Nitrogen fertilisation effects on the quality of selected crops: a review

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Abstract

The effects of nitrogen (N) fertilisation on the quality of selected cereal crops (wheat, barley, maize and oats) and fruit crops (apples, wine grapes and kiwifruit), with special reference to New Zealand, were reviewed. For cereal crops N fertilisation increases grain protein content accompanied by a decrease in the proportion of essential amino acids, such as lysine, leading to lower protein quality, the degree of which is dependent on crop species. However increased N supply generally improves kernel integrity and strength, resulting in better milling properties of the grain. In apples excessive N application leads to softer fruits with high respiration rates, reduced shelf life and red colour development. In red wine grapes low vine N improves wine quality parameters such as sugar, tannin and anthocyanin concentration. Thus, grape quality potential for red wine production becomes better if soil N availability to the vines is limited. On the other hand, in white wine production low N availability to the vines is unfavourable to wine quality as it reduces the wine's aromatic potential. However vine N status should be at least moderate since excessive vine N uptake is undesirable because it promotes leaf crowding and susceptibility to diseases. In kiwifruit high N rates generally reduce fruit firmness and fruit dry matter content. For these fruit crops monitoring and management of plant tissue N concentration and decreasing tree or vine vigour is important to ensure that a compromise between attaining good yield and minimising quality decline is achieved.

Additional keywords: wheat (*Triticum* spp.), barley (*Hordeum vulgare*), maize (*Zea mays*), oats (*Avena sativa*), apples (*Malus pumila*), wine grapes, kiwifruit

Introduction

The ability to produce a quality product is critical for most crop production systems. Consumers of fruits and vegetables are particularly quality conscious where physical appearance determines acceptance for buying or when making a choice on which product is selected. In addition to appearance, factors such as origin (e.g. local, regional, imported) and production methods (conventional versus organic) can be important in a decision to purchase (Benton Jones, 2012). High quality products also contribute to reduced post-harvest losses since they are purchased and consumed by customers and are not thrown away. Nitrogen (N) is essential for plant growth, part of every living cell and a component of all amino acids and chlorophyll. N nutrition not only affects yield but also quality. N also interacts with soil water and other soil nutrients. The purpose of this review is to assess the role and impact of N on crop quality. This review covers the effects of N nutrition on the quality of selected crops of New Zealand, namely: cereals (wheat, barley, maize and oats) and fruit crops (apples, wine grapes and kiwifruit). Selected New Zealand and international literature were consulted and included in this review. It should be noted at the outset that soil biology and chemistry and physiological process like plant nutrient uptake are complex processes and one of the limitations of reviewing only N and its effect on crop quality is that the importance of other elements, as well as nutrient balances and interactions, or the effect varying soil moisture conditions, are not included.

Crop yield and crop quality

Crop yield is a parameter that is easy to measure and understand as it relates to biomass or quantity of produce per unit area. On the other hand crop quality is subjective because it is comprised of several physical and chemical properties, some of which are not easy to quantify. Quality is defined as "any of the features that make something what it is" or the degree of "excellence or superiority". It is used in various ways in reference to food products such as market quality, edible quality, dessert quality, shipping quality, table quality, nutritional quality, internal quality and appearance quality (Maynard and Hochmuth, 2007). Some of the quality attributes not only relate to physico-chemical properties but also the end use of the product (e.g. table grapes vs. wine grapes). Table 1 shows a range of attributes that are used to assess crop quality.

Table 1: Properties determining crop quality (Wiesler *et al.*, 2004).

Physical characteristics	Chemical composition
• Shape • Size • Weight • Colour • Freshness • Ripeness • Texture • Absence of defects	• Vitamins and minerals • Carbohydrates • Nitrogenous compounds • Lipids • Organic acids • Flavours • Bioactive compounds • Anti-nutrients • Pesticide residues

Nitrogen nutrition, crop yield and quality

The major factors controlling crop quality are fixed genetically and physiologically (Mengel and Kirkby, 2001; Wiesler *et al.*, 2012). Thus external factors such as nutrition do not always influence crop quality. Nutritional effects depend on the influence of particular nutrients on biochemical or physiological processes in the plant. For example the concentration of carbohydrates or sugars in storage tissues, grains and seeds relate directly or indirectly to the supply of plants with N (Mengel and Kirkby, 2001).

N is often the most limiting factor in crop production. Thus application of fertiliser N generally results in higher biomass yields. On the other hand crop quality does not always run parallel with increased crop yields resulting from N fertilisation. Figure 1 illustrates three possible scenarios that could happen to crop quality as N supply (or any added nutrient) increases. In curve 1, as N supply increases crop quality goes hand in hand with crop yield (i.e. crop quality runs parallel with the yield curve – synchronous situation). In curve 2 maximum crop quality is achieved earlier before high crop yield is achieved and then progressively declines as N supply increases (asynchronous situation). In curve 3 crop quality increases as N supply increases but its peak level coincides with declining crop yield (asynchronous situation). There may also be situations when N fertilisation does not lead to any improvement or decline in crop quality.

Cereals

In cereal crops it has long been recognised that N application increases grain protein content, especially when soil N levels are increased above that required for maximum grain yield. The effect of N on grain protein content is also dependent on crop variety and other environmental variables especially soil water status. Soil nitrate-N concentration is positively correlated with grain protein content while available soil water is negatively correlated with it. Therefore, in addition to the genetic potential for high grain yield, adequate fertility and moisture are necessary for high yields of high-protein grain crops (Deckard *et al*., 1984). In general the response of grain protein content to N is sigmoidal rather than linear. Initial additions of N have no effect or decrease protein concentration, because yield is increased at a greater rate than N uptake. Thereafter protein content increases linearly with increasing N supply until the optimum for yield is attained. Beyond this point increases in protein concentration become incrementally smaller (Kettlewell, 1996).

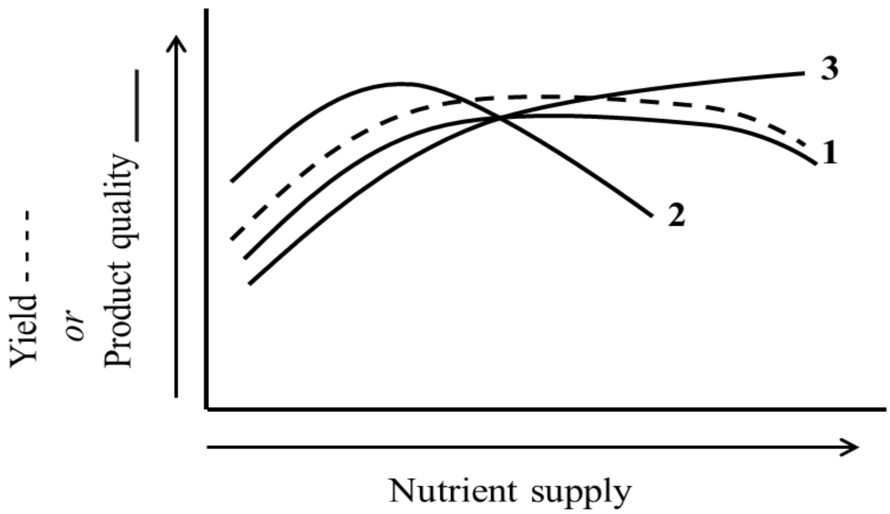

Figure 1: Crop yield (broken line curve) and product quality (solid line curves) either go hand in hand with increasing nutrient supply (curve 1) or not (curves 2 and 3) (Wiesler *et al.*, 2012).

While an abundant N supply increases grain protein content it decreases the relative proportion of the essential amino acids lysine and threonine (Blumenthal *et al.,* 2008; Wiesler *et al.,* 2012) thus reducing the quality of the protein. Essential amino acids are those which cannot be synthesised by humans and animals and therefore need to be supplied externally as part of the diet. Increasing N supply generally improves kernel integrity and strength resulting in better milling properties of the grain (Blumenthal *et al.,* 2008).

Cereal endosperm proteins are classified into four fractions according to their solubility in different solvents. The four fractions are albumin, globulin, prolamin and glutelin. The proportions of the four protein fractions are dependent on the specific cereal species, variety and production environment. For example, the prolamin fraction may account for 50 to 60% of the total protein in maize and sorghum, 35 to 45% in wheat and barley, but only 10 to 15% in oats. Prolamins in maize, wheat, barley and oats are designated as zein, gliadin, hordein and avenin, respectively. The glutelin fraction in wheat is also called glutelin. Each of the four protein fractions has a different amino acid composition. Prolamins have low levels of several essential amino acids especially lysine and high levels of others such as glutamine and proline. Albumins and globulins have considerably less proline and amide-N and more cysteine, glycine and basic amino acids. The amino acid composition of glutelins generally is intermediate between the prolamins and albumins-globulins (Deckard *et al.,* 1984). These protein fractions are affected by N fertilisation in varying degrees as discussed later.

Wheat (*Triticum* spp.)

The composition of amino acids in wheat protein is affected by N fertilisation. The major protein fraction increased by N fertilisation of wheat is the prolamin fraction which contains low levels of essential amino acids especially lysine. Therefore increasing the protein concentration by N fertilisation frequently decreases the nutritional quality of the protein, i.e. the lysine concentration (as a percentage of protein) decreases with increasing protein percentage, even though the concentration of lysine as a percentage of the dry weight increases. This negative relationship between percentage of lysine in the protein and the percentage of protein in the grain is curvilinear since the reduction in lysine percentage is proportionally smaller as the grain protein percentage increases (Deckard *et al.,* 1984; Kettlewell, 1996).

In New Zealand improvements in wheat grain quality with increasing N fertilisation have been reported by several researchers. Sheath and Galletly (1980) studied the effects of sowing time and N applications (0 and 90 kg N/ha) on the grain yield and quality of four wheat cultivars in North Otago. N application at the start of tillering resulted in the improvement of baking scores (as measured by mechanical dough development) regardless of cultivar and location. N application also increased dough strength as measured by work input required for dough development (Watt-hours per kg of dough).

Stephen and Saville (1989) studied the effects of N fertiliser rates (0 to 200 kg N/ha) on grain yield and milling and bread making quality of late autumn-sown wheat in Leeston over two cropping years (dry and wet) and reported that N applied at tillering improved grain yield, flour protein content, dough water absorption, loaf volume, loaf texture and mechanical dough development bake score. However the overall mean rate of response in grain yield to fertiliser N was lower in the drier crop year than in the wetter crop year. On the other hand overall mean rates of response to fertiliser N of all the wheat quality parameters mentioned earlier were higher in the drier cropping year.

Martin *et al.* (1992) studied the effect of N rate (0, 50 and 100 kg N/ha) and timing of N application (tillering and booting stages) on grain yield, milling and baking characteristics and protein content of six wheat cultivars on an N-depleted site in Lincoln, New Zealand. They found that grain yield and mechanical dough development bake score increased with increasing N rate regardless of time of application. N fertilisation also improved flour and bread making quality especially when applied at booting stage. As far as proteins are concerned N application had no significant effect on the level of albumin and globulin proteins. For the gliadin proteins there was a highly significant effect of some N versus no N application, but other N treatments had no significant effect. An extra 50 kg N/ha at booting stage gave significant increases in both high molecular weight and low molecular weight glutenins. Glutenins have been shown affect the visco-elasticity of the dough. They concluded that late application of N is a very effective way of improving grain quality and has the advantage of the N being used more efficiently than applications made at earlier growth stages.

De Ruiter and Martin (2001) investigated the effects of N (0, 150 and 250 kg N/ha) and sulphur (S) (0 and 50 kg S/ha) fertilisation on wheat quality in two cultivars ('Monad' and 'Otane') in Lincoln. They found that the effect on N on wheat quality was independent of the S effect. They reported that, regardless of cultivar, work input required for dough development (Watt-hr/kg) and water absorption (%) increased significantly with increasing N fertiliser rate.

Barley (*Hordeum vulgare* L.)

For most cereals achieving a high protein percentage is a general goal because of the importance of protein in the human diet. However for malting barley (*Hordeum vulgare* L.) N fertilisation should provide good grain yields without exceeding the desirable kernel protein percentage because, although protein is necessary for malt production, excessive amounts have undesirable effects on the malting and brewing processes. Malt yield depends on the starch content of the grain and both relate inversely to the grain N content i.e. the higher the N concentration in the grain the lower the malt yield (Stephen, 1982). Undesirable effects include an increased steeping time, uneven germination, increased malting losses and increased soluble protein in the brewing product (Deckard *et al.,* 1984). In New Zealand a high grain content of more than 2% N is usually regarded as unsuitable for malting (de Ruiter and Haslemore, 1996). The work of de Ruiter and Haslemore (1996) in Marton and Aorangi has shown that fertiliser N caused abnormally high screening (passing a 2.36 mm sieve) levels, small grain size and a high grain N concentration which are all negative qualities for malting.

Maize (*Zea mays*)

The protein biological value of maize is low due to the low concentration of the essential amino acids lysine and tryptophan although opaque-2 hybrids have been developed with higher levels of these two amino acids (Blumenthal *et al.,* 2008). Maize kernel protein percentage generally increases with N fertilisation. Maize hybrids grown without N fertiliser may contain only about 6% protein but increase to 12% or more under high N regimes. The increased protein induced by N application in normal hybrids is primarily zein while the increased protein of the opaque-2 hybrids due to N application appears to be proportionally distributed to all four protein fractions (Tsai *et al.,* 1980 cited in Deckard *et al.,* 1984). The formation of large amounts of zein under high rates of N fertiliser may increase yield but reduce protein nutritional quality since zein is deficient in lysine and tryptophan. However this may be compensated for in some cases since N fertiliser application increases the size of the germ which has a better amino acid balance than the endosperm (Bhatia and Rabson, 1987 cited in Blumenthal *et al.,* 2008). The opaque-2 hybrid on the other hand does not accumulate additional protein as zein, so the lysine concentration (on a percentage protein basis) remains relatively constant regardless of N rates (Tsai *et al.,* 1983). Tsai *et al.* (1992) reported that protein yield increase from N application is accompanied by an increase in the amount of zein present in the endosperm, creating harder, less brittle and more translucent grain.

In Manawatu, Cheetham *et al.* (2006) applied ammonium sulphate to five maize varieties at three N rates (0, 125 and 250 kg N/ha), and found that N fertiliser significantly increased grain yield primarily by increasing grain weight. However it had no effect on grain quality parameters such as grain N concentration, grain hardness and bulk density. Only the 200-grain weight significantly increased with N fertilisation.

Oats (*Avena sativa*)

Oat grains contain a particular polysaccharide which plays a role in human nutrition. This compound is a β-glucan that is important in lowering blood cholesterol level in humans (Mengel and Kirkby, 2001). Desirable qualities of milling oat varieties include high β-glucan content, low hull content (high groat content), high groat protein, low oil concentration and low kernel breakage (Yan *et al.,* 2007). Quality responses of oats to increased N fertilisation can be variable. Relative to wheat and barley, N fertilisation does not negatively alter the amino acid composition of oat grains. High or late N fertiliser dressings predominantly increase the concentration of glutenin, a grain protein with a moderately high proportion of lysine. For this crop, therefore, an increase in grain proteins by a late N dressing is not detrimental to the nutritional value (Mengel and Kirkby, 2001).

In Canada, May *et al.* (2004) reported that physical seed quality decreased (plump seed decreased and thin seed increased) with delayed seeding and increasing N fertiliser rates (15 to 120 kg N/ha) and concluded that the optimum N rate will thus involve a trade-off between yield and quality. They recommended early seeding with an N rate from 40 to 80 kg N/ha. If seeding is delayed only 40 kg N/ha should be applied to maintain oat quality. Higher rates of N fertiliser were shown to result in increased protein accompanied by a reduction in plump kernels and lower oil content.

In Mexico, Rivera-Reyes *et al.* (2008) examined agronomic factors affecting oat seed quality and showed that to increase yield and seed quality a plant density of 40 kg/ha and fertilisation rate of 60 kg N/ha are required. In Turkey, Güler (2011) reported that higher levels of N fertiliser (up to 100 kg N/ha) increased β-glucan content and 1000-kernel weight and test weight. Analysis of oat yield and quality data from nine locations over seven years in Canada and Northern USA revealed a negative association between protein content and yield and a positive association between protein and β-glucan content (Yan *et al.*, 2007). This suggests that selection for high levels of nutritional quality properties may be difficult when higher yielding cultivars are desired (Ames *et al.,* 2014).

Fruit Crops

In general, excessive N fertiliser lowers fruit colour development, delays maturity, increases time-to-colour-break and causes uneven fruit ripening. These effects vary a lot and depend on species, cultivar, environmental conditions and management practices. Optimum N results in fruits with high soluble solids. High N can increase the acid content of citrus. Above-optimum N increases the incidence of some postharvest and storage problems (Locascio *et al.*, 1984). The higher N content in fruits leads to decreased calcium (Ca) content and Ca/potassium (K) ratio as a consequence of which the susceptibility of the fruit to abrasions, bruising injury, physiological disorders and various pathogens is enhanced. On the other hand a deficiency of N results in small fruit size, poor fruit colour and flavour, low overall production and increased decay during storage. The balanced, judicious, timely and split application of N is known to increase the flavour synthesis in fruits (Barman *et al*., 2015).

Apples (*Malus pumila*)

Increased N application rates on apples result in softer fruits with high respiration rates. Over-use of N reduces apple firmness, potentially resulting in more damage in transit and storage, and a reduced shelf life, as studies in North America show. Over-use of N can also reduce the red colouration of red apples. This occurs because of the imbalance in the essential amino acids as a result of excess soil N content (Barman *et al*., 2015). On the other hand trials in North America and Italy show that N has a positive effect on the soluble solids content of fruit (http://www.yara.us/agriculture/crops/apple/).

Marsh *et al.* (1996) surveyed orchards in Hawke’s Bay and Canterbury, New Zealand and showed that late season (February) leaf N concentration in ‘Fuji’ apples consistently showed a negative relationship with fruit red colour and chroma. There were variations with season and with region, but the data confirmed a general trend of high leaf N (>2.5 %) giving low chroma and low red colour. Their results agree with the findings of other workers (Boynton and Cain, 1943; Weeks *et al.*, 1958 cited in Marsh *et al.*, 1996), who observed a decline in fruit red colour of 'Mclntosh' apples with increasing leaf N concentration. The authors also noted that there seems some evidence that the effect of N is independent of a tree vigour effect on fruit red colour. They suggested that management of leaf N concentration and decreasing tree vigour is important in maximising fruit colour development in ‘Fuji’ apples. However this can be considered advantageous in green apples by improving greenness and minimising red colours.

Wine grapes

Adequate N is important not only for fruit yield but also for maintaining an optimum N concentration in the berries for fermentation. Yeast strains vary in the efficiency with which they use combined and mineral N for berry growth. The critical measure of berry N for satisfactory fermentation and ultimately wine quality is the yeast assimilable N (YAN) comprising of ammonium-N and amino acid N (excluding proline) (White, 2009). YAN in the juice should be in the range of 200 to 480 mg N/l, with the optimum around 300 mg N/l, depending on the yeast strain. If YAN is too low the fermentation rate becomes sluggish and may become "stuck". "Off" odours such as from hydrogen sulphide (H_2S) can be produced. Wine makers correct this problem by adding monoammonium phosphate or diammonium phosphate in the must during fermentation, but experiments in Western Australia suggest that N supplied in the vineyard produces wines of better flavour and aroma than those produced when N is added in the winery. On the other hand if YAN is too high, fermentation becomes too rapid and poor quality wine is produced, particularly in the case of red grapes. Residual protein in the must after fermentation causes haze in the wine. Especially when coupled with plentiful water too high an N supply to the vine also leads to excess vigour (White 2009; White *et al.*, 2012).

Due to the important role of N on grape quality attributes assessment of vine N uptake conditions is very important in viticulture. Grape quality potential for red wine production is correlated with vine N status, particularly when soil moisture status is not limiting. Low vine N status reduces shoot growth, vigour, berry size and yield, and increases grape sugar, tannin and anthocyanin concentration (Choné *et al.*, 2001a; Trégoat *et al.*, 2002; van Leeuwen *et al.*, 2007 cited in van Leeuwen, 2010). Thus grape quality potential for red wine production becomes better if soil N availability to the vines is limited. Using an N balance approach White (2009) estimated that the appropriate amount of N fertiliser for a 10 tonne/ha crop for a fertile and an infertile site to be small (12 and 32 kg N/ha/y, respectively) and remarked that this is consistent with the N fertiliser practice in the Bordeaux region of France and the Willamette Valley of Oregon, USA where about 30 kg N/ha/y is applied. However the rate of N input can be two to three times higher on young vines (up to 2 years old) and on sandy soils with low organic matter content.

On the other hand in white wine production, low N availability to the vines is not favourable to wine quality. It has been shown to reduce aromatic potential in Sauvignon blanc grapes (Choné *et al.*, 2006 cited in van Leeuwen, 2010). Even though vine N status should be at least moderate, excessive vine N uptake is undesirable because it promotes leaf crowding and susceptibility to diseases, particularly *Botrytis cinerea* (Gysi, 1984 cited in van Leeuwen, 2010).

Kiwifruit

N is generally applied at relatively high rates in kiwifruit compared with other perennial horticultural crops. High levels of plant-available N encourage strong vegetative growth and may impair fruit quality. Nitrogen is major element that affects storage longevity. In a review on the effects of nutrition on the storage quality of green kiwifruit Prasad and Spiers (1991) showed that fruit N concentration or petiole nitrate-N status are both negatively correlated with fruit firmness (r values ranged from -0,32 to -0.68) although in a few cases the correlations were insignificant. This was acknowledged by the authors who indicated that it is clear that in such cases other factors influence fruit softening. On the other hand Buwalda *et al.* (1990) reported in a seven year fertiliser N rate trial on an Ultisol in Pukekohe, New Zealand, that while N supply (up to 200 kg N/ha) negatively affected fruit firmness immediately post-harvest, there were no significant effects on fruit firmness after 12 to 20 weeks of storage. Also the soluble solids content of the fruit was not significantly affected by the rate of applied N fertiliser. Boukouvalas and Chouliaras (2005) indicated that kiwifruit containing less than 2% leaf N can be stored longer than fruits produced by vines containing more than 2% leaf N. Excess concentration of N in fruit juice facilitates flesh softening.

Mills *et al.* (2008a) applied N rates of 0, 145 and 295 kg N/ha to gold kiwifruit ('Hort16A' variety) on a pumice orchard soil in Te Puke, New Zealand and monitored the concentration of N, P, K, Ca and Mg in the fruit (and leaves) for two years. The high N treatment gave significantly higher fruit N concentration at harvest in both years. High fruit N content in kiwifruit has been linked to low fruit dry matter content in a survey of 24 commercial kiwifruit orchards in New Zealand (Clark *et al.,* 2001 cited in Mills *et al.,* 2008a) and this was also confirmed in this study. Fruit P concentration increased with increasing N rate whereas the opposite was true for fruit Ca concentration. Potassium and Mg concentrations were unaffected by N fertilisation. It was concluded that N application influences the uptake and accumulation of other minerals. Also a reduction of N application was suggested that should not lead to reduction in productivity over a two-year period and would reduce nitrate leaching rates.

In a follow-up paper Mills *et al.* (2009) showed that N fertilisation resulted in higher total carbohydrate concentration but lower total fruit carbohydrate concentration over a two-year period. Vegetative vigour was increased in the N-fertilised vines relative to unfertilised vines. They suggested that zero or low N input appeared to have favoured the partitioning of carbon to fruit. This information can be used as a tool to manipulate both vegetative vigour and fruit quality. Lowering N application rate also reduces the risk of nitrate leaching from kiwifruit soil types which are usually free draining. It should be noted, however, that the soil total N of this experimental site was rather high (0.41%) with high N mineralisation potential (reaching about 200 mg mineral N/kg after 4 months of incubation) (Mills *et al.,* 2008b). Thus, under this condition, it may well be advisable to reduce the rate of N fertiliser application to avoid any negative effects on kiwifruit quality but not necessarily on soils with much lower N fertility levels.

Boyd *et al.* (2010) carried out a subsequent N fertilisation and thinning experiment in the same orchard site used by Mills *et al.* (2008a) over two years and found that vines receiving no added N were less vigorous than vines receiving 105 and 210 kg N/ha. The reduction in growth primarily occurred in leaf biomass rather than shoot biomass. Reducing N inputs from 105 to 0 kg N/ha increased fruit dry matter concentration (by about 0.6 to 0.8 percentage units) and advanced maturity as evidenced by higher soluble solid concentration and lower flesh hue angle. This trend was seen in both years and on both harvest dates within each year. This agrees well with earlier results reported by Mills *et al.* (2008a).

Conclusions

Quality responses of different crops to increasing rates of N fertiliser can differ in magnitude and direction but some general trends have been shown from the various studies considered. The rate of N that needs to be applied depends heavily on the kind of crop under consideration and the quality effects N exerts on the final product. In situations where product quality is affected negatively a compromise between attaining yield increase while minimising quality decline with increasing N application needs to be arrived at. Where increasing N application does not result in lowering the quality of a crop N fertilisation can be increased until it attains the economically optimum rate with respect to yield and N use efficiency and/or environmental considerations. There is considerable opportunity to target higher N fertilisation rates in less quality-sensitive crops (e.g. wheat, oats, maize) to arrive at an optimal N with a balance of both yield and quality considerations.

One of the problems that lead to differing effects of N fertiliser on crop quality is that there are many published reports from field experiments conducted in different countries where only the yield and crop quality data have been collected. The reasons for the differing or conflicting conclusions are often unknown since usually no growth or physiological parameters have been measured to help understand the mechanisms involved. Also environmental data are inadequate to understand the interactions between N fertilisation and environment. It is suggested that future work on the physiological basis of N effects on crop quality be given greater attention. Hopefully some careful physiological investigations and inclusion of environmental data (e.g. rainfall, temperature, etc.) can yield far more useful information than lots of empirical field experiments. Also more research on the impacts of N fertilisation on crop quality on other economically important crops not covered in this review should be encouraged.

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