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Review

Crop responses to nitrogen overfertilization: A review

Francisco Albornoz

Departamento de Ciencias Vegetales, Facultad de Agronomía e Ingeniería Forestal, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Macul, Santiago, Chile

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ABSTRACT

Nitrogen-containing fertilizers are commonly used in modern agriculture, but the application rate in most fields exceeds crop demand, with short- and long-term negative consequences. Reduction in the quality of the products, assessed by organoleptic characteristics and compounds related to health, such as nitrate, are commonly reported. Even yield losses, depending on site-specific conditions, can result from N overfertilization. This literature review summarizes the research of the past 20 years that describes the response of crops to high rates of N fertilization, with a detailed analysis of the conditions and agricultural practices that lead to nitrate accumulation in leafy green vegetables.

Contents

1. Introduction

Nitrogen (N) is an essential nutrient required by crops for optimal growth and development. Nitrogen is involved in many physiological and metabolic processes and is key in the structural conformation of plants because it is a primary constituent of proteins, enzymes and nucleic acids (Maathuis, 2009). Therefore, as a limiting resource in agriculture, N is as important as the availability of water (Sinclair and Rufty, 2012).

The development of the modern fertilizer industry, which began in the late XIXth century with the export of sodium nitrate and bird guano from Chile and Peru to the Northern Hemisphere (Melillo, 2012), supported the demands of a growing population that required high yields. During the 1960's, the 'Green Revolution' provided further encouragement for growers to use high-inputs of nitrogen fertilizers to obtain the maximum yields possible with newly developed crop genotypes (Tilman et al., 2002; Good and Beatty, 2011). By the end of the XXth century, environmental problems such as groundwater contamination, release of greenhouse gases and eutrophication of aquatic ecosystems were correlated with heavy N fertilization of fields (Byrnes, 1990; Smith et al., 1999; Harrison and Webb, 2001; Robertson and Vitousek, 2009), which forced the implementation of regulatory policies in Europe and the USA to limit the inputs of fertilizers to agricultural fields (Tilman, 1998).

Following continual applications of N-containing fertilizers, N either accumulates in soils or is lost by runoff or lixiviation (Ju et al., 2004; Najera et al., 2015). When the N supply exceeds the demand, several physiological responses occur that result in poor quality of the products, which reduces profits for growers. Organic farmers, and most recently agroecologists, argue that poor quality products and reduced profits support the use of fertilizers that promote biological cycles within soils to promote N release in synchrony with the environment (Altieri and Nichols, 2003).

When the rate of N application exceeds the requirements of the crop, yield reductions can also be observed.

E-mail address: fralbornoz@uc.cl

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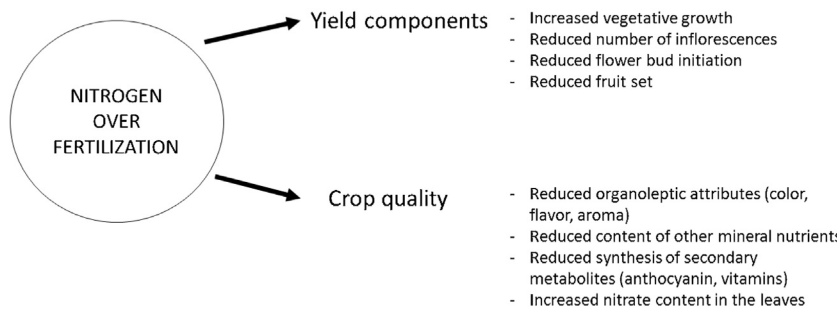

Fig. 1. Schematic of the primary effects of N overfertilization on yield parameters and produce quality.

Based on the literature review, the responses of crops to N overfertilization are summarized in Fig. 1, with a description of the primary characteristics of quality that are affected. Additionally, alternatives are reviewed that can be used to reduce the negative effects of N overfertilization.

2. Yield responses to excess N fertilization

Yield reductions for a variety crops occur at high doses of N fertilization, particularly for fruit trees and fruity vegetables (e.g., tomato, cucumber and zucchini) (Weinbaum et al., 1992; Jackson and Lombard, 1993; Tagliavini et al., 2000; Erel et al., 2008; Stefanelli et al., 2010).

In sweet cherry with fertigation, yield losses of 6–39% occur at 168 mg N L^{-1} compared with 84 mg N L^{-1} (Nielsen et al., 2007). Similarly, in a recent study of citrus trees in Florida, the optimum N fertilization rate for the maximum yield is 260 kg N ha^{-1} $year^{-1}$, with a quadratic pattern in yield reductions at higher rates of fertilization (Alva et al., 2006). In olive trees, the number of inflorescences per branch decreases with each increase in the available N in the root zone above 3.4 mM, which reduces the fruit set (Erel et al., 2008).

In Cabello et al. (2009), the optimum N fertilization rate for melons is 90 kg N ha^{-1} for a marketable yield of 42.9 Mg ha^{-1}, which is reduced by 15% with a N fertilization rate of 390 kg N ha^{-1}. A similar effect is observed in cucumbers, and the reduction in marketable yield is associated with a decrease in activity of the enzyme nitrate reductase in the leaves and a consequent reduction in the export of amino acids to the fruits (Ruiz and Romero, 1999).

The yield losses in crops receiving high rates of N fertilization are primarily because of reduced fruit set, which is caused by the increase in vegetative growth that occurs with the excessive uptake of N (Weinbaum et al., 1992). In some species, such as apples and cherries, flower bud initiation is antagonistic with spur vegetative growth, and flower buds develop only 2–4 weeks after growth of the spur has ceased (Koutinas et al., 2010). Generally, however, light intensity is one of the most important factors affecting flower bud initiation and development (Wilkie et al., 2008), and with excess N, flower bud development and fruit set are negatively affected because the increase in vegetative growth increases shading by foliage (Weinbaum et al., 1992). Additionally, Fernandez-Escobar et al. (2008) found that the effective pollination period in olive trees is reduced because of a decrease in the longevity of the ovules under high, as well as deficient, N fertilization.

For cereal crops, the yield losses associated with high N inputs were studied as early as 1950 to describe the field conditions leading to the symptom of 'haying-off' that occurred primarily in dryland wheat (Van Herwaarden et al., 1998). Crops affected by this disorder ripen prematurely, which results in pinched grains with a high protein concentration. This disorder is associated with high N availability in soils during the initial stages of the crop, which leads to vigorous vegetative growth. However, during post-anthesis, the availability of water is not sufficient to support the evapotranspirative demand, and the crop matures with grains low in carbohydrates and high in proteins (Van Herwaarden et al., 1998).

Other authors report yield losses in wheat with rates of N fertilization above 240 kg N ha^{-1} (Wang et al., 2011), which has been attributed to an osmotic restriction, particularly with nitrate-N fertilizers (Huett, 1996).

3. Effects on crop quality

The quality of agricultural products is assessed based on characteristics such as color, flavor, taste and appearance; however, each year more consumers are concerned about the nutritional quality of fruits and vegetable products (Schreiner et al., 2013). The consumer conception that fruits and vegetables offer 'healthy foods' is based primarily on the content of secondary plant metabolites, including phenolic compounds, glucosinolates (exclusive to Brassicaceae), flavonoids and carotenoids (Schreiner et al., 2013), in addition to the absence of harmful compounds such as nitrate (Konstantopoulou et al., 2010).

Low inputs of N fertilizers enhance these positive characteristics of quality (Stefanelli et al., 2010); however, with excessive N fertilization, reductions occur in some of these quality parameters in different crops. For example, the concentration of anthocyanin in blueberries cv. 'Duke' decreased with an increase in the rate of N fertilization, an effect that was accompanied by a reduction in fruit size (Ehret et al., 2014). Similarly, the concentrations of vitamin C and phenolic compounds decrease in a variety of vegetable products that include spinach, tomato and lettuce (Bourn and Prescot, 2002; Zhao et al., 2006; Rembialkowska, 2007; Wang et al., 2008; Konstantopoulou et al., 2010; Lairon, 2010). To explain these effects under an ample N supply, plant metabolism likely shifts toward more N-containing compounds (proteins) to the detriment of compounds that contain more carbon (Rembialkowska, 2007).

High rates of N application also affect the sugar content in products such as potato and sugar beet (Mengel et al., 2001), tomato (Parisi et al., 2006), apples and pears (Mattheis and Fellman, 1999), grapes (Jackson and Lombard, 1993), and carrots (Smolen and Sady, 2009).

The concentrations of mineral elements are also reduced at high N application rates, and significant reductions occur in the calcium concentrations of tomatoes, cucumbers, apples and kiwis (Sams, 1999; Wang et al., 2008; Fallahi et al., 2010); these reductions are important because the postharvest life of the product is limited because of a reduction in firmness (Nielsen et al., 2009).

High rates of N application also reduce the red coloration in apples, peaches and nectarines, which is an effect directly related to a decrease in chlorophyll degradation (Kays, 1999; Wargo et al., 2003; Nielsen et al., 2009; Wang and Cheng, 2011).