP* effect reflects increasing willingness to pay to prevent N pollution, making *GDP* a major determinant for external costs of N-pollution of waters in Europe[13], but less so for the USA and the rest of the world[61].

In the Netherlands and many areas with intensive use of manure or urea fertilizer ammonia losses are mainly associated with manure and impacts of ammonia containing aerosols on human health dominate N pollution cost[3,44]. Globally, ammonia losses depend on the choice between ammonia (often urea) or nitrate type fertilizer (often CAN), the use of manure, and the application of low emission techniques. All these factors will change considerably in the near future due to improved management to increase cost-efficiency and by environmental regulation.

References

1 Bodirsky, B. L. *et al.* Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nature communications* **5**, 1-7 (2014).

2 Chen, X. *et al.* Producing more grain with lower environmental costs. *Nature* **514**, 486-489, doi:10.1038/nature13609 (2014).

3 Sutton M.A. *et al.* Our nutrient world. The challenge to produce more food & energy with less pollution. 114 (Centre for Ecology and Hydrology (CEH), Edinburgh UK,, 2013).

4 Steffen, W. *et al.* Planetary boundaries: Guiding human development on a changing planet. *Science* **347** (2015).

5 Sutton, M. A., Howard, C.M., Kanter, D.R., Lassaletta, L., Móring, A., Raghuram, N., Read, N. The nitrogen decade: mobilizing global action on nitrogen to 2030 and beyond. *One Earth* **4**, 10-14 (2021).

6 Foley, J. A. *et al.* Solutions for a cultivated planet. *Nature* **478**, 337-342, doi:10.1038/nature10452 (2011).

7 Sutton, M. A. *et al.* Too much of a good thing. *Nature* **472**, 159-161 (2011).

8 Oenema, O. *et al.* Nitrogen Use Efficiency (NUE) - an indicator for the utilization of nitrogen in agriculture and food systems. 48 (2015).

9 Angus, J. F. & Grace, P. R. Nitrogen balance in Australia and nitrogen use efficiency on Australian farms. *Soil Research* **55**, doi:10.1071/sr16325 (2017).

10 ten Berge, H. F. M. *et al.* Maize crop nutrient input requirements for food security in sub-Saharan Africa. *Global Food Security* **23**, 9-21, doi:10.1016/j.gfs.2019.02.001 (2019).

11 Clegg, M. D. & Francis, C. A. in *Sustainable agricultural systems* (eds Hatfield J.L. & Karlen D.L.) (CRC Press 1994).

12 Pannell, D. J. Economic perspectives on nitrogen in farming systems: managing trade-offs between production, risk and the environment. *Soil Research* **55**, 473-478 (2017).

13 Van Grinsven, H. J. M. *et al.* Costs and benefits of nitrogen for Europe and implications for mitigation. *Environ Sci Technol* **47**, 3571-3579, doi:10.1021/es303804g (2013).

14 Kandulu, J., Thorburn, P., Biggs, J. & Verburg, K. Estimating economic and environmental trade-offs of managing nitrogen in Australian sugarcane systems taking agronomic risk into account. *J Environ Manage* **223**, 264-274, doi:10.1016/j.jenvman.2018.06.023 (2018).

15 Körschens, M. *et al.* Effect of mineral and organic fertilization on crop yield, nitrogen uptake, carbon and nitrogen balances, as well as soil organic carbon content and dynamics: results from 20 European long-term field experiments of the twenty-first century. *Archives of Agronomy and Soil Science* **59**, 1017-1040, doi:10.1080/03650340.2012.704548 (2013).

16 Wei, W. *et al.* Effects of combined application of organic amendments and fertilizers on crop yield and soil organic matter: An integrated analysis of long-term experiments. *Agriculture, Ecosystems & Environment* **225**, 86-92, doi:10.1016/j.agee.2016.04.004 (2016).

17 Sandén, T. *et al.* European long-term field experiments: knowledge gained about alternative management practices. *Soil Use and Management* **34**, 167-176, doi:10.1111/sum.12421 (2018).

18 Bationo, A. *et al.* in *Lessons learned from Long-term Soil Fertility Management Experiments in Africa* Ch. Chapter 1, 1-26 (2012).

19 FAOstat. <http://www.fao.org/faostat/en/#data> (

20 Johnston, A. E. & Poulton, P. R. The importance of long-term experiments in agriculture: their management to ensure continued crop production and soil fertility; the Rothamsted experience. *Eur J Soil Sci* **69**, 113-125, doi:10.1111/ejss.12521 (2018).

21 Glendining, M. J. *et al.* The effects of long-term applications of inorganic nitrogen fertilizer on soil nitrogen in the Broadbalk Wheat Experiment. *The Journal of Agricultural Science* **127**, 347-363 (1996).

22 Ladha, J. K., Reddy, C. K., Padre, A. T. & van Kessel, C. Role of nitrogen fertilization in sustaining organic matter in cultivated soils. *J Environ Qual* **40**, 1756-1766, doi:10.2134/jeq2011.0064 (2011).

23 van Grinsven, H. J. M. *et al.* Losses of Ammonia and Nitrate from Agriculture and Their Effect on Nitrogen Recovery in the European Union and the United States between 1900 and 2050. *J Environ Qual* **44**, 356-367, doi:10.2134/jeq2014.03.0102 (2015).

24 van Grinsven, H. J. M. *et al.* Management, regulation and environmental impacts of nitrogen fertilization in northwestern Europe under the Nitrates Directive; a benchmark study. *Biogeosciences* **9**, 5143-5160, doi:10.5194/bg-9-5143-2012 (2012).

25 Richards, I. R. Energy balances in the growth of oilseed rape for biodiesel and of wheat for bioethanol. 38 (Levington Agriculture Ltd. Levington Park lPSWlCH Suffolk IP10 2000).

26 Bouwman, L. *et al.* Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period. *Proc Natl Acad Sci U S A* **110**, 20882-20887, doi:10.1073/pnas.1012878108 (2013).

27 Schlegel, A. J. & Havlin, J. L. Corn Yield and Grain Nutrient Uptake from 50 Years of Nitrogen and Phosphorus Fertilization. *Agronomy Journal* **109**, 335-342, doi:10.2134/agronj2016.05.0294 (2017).

28 Greenwood, D. J., Lemaire, G., Gosse, G., Cruz, P., Draycott, A., & Neeteson, J. J. Decline in percentage N of C3 and C4 crops with increasing plant mass. *Annals of botany* **66**, 425-436 (1990).

29 USDA. <http://plants.usda.gov/npk/> (

30 Hütsch, B. W. & Schubert, S. *Advances in Agronomy* 37-82 (2017).

31 Schils, R. *et al.* Cereal yield gaps across Europe. *European Journal of Agronomy* **101**, 109-120, doi:10.1016/j.eja.2018.09.003 (2018).

32 Europe, F. Forecast of food, farming and fertilizer use 2019-2029. VOLUME 2: Country data and national scenarios. (Brussels, 2019).

33 van Ittersum, M. K. *et al.* Yield gap analysis with local to global relevance—A review. *Field Crops Research* **143**, 4-17, doi:10.1016/j.fcr.2012.09.009 (2013).

34 Ladha, J. K. *et al.* Global nitrogen budgets in cereals: A 50-year assessment for maize, rice, and wheat production systems. *Sci Rep* **6**, 19355, doi:10.1038/srep19355 (2016).

35 Fageria, N. K. & Baliga, V. C. Lowland Rice Response To Nitrogen Fertilization. *Communications in Soil Science and Plant Analysis* **32**, 1405-1142 (2001).

36 De Datta, S. K., Samson, M. I., Obcemea, W. N., Real, J. G., & Buresh, R. J. Direct measurement of ammonia and denitrification fluxes from urea applied to rice. . *Soil Science Society of America Journal* **55**, 543-548 (1991).

37 Dobermann, A. R. in *IFA international workshop on enhanced-efficiency fertilizers, Frankfurt, Germany, 28-30 June, 2005.* (International Fertilizer Association (IFA)).

38 Liebscher, G. Untersuchungen über die Bestimmung des Düngerbedürfnisses de Ackerböden und Kulturpflanzen. *J. für Landwirtschaft* **43**, 49 (1895).

39 De Wit, C. T. Resource use efficiency in agriculture. *Agricultural Systems* **40**, 125-151 (1992).

40 Mitscherlich, E. A. *Die Bestimmung des Düngerbedürfnisses der Bodens.*, Vol. 3e Auflage 1930 (Paul Parey, 1924).

41 Cassman, K. G., Dobermann A. Nitrogen and the future of agriculture: 20 years on. *Ambio*, doi:https://doi.org/10.1007/s13280-021-01526-w (2021).

42 Palm, C. A., Giller, K. E., Mafongoya, P. L. & Swift, M. J. Management of organic matter in the tropics: translating theory into practice. *Nutrient Cycling in Agroecosystems* **61**, 63-75, doi:10.1023/a:1013318210809 (2001).

43 Dobermann, A. *et al.* Nitrogen Response and Economics for Irrigated Corn in Nebraska. *Agronomy Journal* **103**, 67-75, doi:10.2134/agronj2010.0179 (2011).

44 Van Grinsven, H. J. M. *et al.* Reducing external costs of nitrogen pollution by relocation of pig production between regions in the European Union. *Regional Environmental Change* **18**, 2403-2415, doi:10.1007/s10113-018-1335-5 (2018).

45 FAO. World fertilizer trends and outlook to 2022. (FAO, Rome, Italy, 2019).

46 Abrol, Y. P. *et al. The Indian nitrogen assessment: Sources of reactive nitrogen, environmental and climate effects, management options, and policies*. (Elsevier, 2017).

47 Kanter, D. R., Zhang, X. & Mauzerall, D. L. Reducing nitrogen pollution while decreasing farmers' costs and increasing fertilizer industry profits. *Journal of environmental quality* **44**, 325-335 (2015).

48 Quemada, M. *et al.* Exploring nitrogen indicators of farm performance among farm types across several European case studies. *Agricultural Systems* **177** (2020).

49 Andreyeva, T., Long, M. W., & Brownell, K. D. . The impact of food prices on consumption: a systematic review of research on the price elasticity of demand for food. . *American Journal of Public Health* **100**, 216-222 (2010).

50 Hijbeek, R. *et al.* Nitrogen fertiliser replacement values for organic amendments appear to increase with N application rates. *Nutrient Cycling in Agroecosystems* **110**, 105-115 (2018).

51 West, G. B., Brown, J. H. & Enquist, B. J. A general model for ontogenetic growth. *Nature* **413**, 628-631 (2001).

52 Mueller, N. D. *et al.* Closing yield gaps through nutrient and water management. *Nature* **490**, 254-257, doi:10.1038/nature11420 (2012).

53 Westhoek, H. *et al.* Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Global Environmental Change* **26**, 196-205, doi:10.1016/j.gloenvcha.2014.02.004 (2014).

54 Barreiro-Hurle, J., Bogonos, M., Himics, M., Hristov, J., Pérez-Domiguez, I., Sahoo, A., Salputra, G., Weiss, F., Baldoni, E., Elleby, C. . Modelling environmental and climate ambition in the agricultural sector with the CAPRI model. Exploring the potential effects of selected Farm to Fork and Biodiversity strategies targets in the framework of the 2030 Climate targets and the post 2020 Common Agricultural Policy. 93 (Joint Reseach Centre, 2021).

55 Sutton, M. *et al.* in *Frontiers 2018/19: Emerging Issues of Environmental Concern* 52-64 (United Nations Environmental Programma, 2019).

56 Hajer, M. A., Westhoek, H., Ingram, J., van Berkum, S. & Ozay, L. *Food systems and natural resources*. (United Nations Environmental Programme., 2016).

57 Hijbeek, R. *et al.* Do organic inputs matter – a meta-analysis of additional yield effects for arable crops in Europe. *Plant and Soil* **411**, 293-303, doi:10.1007/s11104-016-3031-x (2017).

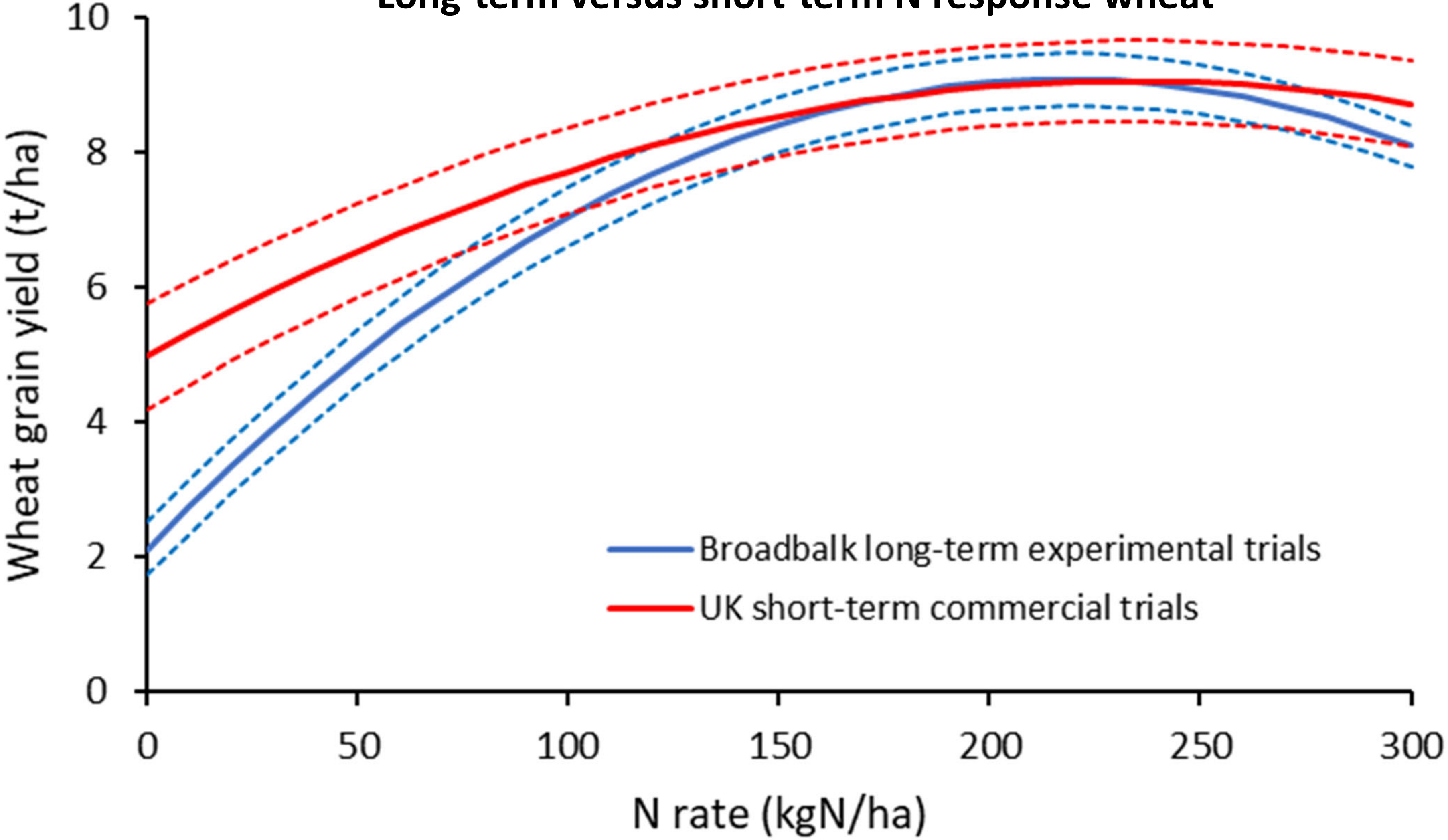
58 MacDonald, A. J. *et al.* Rothamsted Long-term experiments. Guide to the Classical and other Long-term experiments, Datasets and Sample Archive. (Rothamsted Research, Harpenden, Herts, AL5 2JQ, UK, 2018).

59 Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J. & Garnier, J. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environmental Research Letters* **9** (2014).

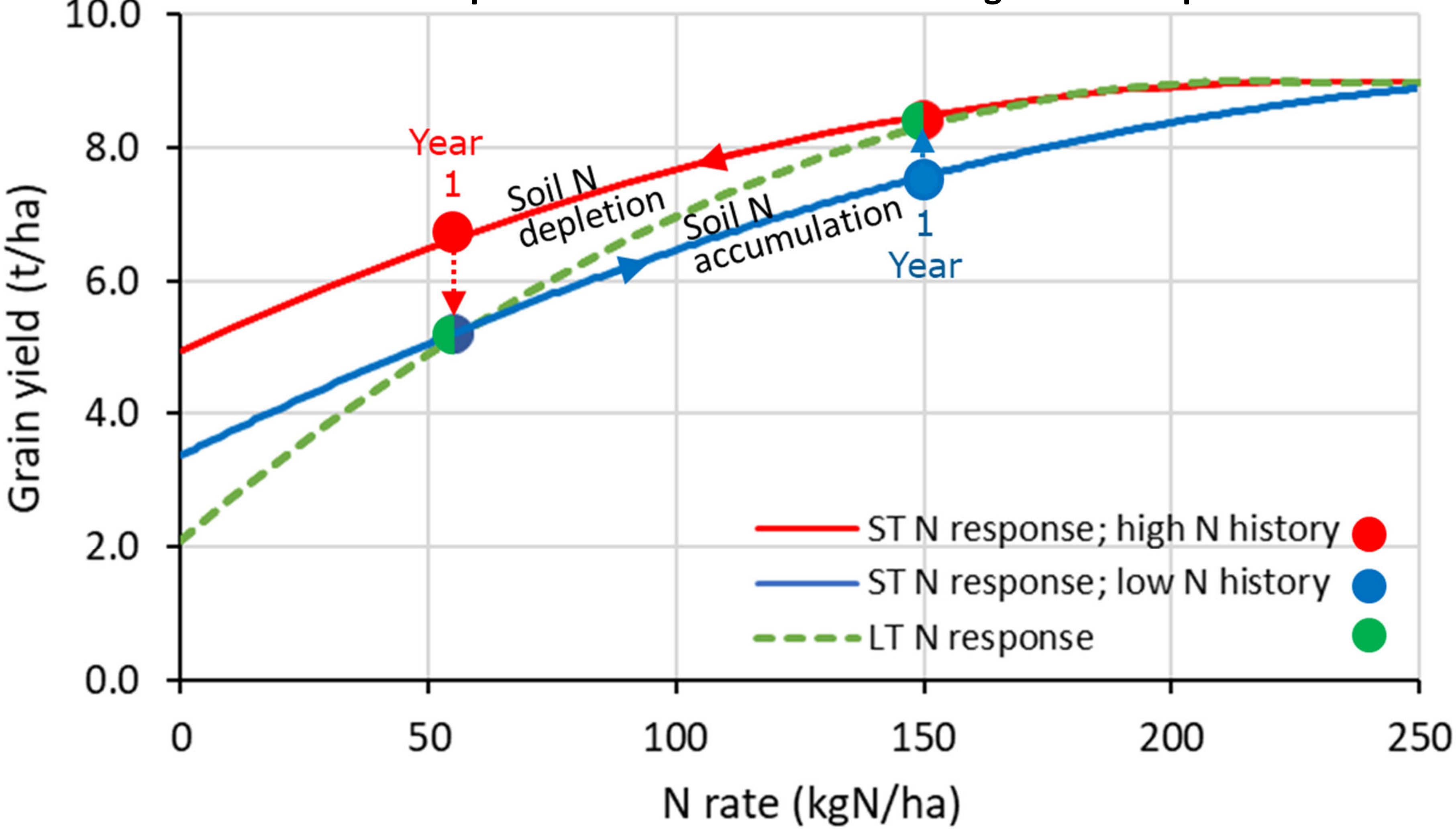
60 Van Grinsven, H. J. M., Tiktak, A. & Rougoor, C. W. Evaluation of the Dutch implementation of the nitrates directive, the water framework directive and the national emission ceilings directive. *NJAS - Wageningen Journal of Life Sciences* **78**, 69-84, doi:10.1016/j.njas.2016.03.010 (2016).

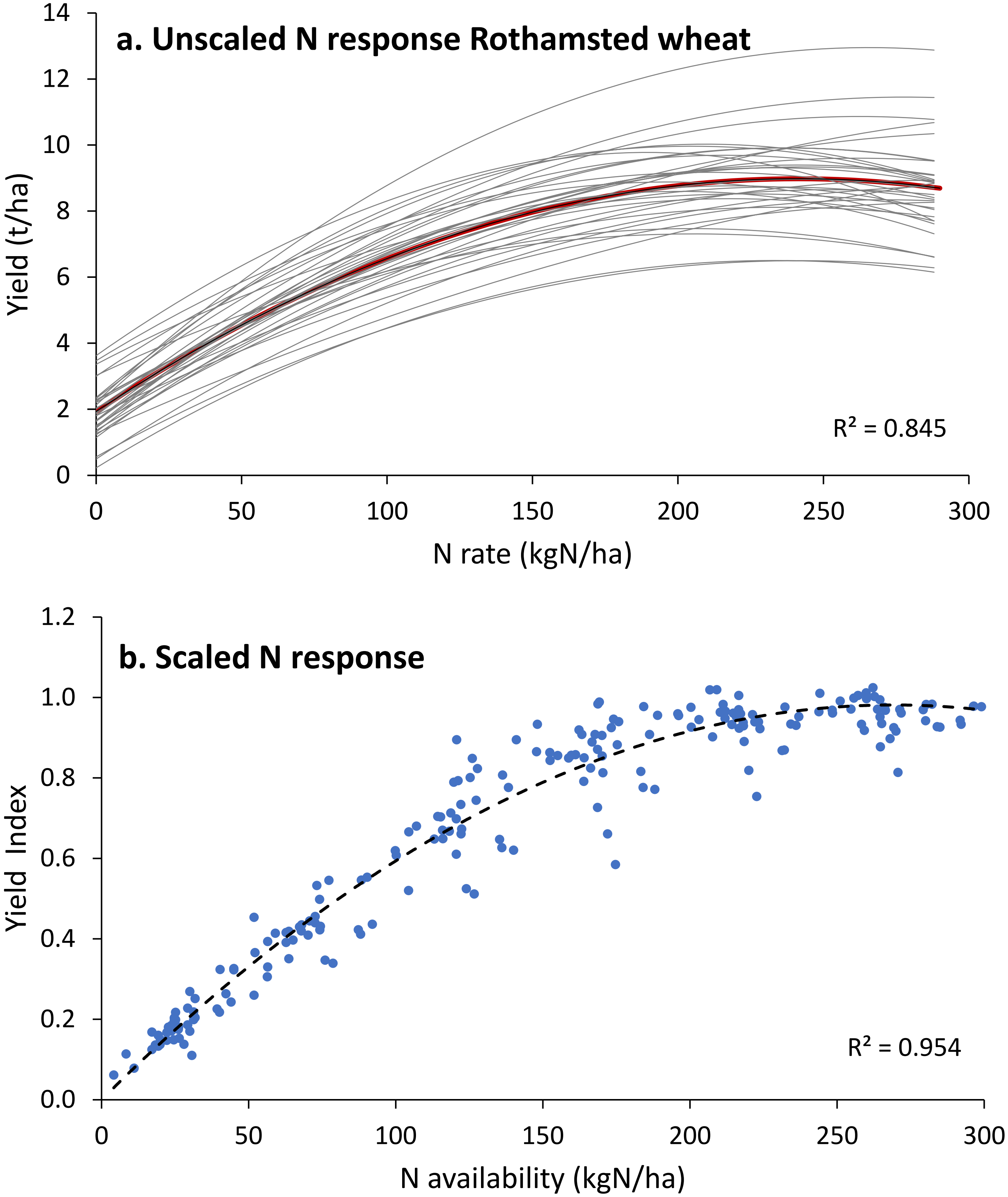
61 Brouwer, R. & Neverre, N. A global meta-analysis of groundwater quality valuation studies. *European Review of Agricultural Economics*, doi:10.1093/erae/jby043 (2018).

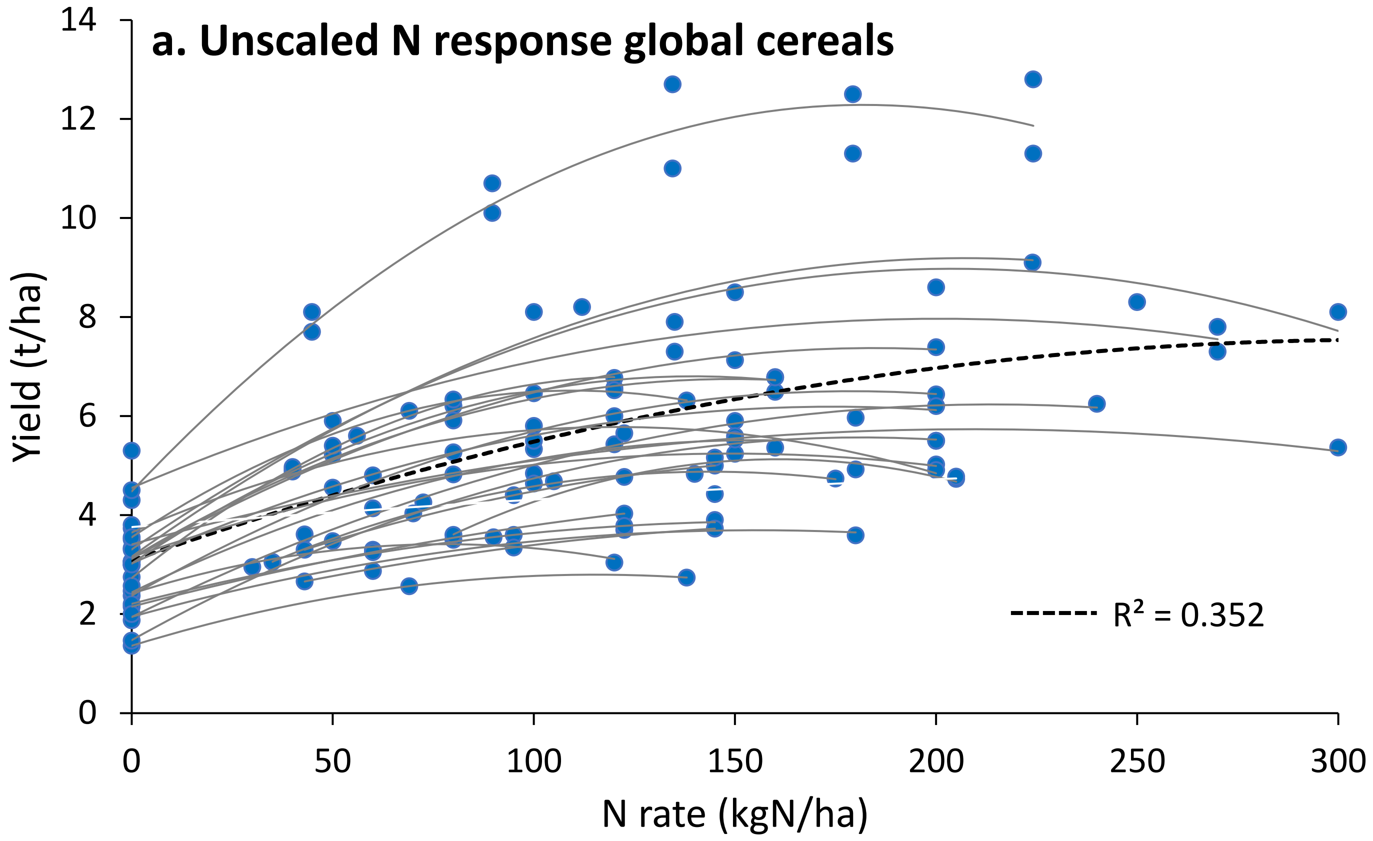
Long-term versus short-term N response wheat

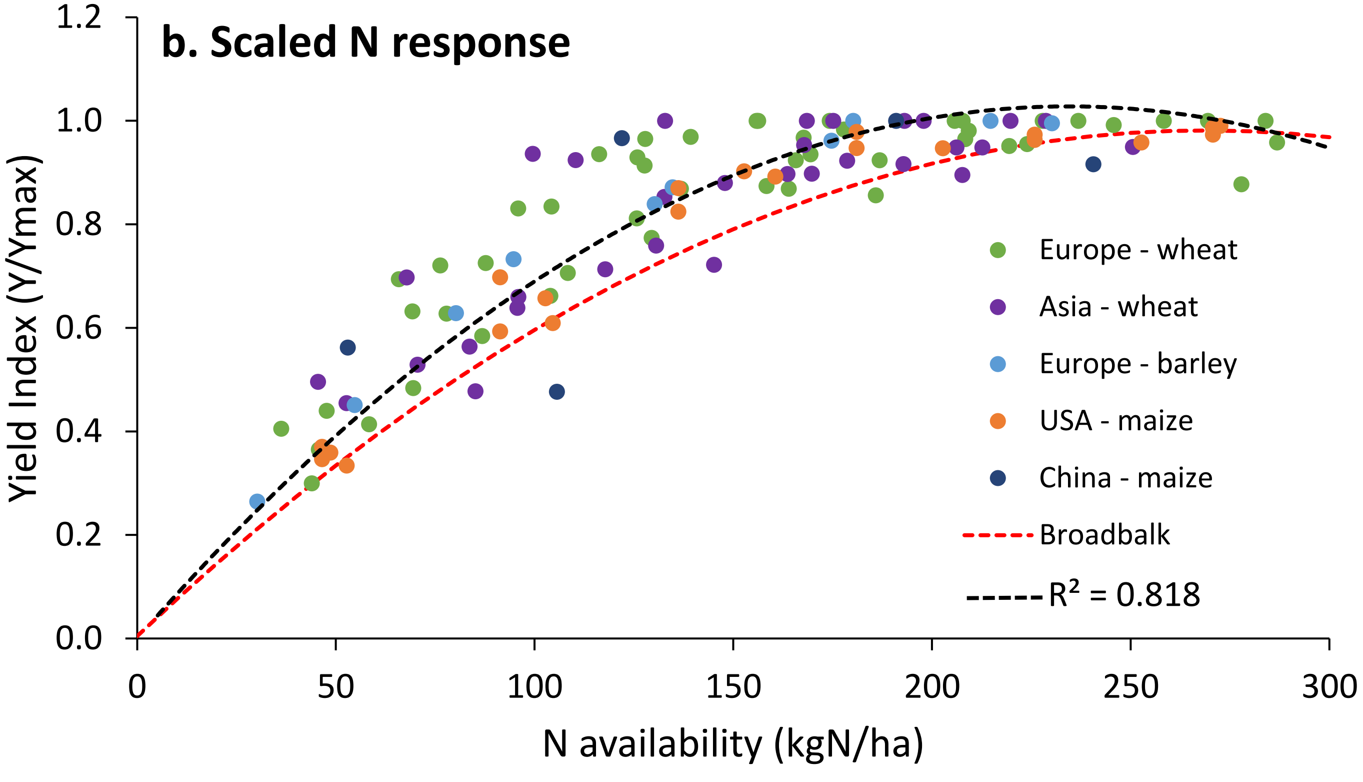


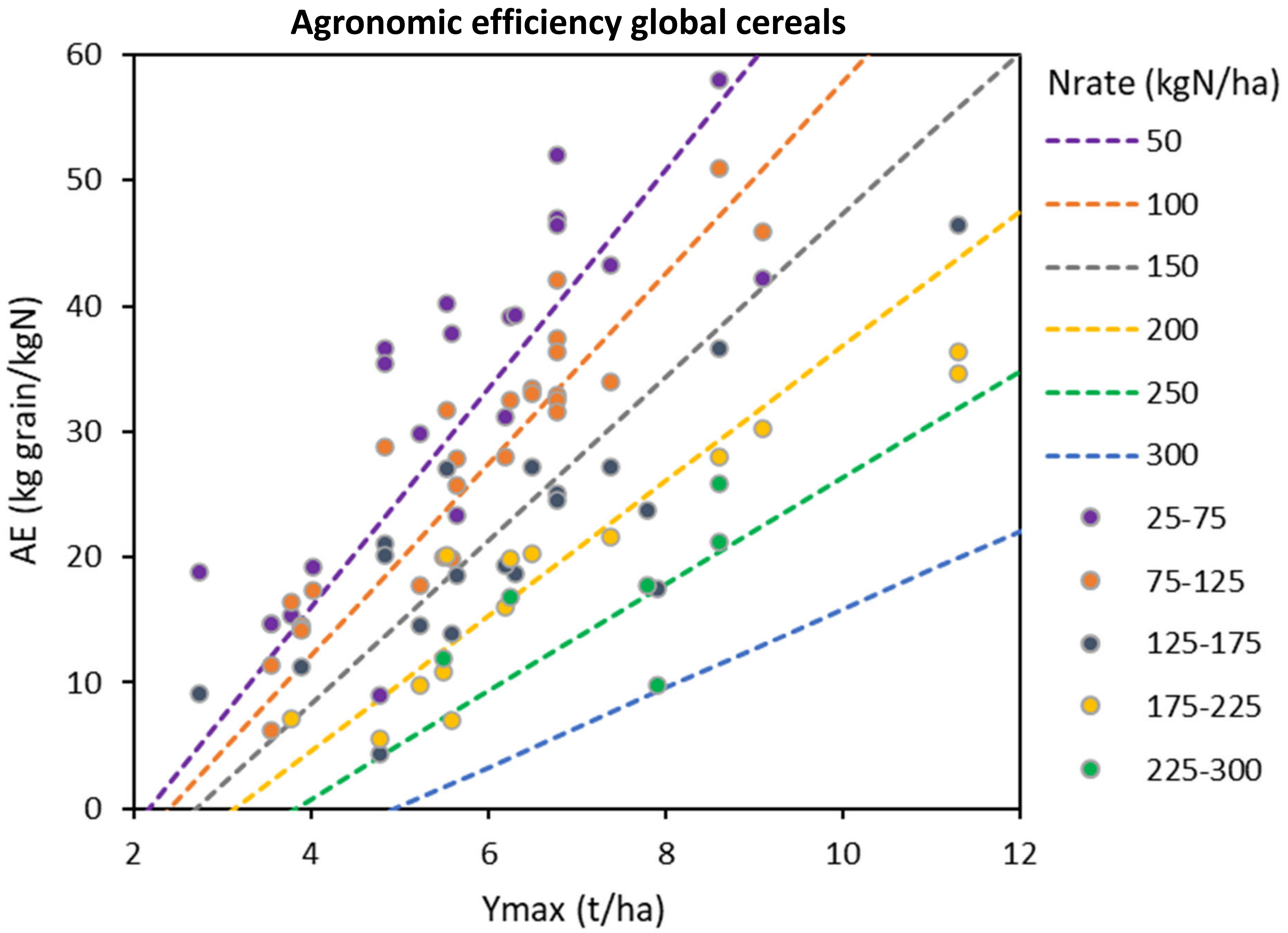
Concept difference short-term and long-term N response

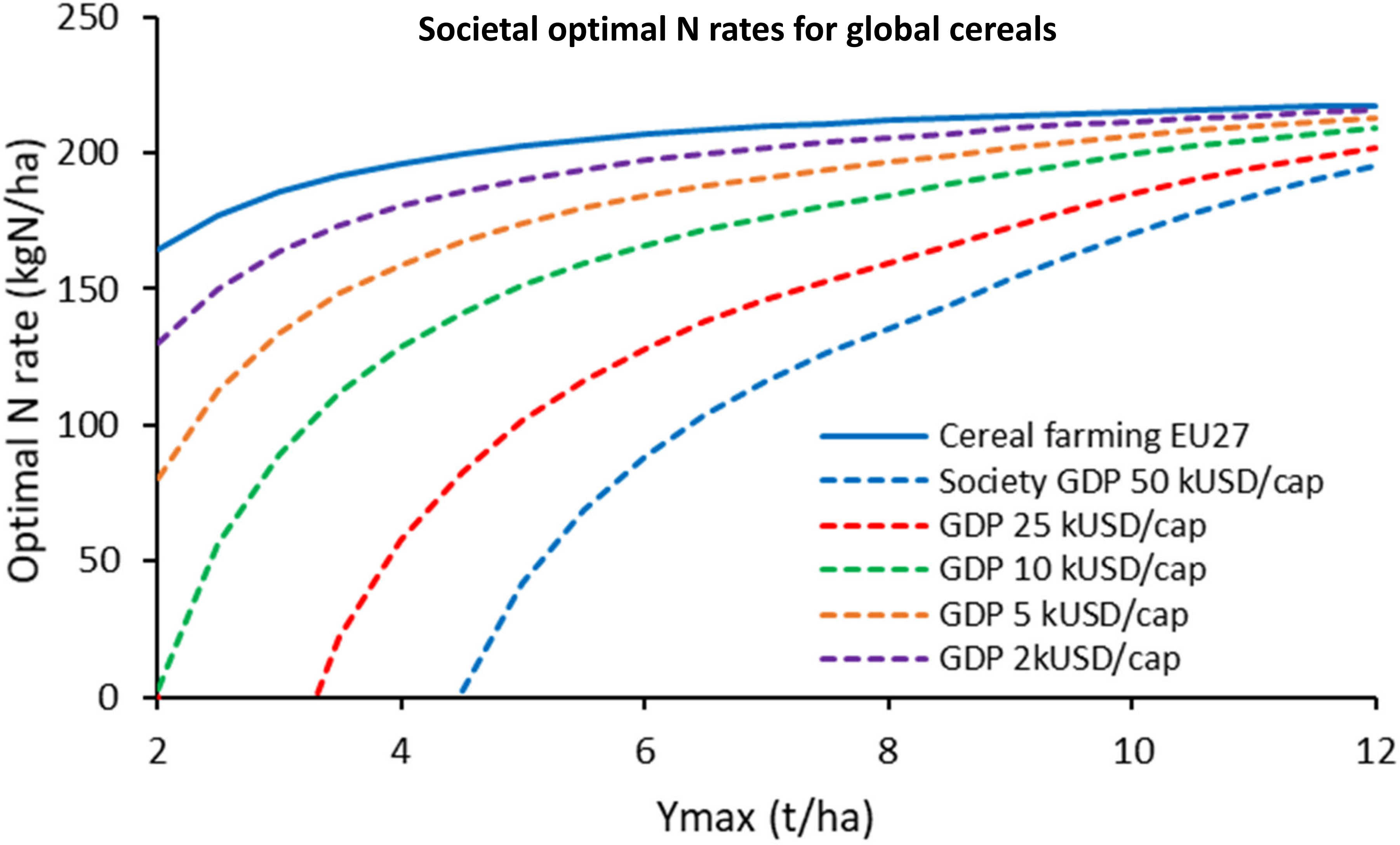


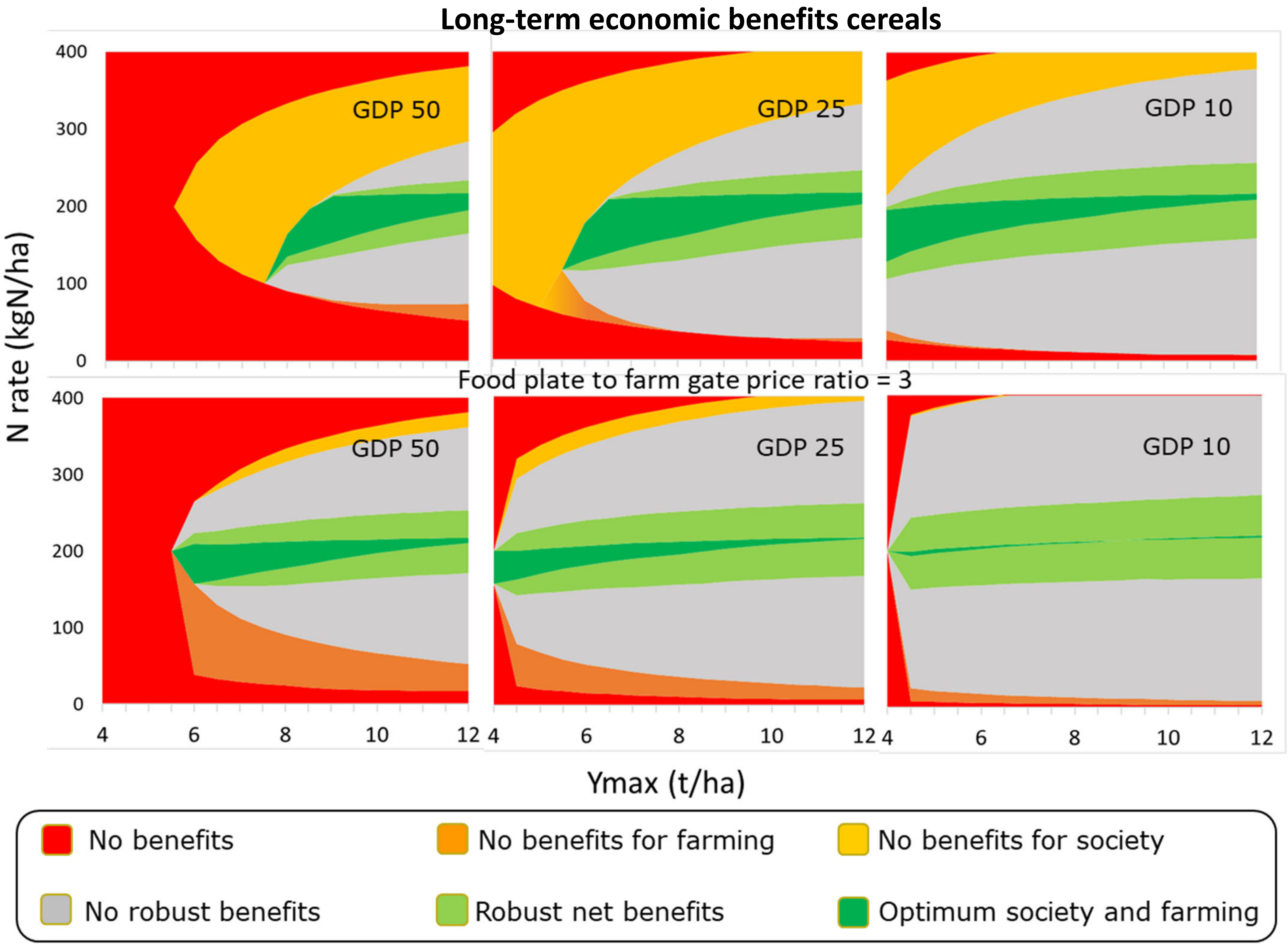

a. Unscaled N response Rothamsted wheat
Yield (t/ha)
14
12
10
8
6
4
2
0
R² = 0.845
0
50
100
150
200
250
300
N rate (kgN/ha)
b. Scaled N response
Yield Index
1.2
1.0
0.8
0.6
0.4
0.2
0.0
R² = 0.954
0
50
100
150
200
250
300
N availability (kgN/ha)


a. Unscaled N response global cereals
Yield (t/ha)
0
2
4
6
8
10
12
14
N rate (kgN/ha)
0
50
100
150
200
250
300
R² = 0.352


b. Scaled N response
Yield Index (Y/Ymax)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
N availability (kgN/ha)
0
50
100
150
200
250
300
Europe - wheat
Asia - wheat
Europe - barley
USA - maize
China - maize
Broadbalk
R² = 0.818


Agronomic efficiency global cereals
AE (kg grain/kgN)
0
10
20
30
40
50
60
Ymax (t/ha)
2
4
6
8
10
12
Nrate (kgN/ha)
50
100
150
200
250
300
25-75
75-125
125-175
175-225
225-300


Societal optimal N rates for global cereals
Optimal N rate (kgN/ha)
250
200
150
100
50
0
2
4
6
8
10
12
Ymax (t/ha)
Cereal farming EU27
Society GDP 50 kUSD/cap
GDP 25 kUSD/cap
GDP 10 kUSD/cap
GDP 5 kUSD/cap
GDP 2kUSD/cap


Long-term economic benefits cereals
N rate (kgN/ha)
400
300
200
100
0
GDP 50
GDP 25
GDP 10
Food plate to farm gate price ratio = 3
400
300
200
100
0
GDP 50
GDP 25
GDP 10
4
6
8
10
12
Ymax (t/ha)
No benefits
No benefits for farming
No benefits for society
No robust benefits
Robust net benefits
Optimum society and farming