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# Optimization of Nitrogen in Durum Wheat in the Mediterranean Climate: The Agronomical Aspect and Greenhouse Gas (GHG) Emissions

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Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.70195>

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## Abstract

Durum wheat (*Triticum turgidum* L. subsp. *durum*) is the most cultivated cereal crop in the Mediterranean basin, traditionally grown under rainfed conditions using conventional tillage. Agronomical practices, soil type and climate variables are known to influence crop productivity. Their interaction effect is very complex and the time in which they occur strongly affects yield and quality. The nitrogen supply, in combination with climatic conditions, is the main constraint determining the physiological performance, grain yield and quality response of wheat. In addition, the N formulation, fertilizer management, crop sequence, seasonal trends, and the supply of residual and mineralized N influence the response of wheat to N fertilizer. N fertilizer management must be optimized to prevent N deficiency in the critical crop growth period, to avoid yield and quality losses and also prevent the excessive application of N fertilizer, thus reducing the environmental impact. The split application of N fertilizer is a promising strategy that satisfies plant needs and reduces N losses through improved nitrogen use efficiency (NUE). Such a strategy can result in a remarkable reduction in greenhouse gas (GHG) emissions and the carbon footprint of Italian durum wheat, considering that the highest proportion of the total emissions deriving from N fertilizer production and its application.

**Keywords:** durum wheat, nitrogen, nitrogen use efficiency, greenhouse gas emission (GHG)

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## 1. Introduction

Wheat is one of the main sources of carbohydrate foods worldwide, and as such its cultivation is considered strategic, along with other important cereals grown widely across other continents [1].

From 1950 to 1990, the production increased exponentially due to the combined effect of genetic improvement and new agronomic techniques, which allowed the crop yield to increase massively [2].

This increase in production is strongly related to the use of nitrogen, which is essential for the life of the crop and is a limiting input factor for the crop productivity [3]. Since the 1960s, there has been a ninefold increase in the use of nitrogen, and this is expected to grow by another 40–50% over the next 40 years [4].

The application of nitrogen fertilizer greatly improves agricultural productivity but increases the risk of aquifer pollution, estimated in the EU alone to be by 20% [5], also due to inefficient use of the fertilizer.

Sustainable agriculture is a very broad concept and includes ecological, economic, and social aspects.

“Sustainable agriculture” definition was defined by Congress in the 1990 “Farm Bill,” [Public Law 101–624, Title XVI, Subtitle A, Section 1603 (Government Printing Office, Washington, DC, 1990) NAL Call # KF1692.A31 1990]. Under that law, the term “sustainable agriculture” means an integrated system of plant and animal production practices having a site-specific application that will, over the long term:

- satisfy human food and fiber needs;
- enhance environmental quality and the natural resource base upon which the agricultural economy depends;
- make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls;
- sustain the economic viability of farm operations; and
- enhance the quality of life for farmers and society as a whole.

The Food and Agriculture Organization [2] has developed a common vision and an integrated approach to sustainability across agriculture, forestry, and fisheries. This unified perspective, valid across all agricultural sectors and taking into account social, economic, and environmental considerations, ensures the effectiveness of action on the ground and is underpinned by knowledge based on the best available science. It can be adapted at community and country levels to ensure local relevance and applicability.

From an environmental point of view, sustainability means a respectful farming system in terms of the use of natural resources such as water, soil fertility, and biodiversity, and a reduction in the

use of chemicals. The study of energy systems has gained considerable importance in this regard, with the aim of reducing the use of fossil energy and, consequently, the emission of greenhouse gases into the atmosphere. The study of cropping systems that use improved crops and conservative systems becomes crucial for increasing the accumulation of organic matter in the soil.

The effect of climate change is of particular concern in agriculture, as it significantly affects crop yields and their inter-annual variability, and can potentially affect their traditional territorial distribution.

The phenomenon of climate change affects the whole planet but is very much observed at the Mediterranean basin level, where the climate is characterized by hot dry summers and mild wet winters. The main field crops are winter cereals, in particular durum wheat, which grows in the range of 200–600 mm per year [6]. Durum wheat and other cereals are typically sown in October to December and harvested in May to June.

The conditions for growth during this period are favorable for cereal crops, ensuring an optimal course of their cycle until the end of April. After this period, the phenomena of water and thermal stress during the final filling-ripening stage are likely.

Variable climatic conditions cause water stress with large fluctuations in both grain yield and in the physical property of the grain (hectoliter weight, 1000 seed weight), and also in grain protein content and composition, which has considerable effects on the rheological properties of semolina [7–9].

Nitrogen fertilization is a particularly significant parameter in the technique of wheat cultivation, in terms of its effects on specific agronomic characteristics, the production level, and the quality and quantity of grain proteins [10].

In the absence of other limiting factors, primarily the availability of water, wheat response to increasing nitrogen doses in terms of crop production and/or protein content is influenced by the level of chemical fertility of the soil [11]. The combined effect of nitrogen availability and optimum water conditions is evident in the tillering phase.

The effect of nitrogen and water deficiency is then evident in the subsequent phases of heading and spike emission/flowering, when stress conditions can cause an increase in flower abortions and a reduction in vegetation.

The effect of water stress, combined with high temperatures, contributes to determining the productivity and quality of wheat grain [10].

In Mediterranean environments, the crop response to nitrogen fertilization is conditioned by climate change (precipitation during the March–May period), agronomic practice (normal or conservative soil management), the quantity and number of fertilizer operations, and the type of fertilizer applied [12–14].

The effect of nitrogen availability, in optimum water conditions, is evident from the tillering phase. The combined effect of nitrogen and water deficiency is also evident in subsequent phases of heading and spikelet initiation/flowering, when stress conditions cause an

increase in flower abortions and a reduction in vegetation [15, 16]. Management strategies, including the alteration of sowing time to avoid if possible the stressful period and using resistant wheat varieties would therefore be valuable to sustain productivity. In fact, alternative wheat management options have been proposed and tested worldwide to evaluate their performance with respect to yield [17]. These durum wheat cultivation management systems are necessary to maintain acceptable levels of grain yield with lower economic and environmental costs. One of the most effective and widely spread practices in wheat production is the use of a no-tillage system. This system has been increasingly adopted in dry areas as it enables water to be conserved in low rainfall regions. In addition to improving wheat productivity through improved soil quality [18], no-tillage represents an option to lower the environmental impact. It can save energy (a major direct expense for farmers in terms of fuel costs) through the reduction in mechanical operations for tillage and by lowering the emissions of GHGs, as compared to conventional tillage no-tillage acts as a sink source of soil emissions.

This chapter is a review of international studies that focus on the environmental implications of nitrogen fertilizer application in durum wheat, with respect to yield and quality response. Factors controlling wheat response to N fertilizer application are also discussed. The aim of this chapter is to identify options for enhancing NUE to achieve a more sustainable fertilization management of durum wheat in the Mediterranean environment.

## 2. Wheat diffusion and statistics

According to data collected between 2008 and 2013, cereal cultivation covered an area of more than 700 million hectare worldwide with a total production of 2.6 billion tonnes.

Wheat, as the main constituent of bread and durum, is the primary global cereal crop in terms of surface area invested, with more than 220 million hectares. By comparison, maize covers 184 million hectares and rice 162 million, according to FAO data.

Corn and rice are the top two crops in terms of productivity, while wheat is third with 729 million tonnes (**Table 1**).

Wheat production is mainly concentrated in Europe and Asia, where the crop's importance is increasing continuously, unlike on other continents where productivity has remained stable, or as in America, where the choice of alternatives crops (i.e., soybean) has led to a contraction in wheat production (**Figure 1**).

Improvements in cultivation, agricultural techniques, and mechanization have led to better wheat cultivars, and thus an increase in productivity.

The adoption of best agronomic practices has also been important in improving the sustainable production of cereals. Precision farming systems for the assessment of the physiological state of plants and conservative cultivation systems that ensure the optimization of inputs have enabled a higher level of soil water storage, resulting in an increase in crop production [18].

Species	Surface (ha)	Total production (tonnes)
Maize	184,800,969	1,037,791,518
Rice	162,716,862	741,477,711
Wheat	220,417,745	729,012,175

**Table 1.** Statistical data of the main cereal crops [2].

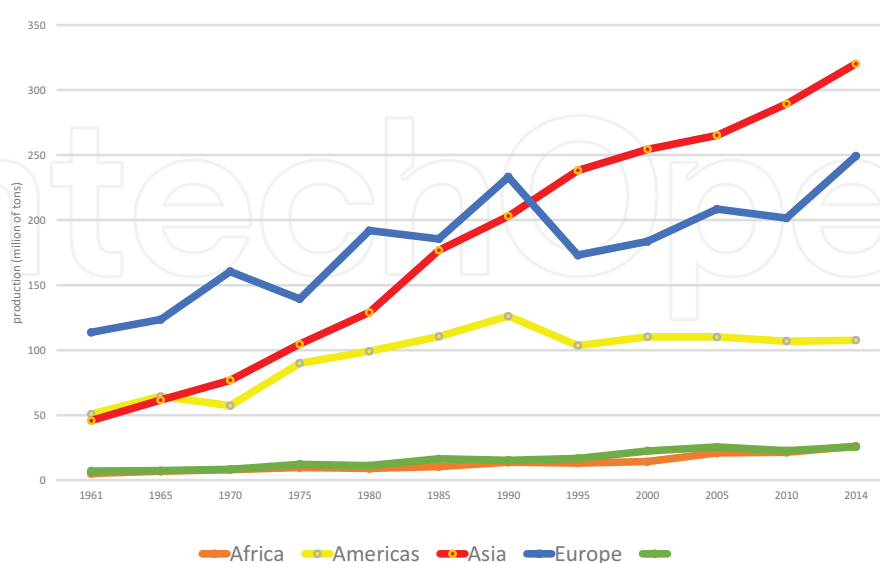
Conservative farming practices enabling the ability to retain water have been applied in countries such as Turkey, particularly in drought seasons, leading to an impressive yield increase in some regions [1].

FAO has consequently pushed key producer countries to change their farming practices so they meet sustainability criteria.

Durum wheat (*Triticum turgidum* L. subsp. *durum*) is a minor cereal crop representing just 5% of all wheat grown. It is thought to have originated in the Fertile Crescent (Mesopotamia) and is an allotetraploid (two genomes: AABB) with a total of 28 chromosomes ( $2n = 4x = 28$ ), containing the full diploid complement of chromosomes from each of its progenitor species.

Durum wheat is mainly cultivated in three basins: the Mediterranean, the northern US and Canada, and within the desert areas of the south-west US and northern Mexico. Other much smaller areas where durum wheat is cultivated include Russia and Kazakhstan, Australia, India, and Argentina (Figure 2).

In 2015, global production of durum wheat reached about 36 million tonnes, according to the International Grain Council [19]. Eurostat [20] reported that about 7.5 million tonnes of



**Figure 1.** Trend of wheat production from 1961 to 2014.

durum wheat was produced in Europe in 2015/16, of which almost half (3.9 million tonnes) was produced in Italy (**Figure 3**), making it the primary durum wheat producer in Europe, followed by Turkey and France with average production of 2.7 and 1.7 million tonnes, respectively.

Smaller producers in the Mediterranean basin are concentrated in Morocco, Algeria, and Tunisia, mainly due to the effect on the crop cycle of the dry climate that often occurs there. The consumption and manufacturing of durum wheat is concentrated around the Mediterranean Sea, where the main food products of durum wheat are consumed: pasta, couscous, bulgur, and bread, which are obtained from four completely different technologies.

An additional 5 million tonnes guaranteed that local production is in fact required, which is mainly imported from North America.

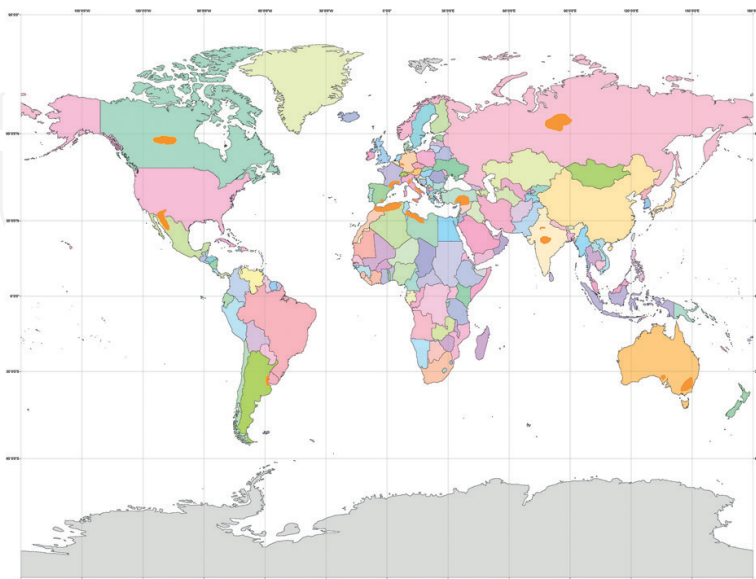
The total production in the Mediterranean Basin under the winter cycle varies significantly, as the agronomic yields are highly influenced by rainfall during the spring period, and the total production can fluctuate between approximately 14 and 20 million tonnes in different years.

Currently, due to immigration to Europe and the growing popularity of pasta worldwide, increasing quantities of couscous are produced in Europe, and an increasing amount of pasta is produced in Northern Africa and in Tunisia.

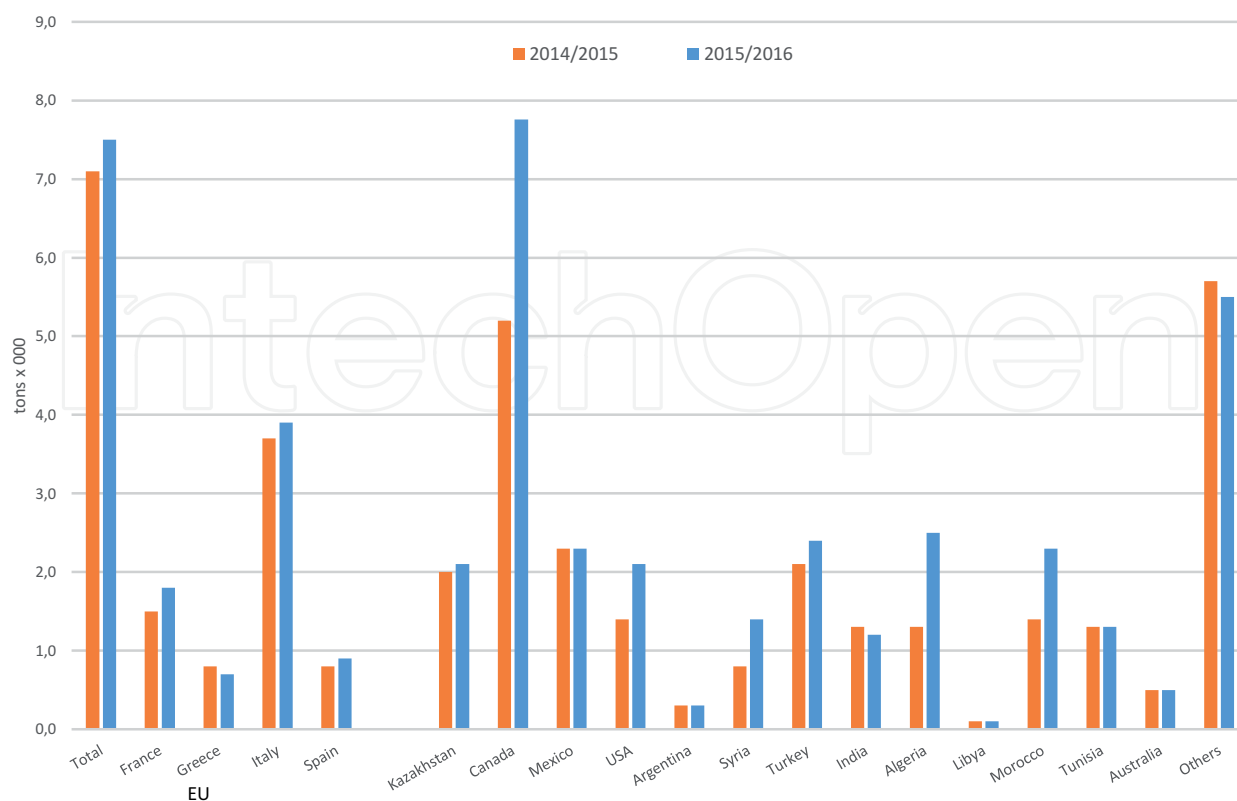
Turkey is becoming an important exporter to the Middle Eastern and African pasta markets, where durum wheat is used for both bulgur and pasta production.

French breeding companies produce durum wheat varieties from commercial lots, which are very well managed from both agronomic and segregation points of view.

Semolina (milled durum wheat) is the raw material for four different food products: pasta, couscous, bulgur, and bread, all of which are typical of the Mediterranean diet. To ensure



**Figure 2.** World map with the territories where durum wheat is grown highlighted in red (Eurostat).



**Figure 3.** Main world producers of durum wheat (Eurostat).

a constant and sufficient supply in the Mediterranean basin, its cultivation and associated agronomic practices must be modified, to cope with the projected change in climate events. Meeting the increasing demand for durum wheat is a challenge even under current conditions, with the reductions from year-to-year variation in grain yield due to irregular and seasonal rainfall distribution. Under the winter cycle of the Mediterranean basin, rain-fed durum wheat production can experience remarkable yield losses due to insufficient rainfall, particularly during the spring.

### 3. Nitrogen consumption for wheat production

Nitrogen ( $N_2$ ) is the main component of our atmosphere, at a percentage of 78.084%. It is essential for various metabolic reactions and vital processes, and is involved in various reactions that occur through air, soil, and water. It thus undergoes various chemical and biological transformations.

Nitrogen is a crucial mineral element and is involved in several fundamental compounds (amino acids, nucleic acids, chlorophyll, cytokines, polyamines, and secondary metabolites) essential for the biological plant cycle [3].

The agricultural world is heavily dependent on the nitrogen cycle, and sometimes the excessive use of nitrogen results in increased agricultural production [21]. More than 100 million Mt of  $N$  year<sup>-1</sup> of reactive  $N$  is industrially produced by the Haber-Bosch process using fossil



fuels as energy sources, and of this 50% is applied to the three main cereals (maize, 16%; rice, 16%; and wheat, 18%) that provide the bulk of human food calories and proteins consumed either directly as grain or indirectly through livestock products [22].

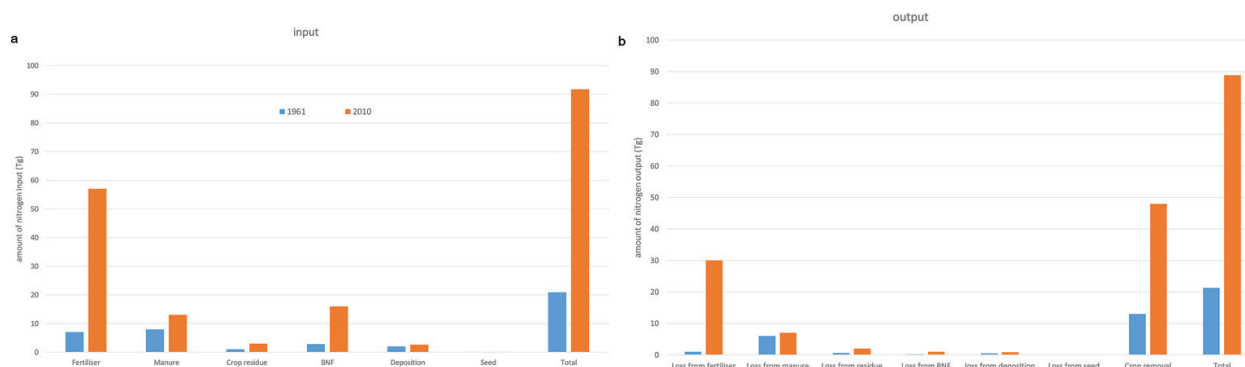
Most nitrogen is contained in seeds, which have an average protein content of 12%, slightly higher in hard wheat than tender. In straw, the content ranges from 3.5 to 4.8% [23].

The average content of N in protein is about 6%.

In global terms, it is almost certain that additional N fertilizer will be required, which can be offset to some extent by management practices that improve nitrogen use efficiency (NUE).

According to some studies [22], the amount of nitrogen used on maize, rice, and wheat from 1961 to 2010 increased, which has been justified by the linear increase in production and the consequent N asportation.

Considering the balance between the input and output of nitrogen, there has been a strong increase of fertilizer application from 1961 to date, estimated at 10 times, and a consequent increase in fertilizer losses (**Figure 4**), which has an environmental impact.



**Figure 4.** Estimated N inputs and outputs in 1961 and 2010 (from Ladha et al. [22]).

#### 4. Agronomical implications of nitrogen use and the system of optimizing nitrogen use on durum wheat

Wheat is very sensitive to nitrogen deficiency and is highly reactive to the element. One of the most obvious responses to nitrogen deficiency is chlorosis, as a result of the lack of chlorophyll synthesis and reduced cell size and proliferation, leading to a stunted, reduced leaf surface and a yellowish (chlorotic) appearance of the crop.

Chlorosis is particularly apparent initially on mature leaves, and later on, the last growing leaves, as the N is shifted from old leaves to new to support growth. Thus, the older leaves dry out and cause poor plant growth and reduced yield.

Plants with an adequate amount of nitrogen grow rapidly and have dark green leaves and stems that grow very fast. Nitrogen is the mineral element most absorbed by plants and is placed in a plant's organs according to its physiological needs (seeds, leaves, and stems).

Nitrogen promotes digestion and increases vegetative growth, the number of heads per plant and the dimension of the spike, the weight of the kernels and the protein content [24].

Excess nitrogen may favor lodging, particularly in tall grain varieties, and retard the cycle with stress on grain filling if the season course is dry. The culture is also more susceptible to rust and septoria attacks.

Therefore, responses to increasing doses of nitrogen fertilizers on the yields are variable due to the sensitive influence of pedoclimatic conditions and the effect of crop precession. An optimum climatic performance in the filling phase of the kernels can favor both the accumulation of amidaceous and protein substances, so the availability of nitrogen in the soil at this time is critical to the qualitative improvement of the grain.

The calculation of N removal from seed durum wheat with 11% protein is [25]:  $SEED\ t\ ha^{-1} \times 0.11 \times 2.34$  (correction factor) = X kg N ha<sup>-1</sup> required.

This results in about 25.7 kg/ha of N being removed from 1 tonne of seed wheat. Studies have reported that in general between 24 and 28 kg/tonnes is removed from durum wheat grain.

Nitrogen in the plant is a basilar element, as it is essential to the plant's vital activity. The following distribution of nitrogen in the plant at different stages has been reported in several studies:

Recommendations of the correct dose of N fertilizer to be applied should take into account the different N source (**Figure 4**), which is calculated based on the following equation: (**Table 2**)

Plant part	Dry matter	Nitrogen
<b>Anthesis</b>		
Total (kg/ha)	7644	84.3
Shoot (%)	84	80
Root (%)	17	20
<b>Harvest</b>		
Total (kg/ha)	7422	71.7
Straw (%)	71.4	35.7
Grain (%)	28.6	64.3

**Table 2.** N distribution balance in wheat plant.

$$\text{N amount}(D) = \text{crop N demand}(F_c) - \text{environmental inputs}(E) + \text{environmental removal}(U) \quad (1)$$

and, in more detail:  $D = F_c - (P + M + C_p) + (L + V + De + Um)$

where

- $F_c$  is crop N demand
- $E$  represents the amount of nitrogen that can be used from the culture but is not distributed with the fertilizer, and which is derived from: atmospheric precipitation ( $P$ ); mineralization of soil organic matter ( $M$ ); contributions arising from the previous crop ( $C_p$ ); and  $U$  represents the amount of N that the environment removes due to the possible utilization by plants through:
  - leaching ( $L$ )
  - volatilization ( $V$ )
  - denitrification ( $De$ )
  - immobilization into soil organic matter ( $Um$ )
- **Atmospheric precipitation (P)**
  - The amount of nitrogen from rain varies widely due to geographical position and fluctuations throughout the year, which makes it extremely difficult to generalize. However, in the Mediterranean climate, we can estimate a supply of nitrogen from atmospheric precipitation ranging from 20 kg/ha to 30 kg/ha for the entire crop cycle of wheat.
- **Mineralization of soil organic matter (M)**
  - Soil nitrogen (N) content ranging between 0.05% and 0.2%. Considering a 30-cm layer of soil depth, this values correspond to an amount of total N between 1,950 to 7,800 kg/ha, higher than those necessary for the cultivation of wheat (**Figure 5**).
  - Approximately 98%, however, is contained in the organic substance soil (humus) and is not absorbable by plants. The organic matter is gradually decomposed by microorganisms and atmospheric agents, and the nitrogen content is transformed into mineral form, which is then absorbable by plants.
  - This complex set of processes is known as the mineralization of the organic matter. In warmer climates and sandy soils, 3% of nitrogen can be freed each year and 1% in more temperate climates and with clay soils. A 30-cm layer of soil, therefore, releases 40–80 kg/ha of nitrogen.

#### 4.1. Contributions from the previous crop ( $C_p$ )

Previous crops such as legumes have certain characteristics that can result in nitrogen production. The legume species are able to establish a high amount of nitrogen for the symbiotic bacteria, which partly remain in the roots and enter into the cycle of organic soil

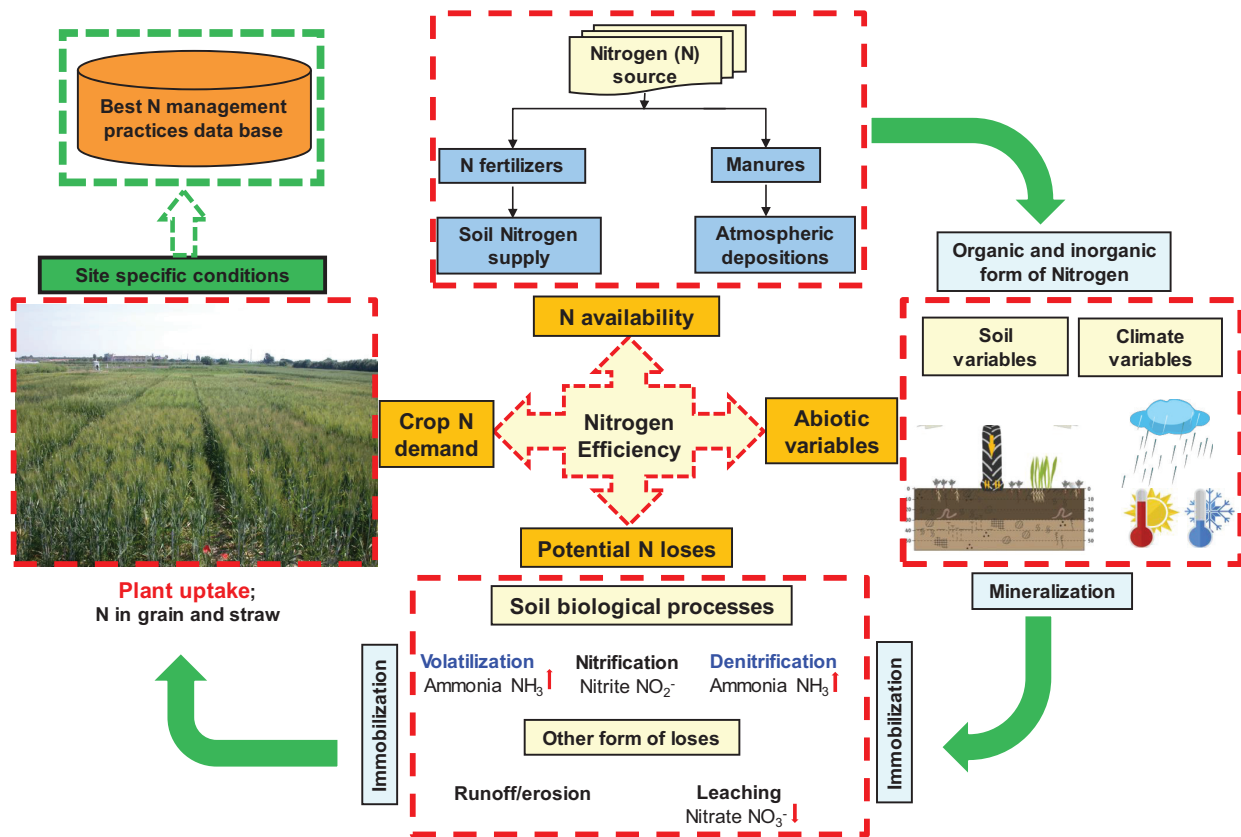


Figure 5. Potential fate of nitrogen in the agricultural system (in the case of durum wheat).

matter. Legumes leave nitrogen in the soil in available form for the crops that follow under a rotation system, but providing an accurate value of the quantity individual species is difficult. However, it can be estimated at about 30 kg/ha on average for perennial legume species and 20 kg/ha for annual species [26].

Nitrogen can also be derived from organic fertilization carried out in previous years.

#### 4.2. Leaching (L)

Leaching is the movement of nitrogen in percolating water along the profile of the soil, when it exceeds that taken up by the root layer of plants.

As a result of leaching, nitrogen is not utilized by the crops and it thus represents both a nutritional and economic loss.

Normally leaching affects nitric form, even in sandy soils and it can also affect the ammonia form.

The water constitutes the vehicle by which the nitrate N in the soil moves, and nitrogen leaching is, therefore, a phenomenon that, for the parity of nitrates present in the soil, is closely dependent on its water balance.

Leaching is the main, if not the only, type of nitrogen removal affected by the environment.

### 4.3. Volatilization (V)

Nitrogen volatilization occurs in the soil when it forms gaseous ammonia. The rate of this phenomenon depends on the level of humidity, the temperature, and the pH of the soil.

Volatilization is higher in alkaline soil, when the temperature can reach 30°C and where the ammonia or the sources of it (urea and ammonium sulphate from fertilizers) are applied.

### 4.4. Denitrification (De)

Denitrification is the progressive reduction of nitrate to gaseous compounds, such as nitrous oxide and molecular nitrogen, which pass into the atmosphere.

In Italian agricultural soils, nitrogen lost by denitrification does not appear to reach very significant levels, except in special cases such as paddy fields, and has been estimated at 1–5 kg/ha per year.

### 4.5. Humification

Humification is the transformation of the organic substance in humus by microorganisms, occurring within the soil. Humification is a process that requires nitrogen, and if there is not an enough amount in the organic matter, the level of microorganisms in the soil is reduced, which reduced N availability to the crop.

To prevent fertility decreasing, the soil humus content must remain unchanged over time, and the humification value must equal that of the mineralization. Sufficient organic matter (crop residues or fertilizers) is, therefore, necessary to restore the proportion of humus and thus the organic nitrogen of the soil.

The response of wheat to N fertilizer is influenced by different factors: soil management, N fertilizer management, and timing of application, soil properties, crop sequence, seasonal trends and the supply of residual and mineralized N.

The agronomic efficiency of N fertilizer in a Mediterranean climate may be lower than that in temperate zones as the climatic conditions are largely outside the control of farmers, and it is difficult to predict the amount of N to apply to attain optimum growth.

### 4.6. Nitrogen use efficiency

This is the efficiency ratio of output (economic yield) to input (fertilizers) and increases in environmental and economic pressure make it a priority to optimize nitrogen use efficiency (NUE) in agriculture [27].

NUE has various definitions, but that of Moll et al. [28] is one of the most complete, as it does not only refer to the nitrogen of manure and fertilizers:

$$\text{NUE} = \frac{\text{N uptake}}{\text{N available}} \times \frac{\text{Seed yield}}{\text{N uptake}} \quad (2)$$

Here, the term “N available” also refers to the amount of N derived from mineralization of S.O. soil, atmospheric deposition, and bacterial nitrogen fixation. For simplicity of analysis, in many cases, the nitrogen arising from environmental inputs is defined as the absorption of a crop not fertilized.

The different viable approaches for the enhancement of NUE are explored in more detail in the introductions of each individual experiment. Several tools and strategies are available to improve the NUE, such as systems for genetic breeding that include genetic parameters and agronomical tools [29].

#### 4.7. Breeding for NUE

Genetic improvements aimed at optimizing the NUE are crucial for achieving the economic benefits farmers seek, and result in a reduction of the environmental impact of nitrogen.

The increase in yield brought by a new cultivar results in an increase in nitrogen consumption, which apparently is the aspect that has been able to increase the yield from old to new varieties [30]. Indeed, studies have reported that Cimmyt varieties saw a gain in NUE of between 0.4 and 1.1% annually from 1962 to 1985 [31, 32].

Several components affect the level of NUE improvement. In particular, the N Harvest Index (NHI) component contributed to an estimated 0.15% improvement in the NUE per year, which was aimed at reducing the amount of straw produced during harvesting [33–35] (**Table 3**).

Other physiological, metabolic and physical-chemical components can help improve NUE by reducing the contribution of nitrogen fertilizer.

Aspects that act on both the cellular scale and the whole plant include root absorption, nitrate assimilation, N distribution, photosynthesis, senescence, nitrogen rebuilding, accumulation, and wheat composition. These have been taken into account in genetic improvement work [36] and are reported in **Table 4**.

Period	Genotypes	N level (kg N/ha)	NUE (% per year)	References
1962–1985	8	0	1.2	Ortiz-Monasterio et al. [31]
		75	0.4	
		150	0.6	
		300	0.9	
1977–2007	24	0	0.35	Sylvester-Bradley and Kindred [30]
		200	0.58	
1985–2010	195	150	0.37	Cormier et al. [34]
		250	0.3	

**Table 3.** Assessment of yearly percentage genetic gain in nitrogen use efficiency (NUE) from a direct comparison of old and modern cultivars [35].

Traits	Species	References
Root length density at depth	<i>T. aestivum</i> , <i>H. vulgare</i> , <i>O. sativa</i>	Gregory and Brown (1989), Steele et al. (2006), Reynolds et al. (2007) and Manschadi et al. (2006)
Glutamine synthetase (GS) activity	<i>T. aestivum</i> , <i>Z. mays</i>	Habash et al. (2001), Hirel et al. (2001), Masclaux et al. (2001) and Martin et al. (2006)
Alanine aminotransferase (AlaAT) activity	<i>O. sativa</i> , <i>B. napus</i>	Shrawat et al. (2008) and Good et al. (2007)
RuBisCo CO <sub>2</sub> specificity factor	<i>G. partitida</i>	Uemura et al. (1997)
Introduction of C4 "Krantz" anatomy into to C3 species	<i>Oryza</i> spp.	Hibberd et al. (2008)
Specific leaf N content	<i>Triticum</i> spp.	Austin et al. (1982) and Semenov et al. (2007)
Vertical N distribution with leaf layer	<i>T. aestivum</i> , <i>S. altissima</i>	Hirose and Werger (1987) and Critchley (2001)
Leaf posture	<i>T. aestivum</i>	Araus et al. (1993)
Leaf photosynthetic rate post-anthesis	<i>Z. mays</i> , <i>T. aestivum</i> , <i>O. sativa</i>	Reynolds et al. (2001, 2005), Wang et al. (2002) and Ding et al. (2007)
Stem N storage	<i>T. aestivum</i>	Critchley (2001)
Stay-green	<i>T. aestivum</i> , <i>T. durum</i> , <i>S. bicolor</i>	Borrell and Hammer (2000), Spano et al. (2003) and Verma et al. (2004)
N remobilization efficiency post-anthesis	<i>S. bicolor</i>	Borrell and Hammer (2000)
Post-anthesis N uptake	<i>T. aestivum</i>	Triboi et al. (2006)

**Table 4.** Physiological aspects studied for nitrogen use efficiency [36].

#### 4.8. Effect of soil type

The soil-plant-environment system is very complex due to the interactions of several factors that affect plant growth, development, and the final yield. Agricultural soil represents the major source of nutrition for crop survival, and therefore, a good balance of macro- and micro-elements in the soil is fundamental to ensuring a better crop response.

Agriculture intensification has become common practice in different parts of the world to provide sufficient food for the increasing population, and while the high amounts of external inputs such as inorganic fertilizers have led to considerable increases in overall food production worldwide, they have resulted in continuous environmental degradation, particularly of the soil. This deterioration of soil quality and the reduction in agricultural productivity due to nutrient depletion, organic matter losses, and erosion have in turn led to a greater use of chemical inputs, particularly nitrogen. Today, N fertilizer is considered one of the main inputs for crop production, and any lack of N will lead to disruption of plant growth, which will result in economic losses. Nitrogen in the soil is present in soluble form as organic N (Org-N), as ammonium nitrogen (NH<sub>4</sub><sup>+</sup>-N), and as nitrate nitrogen (NO<sub>3</sub><sup>-</sup>-N). The nitrogen cycle is extremely dynamic and complex, so climatic conditions and the physical and chemical properties of a

particular soil can influence the microbiological processes responsible for mineralization, fixation, and denitrification of soil nitrogen. The N availability in the soil is known to be largely controlled by bacteria, so the rate of N cycling is dependent on factors such as soil type, soil moisture, temperature, and pH. Generally, the application of N fertilizer in wheat field depends on the availability of soil nitrogen and the potential losses. The effect of soil moisture on the response of wheat to N fertilizer application has been studied extensively, and the research has found that soil moisture must be considered in N fertilizer management for all soil types. The literature review shows that yield response varies with different nitrogen and moisture levels. In rain-fed areas, for example, soil moisture must be reserved when selecting fertilizer rates.

The application of N to wheat should be timed so an adequate amount is supplied when the crop needs it. As the nitrogen cycle is biologically influenced by prevailing climatic conditions, along with the physical and chemical properties of a particular soil, the choice of a suitable N fertilizer formula to be applied in a specific soil is fundamental. The electrical charges of soil particles vary according to the soil texture, so understanding the chemical properties and therefore, the chemical reactions within the soil will inform recommendations as to when fertilizers can be applied to soils. Soil scientists indicate that these reactions have a major influence on when fertilizer can be applied and how efficiently it is taken up by the crop. Clay particles in the soil have a negative electrical charge, so the amount of clay present in the soil surface is an important factor in these reactions. Clay particles with negative charges will react with components of the fertilizer that dissolve as positively (+) charged particles (cations) when added to soil. For example, the application of N fertilizers that include more ammonium (positive charges) and less nitrate (negative charges) forms of N can reduce the potential for losses in the short term. Ammonium ( $\text{NH}_4^+$ ) forms of N bind to soil particles with negative charges and will not be subjected to losses through leaching or denitrification, therefore, increasing N availability for the plant. However, if not all of the applied ammonium is taken up by the plant, soil bacteria will convert the remaining amount to nitrate ( $\text{NO}_3^-$ ), a form that is not bound to soil particles and can be lost when excessive rainfall leaches or saturates soils. Low soil temperatures can affect the transformation process as they minimize the activity of the nitrifying bacteria, which can naturally help prevent losses of ammonium forms of N.

#### **4.9. Effect of soil management on nitrogen application in wheat**

Soil is managed to ensure that sufficient nutrients are available for plant growth and development, and therefore, good soil management is critical for crop productivity. Poor soil management can lead to erosion, loss of fertility, deterioration of soil structure, and poor crop yields [37]. Understanding the nutritional status of the soil is important in any N fertilizer management plan, and involves the knowledge of different soil components such as microorganisms (densities, diversity, and activity), organic matter and the biological processes by which microorganisms make micro- and macroelements available to the plant, through the decomposition of organic matter. Soil microorganisms have many physical and chemical effects on plants. For example, their secretions help dissolve minerals, and they convert inorganic substances into other forms, making them available to plants. They also aerate the soil and help decompose organic matter [38].



Direct and indirect interventions can improve biological soil management. Direct methods attempt to alter the abundance or activity of specific groups of organisms [39]. Seeds or roots can, for example, be inoculated with rhizobia, mycorrhizae, fungi, and rhizobacteria to enhance soil fertility. Most agricultural practices are in fact indirect methods, such as incorporating plant residues into the soil, introducing legume crops and various tillage methods. They provide important sources of nutrition in the fields, and therefore, must be considered when applying N fertilizers [40]. Many studies have reported that the incorporation of straw, together with the N-rich aboveground biomass of the crops promotes the immobilization of soil mineral N, restores soil organic matter, and improves aeration. The N content in the residue is the input to the soil humus, and thus becomes a part of the supply for future crops. The levels of residual inorganic N in the root profile contribute to the total plant N and should be taken into account when formulating fertilizer recommendations for improving N utilization efficiency. The influence of tillage on the physical, chemical, and microbiological properties of the soil is becoming of great importance when studying issues related to soil fertility and productivity. Several studies suggest that tillage management can have beneficial effects on both grain yield and nutritional quality. Tillage practices such as no-tillage are believed to benefit the soil in terms of improving water retention and the conservation of organic matter in the soil [41].

Conservation agriculture (CA) is an ecologically interesting land management technique, aimed at reducing agronomical inputs related to the reduction of ploughing [42, 43].

The technique may have the potential to reduce the loss of important parameters of soil fertility.

Organic matter (OM) is one such fundamental parameter, and any increase in the soil has obvious benefits in terms of reducing greenhouse gas emissions and thus climate change [17, 37, 44]. An increase in OM, particularly in the more superficial layers, results in an improvement in the physical and chemical properties of the soil, its biological activity and, consequently, in N losses [45].

CA-related studies have also found a tendency to better water conservation and adsorption in the soil; however, under special conditions, CA adoption appears to result in lower NUE rates than conventional systems, largely due to N fertilizer immobilization through crop residues.

Fertilization strategies must therefore be appropriately adjusted by combining the rate, timing, splitting, and source of N, to optimize yield and quality [46].

Soil conditions such as temperature must also be considered, which is found to be lower in a CA system compared to conventional systems. Soil conditions are fundamentally important in N fertilizer management, as they strongly influence the nitrogen cycle. Studies have indicated that, even after CA has been applied for over 10 years, slightly higher doses of fertilizers are still needed to achieve significant yields in winter wheat, with the presence of crop residues on the surface layer.

#### **4.10. Varietal assessment**

Developments in wheat genetics since the 1960s have enabled a substantial increase in the yield potential of many crops, particularly cereals [47].

The large-scale genetic breeding of wheat to reduce the plant size (Rht) has improved efficiency in the redistribution of photosynthesis products (Harvest Index) and has had positive effects on the fertility of the spike [48].

As the upper physiological limit of HI (of approximately 60%) has almost been reached, genetic improvement has been directed toward increasing the capacity to produce above-ground biomass as part of the crop [49].

The maximum yield potential has undoubtedly led to an increase in the general nitrogen needs of non-nitrogen-fixing crops, which have in fact become dependent on substantial levels of mineral fertilizer.

The reduced height of the plants has materially allowed this increase, as the new varieties are much less sensitive to the risk of lodging than the old.

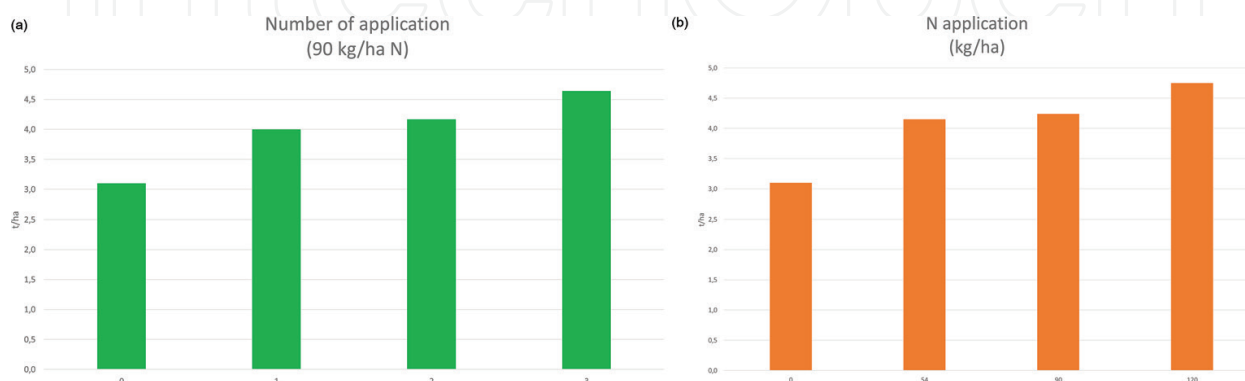
Breeding is an important factor in wheat improvement-related GM production. The over-expression of the French bean in GM wheat has led to an increased grain yield, and consequently NUE, estimated at about 20%. However, difficulties in carrying out experiments with GM materials in Europe have hindered further research into this.

Another gene studied in terms of the ability to modify NUE was the GS1 (Gln-1-3), whose over-expression was able to improve the rice crop index, N collection rate, and N utilization efficiency.

#### 4.11. Time of application

To be effective, the amount of mineral nutrients applied must be consistent with the steps of development and the absorption capacity of the crop. This is known as the subdivision of the N extra dose fractionation best yield, with respect to a unique single intake. With a distributed total dose, nitrogen fertilization is reduced during the early phases (tillering) in favor of the later phases (stem elongation, earing), which encourages a greater absorption of nutrients and increases the efficiency of the crop [14].

Even if traditionally and environmentally the entire dose of N is supplied at the sowing, this approach can be considered valid: the correction of the fertilization dose, with contributions between late tillering and stem elongation, is an economically profitable technique (**Figure 6**).



**Figure 6.** Effect of doses and number of N application on yield response in durum wheat [14].

The most effective nitrogen enhancement is administered during the phases of more intense vegetative activity (raised) and depends on the greater capacity of interception of plants. An experiment in the Mediterranean area (Spain) with a radioactive tracer ( $^{15}\text{N}$ ) has shown that only a small proportion of nitrogen supplied in presowing is effectively intercepted by wheat (14.1%). Nitrogen raised initially is instead absorbed in a greater proportion (54.8%) [50] (**Figure 7**).

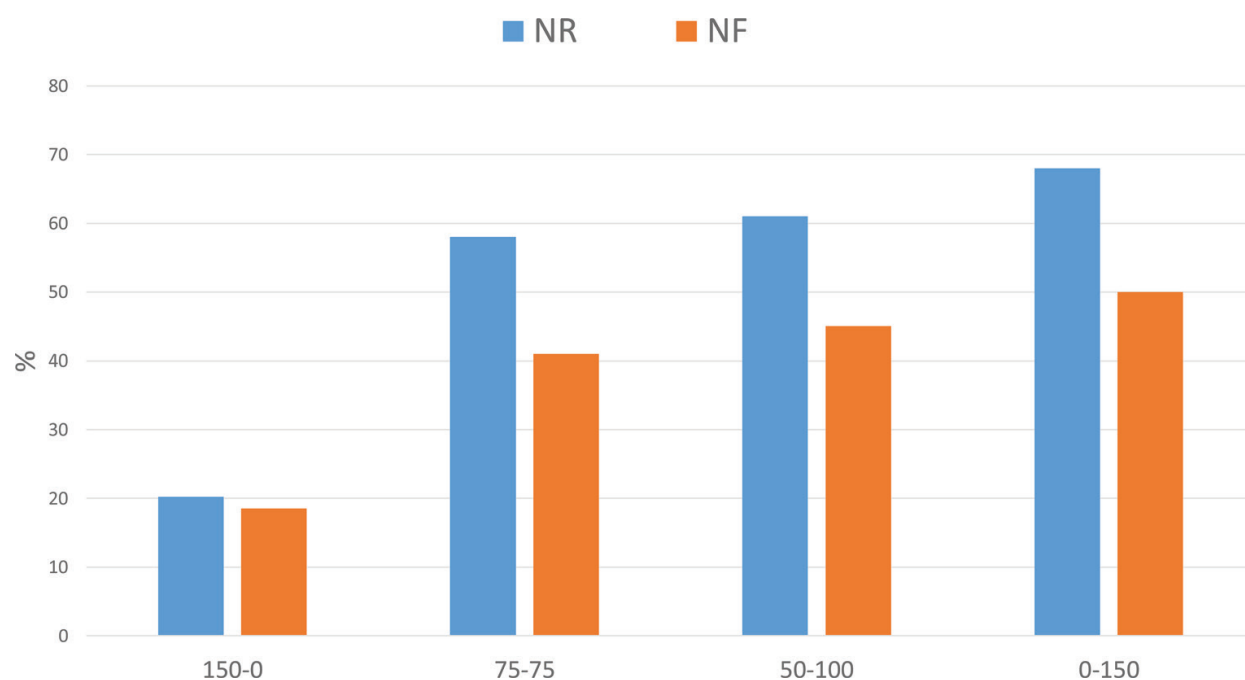
The gross availability of nitrogen resulting from the mineralization of organic matter and from previous crop residues may adversely affect efficiency. Indications have emerged from the study of durum wheat in the same environment [50].

Very late fertilization around the time of earing/flowering, while not having significant effects on the yield, can increase the protein content of kernels and the production of protein per hectare [15, 51].

#### 4.12. Use of precision farming for nitrogen application

Precision farming can represent a sustainable system, making nitrogen more sustainable while achieving the best economic results.

Although there are several definitions of precision agriculture (PF), Pierce and Nowak [52] have summarized it as “a system that provides the tools to do the right thing, the right place, at the right time,” where “the right thing” is an agronomic operation. In fact, recent technological innovations have led to an increase of application opportunities and that definition can therefore be extended.



**Figure 7.** Nitrogen fertilizer recovery (%) of  $^{15}\text{N}$ -labeled fertilizer (NR) and N derived from  $^{15}\text{N}$  fertilizer (NF) in the whole plant at maturity for hard red spring wheat, as affected by N timing [49].

A more extensive definition [53] of PF is “farming management (agriculture, forestry and animal husbandry) based on the observation, measurement and response of the inter- and intra-field quantitative and qualitative variables that influence the production system of the farm.” This aims to define, after site-specific data analysis, a complete decision support system for business management, with the aim of optimizing returns in terms of climate, environmental, economic, productive, and social sustainability [54].

The application of precision agriculture in extensive crops, particularly wheat, has been the subject of various studies [54–57], and involves the acquisition and integration of a large amount of information.

The first input to consider is soil variability. The physical and chemical characteristics of soil vary, which affects the production response [58]. In arid environments, in particular, the spatial variability of the soil factors, combined with climatic factors, greatly influences productivity [59].

Various techniques can be used to obtain soil data, although the approach of sensor-based gathering of crop and soil data is most common [60, 61]. They reported in their reviews that the widely used electrical and electromagnetic sensors provide valuable information about field heterogeneity.

These techniques are more intensive and generally cheaper than conventional sampling and analysis of soil or crop variables [56].

The use of sensors can be considered to spatially diagnose the seasonal pattern of crop conditions during the cycle. Sensors on planes or satellites can potentially collect the reflected electromagnetic radiation from the canopy at small scales of space and time. These remote sensors can evaluate the changes in growth environments from location to location and can potentially gather information about the field, predicting grain yield and nitrogen status [62].

Both passive and active-light proximal sensors can be used to collect the reflected radiation. Passive noncontact sensors depend on sunlight, while active sensors, with their own light sources, enable the assessment of the crop status irrespective of ambient light conditions [63, 64].

Commercial proximal sensors include:

- The passive Yara N-Sensor®/FieldScan (Yara International, ASA, Oslo, Norway).
- FieldSpec® Portable Spectroradiometer (ASD Inc., Boulder, CO, USA).
- The active sensor GreenSeeker® (Trimble Inc.).
- Crop Circle™ (Dutch Scientific, Lincoln, NE).
- SPAD-502 Minolta analytical transmittance, which produces an estimate of leaf chlorophyll content.

Several studies have been conducted on wheat crops using these systems [65, 66], and the data collected must be converted into measures of vegetation, using vegetative indices.

The normalized difference vegetation index (NDVI) is the more precise vegetative normalization index and is based on differences in the red (670 nm) and near infrared (780 nm) spectrums.

NDVI has shown good correlation with N absorption in both bread and durum wheat. Correlations were often more stable when they involved single locations or varieties. An asymptotic tendency was found in the NDVI value for N uptake over 200 kg ha<sup>-1</sup> [67–69].

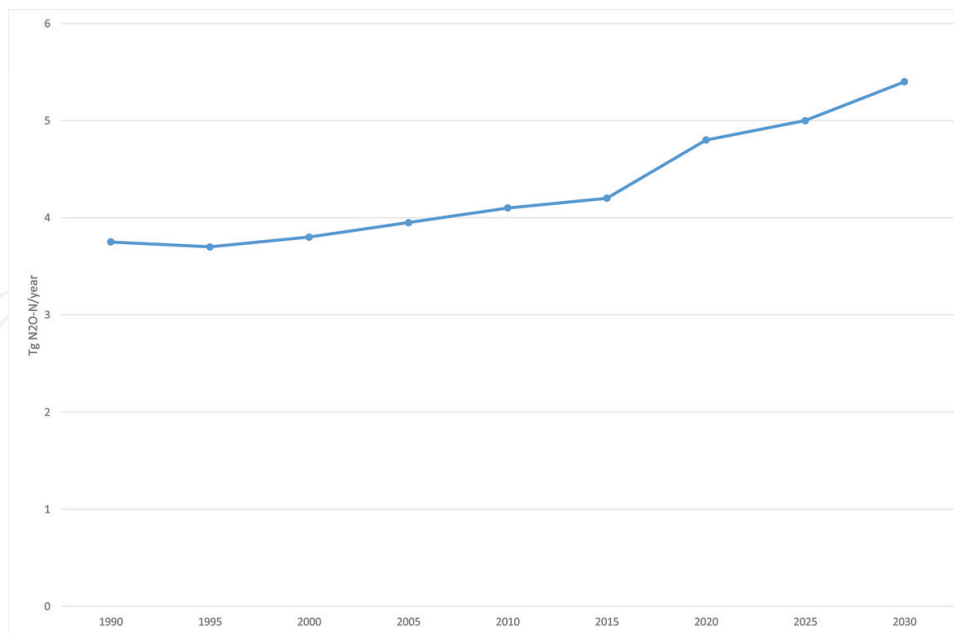
The SPAD value showed a good correlation with the N status in bread wheat [70]. Of all observed indexes, the nitrogen nutrition index (NNI) was the most highly correlated. SPAD close to flowering was closely related to the final grain protein content.

## 5. Implication of nitrogen use on greenhouse gas (GHG) emissions

### 5.1. Problem statement

The rapid increase in the world population over recent decades has led to an expansion in agricultural land in order to provide sufficient food. Consequently, agricultural inputs have been extensively used to increase yield, resulting in serious environmental effects. The emission of anthropogenic gases into the atmosphere is a serious environmental burden, and it is generally accepted that agricultural activities are a major source of several of these gases. Since the industrialization of agriculture, or the so-called green revolution, significant increases in the atmospheric concentrations of these gases have been observed globally. These cause environmental change that will have an impact at both regional and global levels. Carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) are referred to as greenhouse gases (GHGs), as they are considered to contribute most to global warming. The effect of agricultural intensification, in particular the increased use of nitrogen fertilizer, on GHG emissions is likely to increase in the future. The Intergovernmental Panel on Climate Change (IPCC) has indicated that agricultural activities contributed around 10% of the total global GHG emissions [72]. The main agricultural contributors are soil emissions due to inorganic fertilizers and plant residues, in addition to biological processes. N is mainly lost from agriculture soils through nitrous oxide (N<sub>2</sub>O) emissions, which has recently been the subject of considerable attention due to its greenhouse gas effect (300 times worse than carbon dioxide). The increase in population has made it global necessary to produce more foodly, so both the agricultural land area and N<sub>2</sub>O emissions are likely to continue to rise in the coming decades (**Figure 8**). At a global level, agriculture land is estimated to contribute 60% of the N<sub>2</sub>O emissions to the atmosphere annually. Pires et al. [73] derived interesting results from several field experiments. They found that the amount of N fertilizer applied in the agricultural fields is the strongest indicator of N<sub>2</sub>O fluxes in major cropping systems. However, N fertilizer formulation and application timing, and the agronomic practices that determine N availability in the soil such as tillage and waste management can also influence the N<sub>2</sub>O flow, providing an opportunity for mitigation options in agriculture through N management. Several studies [74, 75] have reported that an average of 2% of the N applied to cultivated soils is emitted into the atmosphere as N<sub>2</sub>O. Inappropriate synchronization between N fertilization rate and crop demand would lead to a further increase in emission rates.

Although the N loss from agricultural soils in different gaseous forms is considered the dominant mechanism in agricultural production systems, the manufacturing processes of agricultural inputs such as N fertilizers are also responsible for direct emissions of CO<sub>2</sub> into the



**Figure 8.** Global N<sub>2</sub>O emissions (Tg N<sub>2</sub>O-N yr<sup>-1</sup>) from agricultural soils between 1990 and 2030 (adapted from Reay et al. [71]).

atmosphere [76]. According to the IPCC, nitrogen fertilizer application, crop residues, and N-fixing crops present a direct source of N<sub>2</sub>O emissions in agricultural fields [72] due to the excessive levels of N applied, the higher amount fixed by N-fixing crops, and higher concentrations in plant residue. The remaining N not taken up by the plant can be lost indirectly through surface runoff, leached nitrate (NO<sub>3</sub><sup>-</sup>) in groundwater, volatilization to the atmosphere or by biological soil processes such as nitrification and denitrification, all of which pose environmental concerns.

The environmental consequences of N fertilizer application in agriculture have become of great interest to many researchers worldwide. They aim to understand the mechanism of different N pools (both organic and inorganic forms of N in the soil), their interaction, and the processes by which they enter and leave the soil. N<sub>2</sub>O gas is a natural product of soil microbial activities, so understanding the biological processes and the factors affecting them will help in the international efforts toward the development of mitigation strategies for greenhouse gas emissions from agricultural soil. In addition, to optimize the trade-off between economic development and the impact of agricultural inputs on GHG emissions, environmental issues must be included in any future political agendas, as they are extremely important in terms of agricultural productivity and food security.

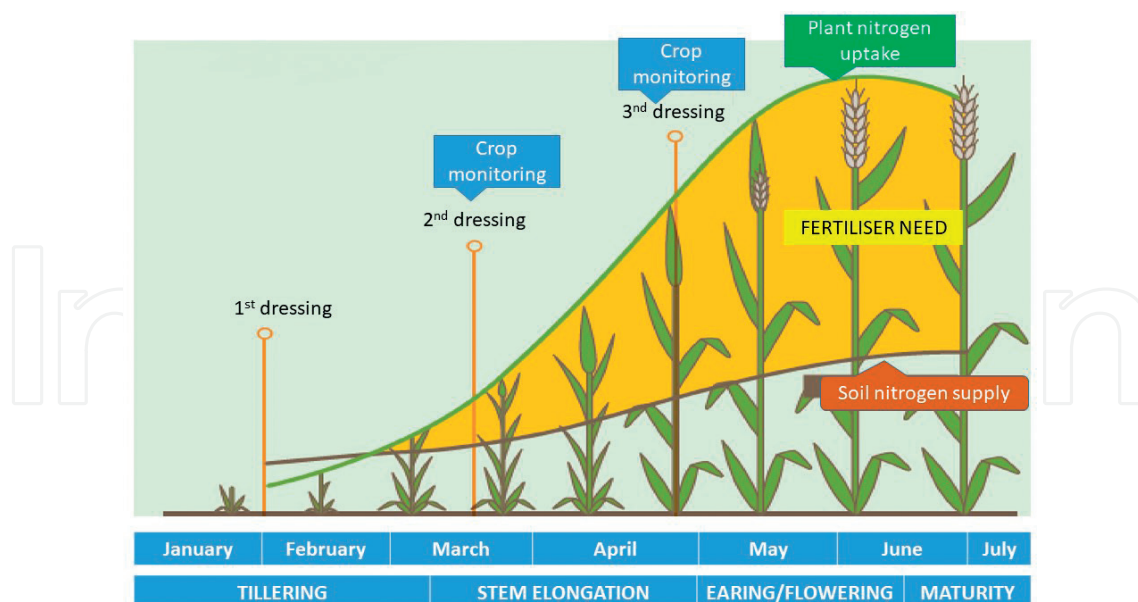
## 5.2. Mitigation strategy

Nitrogen has been widely studied to find ways of improving its efficiency in terms of producing acceptable grain yield and quality with less environmental impact. Recent research efforts have been directed toward reducing N loss from the soil by improving the absorption mechanism and the metabolism of N in the plant. Most have in fact succeeded in reducing

the excessive input of N fertilizers, while maintaining profitable grain yield with less environmental impact. The results indicate that efficiency and effectiveness of N use on crops can be achieved [77] through further synchronizing the timing of N fertilizer application and the N rate with plant nitrogen demand, and its capacity to uptake sufficient amounts of available nitrogen. This strategy is believed to be of paramount importance for the reduction of N<sub>2</sub>O and therefore GHG emissions from the cropping system. As N uptake capacity is generally low at the beginning of the growing season, a large quantity of N fertilizer applied at sowing time will lead to a greater potential for increased N<sub>2</sub>O emissions due to slow plant uptake. Bouwman et al. [77] indicated that not only does the N rate significantly influence N<sub>2</sub>O emissions from fields but also the N fertilizer type, and the time when the N fertilizer is applied throughout the growing season. Hao et al. [78] found that autumn N fertilizer application resulted in significantly greater N<sub>2</sub>O emissions than spring application. Despite being the key factor affecting total GHG emissions in the wheat production system, several studies in the literature found that the increased N fertilizer rate had no positive correlation with grain yield. Therefore, any wheat management option that reduces or eliminates the N fertilizer application (i.e., through the introduction of an N-fixing crop) would result in a significant reduction in total emissions. Rees et al. [79] highlighted the importance of N supply reduction in an emission mitigation strategy. Mosier et al. [80] indicated that improved soil management and better nutrient use efficiency could result in a reduction of 10–30% of total emissions from the soil.

To tackle the projected changes in climate events and the potential effects on crop yield, farmers should focus on the establishment of sustainable wheat production systems through efficient management of agricultural inputs [81]. As N inputs are the main cause of several environmental problems, a priority when establishing such a system would be to make them more efficient. The calculation of nitrogen use efficiency (NUE) as an agro-environmental indicator is important in the agro-policy context [82], as it informs the economic utility of a specific N fertilizer quantity applied to the field with reference to crop yield. However, to obtain the maximum from N fertilizer application in cereal production, Pires et al. [82] suggested that both the environmental and economic pillars of sustainability must be addressed along with agronomic efficiency. Alternative management strategies have recently been proposed to optimize the NUE and therefore increase crop yield, including N fertilizer timing, split applications, site-specific management, crop rotation, crop diversification, biological N fixation, and improved plant traits by genetic breeding, which is believed to help improve yields with a low input of N fertilizer, reducing its losses from the agriculture system [83]. Options such as the use of biological nitrification inhibition by *Brachiaria* roots exudates [84] and the adoption of alternative farming techniques based on no-till continuous cover cropping [85] are other strategies for improving NUE. However, the response to these management strategies can vary, depending on the complex interaction of soil, crop, and environmental factors.

The literature review shows that the yield response varies with the nitrogen and moisture level. The goal of N application to wheat and its timing is to supply adequate N when the crop needs it (**Figure 9**). As the nitrogen cycle is biologically influenced by prevailing climatic conditions, along with the physical and chemical properties of a particular

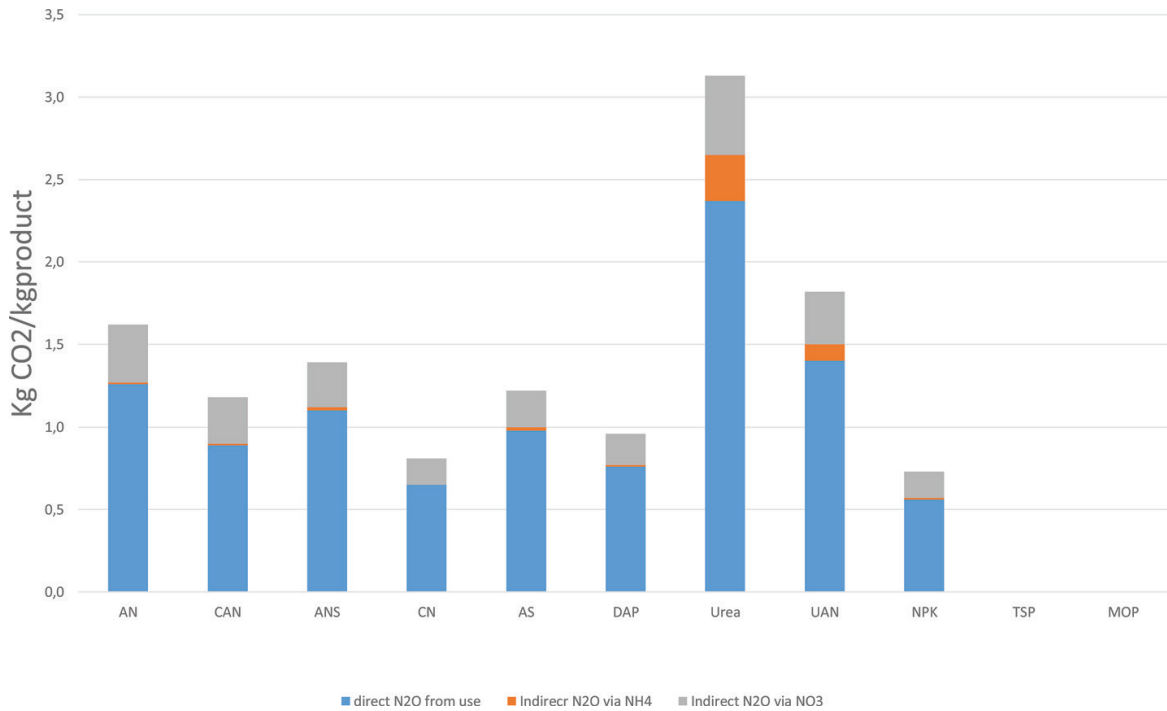


**Figure 9.** Timing and application of N fertilizer in winter durum wheat (from Fertilizers Europe).

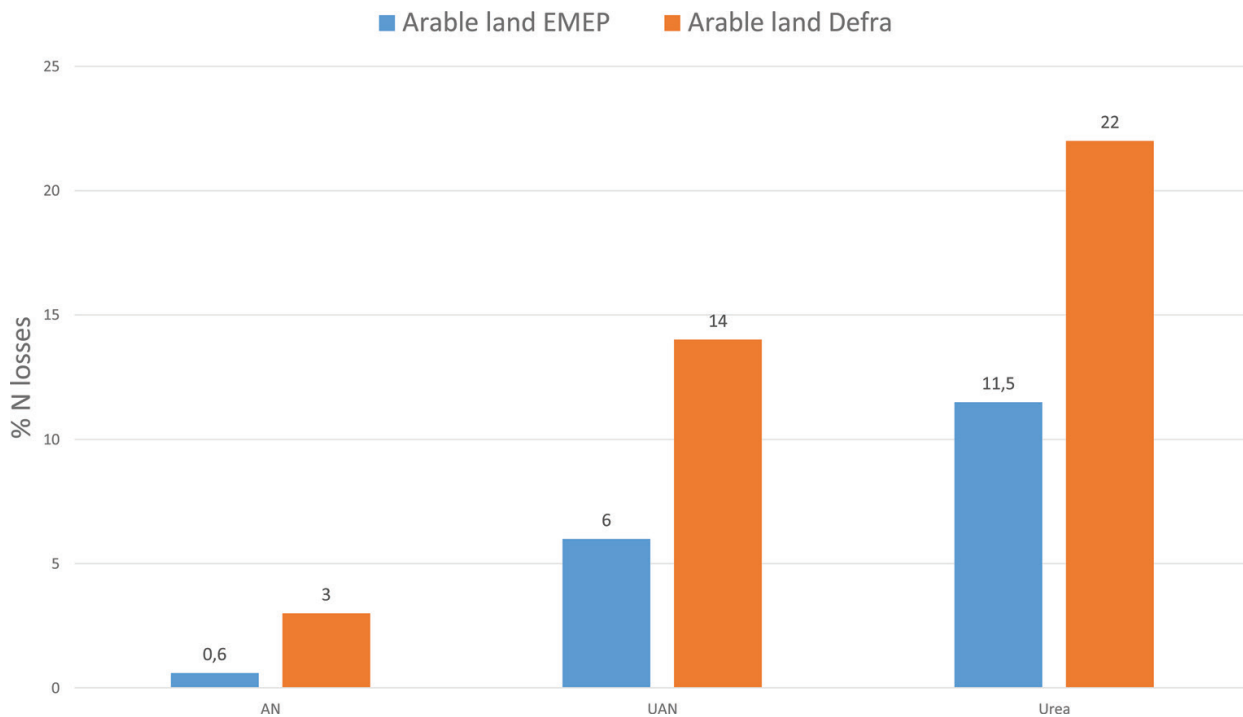
soil, the choice of a suitable N fertilizer formula for a specific soil is fundamental [86]. The electrical charges of soil particles vary according to the soil texture, so studying the chemical properties and reactions within soil particles will help understanding when and which N fertilizers type can be applied to a specific soil. These reactions are believed to have a significant influence on when fertilizer can be applied and how efficiently the crop takes it up. As explained, clay particles in the soil have a negative electrical charge, so the amount of clay present in the soil surface, which the fertilizer first comes into contact with, is an important factor controlling plant response to the N type and the timing. The clay particles with negative charges will react with components of the fertilizer that dissolve as positively (+) charged particles (cations) when added to soil. For example, the application of N fertilizers that include more ammonium (positively charged) and less nitrate (negatively charged) forms of N can reduce their potential for losses in the short term. The application of the correct type of N fertilizer can help reduce  $N_2O$  emissions from the soil, according to the Fertilizers Europe Initiative. **Figure 10** shows comparative  $N_2O$  soil emissions resulting from the application of different nitrogen fertilizers, and **Figure 11** shows N losses via volatilization emissions. In both cases, N losses are significantly higher with urea than other N fertilizers.

Ammonium ( $NH_4^+$ ) forms of N binding to soil particles with negative charges will not be subjected to losses through leaching or denitrification, and therefore, increase the N availability for the plant [87]. However, if the total amount of applied ammonium is not taken up by the plant, soil bacteria will convert the remainder to nitrate ( $NO_3^-$ ), a form that cannot bind to soil particles and will be lost when excessive rainfall leaches or saturates the soil. As identified, soil conditions are important in the transformation process, and nitrifying bacteria activity is minimal in cold soil temperatures, which can naturally help protect ammonium forms of N from losses.





**Figure 10.** Comparative N<sub>2</sub>O emissions from the application of different nitrogen fertilizers (adapted from Fertilizers Europe). AN, ammonium nitrate; CAN, calcium ammonium nitrate; ANS, ammonium nitrosulphate; CN, calcium nitrate; AS, ammonium sulphate; DAP, ammonium phosphates; Urea, urea; UAN, urea ammonium nitrate; NPK, NPK 15-15-15; TSP, triple superphosphate; MOP, muriate of potash.



**Figure 11.** Volatilization losses (% N) from the application of different N fertilizers in arable land; Adapted from Fertilizers Europe; Data from the official European Emission Inventory (EMEP) as well as from a UK Government Department of Environment, Food and Rural Affairs (Defra) study.

## 6. Conclusion

Durum wheat is mainly cultivated in Mediterranean countries, but it is also of great importance in other European countries and in Canada and the United States, which are the world's leading exporters. The quality of durum wheat, often considered only in product market and technological terms, is in fact the result of a complex system that must take into account all the components of the supply chain. Climate change and the consequences of greenhouse gas emissions make crops very susceptible to climate variations, resulting in a variable yield response.

In addition to aspects related to the nutritional, safety, and technological characteristics of the product, it is also necessary to consider those related to the production environment, through the development of agronomic strategies that can improve precision farming, or techniques that can reduce the environmental impact of cultivation (conservative farming).

The possibility of using improved varieties with better efficiency and higher quality standards could offer an opportunity to increase Mediterranean production, making it less dependent on imports from foreign countries. The strategy should include changing the phenological model to avoid stressful times during plant growth. In addition, a comprehensive understanding of the responses of each plant growth phase to environmental variables such as high CO<sub>2</sub> concentration, temperature, and drought, alone or in combination, will help the crop plant adapt to these changes. Nitrogen fertilization is an indispensable agronomic technique that can achieve good levels of production, both quantitatively and qualitatively, and has been extensively studied in the Mediterranean environment.

The application of precision farming systems (drones, NDVI systems, N sensors, etc.) can provide useful indications for the precise application of nitrogen. Many experiments suggest that the best agronomic technique in nitrogen application is the splitting of nitrogen application (sowing, tillering, stem elongation, and if necessary grain filling), which appears to be more efficient than the application divided once, which gives a 15% increase, or twice, where the increase is 7%. This strategy appears to be effective in reducing the loss of soil nitrates through leaching runoff and denitrification, which is more of a risk during the winter period, when the rainfall in the Mediterranean climate is concentrated. In fact, several types of nitrogen efficiency, and efficiency in N fertilization, increase when the fertilizer is applied at the stem elongation phase, while higher levels of N at the sowing time and tillering result in poor efficiency. The splitting application of nitrogen appears to be an effective method of avoiding environmental problems associated with the potential loss of this element, but more importantly could maximize the efficiency of the fertilization of wheat, increasing the yield in the Mediterranean region and providing a rational management strategy for the crop.

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