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Agriculture pollution control policies :

A case study of nitrate pollution in the Apulia region (Southern Italy).

Elie Fares

Série "*Master of Science*" n°64

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Institut Agronomique Méditerranéen de Montpellier

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Abstract:
Intensive agriculture causes many forms of environmental pollution. In this work, a method of coupling agronomic and economic models is used to analyse the effect of different agro-environmental policies addressing nitrate pollution. The scale has been selected to focus on the farm response to different policies. The study covers two typical farms in the Apulia region (Southern Italy, the first in Brindisi and the second in Cerignola. The 14-hectare Brindisi farm grows the following horticultural crops: tomato, lettuce and sweet melon. The Cerignola has an area of 30 ha and is under cereal crops like wheat, sorghum, maize and sunflower. Different levels of irrigation and nitrogen were introduced. The agronomic model CropSyst was used to simulate yield and nitrate leaching. These outputs, in addition to other economic outputs, were used as inputs in a non-linear optimisation model written in GAMS language with the objective of maximising the farmer's income. A multi-criterion approach was used to analyse the impacts of agricultural policies on the reduction of nitrate pollution: increased water pricing, subsidies for cross-compliance activity, flat-rate and block-rate taxes on N-fertilisers. A 50% reduction of pollution on cereal farms indicates that water pricing has a social cost of € 5 per ha^{-1}; flat-rate taxes have a social cost of € 27 per ha^{-1} , the social cost of cross-compliance is also € 27 per ha^{-1} and block-rate taxes have a cost of €31 per ha^{-1}. The results for horticultural farms indicate that block-rate tax has a social cost of € 337 per ha^{-1}, that of water pricing is € 509 per ha^{-1}, the social cost of cross-compliance is € 652 per ha^{-1} and flat-rate taxes € 1127 per ha^{-1}.

Keywords: modelling, nitrate pollution, subsidy, policy, water pricing, taxes, agriculture, environment.

Résumé :
L'agriculture intensive est à l'origine de plusieurs formes de pollution environnementale. Dans ce travail, la méthode de couplage des modèles agronomiques et economiques est employée pour analyser l'effet de différentes politiques agro-environnementales sur la pollution de nitrate. L'étude considérera deux fermes typiques de la region de Pouille (Sud de l'Italie): la premiere est située à Brindisi et la seconde à Cerignola. La surface de la première ferme est de 14 ha, avec les cultures horticoles suivantes: tomate, laitue et melon. Celle de Cerignola a une superficie de 30 ha cultivée de cultures céréalières comme le blé, le sorghom, le maïs et le tournesol. Différents niveaux d'irrigation et d'azote ont été rapportés. Le modèle agronomique CropSyst a été employé pour simuler le rendement et pour estimer la lixiviation des nitrates. Ces sorties, en plus d'autres données économiques, ont été employées dans un modèle non linéaire d'optimisation, écrit en langue GAMS. La fonction objective était de maximiser le revenu du l'agriculteur. Une approche multi-critères a été employée pour analyser les impacts des politiques agricoles sur la réduction de la pollution par les nitrates, comme: l'augmentation du prix de l'eau, subventions pour l'activité de cross-compliance et les taxes sur des engrais azotés. Les résultats indiquent qu'avec une réduction de pollution de 50% pour les cultures céréalières, l'augmentation du prix de l'eau est associés à un coût social de 5 €.ha^{-1}, de 27 €.ha^{-1} pour les taxes plates et pour l'activité de cross-compliance, de 31 €.ha^{-1} pour les taxes en bloc, alors que pour les horticultures, les resultats indiquent que les taxes en bloc on un côut social de 337 €.ha^{-1} ; suivi de l'augmentation du prix de l'eau associé à un coût social de 509 €.ha^{-1}, le côut social pour l'activité de cross-compliance est de 652 €.ha^{-1} et pour les taxes plates, le cout social est de 1227 €.ha^{-1}.

Mots clés: modélisation, pollution en nitrate, primes, politique, prix de l'eau, taxes, agriculture, environnement.

Agriculture pollution control policies: A case study of nitrate pollution in the Apulia region (southern Italy)

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Ce *Master* est le numéro 64 de la série Thèses et *Masters* de l'Institut Agronomique Méditerranéen de Montpellier.

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a case study of nitrate pollution in the Apulia region (Southern Italy)

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Agriculture pollution control policies:
A study case of nitrate pollution in
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List of abbreviations

D: deep percolation
DM: dry matter
ET: evapotranspiration
HI: harvest index
PET: potential evapotranspiration
S: surface run-off
WUE: water use efficiency
Y: yield

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Chapter 1
Statement of the Problem

I. Introduction

Water is an essential input in the various economic sectors of society. However, agriculture is the major consumer with an allocation for irrigation of between 70% and 80% of total water consumption (Hamdy and Lacirignola, 1997). Excessive or inappropriate use of water in irrigation leads to serious degradation of the environment. One of the negative externalities in irrigated fields is nitrate leaching leading to the pollution of ground and surface water and the endangering of human life when this pollution reaches drinking water

Controlling water pollution caused by agriculture is difficult because of its nature. Agricultural pollution generally affects large areas and its sources are diffuse and difficult to identify. It depends not only on rainfall patterns, the slope of the land and soil characteristics but also on farmers' land use and choices of crop, production techniques, use of fertilisers and pesticides, etc., and vary in time and space. Farmers' decisions are in turn affected by market prices for inputs and outputs, as well as by government agricultural support policies. In contrast with many industrial and municipal situations, few pollution control alternatives are readily available for installation on farms. Pollution control measures must rely heavily on approaches that affect farmers' land use and management decisions. Thus, agricultural policies that directly influence these decisions and 'environmental policies' to control agricultural water pollution must be co-ordinated and pursued with the same goals. Agricultural water pollution is becoming a major concern not only in developed regions such as the European Union (EU), the United States of America (USA), Canada, Australia, etc. but also in many developing countries.

The intensification of agricultural practices and in particular the growing use of fertilisers and pesticides and the specialisation and concentration of crop and livestock production have had an increasing impact on water quality. The main agricultural water pollutants are nitrates, phosphorus, and pesticides. Rising nitrate concentrations threaten the quality of drinking water, while high pesticide use contributes substantially to indirect emissions of toxic substances. Increasing levels of nitrates and phosphorus in surface water reduces its ability to support plant and animal life and makes it less attractive for recreation.

Nitrate pollution has become an important cause of water contamination since the mid-twentieth century. Leaching of nitrate pollutes ground water and surface water, causing the deterioration of the quality of water used by all the other sectors and public health problems.

The question behind such problem has a strong economic implication: “Who is going to pay for pollution?”

Nitrate pollution has two causes. The first is industrial pollution, referred to as pointsource pollution. The detection, measurement and control of pointsource pollution is easy. The second is the nitrate pollution caused by agriculture. This is known as non-pointsource pollution and is difficult to detect in space, to quantify and to control effectively. This type of pollution is affected by natural events (mainly rainfall) and agricultural practices

The policy measures used to control this type of pollution are land retirement, effluent taxes, pollution reduction standards, irrigation water pricing, incentives for the adoption of less pollutant agricultural practices (increased irrigation efficiency), taxes on nitrogen fertilisers applied, block-rate taxes on nitrogen fertilisers applied and cross-compliance subsidies.

The present work is focused on nitrate pollution. The aim of the study is to investigate the effectiveness of certain agricultural pollution control policies.

II. Study objectives

The objectives were to test the hypothesis that different types of specialised farming systems respond differently to different economic control policies and to evaluate the degree of control effectiveness.

A cost-effectiveness analysis method was used to evaluate alternative policies for reducing nitrate pollution in irrigated agriculture in two representative specialised farms.

Because nitrogen pollution depends on both local conditions such as climate and soil and also on the type of agricultural production and agricultural practices, it is increasingly recognised in recent literature that the application of uniform policies to nonpoint pollution problems may lead to sub-optimal regulation.
This approach leads to the following objectives:

- measuring the impact on income associated with specific environmental targets, i.e. how changing water pricing will affect the level of nitrate pollution, farmers' behaviour, crop production, cropping patterns and farmers' incomes;
- a tool for the evaluation of alternative policies, i.e. defining the level of subsidies awarded on condition that environmentally friendly agricultural practices are used;
- a decision support tool for the better definition of agro-environmental and rural policies.

III. Methodology

The methodical approach combines a biophysical crop-growth simulation model and a mathematical programming model at farm level, leading to "bio-economic" modelling. This methodological approach has been developed during the past decade in several parts of the world (Europe, the USA and Australia).

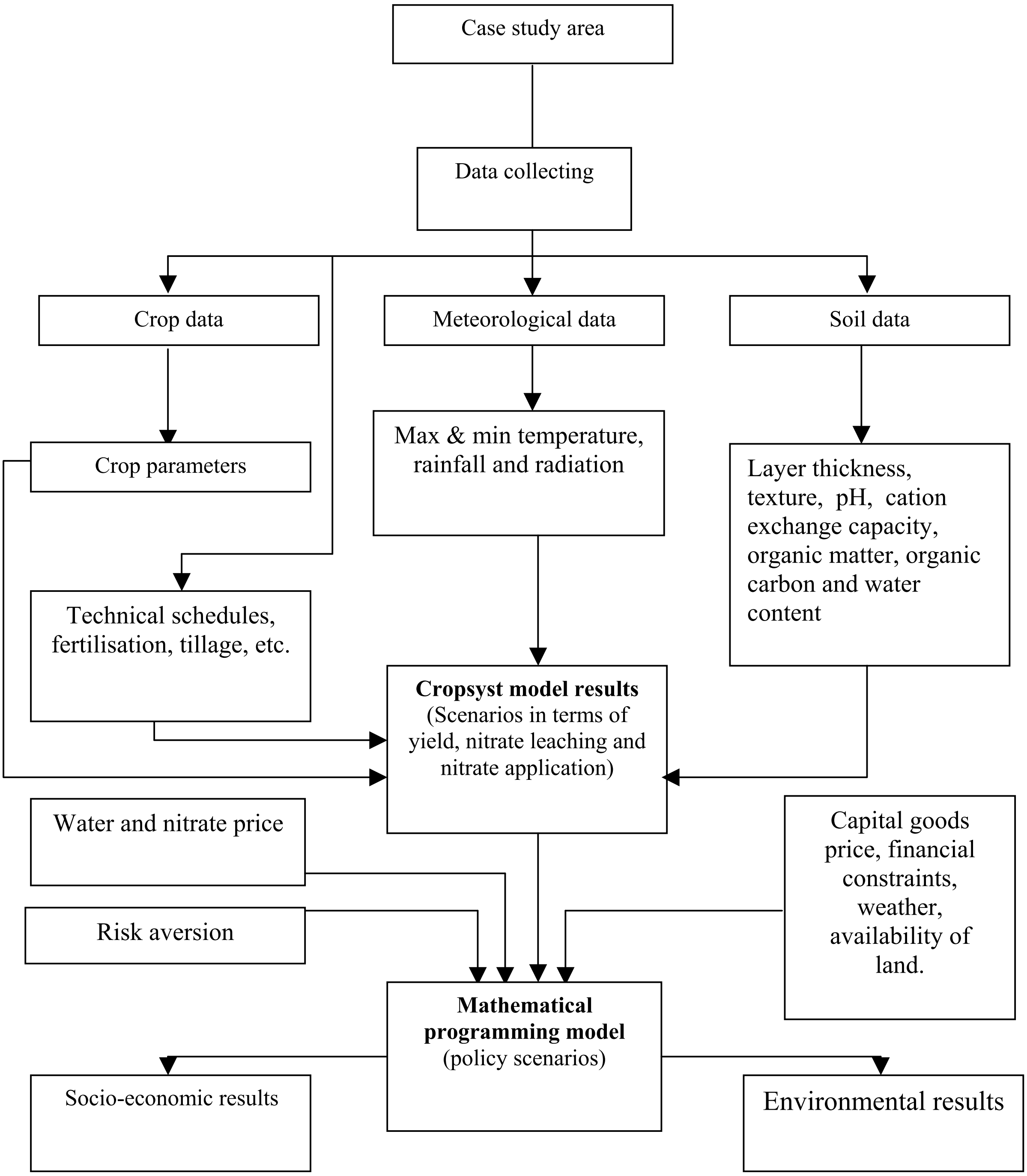
- The first step consists of use of the agronomic simulation model that considers the interaction of crop growth with climate, soil and agricultural practices, including irrigation and fertilisation.
- The second step is the incorporation of information from the biophysical model in economic model. The output of the agronomic model is the input for the economic model to investigate the form of response to price of products and production costs, such as labour, fertilisers, irrigation, etc.

This is followed by multi-scenario analysis in which changing policy shows the effects on farmers' income and the environmental impacts of agricultural production. The methodological approach is outlined in Fig. 1.

The study areas are Brindisi and Cerignola in the Apulia region (south of Italy). This region is characterised by irregular rain distribution over the year, as in the whole of Southern Italy, with a relatively long dry period in spring and summer. Average rainfall is about 460 mm, distributed from October to May.

Water is very limited in comparison with annual climatic demand of about 1200 mm.

Fig. 1. The methodology



Chapter 2 : Bibliographic Review

Increasing productivity in agriculture requires the use of plant nutrients such as nitrogen, phosphorus and potassium in the form of fertilisers. However, when these elements are applied in excess of plant requirements, they can pollute surface and groundwater (Devinder et *al.,* 2000).

Global industrial production of nitrogen fertilisers has increased steeply from practically zero in the 1940s to roughly 80 million metric tons per year. Only 18% of the nitrogen inputs in fertilisers is taken up by crops in the USA and Europe, This means that an average of 174 kg per ha^{-1} surplus N is left on cropland each year (Carpenter, 1998).

Nitrogen influences crops in three distinct ways. Two involve the quantity of the yield (leaf area and crop development), and the third its quality (crop quality).

Nitrogen fertilisers have been applied in very large amounts to field crops in many countries since the 1950s. The international consumption of nitrogen increased from 59 to 82 million tonnes from 1980 till 1988 (Frankard *et al.,* 1990). Since plants are often unable to use all the nitrogen applied to the fields, some is left in the soil and may leach into ground water. In addition, not all the nitrogen applied goes into the soil; some is washed off the fields in runoff and flows into surface water such as streams and rivers. The runoff problem is often greatest when manure is used as fertiliser.

I. Principal forms of nitrogen

1. Ammonium

Ammonium is present in the air, generally as small particles of carbonate or nitrate. The soil can absorb it during rainfall events. However, ammonium salts in the soil result from the mineralisation of organic matter (Deysson, 1982).

2. Nitrates

It has long been known that nitrates are mainly taken up by plants and at first sight are the most common and the best nutrient for green plants (Righter, 1993).

Plants take up NO_3^- and if this anion is present in excess in the soil solution may absorb it excessively with consequent increasing tenderness of tissues and delay in fructification.

3. Organic nitrogen

The average organic matter content of soils ranges between 1 and 4% by weight and includes almost 5% organic nitrogen, corresponding to about 2,000 to 8,000 kg organic nitrogen per hectare (El Hassani and Persoons, 1994).

II. The dynamics of nitrogen in the soil

The rate of mineralisation organic matter of is fairly variable, with the release about 20 to 80 kg mineral nitrogen per hectare per year (Mustin, 1987) depending on the nature of organic humus in the soil, temperature, moisture content, pH, etc., which influence the microbial life responsible for mineralisation.
Nitrogen applied in fertiliser or manure is converted to plant-available-nitrate by soil bacteria. The growing plants consume part of this nitrate. Growing bacteria also consume nitrates. When sufficient decomposable organic matter is present, soil bacteria can remove a significant amount of nitrate-nitrogen through a process called immobilisation. Another group of bacteria converts nitrate to a gaseous form when oxygen is limited; this is called denitrification. The nitrates not taken up by crops, immobilised as

organic matter or converted into atmospheric gases by denitrification, can leach out of the root zone and possibly end up in ground water (Devinder et *al,* 2000).

III. The nitrate problem

Nitrate is a widespread contaminant of ground and surface waters world-wide (Hallberg, G.R. 1989, Puckett, L.J. 1995).

Nitrate is a potential threat to human health—especially that of infants—in two ways: causing the condition known as methaemoglobinemia, also called "blue baby syndrome" (Fraser and Chilvers, 1981) which affects children under the age of 6 months, and stomach cancer (Hill *et al.,* 1973). The current public health standards for safe drinking water require that a maximum contamination level (MCL) should not exceed nitrate concentrations of 10 ppm as nitrate-nitrogen or 45 ppm as nitrate. Nitrate is converted to nitrite, which then combines with haemoglobin to form methaemoglobin, thus decreasing the ability of the blood to carry oxygen (Kross, B.C. *et al.,* 1993, Bruning-Fann *et al.,* 1993). Furthermore, it has an environmental impact such as the eutrophication of freshwater leading to loss of aquatic diversity (aquatic plants, fish, etc.). The accumulation of nitrate in the environment results mainly from non-pointsource runoff, leaching, over-application of nitrogenous fertilisers and poorly treated or untreated sewage. In addition, many industrial processes including paper and ammunition manufacturing produce nitrate-containing wastes. Because agriculture is involved in the nitrate pollution problem, farmers and rural communities are the most threatened populations.

IV. Factors affecting nitrate leaching

1. Fertilisers

The degree of nitrogen leaching is influenced by fertiliser types (ammoniac, nitrate or organic) as well by application methods. Nitrate leaching may be greater when a fertiliser contains nitrate in comparison with situations in which ammoniacal nitrogen is the major component of the fertiliser. Greater losses are likely when all the nitrogen is applied in a single application compared to split applications. The leaching of fertilisers can be reduced to a minimum by matching fertiliser application to crop nitrogen requirements.

2. Soil types

Nitrogen fertilisers or manure used on sandy soil are more exposed to leaching to groundwater that on clay soil because water carrying nitrates moves rapidly through sandy and other coarse-textured soils. Soil thickness and the distance between the root zone and the groundwater also determine the vulnerability of an aquifer to pollution. The closer the plant's roots are to the water table, the more rapidly nitrates enter ground water. Nitrate leaching from shallow soils on fractured rocks such as limestone can cause extensive contamination of groundwater.

3. Crop types

Crops that are likely to increase nitrate leaching are those that have high N requirements, high economic value and whose use of N tends to be inefficient. High-value crops such as nursery crops, greenhouse crops, orchard and vegetable crops are more likely to receive high application rates of N fertilisers. Any excess of N that is not used by the plants may become a source of pollution.

4. Irrigation

Water applied in amounts exceeding evapotranspiration often leads to runoff or deep percolation. As nitrates are highly soluble salts, moving water dissolves some of the nitrates present. This will lead to the contamination of surface and groundwater. The use of irrigation therefore increases the probability of nitrate pollution. A study performed by Burkat and Kolpin (1993) showed that the frequency of excess nitrate of a well was larger when irrigation was used, even at a distance of 3.2 km from a well (41%), than when no irrigation was used (24%). Furthermore, nitrate pollution is also linked to the amounts and times of watering and to application efficiency.

V. Water pollution by nitrates

Movement of rainwater to groundwater often occurs in a climate with rainfall exceeding evapotranspiration. A proportion of the water received through precipitation becomes surface runoff and flows from the land via rivers and streams. Because nitrates are highly soluble salts, when water moves on the surface of the soil, they dissolve some of the nitrates present in the surface layers of the soil.

Another fraction of precipitation seeps into the soil and recharges the groundwater. This seepage water dissolves nitrates and carries them to the groundwater. Most of the flow in mountain streams results from groundwater. Thus, nitrates that were initially lost through leaching to groundwater can contribute to nitrate pollution of surface water such as streams, rivers and lakes.

VI. The socio-economic environment

The challenge is that of using an integrated approach to land and water to develop management strategies that (i) minimise unproductive water losses and (ii) guarantee the long-term productivity of the soil. A crucial point from the agro-hydrological point of view is that nutrient and moisture issues cannot be addressed separately as one is the limiting factor for growth when the other is abundant. The management practices proposed for tackling this prior condition for successful agricultural performance can only form a sustainable solution if they are accepted within the socio-economic context.

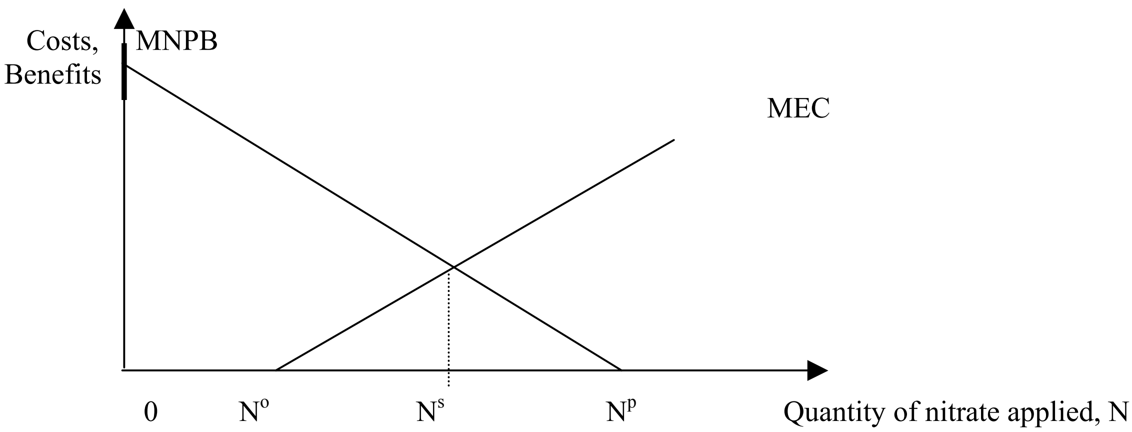
The design of economically efficient agri-environmental policies requires tools that can quantify the relationships between agricultural production and the economy on the one hand and nitrogen loading on the other. The complexity of the problem is further aggravated by the non-point nature of agricultural nitrogen pollution. Nitrogen pollution depends on local conditions such as climate, soils and agricultural production practices.

Thus, applying uniform policies to non-pointsource pollution problems may lead to suboptimal regulation but the degree of inoptimality depends on the spatial heterogeneity of the relevant conditions (Opaluch and Segerson, 1991, Mapp *et al.,* 1994, Fleming and Adams, 1997). In contrast, the number of studies at more aggregate levels (top-down studies) is very limited and most are not precise with respect to the modelling of policy responses and emissions as the site-specific properties of pollution are approximated by the use of regionalised models (Helming, 1996; Paaby *et al.,* 1997).

A framework is presented here in which the effects of agriculture on the economy and on nitrogen pollution can be modelled. The analytical framework quantifies relationships between agricultural production and the economy on the one hand and nitrogen loadings on the other, and is used for determining the relative importance of the contribution of various farm types to nitrogen loading and the economy.

The use of nitrogen fertilisers has increased in agriculture because of plant response to nitrogen input. Meanwhile, a number of side-effects can be found in the form of damage to the physical environment and human health, and nitrate pollution is considered as a non-pointsource externality. An externality is a factor that occurs when, in addition to normal production (e.g. agricultural production), other products are created that may be advantages or disadvantages for other groups in society (e.g. nitrate leaching). These externalities are not generally considered in market transactions (Stiglitz, 2000). This externality side of nitrates is shown in Figure 2 by Hanley (1990). The marginal external cost (MEC),—the cost of this side-effect of the production activity—paid by the victim or society shows that pollution increases as the amount of nitrate applied rises. As pollution increases, water with a low nitrate content becomes increasingly scarce, thus raising the cost of each additional unit of emission.

Fig. 2. The nitrate externality (Hanley, 1990)



The MEC function originates at point N°; below this point nitrates are assimilated by the ecosystem. As nitrogen inputs rise, then, *ceteris paribus*, the crop output will also increase. These output increases will decline in marginal terms due to diminishing returns. The marginal net private benefit (MNPB) is constructed assuming "price-taking behaviour" by the farmers; it is what will is called in the next sections the net revenue of the farmers. Given a constant output price and a fixed amount of all other inputs, MNPB falls as nitrogen input rises. Market inefficiency then occurs as farmers choose input N^p that maximises short-run profits whereas society would prefer input use N^s, which maximises net social benefit (and all other conditions for allocation efficiency hold).

However, this approach is complicated by the dynamic nature of the problem. Nitrates may take up to 40 years to travel from the soil to groundwater, depending on the nature of the intervening rock layers. Given the large conceptual and methodological problems associated with estimating contemporaneous external costs, this is, for all practical purposes, an impossible task (Hanley, 1990). This means that policies aiming at reducing nitrate pollution may have no direct impact on water quality. This may take many years to appear.

VII. Policies

Four types of policy can be used to regulate non-pointsource pollution. These are non-point incentives, non-point standards, management practice incentives and management practice standards. Non-point incentives place a tax on inputs for individual firms, whereas non-point standards limit the total emissions from each firm. Management practice incentives impose a system of taxes and subsidies on inputs for the production process, while management practice standards specify the actual input levels to be used. All the policies are defined using a non-point production function that gives estimated pollutant emissions as a function of input levels. This function must be made known to individual firms by the regulatory agency for the first two policies. Appropriately specified, these four policies are economically efficient under the deterministic conditions assumed in Griffin and Bromley (1982).

As nitrate leaching gives rise to undesirable environmental side-effects, it is relevant to consider policy options for mitigating these. We may divide these options into two categories: those that attempt to reduce the amount of nitrates entering the environment and those that attempt to remove nitrates once they are present in watercourses.

In the former category, attention is limited to nitrate originating from agricultural sources. The control options are better management of nitrate applications and better application rates.

1. Policy challenges

A policy for controlling agricultural water pollution must specify the nitrate quantity level desired and the measures to be adopted to achieve this goal. Various problems, including incomplete information about the costs and benefits of pollution abatement, make it difficult to determine the optimal level of water quality in terms of economic efficiency. As a result, the choice is often made using other criteria such as human health concerns or the protection of current uses of the water (Scheierling, 1995).

Policies that can affect farmers' land use and production decisions include voluntary measures such as education and training, moral persuasion, and technical assistance, regulatory measures such as performance standards (maximum discharge rates or maximum pollutant levels) and direct controls of outputs, inputs or technology and incentive-based measures such as taxes, subsidies, and transferable discharge permits. For pollution from a single source, Scheierling (1995) finds that it is often more efficient to adopt incentive-based measures, in particular an emissions tax, than regulatory measures for achieving a desired level of emission reduction. However, since agricultural emission sources are diffuse, they cannot be addressed directly with an emissions tax or a subsidy. Other incentive-based measures that could be used as proxies, such as taxes on output or on purchased inputs, do not provide efficient incentives for farmers to modify the ways in which they use inputs (e.g. fertiliser application methods and timing) even though such changes could significantly reduce agricultural pollution. Tax-based measures may therefore not be as effective in controlling pollution from diffuse sources as certain other regulatory alternatives (Scheierling, 1995).

The choice of appropriate measure is made more difficult by the fact that besides efficiency, environmental policy objectives often include other criteria such as equity, acceptability, administrative simplicity and risk reduction. It is clear that no single measure can meet all the criteria and a mix of measures will be imperfect in terms of meeting any single criterion. An effective policy therefore involves compromises.

Given these challenges, it is not surprising that effective control of agricultural water pollution is still an unresolved issue in many parts of the world. In the European Union, for example, the situation has been intensified by a supranational agricultural policy that for decades has stimulated agricultural production and, indirectly, pollution. Environmental policy measures to reduce this pollution have to "compete" with agricultural policy measures.

2. Agricultural policies

During the second half of the 1980s, a variety of new measures were adopted to solve the agricultural policy crisis. Their main feature is a reduction in support prices for a range of agricultural products. Compensation for price reductions is granted through a range of direct payments made in connection with programmes, such as rotational set-asides and maximum livestock densities, that are designed to limit production.

An agro-environmental package is also included that aims at more environmentally friendly methods of production. Subsidies are offered to farmers who reduce livestock density, decrease fertiliser and pesticide use or a switch to organic farming or other more extensive forms of production (Scheierling, 1995).

A. Water pricing police

Some argue that water should be treated as an "economic good" and thus its allocation will be improved. But others argue for the consideration of water as a "social good" because water is crucial to human survival.

In any case, water pricing is a key method for the improvement of water allocation and the encouragement of conservation of the environment. The price of water should be considered as a component of integrated water management.

Countries implement water pricing schemes to attain short-term and long-term policy goals to recover costs, encourage water conservation and protect the environment (Dinar and Subramanian, 1997). This is an occasion for the concept of full cost recovery, which is the process of directly or indirectly capturing and directing to public agencies a portion of revenue resulting from government actions to provide irrigation services, regardless of whether or not the funds are used to pay any construction or operation and maintenance costs. In practice, the criteria for successful recovery can vary from only a small fraction of operation and maintenance costs to more than 100% of the total costs of construction and operation and maintenance (Abu Zeid, 1995).

The costs of supplying irrigation water consist of the variable costs of processing and delivering water to end users and the fixed costs of capital operation and maintenance (O and M). Variable costs depend on the amount of water delivered, while fixed costs do not (Tsur and Dinar, 1997).

B. Nitrogen taxes

Mineral nitrogen is a major issue of environmental concern. It is believed that the combination of relative prices for variable inputs and outputs has contributed to this externality problem. Economic instruments such as taxes can be used to internalise the externality problem into farmers' behaviour (Helming and Brouwer, 1887).

C. Cross compliance subsidy

This type of policy makes the application of certain agricultural practices a condition for receiving a subsidy. In the USA, for example, the access to any agricultural subsidy is conditioned by the application of tillage regulations in order to reduce soil erosion. In Europe, a typical case is the condition of respect of a maximum amount of animals per hectare to receive a specific subsidy for cattle farming. In an attempt to reduce nitrate pollution, a condition for receiving the subsidy could be the respect of a certain amount of fertiliser per hectare of crop, together with other technical characteristics.

Baldock (1993) gives a complete definition of this type of policy. The receipt of agricultural support is made contingent upon farmers undertaking specific environmental activities. The penalty for non-compliance with an environmental regulation is linked to the agricultural goals as well as to the environmental goal.

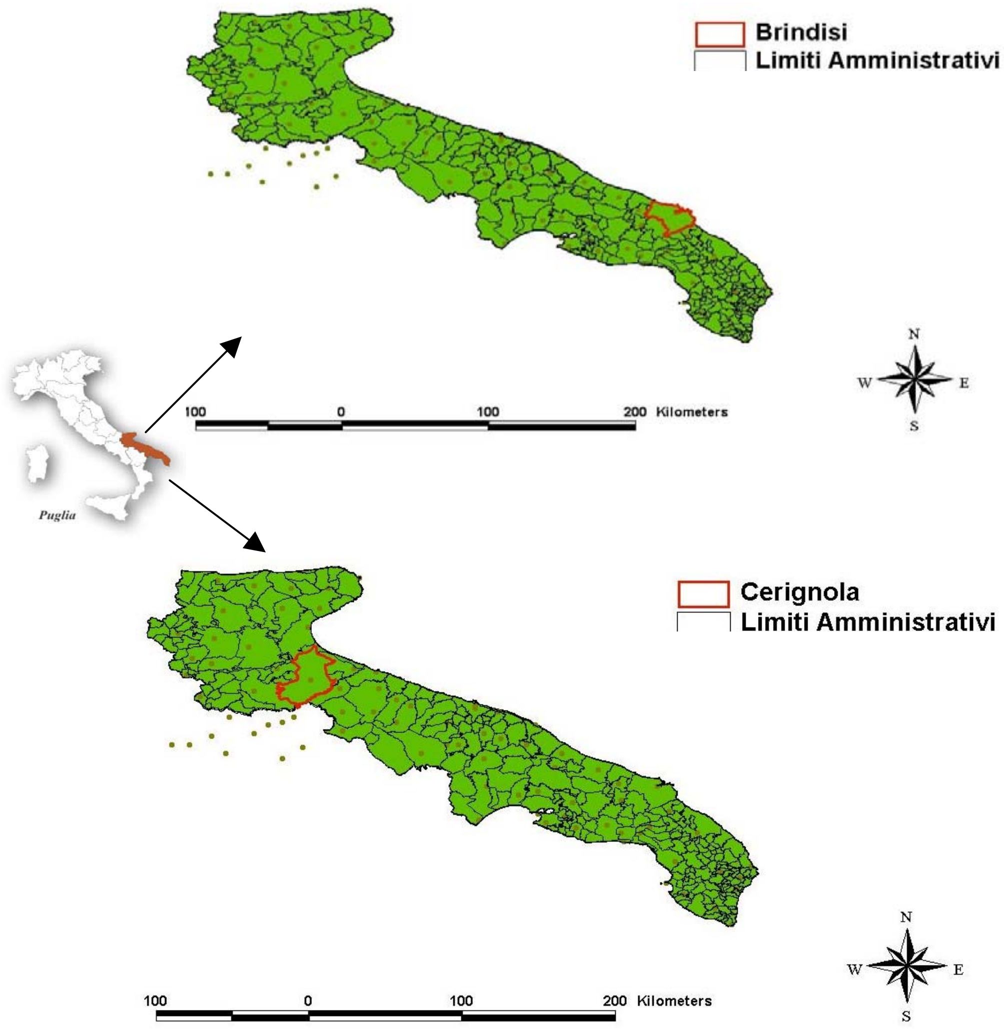
Cross compliance can be attached to a single measure, like direct payments, but it can also be attached to a larger range of benefits such as crop insurance or loans (Baldock, 1993).

Chapter 3
Material and Methods

I. Study area

The impact of agricultural activities on water quality can be performed at a range of spatial scales, e.g. at regional, catchment or local scales.

Figure 3: The two study areas are Cerignola and Brindisi in the Apulia region



The local scale was selected in this study to focus on farm response to control policies. Two typical farms of the Apulia region (Southern Italy) are examined: the first is in Brindisi and the second in Cerignola (Fig. 3).

The Brindisi farm has an area of 14 hectares under the following horticultural crops: tomato, lettuce, melon, lettuce, olive and almond. The Cerignola farms has an area of 30.5 hectares under cereal crops such as wheat, sorghum, maize and sunflower and tree crops such as grape vines and olive. The two farms are typical of those found in the region. Trees were not included in this study as it is difficult to simulate tree responses in an agronomic model approach.

The production structure, input use and value added at each farm are monitored by the Istituto Nazionale di Economia Agraria (INEA). INEA describes output, production and a comprehensive number of economic variables.

The farm sample is stratified according to the following criteria: revenue, agricultural area, farm type and farm location.

Soils range from sand to sandy-clay. The mean annual precipitation in 1930-1992 serial data is 557 mm, varying from about 577 mm in the eastern parts of Apulia to about 537 mm in the western part. This region is characterised by irregular rain distribution over the year, with a relatively long dry period in spring and summer. The mean monthly temperature varies from 6°C in January and February to 29°C in June and July in the eastern part and from 3°C in January to 33°C in July in the western part of the region.

II. Methodological framework

The methodology consists of multi-scenario analysis that, by changing the price of water or applying subsidies and taxes shows the effects of the latter on farmers' incomes and nitrate pollution. This makes it possible to identify a set of water pricing, nitrogen tax and subsidies corresponding to losses in farmer's incomes.

Such a methodological approach, on nitrate pollution in the present work, has previously been applied successfully to studies addressing erosion and agricultural externalities (Deybe, 1994, Flichman *et al.*, 1995, Donaldson *et al.*, 1995, Boussemart *et al.*, 1996, Blanco, 1996, Dalton and Masters, 1997, Louhichi *et al.*, 1999, Mimouni, *et al.*, 2000). The methodology used was the coupling of an agronomic simulation model (CropSyst) and a multi-objective non-linear programming model (MOPM).

1. Agronomic model

CropSyst is a user-friendly, conceptually simple but multi-year, multi-crop daily time-step simulation model with a mechanistic approach. It includes a variety of agronomic management options (irrigation, fertilisation, tillage, residue management, choice of cultivars and rotation) and environmental impact analysis capabilities (erosion and leaching of chemicals).

The model was developed to serve as an analytical tool for studying the effect of cropping system management on productivity and the environment. The model simulates the soil water balance, the soil-plant nitrogen balance, crop phenology, crop canopy and root growth, dry matter production, yield, residue production and decomposition and soil erosion by water. Agricultural planning is a broad management field (Glen J. J. 1987).

Irrigation management consists of determining when to irrigate, the amount to apply at each watering and during each stage of plant growth, and the operation and maintenance of the irrigation system.

The primary objective is to manage the production system for profit without compromising the environment. Most irrigation water management concepts include salinity control and the improvement of the soil-air-water environment. The benefits include increased, forecastable yields, enhanced crop quality and reduced farming risks.

During the past 25 years, the development and application of computer models to describe the main aspects of crop growth and yield processes and links as influenced by water availability have been substantial.

This development has resulted from better understanding of soil-plant-atmosphere processes. The development of computer simulation tools has led to several modelling applications in irrigation management (Pereira *et al.,* 1992, 1995.)

Crop systems are highly complex. Weather, soil physicochemical factors, pests, diseases, weeds, and interactions of these factors affect the crop in the field.

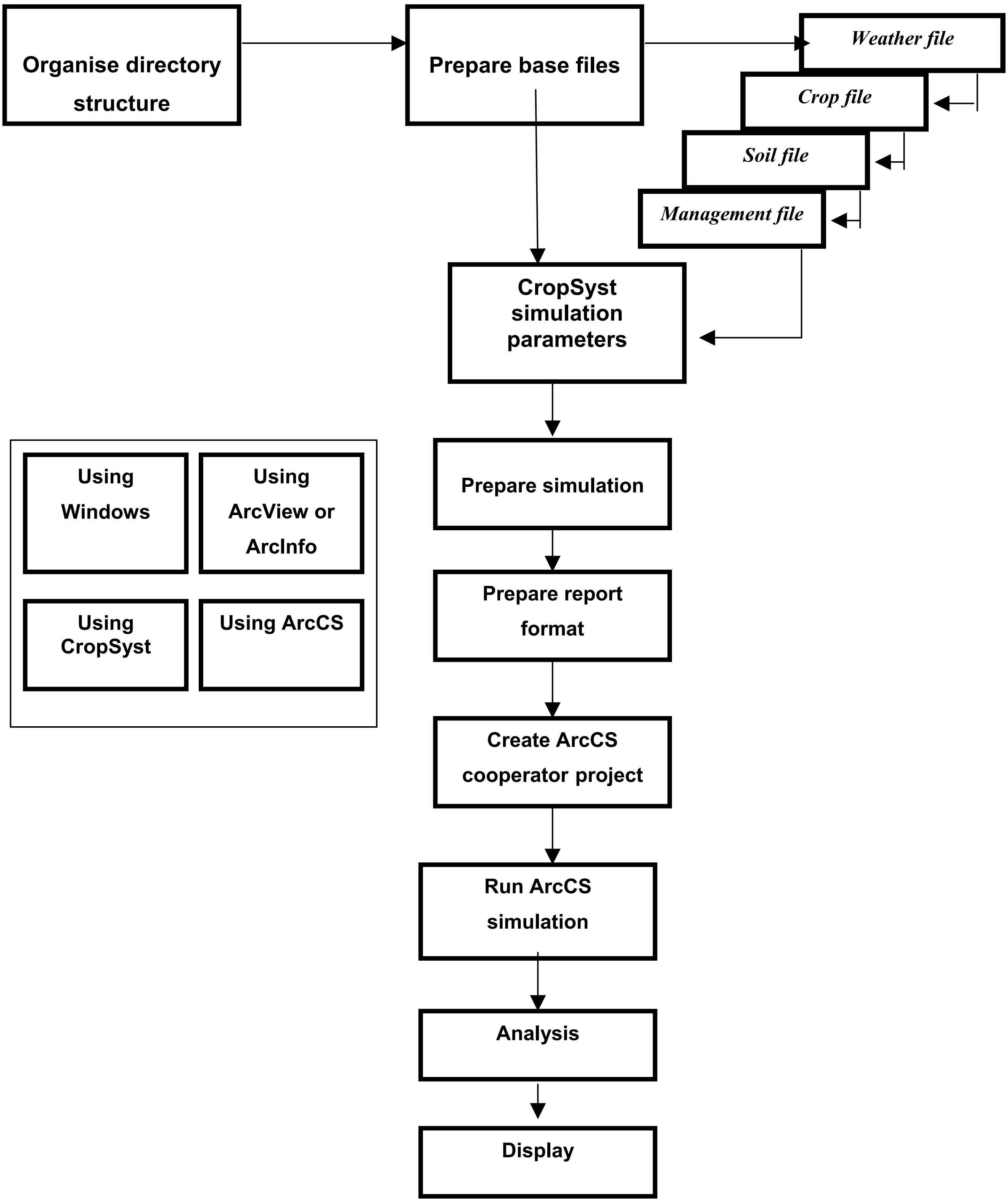
Crop simulation models are a mixture of empiricism and mechanism and even the most mechanistic models make use of empiricism at some hierarchical level.

A mechanistic crop model is generally considered to be based on physiological and physical processes and considers cause and effects at the process level. Material (carbon, nitrogen, water) and the energy balance are usually included. However, the most useful models for studying irrigation management of crops under various weather and soil conditions have mainly been functional models. The term *dynamic* is used to indicate that the crop model responds to daily (or more frequent) changes in the environment and that the event occurring in the first period affects the initial conditions of the second period. In fact these are recursive simulation models.

A number of crop modelling groups have attempted to optimise water and nitrogen management using long-term historical weather data (Hood *et al.,* 1987).

Crop models also can be integrated with optimisation procedures to allow the computer to automatically search for the irrigation strategy that maximises profit or satisfies other objective optimisation functions. Other objective functions may include energy use considerations for, water use efficiency (WUE), nitrogen leaching and water availability constraints.

Fig 4. Flow chart of the CropSyst model



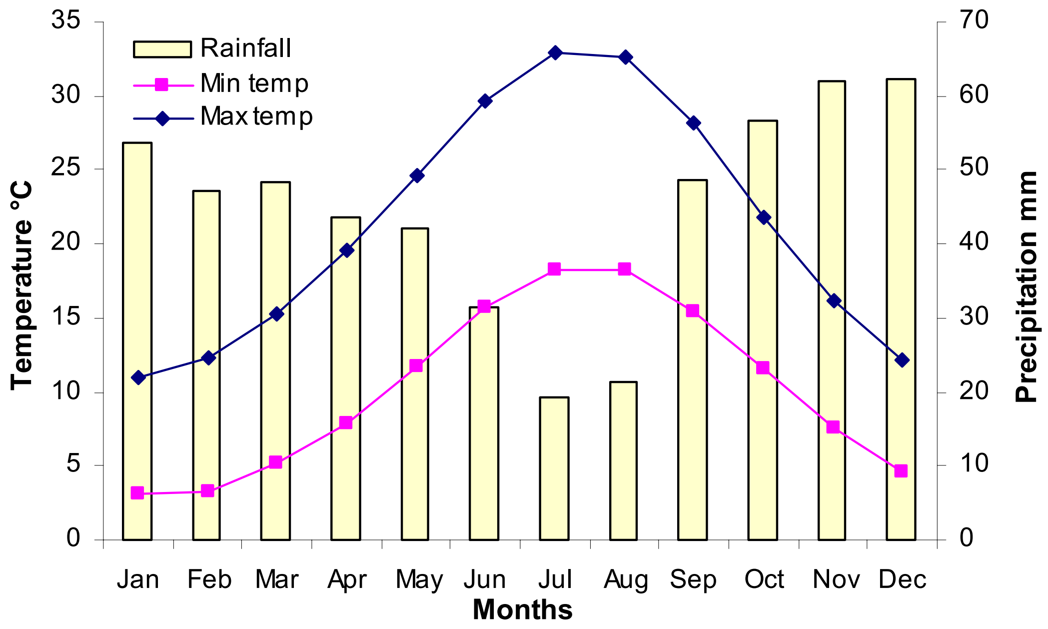
2. Agronomic data

For CropSyst, climatic data and soil data were used in addition to crop parameters to calibrate the model and for the management scheduling to run it.

The climatic file used in this work consists of a set of 12 years of daily data comprising temperatures (min and max), precipitation and radiation. This set is representative of 61 years of data.

Cerignola
Average rainfall is approximately 537 mm per year, with a maximum temperature of 33°C in July and a minimum temperature of 3°C in January and February. Rainfall distribution is typical of a Mediterranean climate with the highest value in November and December (≈60 mm per month) and the lowest in July and August (≈18 mm per month). Monthly temperature and rainfall distributions for the Cerignola farm are shown in Fig. 5.

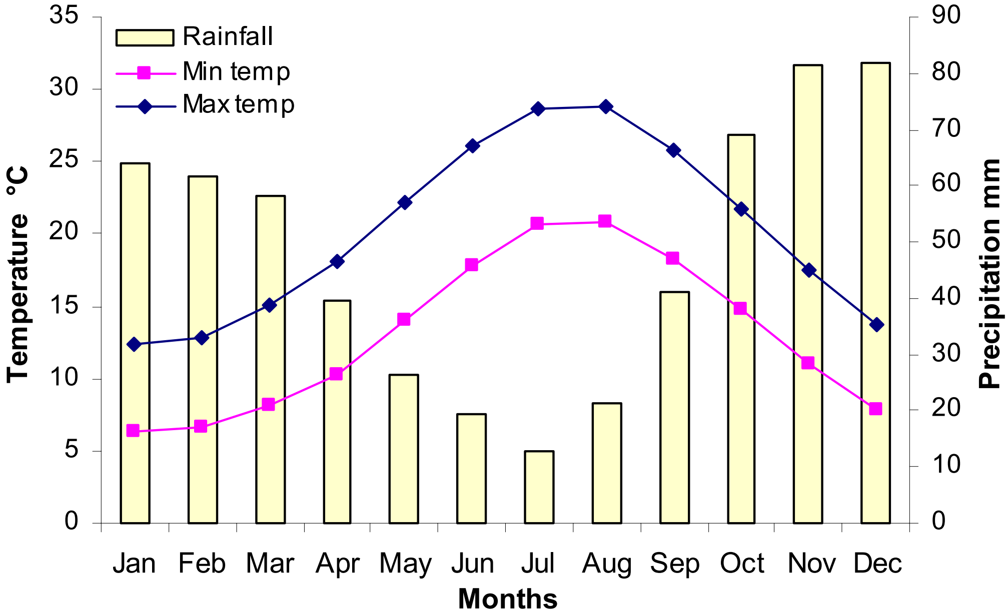
Fig 5. Rainfall distribution and monthly average maximum and minimum temperatures for the climatic series for the Cerignola farm



Brindisi Average rainfall is about 577 mm per year. The maximum temperature is 29°C in July and the minimum is 6°C in January and February. Rainfall is about 80 mm in November and December and falls gradually to the lowest values of about 10 mm in July.

Monthly temperature and rainfall distributions for the Brindisi farm are shown in Fig. 5.

Fig 6. Rain distribution and average maximum and minimum temperatures for the Brindisi farm



The soil data inputs for the different soil layers are layer thickness, texture, pH, cation exchange capacity and organic matter and organic carbon contents.

The Cerignola soil is sandy and that of Brindisi is sandy-clay. The characteristics are shown in Tables 1 and 2.

Table 1. Physical and chemical characteristics of Cerignola soil

Profile		**Texture**			**pH**	**C.org**	**CSC**
Upper limit (cm)	Lower limit (cm)	Sand (%)	Loam (%)	Clay (%)		(%)	(meq/100g)
0	20	64	8	28	7.89	0.077	23.5
20	30	64	7	29	7.94	0.538	22.5
30	40	38	10	52	7.71	0.504	40.1
40	50	65	5	30	7.91	0.336	24.9
50	70	54	6	40	7.84	0.285	31.5
70	90	81	3	16	8.03	0.101	16.1
90	105	69	4	27	7.99	0.067	25.1
105	115	82	2	16	8.01	0.05	19.1
115	130	57	9	34	7.89	0.05	27.5

Table 2. Physical and chemical characteristics of Brindisi soil

Profile		Texture			pH	C.org	CSC
Upper limit (cm)	Lower limit (cm)	Sand (%)	Loam (%)	Clay (%)		(%)	(meq/100g)
0	40	47	12	41	7.77	1.126	30.5
40	80	54	7	39	8.13	0.991	32.1
80	100	57	9	34	8.25	0.924	27.5

A. Crops and management

The existing crops are wheat, sunflower, sorghum, maize, tomato, melon and lettuce. For each crop, five different levels of irrigation were considered with five different levels of fertiliser application

B. CropSyst calibration and validation

Yield responses to water and nitrogen fertiliser were calibrated and validated under different climate conditions using experimental data. The calibration and validation procedures could only be performed for the yield response of different crops and no data were available for nitrate leaching.

On the horticultural farm, cash crops like tomato and melon are cultivated under optimum conditions such as providing plants with all the water needed and the fertiliser required to ensure maximum yield. The program was calibrated and validated on this basis. The default values in the crop file of the program were used for the cereal crops (wheat, sorghum, maize and sunflower). The program was run and gave the same yields as in reality so these values are appropriate for the region.

C. Scenario simulation

After calibration and validation, six amounts of water were applied with schedules and applications as follows: I0 is the rainfed condition. The 5 levels I1, I2, I3, I4 and I5 represent the attitude of the farmer and the schedules of irrigation that the farmer could use and are shown in Table 3. In addition to these 5 techniques, five levels of nitrogen fertiliser were applied to each crop (F1, F2, F3, F4 and F5). These are shown in Table 4. The simulated values under optimum management (with no restrictions on the use of nitrate and water) are shown in Table 3 for information about the results of different combinations in terms of yield values, nitrate leaching and other outputs

Table 3. Water iteration applied to each crop

	Water volume ($m^3.ha^{-1}$)				
Crop / water	**I1**	**I2**	**I3**	**I4**	**I5**
Tomato	2000	2500	3000	3500	4000
Lettuce	300	800	1300	1800	2300
Melon	2000	2500	3000	3500	4000
Wheat	0	500	1000	1500	2000
Sorghum	800	1100	1500	1900	2200
Maize	500	1000	1500	2000	2500
Sunflower	500	1000	1500	2000	2500

Table 4. Nitrogen fertiliser applied to each crop

	N fertiliser (kg.ha^{-1})				
Crop / N	**F1**	**F2**	**F3**	**F4**	**F5**
Tomato	70	120	170	200	250
Lettuce	100	150	200	250	300
Melon	150	200	250	300	350
Wheat	40	60	80	100	120
Sorghum	20	70	120	220	250
Maize	70	720	170	220	250
Sunflower	20	70	120	150	170

Table 5. Nitrogen fertiliser, water applied and yield obtained for each crop (as given by CropSyst under optimum management conditions)

Crop	**Water (m^3.ha^{-1})**	**Nitrate applied (kg.ha^{-1})**	**Yield (kg.ha^{-1})**
Tomato	4960	335	23300
Lettuce	3400	350	31189
Melon	4570	360	32200
Wheat	1000	112	5200
Sorghum	2250	203	5671
Maize	2300	268	8634
Sunflower	2920	273	5153

3. Economic model

If we can achieve and adequate reproduction of the technical and the economic universe of agricultural production and assume a reasonably good utility function to be maximised or minimised, we can then build a "positive" model that can be used not for advising an agent on the best way to use his resources but to simulate scenarios (Flichman, 1997).

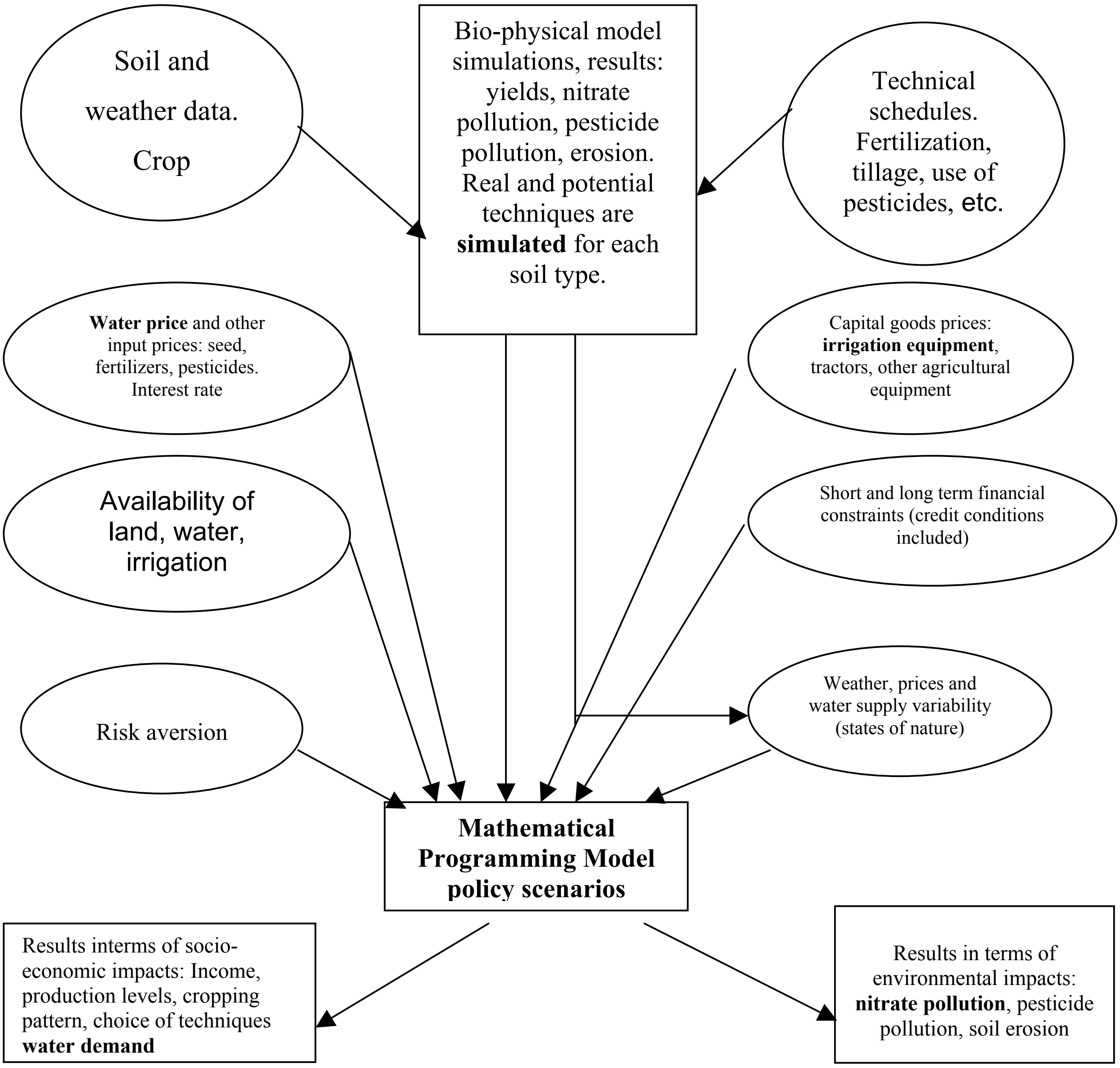
In other words, a mathematical programming model (MPM) can be built in order to make forecasts rather than advise a decision centre. This is why the model must be calibrated and validated to reproduce the behaviour of a real system in order to allow us to change certain parameters (policy parameters, such as prices, taxes, tariffs, subsidies, etc.) and perform forecasting analysis of the impact of these changes on the system. In any case, a positive model of this type can be used for indirect help in decision-making.

A mathematical multi-criterion economic model is used with a linear combination of revenue (positive) and risk (negative).

The risk is represented by the standard deviation of income in different states of nature. The model chooses the optimal solution that has the highest net revenue and with low risk according to climatic variability and the variability of market prices.

The structure a positive bio-economic model is shown in Figure 7. (Flichman, 1995).

Fig 7. Structure of a positive bio-economic model (Flichman, 1995)



4. Economic inputs

The principal economic variables include the price of irrigation water, the cost of applying the water and the price received for the crop. The optimum water depth applied water depends on the crop-water production function. Management of irrigation systems for the highest benefit requires understanding of the many physical, biological and socio-economic factors involved in crop production. The more information the water manager has, and the better that information is, the better the decisions he can make.

The economic model was constructed using the GAMS (General Algebraic Mathematical System) language. All combinations of the four different sets define the "activity" in GAMS: crop, irrigation method and the amounts of water and nitrate applied. Management was the same for all crops. With an average price of water of € 0.103 per cubic metre, the results of the base run model in terms of cropping pattern, nitrate percolation, nitrate applied, water used and farmers' revenue are provided in Tables 6a and 6 b for cereals and in Tables 7a and 7b for horticultural crops.

Table 6 a. Different variables per hectare and for the whole area

	Total area (ha)	per unit (1 ha)
Revenue (€)	6183	203
Water used (m^3)	29430	965
Nitrate applied (kg)	5893	193
Percolation of nitrate (kg)	616	20

Table 6 b. Cropping pattern

Crop / water / fertiliser used	Area (ha)
wheat.I1.F4	0.1
wheat.I1.F5	1.3
wheat.I2.F4	0.9
wheat.I2.F5	2.6
wheat.I3.F5	0.1
wheat.I4.F5	2.5
sorghum.I0.F5	4.5
maize.I0.F1	0.4
maize.I0.F2	1.3
maize.I0.F3	1.3
maize.I0.F4	3.2
maize.I0.F5	5.6
maize.I2.F5	0.9
maize.I4.F4	1.5
maize.I4.F5	3.2
maize.I5.F5	0.9

Table 7 a. Different variables per hectare and for the whole area (summer or winter farming)

	Total area	per unit (hectare)
Revenue (€)	75805	2707
Water used (m^3)	92821	3315
Nitrate applied (kg)	7268	260
Percolation of nitrate (kg)	2837	101

Table 7 b. Cropping pattern

Crop / water / fertiliser used	Area (ha)
tomato .I4.F3	0.4
tomato .I4.F4	1.4
tomato .I4.F5	1.4
tomato .I5.F3	0.8
tomato .I5.F4	1.4
tomato .I5.F5	1.7
lettuce.I2.F4	2.3
lettuce.I2.F5	0.8
lettuce.I3.F4	2.1
lettuce.I3.F5	0.5
lettuce.I4.F2	1
lettuce.I4.F3	1.7
lettuce.I4.F4	2.3
lettuce.I4.F5	2.9
lettuce.I5.F3	0.4
lettuce.I5.F4	1.8
lettuce.I5.F5	2.5
melon .I3.F4	1
melon .I3.F5	0.5
melon .I4.F1	0.2
melon .I4.F2	0.4
melon .I4.F3	0.5

Yields
Yields were estimated using CropSyst with the average yields of twelve years to calculate the farmer's profit. Two yield variability features were also taken into account:

1. variability resulting from the area cultivated per crop (10%): considering that the yield varies from a minimum when the entire area allowed is cultivated to a maximum value when the minimal area is cultivated;
2. climatic variability taking into account five different climatic years.

Nitrate percolation
CropSyst estimates nitrate percolation according to the crop and the techniques used. Nitrate percolation is expressed as $kg.ha^{-1}$ N descending below the maximum root depth.

Crop rotations
A coefficient of rotation was applied to each crop. Because of problems of nutrition and resistance to certain pathogens, some crops could not be grown on the same land for two years running. These rotation coefficients are shown in Table 8. A rotation coefficient of 0.25 means that tomato, for example, cannot be grown on more than 25% of the total land area.

Table 8. Crop rotation coefficient

Crop	Rotation coefficient
Tomato	0.25
Melon	0.25
Lettuce	0.50
Wheat	1.00
Sorghum	0.60
Maize	0.60
Sunflower	0.60

Costs and prices
The costs are:

- the production cost of each crop excluding irrigation (water, labour and equipment) and fertiliser
- the irrigation labour cost for each crop.
- fertiliser
- irrigation water
- various equipment according to operations and equipment.

The cost is defined for each crop, quantity of water and nitrate applied and irrigation method.
Average crop prices are used with 20 different market states.
A multi-criterion model was constructed using all these inputs. The two objectives were:
- maximising farmers' profit
- minimising risk.
The variables observed were:
- the quantity of water and fertiliser used
- nitrate percolation.

The objective function (U) of the model that is maximised is:

$$Z - \varphi^{*} S_{v} = U \qquad (1)$$

In which Z is the farmer's total net revenue (€).
φ, coefficient for the risk aversion parameter (taken as 1.65, assuming a normal distribution of revenue for all the states of the system, this value makes the probability of a revenue higher than U $\geq 95\%$)
S_v, standard deviation of the variance of the revenue calculated using the yield variability according to states of nature and price variability of the price according to states of the market.
Z, the average revenue calculated using the following equation:

$$Z = \sum\left(Y * P + S_b\right) * X - \sum\left(C_o + LB * L_C + F_N * C_N + C_e\right) * X - T * A - P_w * W_w \qquad (2)$$

In which Y is the average yield of the crops for each technique (kg/ha) that varies with the area used:

$$Y = Y\max - \left(\left(Y\max - Y\min\right)R_{coef} * A\right) * X \qquad (3)$$

Where $Y\max$ is the maximum yield reached when the area used is minimal (kg.ha^{-1}).

$Y\min$ is the minimum yield reached when the area used is maximum (kg.ha^{-1}),

R_{coef} is the rotation coefficient for each crop (%),

A is the total area (ha),

X is the actual area used (ha),

P is the average price of the crops, without irrigation and fertiliser (€. kg^{-1}),

S_b the subsidies awarded for certain crops (€. ha^{-1}),

C_O the crop production cost (€. ha^{-1})

LB labour (hours.ha^{-1}),

L_C labour cost (€. hour $^{-1}$)

F_N the amount of nitrogen fertiliser (kg. ha^{-1}),

C_N the cost of the nitrogen fertiliser (€. kg^{-1}),

C_e the cost of irrigation equipment (€. ha^{-1}),

T the fixed tariff for irrigation (€. ha^{-1}),

P_w the price of one cubic metre of water (€. m^{-3}),

W_w the total quantity of water applied (m^3).

The standard deviation of the revenue was calculated as:

$$S_v = \sqrt{DEV^2 / N * M} \qquad (4)$$

In which,

N = the number of states of nature (5 different climatic years)

M = the number of states of the market (20 different market prices)

And,

$$DEV = Z - Z_1 \qquad (5)$$

In which,

$$Z_1 = \sum\left(Y_v * P_m * P_i + S_b\right) - \sum\left(C_o + C_m + H_L * C_L + F_N + C_N + C_e\right) - T * A - P_w * V_w \qquad (6)$$

With Y_v being the yield that varies according to area and climate

$$Y_v = Y_n / Y_m \qquad (7)$$

In which Y_n represents yields that vary with climatic years given by the output of CropSyst (kg.ha^{-1}),

Y_n is the average yield between $Y\max$ and $Y\min$ (kg.ha^{-1}),

P_m is the average price of the 20 different market states for the crops (€.kg^{-1})

P_i is the variability of P_m .

5. Policy scenario analysis

After the results of the agronomic model had been obtained, several scenarios were examined in the economic model to reduce the pollution by 50%. Different kinds of policy were used such as water pricing, a flat-rate tax on nitrates, a block-rate tax and cross-compliance subsidies.

A. Water pricing

After the construction of the economic model, simulations were performed to examine the effect of changing the price of water. Ten simulations were performed from a price of € 0.103 to € 0.234 per m^{-3} for cereals and from € 0.104 to € 0.826 for horticulture. They are shown in Tables 9 and 10. The actual price is a flat-rate pricing system. The model gave an optimum solution for each water price. Every solution is characterised by a certain cropping pattern, techniques and methods of irrigation that induce the corresponding levels of water consumption, nitrogen pollution and farmer's net revenue.

Table 9. Water pricing for cereal crops

Levels of water pricing	Euro.m^{-3}
L1	0.104
L2	0.114
L3	0.124
L4	0.134
L5	0.144
L6	0.154
L7	0.174
L8	0.194
L9	0.204
L10	0.234

Table 10. Water pricing for horticultural crops

Levels of water pricing	Euro.m^{-3}
L1	0.103
L2	0.207
L3	0.310
L4	0.413
L5	0.516
L6	0.568
L7	0.620
L8	0.646
L9	0.671
L10	0.826

B. Nitrogen fertiliser taxes

Another way of reducing pollution is to set taxes on the inputs that generally lead to this pollution. Simulations were performed in which taxes were applied per kg N-fertiliser used. The taxes applied to horticultural crops and cereal crops are shown in Tables 11 and 12 respectively.

Table 11. N-taxes for horticultural crops

Levels of fertiliser pricing	**Euro.m^{-3}**
L1	0.00
L2	1.55
L3	2.07
L4	2.58
L5	2.84
L6	3.10
L7	3.36
L8	3.62
L9	3.87
L10	4.13

Table 12. N-taxes for cereals

Levels of fertiliser pricing	**Euro.m^{-3}**
L1	0.000
L2	0.052
L3	0.129
L4	0.155
L5	0.181
L6	0.207
L7	0.232
L8	0.258
L9	0.284
L10	0.310
L11	0.362
L12	0.413
L13	0.465
L14	0.516
L15	0.568
L16	0.620

C. Block-rate nitrogen fertiliser taxes

The tax is a block-rate pricing system that varies from € 0 per m^{-3} to € 1.03 €.m^{-3} for cereals (Table 13) and from € 0 per m^{-3} to € 6.20 per m^{-3} for horticultural crops (Table 14) .

Table 13. Block-rate tax on N applied to cereals

Range (kg. ha^{-1})	**Cost of fertiliser (€.kg^{-1})**
0 - 50	0
50 - 100	0.362
>100	1.03

Table 14. Block-rate tax on N applied to horticultural crops

Range (kg. ha^{-1})	Cost of fertiliser (€.kg^{-1})
0 - 100	0
100 - 200	4.65
>200	6.20

D. Cross-compliance subsidies

Cross-compliance policy sets an amount of N application on the total area of the farm of 2857 kg for cereal farms and 4555 kg for horticultural farms, using the results of the previous models used. To reduce nitrate pollution by 50%, farmers must agree to apply the fixed average of 100 kg N-fertiliser per hectare for the cereal farm and 163 kg N-fertiliser in the horticultural farm (for both activities, in winter and in summer) to obtain a subsidy of € 27 per ha^{-1} for the first farm and € 652 per ha^{-1} for the horticultural farm.

Chapter 4
Results and Discussion

The methodological approach consisted of a combination of a physical model (CropSyst), that considers the interaction of crop growth with climate, soil and agricultural practices (including irrigation), and a mathematical programming model (GAMS) that integrates information from the biophysical model and other economic inputs such as the price of products, production costs, labour, fertiliser, irrigation, etc. A multi-scenario analysis was performed which by changing policies will show the effects on farmers' incomes and the impact of agricultural production on the environment.

Two specialised farms were chosen to test the hypothesis that different types of farming system affect farmers' response to different economic and environmental policies and to evaluate their effectiveness.

This approach led to the objective of a decision support tool for better defining agro-environmental and rural policies. The results are described below.

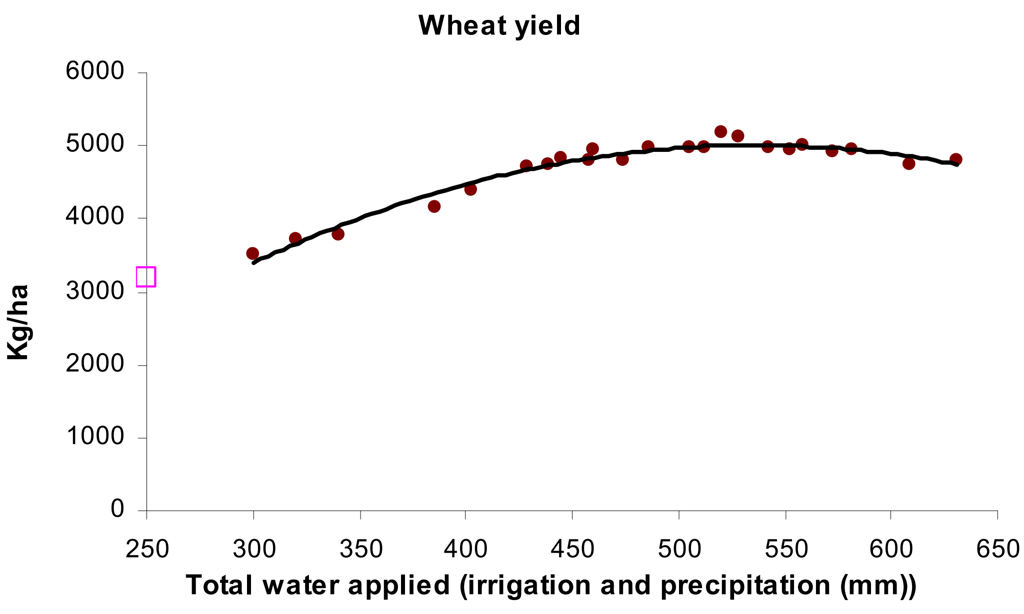
I. Agronomic results

The results of the five techniques and their combinations (the combinations of five levels of water application and five levels of nitrate application) in terms of yield response to the water and nitrate applied on the one hand and to water and nitrate leaching on the other are reported. The two types of cropping system concerned are horticultural crops and cereal crops;

1. Wheat

The wheat yield response to water applied is shown in Figure 8. The average yield under rainfed conditions is about 3200 $kg.ha^{-1}$ without any restriction on the use of nitrogen fertiliser. Precipitation during the wheat cycle is 419 mm and effective rainfall is 380 mm. The maximum value of the wheat yield obtained with application of 530 mm water is 5,200 $kg.ha^{-1}$. A decrease is expected at high values of water applied (greater than 550 mm). This is simulated by the crop-growth model.

Fig. 8. Wheat yield response to water applied

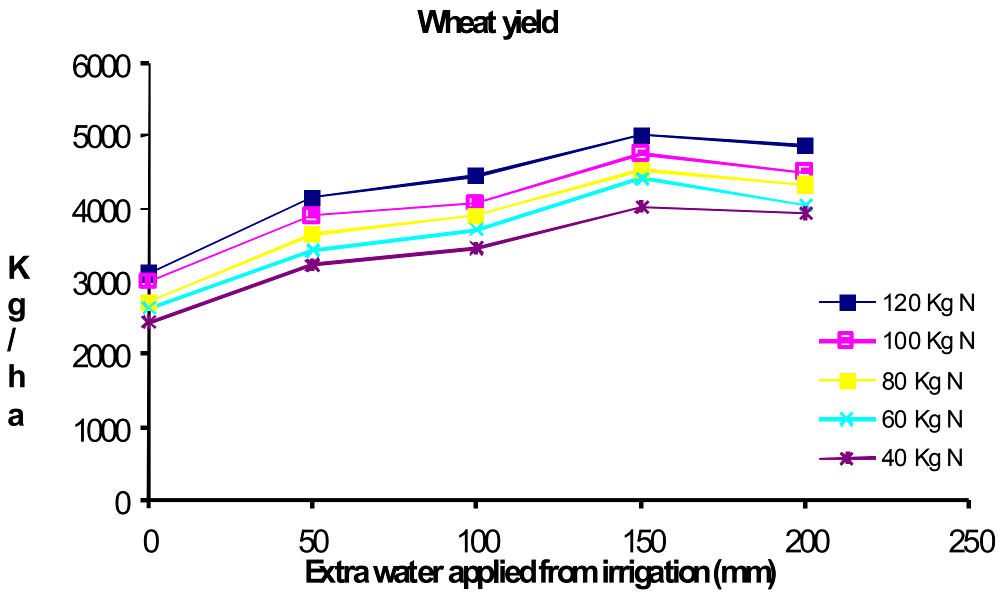


The yields obtained at different combinations of levels of water and nitrate applied are shown in Figure 8.

This figure shows how yield increases with the increase in nitrate and with the increase in water applied as supplemental irrigation at critical stages. It can be seen that the highest yield of 5,200 $kg.ha^{-1}$ is obtained with about 530 mm water (150 mm irrigation and 380 mm precipitation) and with the application of 120 kg nitrate.

This type of response is expected because 150 mm is considered quite sufficient to satisfy the seasonal crop water requirements of wheat under the climatic conditions of the area under study and the extra water received will be partially utilised by the crop.

Fig. 9. Wheat yield variation with the variation of water and nitrate applied



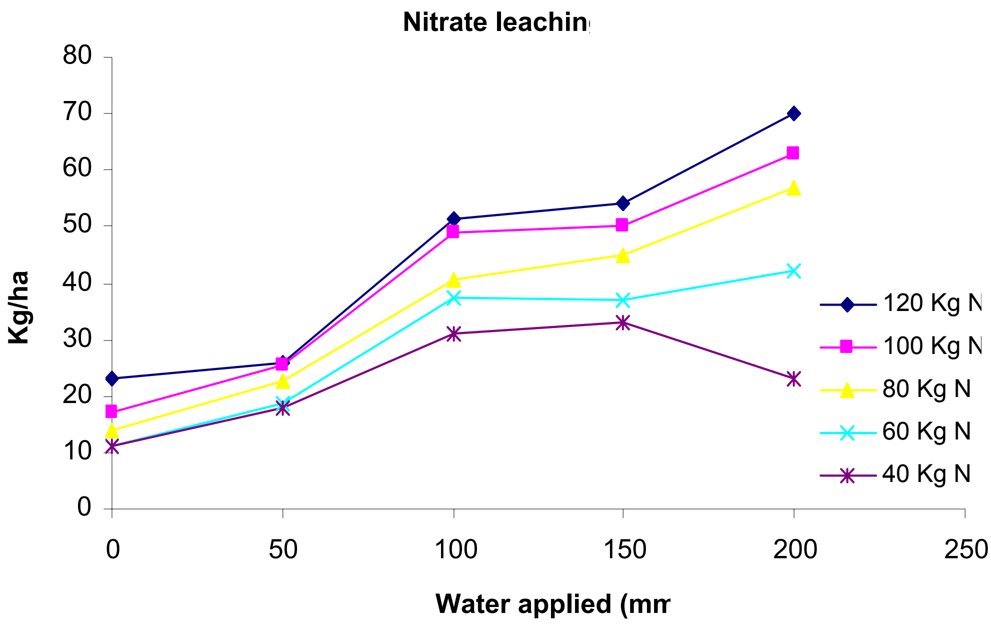
The nitrate percolation corresponding to the different levels of water amounts and nitrate applications is seen in a similar way as for yield.

The nitrate percolation occurring at different amounts of nitrate and water applied is shown in Figure 9. This figure highlights the fact that high levels of nitrate, which give high yields, are always disadvantageous for the environment. The percolation of nitrate increases with the increase of water applied.

The nitrate percolation obtained for the wheat crop varies between 11 to 23 $kg.ha^{-1}$ respectively with an increase of nitrate applied from 40 to 120 $kg.ha^{-1}$ under rainfed conditions, from 18 to 26 $kg.ha^{-1}$ with 50 mm water applied, from 31 to 51 $kg.ha^{-1}$ with 100 mm water applied, from 33 to 54 $kg.ha^{-1}$ with 150 mm water applied and from 23 to 70 $kg.ha^{-1}$ with 200 mm water applied.

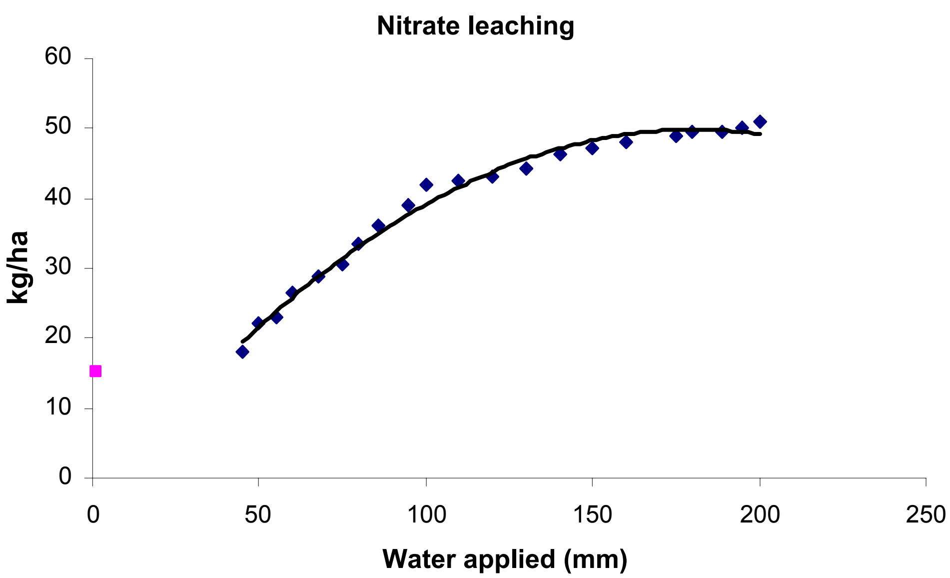
It can also be seen that at low water application levels, large amounts of nitrate are not leached and remain in the soil and can be leached by future precipitation events when there is sufficient rainfall or watering .

Fig. 10. Nitrate percolation in response to different amounts of water and nitrate applied to wheat (five levels of water and nitrate).



Plotting overall average nitrate percolation against actual water applied gives the results shown in Figure 10. It is clear that a rapid increase in nitrate percolation occurs with the increase in water use. It can also be seen that the slope of the relationship between nitrate percolation and water applied is significantly steeper than the slope of the relationship between yield and water applied. As is shown in this figure, 15 kg.ha^{-1} nitrate is leached under rainfed conditions. Application of 50 mm water results in percolation of almost 23 kg.ha^{-1} and nitrate leaching increases with irrigation until it reaches the highest mean value of 51 kg.ha^{-1} at 200 mm. These values were obtained by taking the average values of the previous figure. They are fairly close to the values obtained by applying 80 kg nitrate per hectare: respectively 14 kg.ha^{-1} at 50 mm, 23 kg.ha^{-1} at 100 mm, 40 kg.ha^{-1} at 150 mm and 57 kg.ha^{-1} at 200 mm water applied.

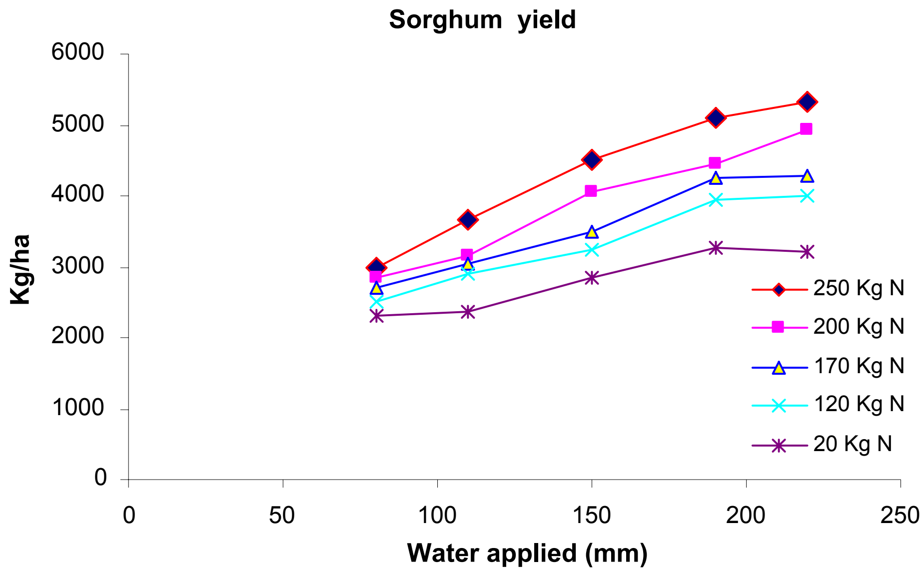
Fig. 11. General pattern of the overall average values of nitrate percolation against water applied.



2. Sorghum

Sorghum yield response to water for each level of nitrate application and each level of water applied is shown in Figure 12 For the first level of irrigation, corresponding to 80 mm water applied, the yield increased from 2,312 $kg.ha^{-1}$, to 2975 $kg.ha^{-1}$ at 250 kg nitrate per hectare, until it reached the maximum value of 5320 kg $kg.ha^{-1}$ at 220 mm of water applied and 4925 $kg.ha^{-1}$ at 200 kg of nitrate applied per hectare. It is clear in this figure that the effect of the nitrate applied per hectare has little influence on the yield, especially when the amount of nitrate applied varies from 200 till 250 $kg.ha^{-1}$. Environmentally speaking, it is better to use the smallest amount of nitrate to reduce nitrate leaching into the subsoil to prevent the pollution of groundwater.

Fig. 12. Sorghum yield variation with the variation of the water and nitrate applied

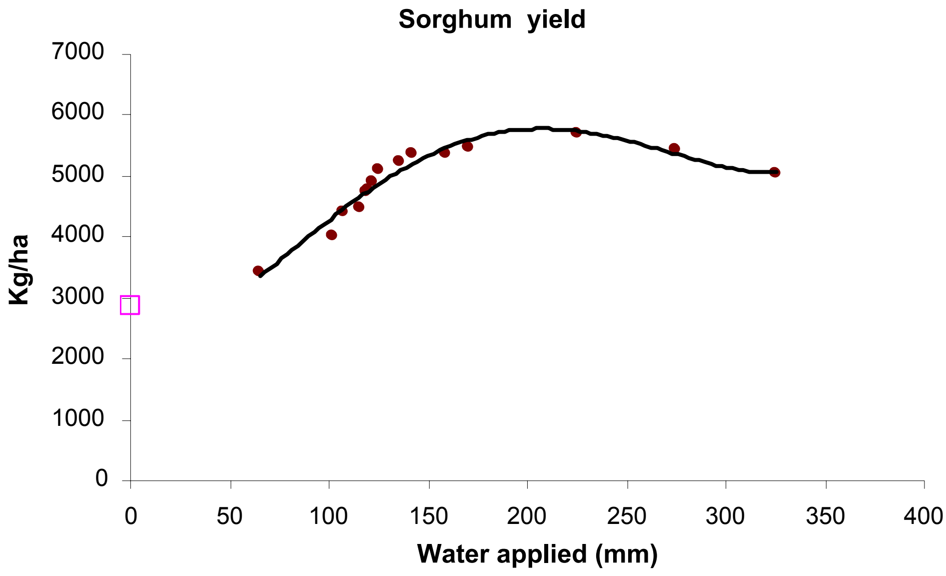


The results of plotting the yield response of sorghum against the water applied are shown in Figure 12. This figure shows a typical response curve of sorghum in the area under study where the yield under rainfed conditions is about 2,850 $kg.ha^{-1}$. Yield increases with the increase in water until it reaches the maximum yield of 5670 $kg.ha^{-1}$ at 225 mm water depth. The yield then decreases to 5,000 $kg.ha^{-1}$ at 325 mm actual water applied.

The highest increment appears when the water applied is increased from 160 mm to 270 mm, giving a yield increase of 200 kg in comparison, change from rainfed to 100 mm supplemental irrigation gives a yield increase of 1500 $kg.ha^{-1}$.

This shows that sorghum is more dependent on water than on nitrate, which is already present in the soil as a result of the fixation of atmospheric nitrogen symbiotic bacteria; this can remain in the soil when water is scarce.

Fig. 13. Sorghum yield response to water applied



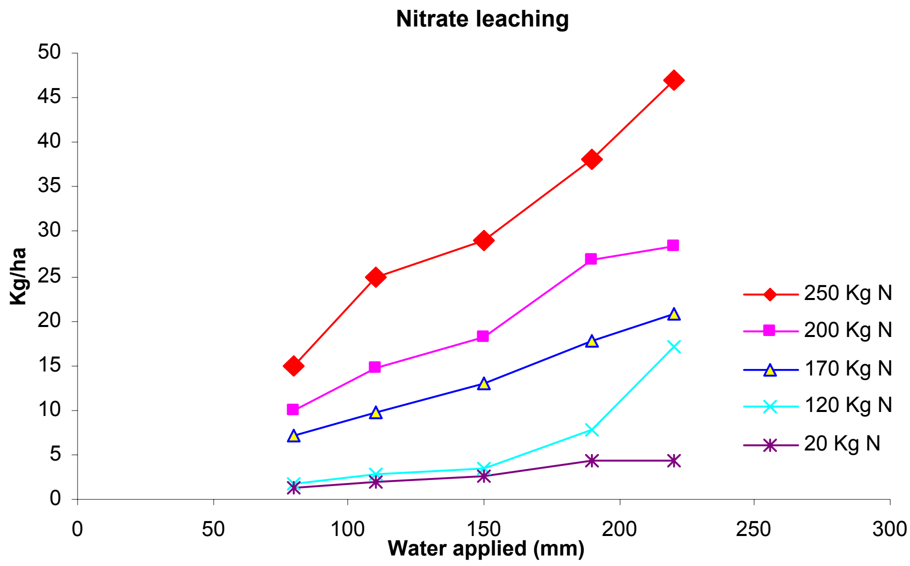
It can be seen in Figure 13 that nitrate percolation under sorghum corresponds to the different water amounts as was shown for yield. This figure highlights the fact that nitrate leaching increases with the amount of water applied. The amounts leached vary between 1 and 2 $kg.ha^{-1}$ for the first two levels of nitrate application.

These first two levels of nitrate correspond to 20 and 120 $kg.ha^{-1}$ application rate. Leaching for the three highest levels of nitrate application (170, 200 and 250 $kg.ha^{-1}$) shows a variation of between 7 and 47 $kg.ha^{-1}$ for the 5 levels of water applied.

If these values are compared with the values obtained for the other crops, it can be seen that the amount of nitrate leached is lower, even for applications of 170 and 200 $kg.ha^{-1}$. Environmentally speaking, the level of 250 kg of nitrate is unacceptable after comparison with Figure 12 showing the sorghum yield obtained at different water and nitrate levels.

It is better to use 200 $kg.ha^{-1}$ and obtain the same yields as for the highest level of nitrate(250 $kg.ha^{-1}$) is used. At 120 kg nitrate, leaching increases from 180 mm water applied to 220 mm until it almost attains the level for 170 kg of nitrate in terms of nitrate percolation.

Fig. 14. Nitrate percolation in response to different quantities of water and nitrate applied to sorghum (five amounts of water and nitrate)

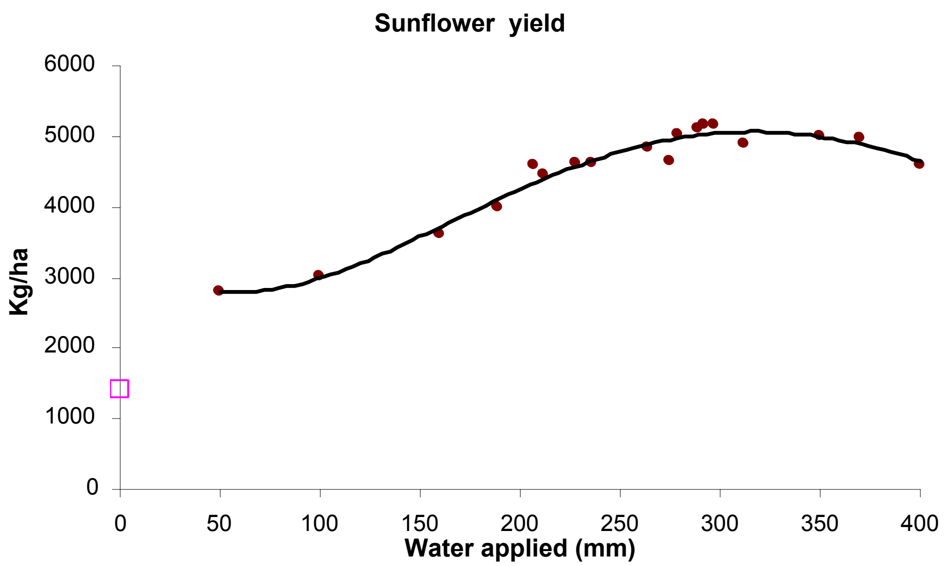


3. Sunflower

It is seen in Figure 14 that sunflower yield increases almost proportionally with the amount of water applied. It starts at 1500 kg.ha^{-1} under rainfed conditions and rises to 2800 kg.ha^{-1} at 50 mm water applied and continues to increase to a maximum at 292 mm, when the yield is about 5150 kg.ha^{-1}.

The yield then decreases for each amount of water applied higher than 292 mm, reaching 4600 kg.ha^{-1} at 400 mm. This is the result of the high soil water content, which has a distinct effect on production by inhibiting root development, preventing respiration and causing waterlogging in the root zone.

Fig. 15. Sunflower yield response to water applied

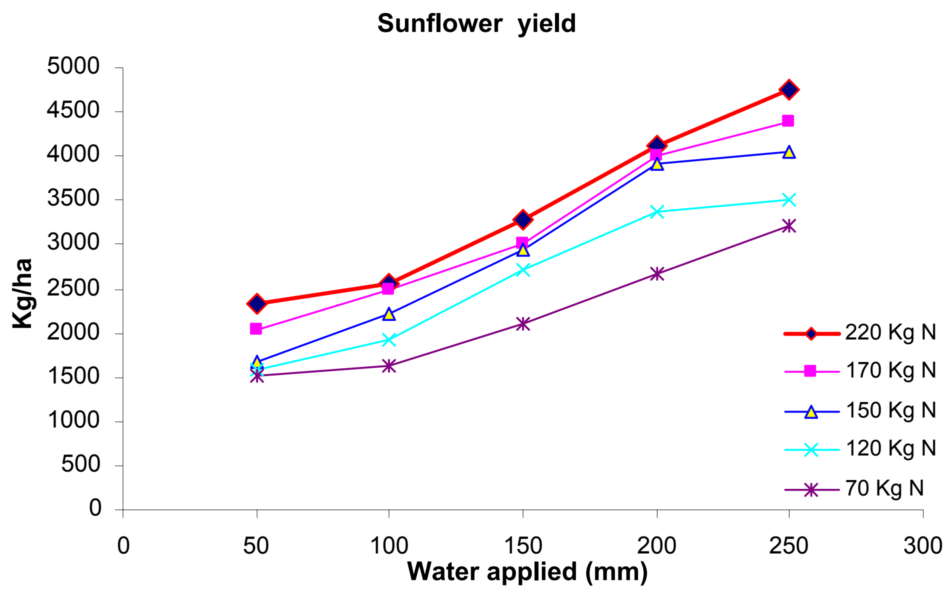


Sunflower yield response to the reference quantity of water applied is shown in Figure 16. The yield of the 5 levels of nitrate in this figure does not vary very much with 50 mm water. In fact, yield varies from 1520 kg.ha^{-1} at 70 kg.ha^{-1} nitrate to 2330 kg.ha^{-1} for 220 kg.ha^{-1} nitrate.

The differences in yield increase with the amount of water applied. For environment-friendly agriculture, it is better to use 150 kg.ha^{-1} nitrate in combination with 250 mm water; this does not result in substantial loss of yield. Examination of the shape of the yield curve corresponding to the application of 70 kg.ha^{-1} nitrate shows the same slope with the increase in water application.

The figure also shows that the application amount exceeding crop water requirements induces limitations for crops and hence a decrease in yield. This is probably caused by the loss of nitrate present in the soil as a result of water flow, preventing crop use of this quantity.

Fig. 16. Sunflower yield variation with the variation of the water and nitrate applied

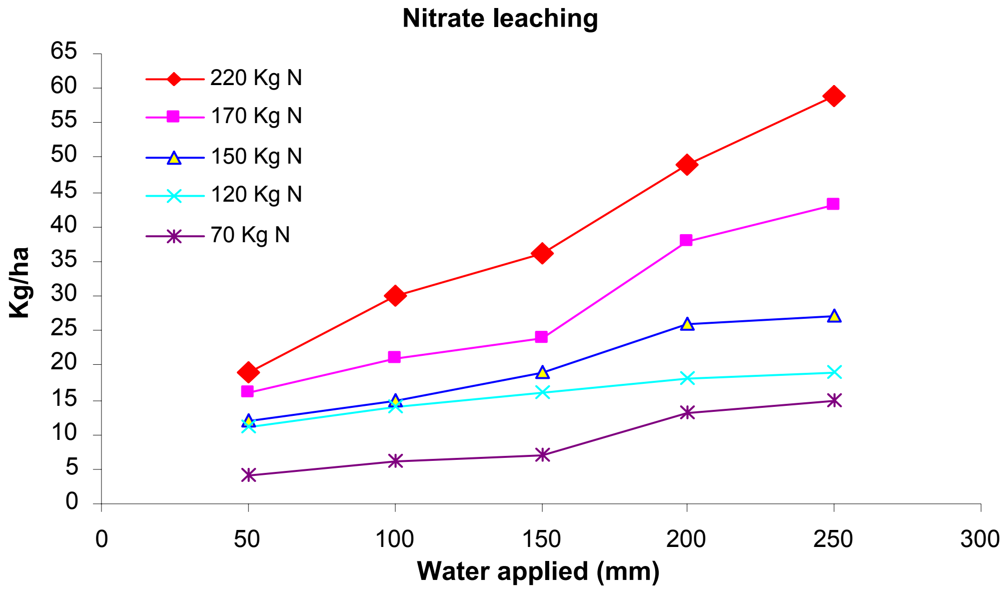


In Figure 13, nitrate percolation under sunflower is shown for five different levels of water applied and five levels of nitrate application. In this figure, nitrate percolation always increases with the increase in nitrate quantity and with water applied. Nitrate leaching under sunflower varies from 4 to 19 kg.ha^{-1} at 50 mm of water applied, from 7 to 36 kg.ha^{-1} at 150 mm and from 15 to 59 kg.ha^{-1} for 250 mm of water applied.

Comparison with the previous figure (Fig. 12) clearly shows that the same yields are obtained at the three highest levels of nitrate, at 200 mm of water applied, and that several levels of nitrate percolation are obtained.

It is therefore economically and environmentally preferable to use the amount of nitrate that gives the least percolation, that is to say 150 kg.ha^{-1} and take into consideration the 200 mm of water to be coupled with this strategy to obtain the highest environment- friendly yield.

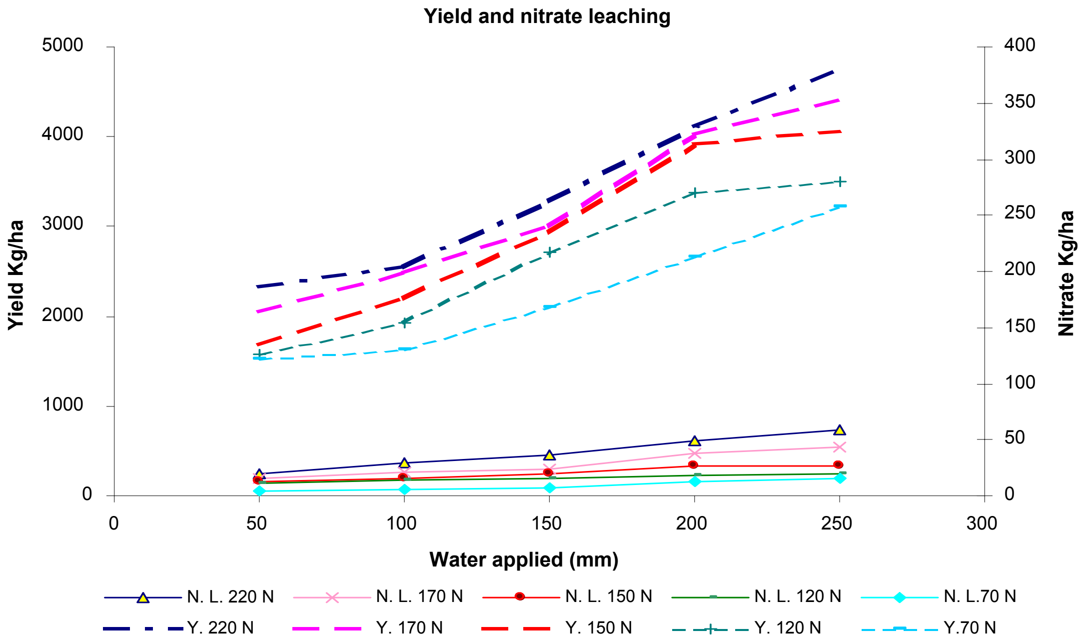
Fig. 17. Nitrate percolation in response to different levels of water and nitrate applied to sunflower



Examination of Figure 18 shows the evolution of yield and nitrate leaching with the increase in water applied. This figure includes Figures 17 and16. It also shows that the yield increases with the increase in water and nitrate application. With increased water application, yield and nitrate leaching also increase but with small water application the risk of pollution by nitrate percolation is low because the quantity leached is acceptable. When yields reach high values, large amounts of nitrate move to the subsoil and pollute ground water.

The use of 220 $kg.ha^{-1}$ nitrate should be eliminated because large amounts of nitrate percolate, even with increased production. For sustainable and environmental agricultural practices, it is recommended that 170 $kg.ha^{-1}$ of nitrate should be used and an attempt made not to apply more than 200 mm water.

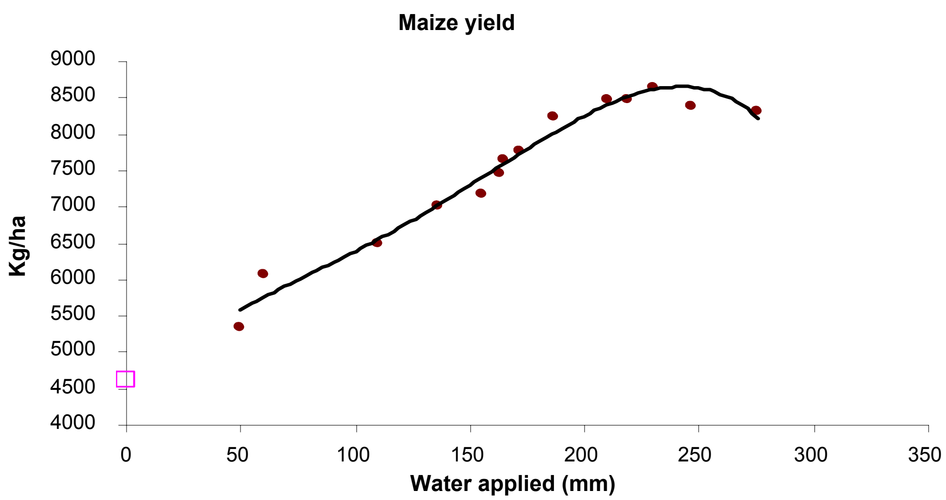
Fig. 18. Nitrate percolation and yield evolution in response to different amounts of water and nitrate applied to sunflower



4. Maize

Figure 18 is a plot of the overall yield response to water applied. Yield of 4520 kg.ha^{-1} under rainfed conditions is increased to 5330 kg.ha^{-1} with the application of 50 mm water, continues to increase to 8634 kg.ha^{-1} with 230 mm and then remains constant to 300 mm and then decreases with water applications higher than 300 mm. This graph also shows that increased water application and increased yield are not proportional. It is clear that the yield at high applications displays a constant stage before beginning to decrease. The crop roots suffer from waterlogging, especially if the amount of the incoming water exceeds the soil infiltration rate. This is a typical curve response for water application in the study area.

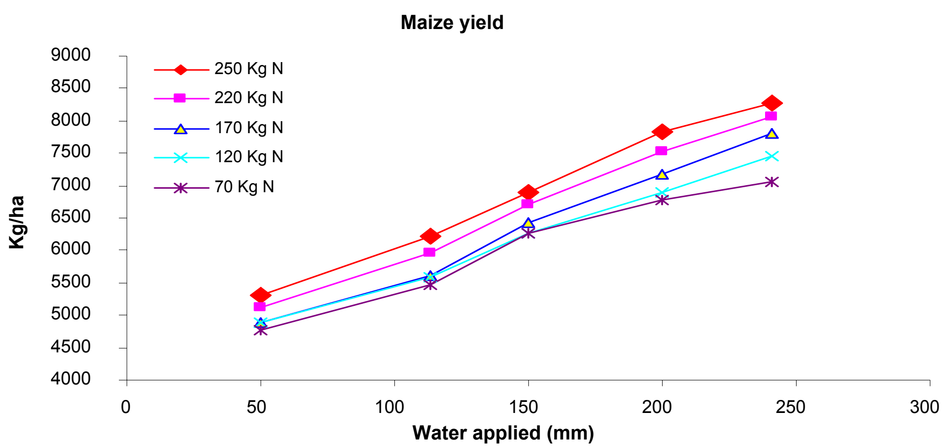
Fig. 19. Maize yield response to water applied.



Maize yield response to the reference quantity of water applied is shown in Figure 19. This shows that for 50 mm water applied, the yields for the 5 levels of nitrate are almost the same. It is thus clear that nitrate application has no effect on the production with low water application amounts. This is because the crop needs more water to use all the nitrate. The difference in yield increases with the increase in water until it reaches the maximum difference of 1200 kg.ha^{-1} at 250 mm of water applied, between 70 kg.ha^{-1} of nitrate and 250 kg.ha^{-1}. The five levels of nitrate shows the same yield increase pattern. For better environmental agriculture, it is advised that 170 kg.ha^{-1} nitrate should be used in combination with 250 mm water; this does not result in a substantial loss of yield.

The yield curve displays a linear increase with the increase in water applied for the three highest nitrate application levels, while for the two lowest levels the shape of the curve is slightly different, showing a slow decrease in yield.

Fig. 20. Maize yield variation with the variation in water and nitrate applied



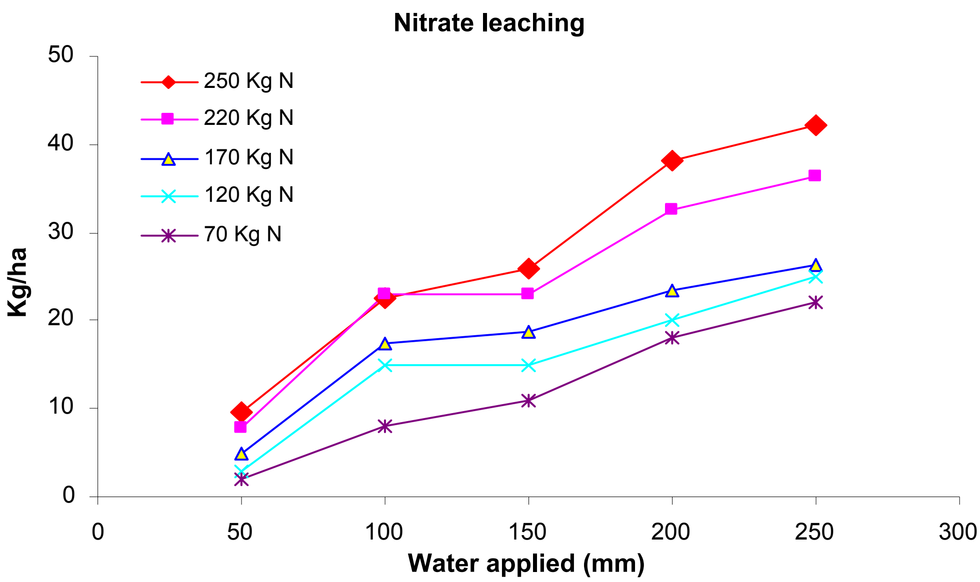
Examination of Figure 21, which shows the evolution of nitrate leaching in each scenario and for the combinations in these scenarios, clearly shows that increased nitrate application at the soil surface is accompanied by increased leaching from the beginning of the crop cycle onwards. It is also clear that the curves are similar to those of nitrate application when the amount of water applied increases.

At 50 mm of water applied by irrigation, the quantity of nitrate leached varies respectively from 2 to 10 $kg.ha^{-1}$ for 70 to 220 $kg.ha^{-1}$ nitrate applied. Maximum values are attained at 250 mm water. The values corresponding to the highest irrigation application vary from 22 $kg.ha^{-1}$ for 70 $kg.ha^{-1}$ nitrate applied to 42 $kg.ha^{-1}$ for 250 $kg.ha^{-1}$.

Examination and comparison of the two figures (Figs. 20 and 21) show that it is economically and environmentally preferable to use 170 $kg.ha^{-1}$ nitrate to obtain high yields and minimum nitrate leached.

With low nitrate applications, the percentage of nitrate leaching varies from 3% to 4.5% while at higher rates of application the percentage of leaching increases to 17% to 31% respectively for 250 kg and 70 kg nitrate applied. It is clear that even with low quantities of nitrate there is always a risk of serious pollution by nitrate leaching. This leads us to improve on-farm irrigation and fertiliser application management.

Fig. 21. Nitrate percolation in response to different amounts of water and nitrate applied to maize

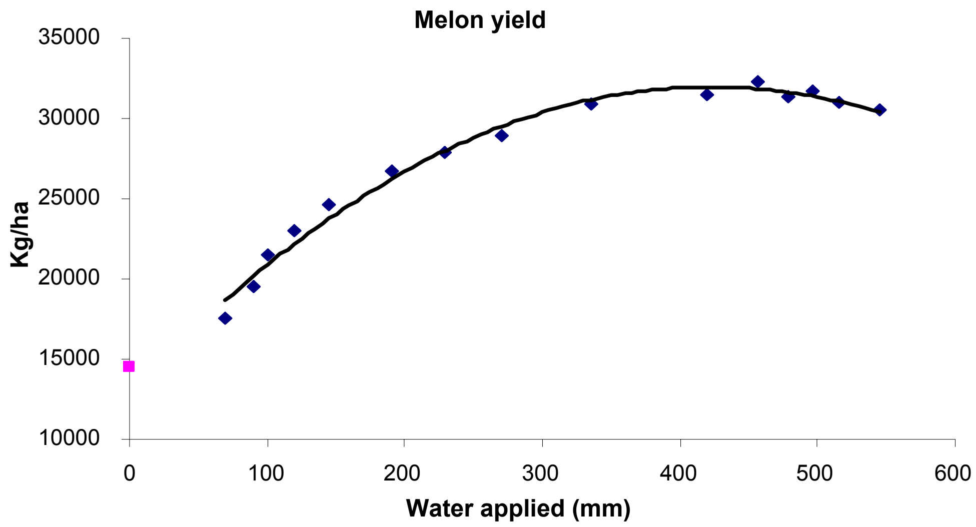


5. Melon

It can be seen in Figure 22 that melon yield increases with the amount of water applied almost proportionally. It starts at 14,500 $kg.ha^{-1}$ under rainfed conditions and rises to 19,100 $kg.ha^{-1}$ with 70 mm water applied and continues to increase to a maximum of 460 mm when the yield is about 32,200 $kg.ha^{-1}$.

The yield then decreases with each amount of water applied in excess of 460 mm to 31,100 $kg.ha^{-1}$ at 545 mm. Further water application causes a decrease in yield as the high soil water content has a negative effect on production by preventing respiration and creating waterlogging of the root zone.

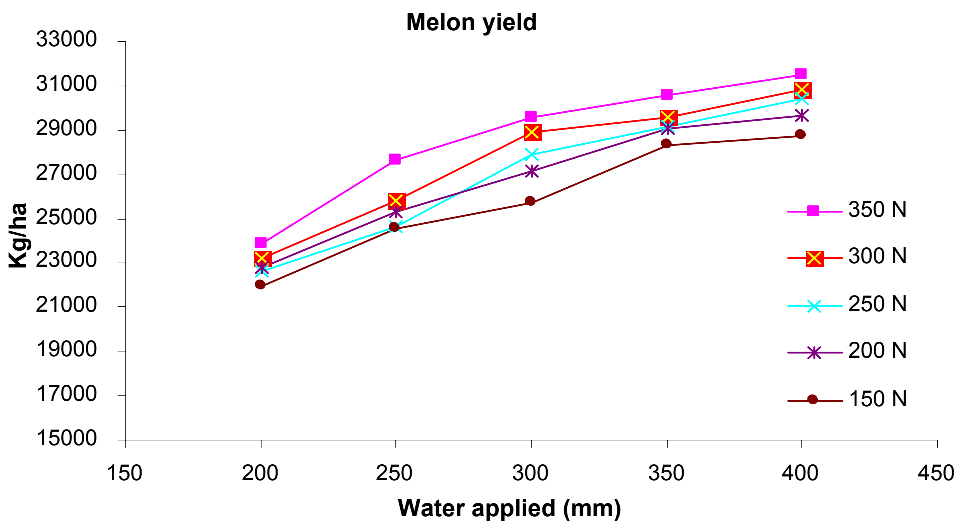
Fig. 22. General pattern of the melon yield response to water applied



The yield response to the water applied in different scenarios and combined with different nitrate levels is shown in Figure 22. The yield obtained at 200 mm water applied is around 23,000 kg.ha^{-1} for all nitrate application levels. Comparison with Figure 23 clearly shows that the highest yields are obtained with the same amount of water but without any restriction of the amount of nitrate applied. Yield increases with the water applied until it peaks at 31,150 kg.ha^{-1} with 400 mm water.

Yields are stable for each amount of water applied in excess of 400 mm. It can be seen that nitrate fertiliser affects melon yield once it is used with restrictions. Melon yields with less than optimum nitrate application reach a maximum of 32,200 kg.ha^{-1} at 460 mm while when more than 400 mm water is applied with limited fertiliser, the yield decreases somewhat. The choice of strategy depends on objectives and on the market price. Lower yields must be accepted for environmentally friendly production or the optimum yield sought.

Fig. 23. Melon yield variation with the variation in water and nitrate applied



Similarly, nitrate percolation corresponding to different water amounts can be seen. In Figure 23, percolation at different amounts of water applied is shown. Percolation does not always increase with the increase in the reference quantity of water applied.

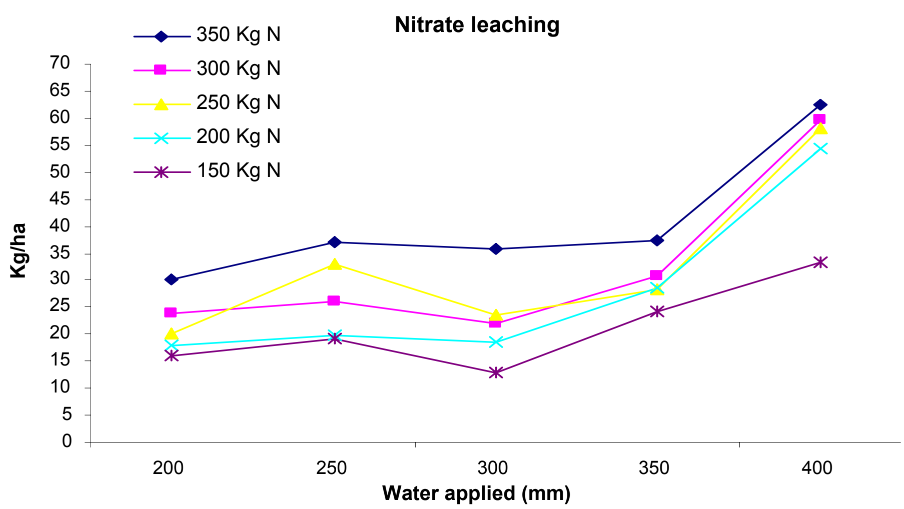
This can be seen in the percolation corresponding to 250 mm water, which is higher than that corresponding to 300 mm. At 250 mm, percolation varies from 19 to 37 $kg.ha^{-1}$. At 350 mm, percolation varies between 24 and 37 $kg.ha^{-1}$.

At 300 mm, nitrate percolation decreases in all the scenarios. Examination of Figure 24 shows that the slope of yield increase is at a maximum with between 250 and 300 mm water applied, explaining why nitrate percolation decreases at this level.

At 400 mm water, percolation is at maximum, with values indicating variation of between 33 and 63 $kg.ha^{-1}$ and a decrease in yield.

Deduction of the relationships linking yield and nitrate percolation from these results shows that yield decreases with the increase in nitrate percolation for water application in excess of 400 mm.

Fig. 24. Nitrate percolation in response to different amounts of water and nitrate applied to melon

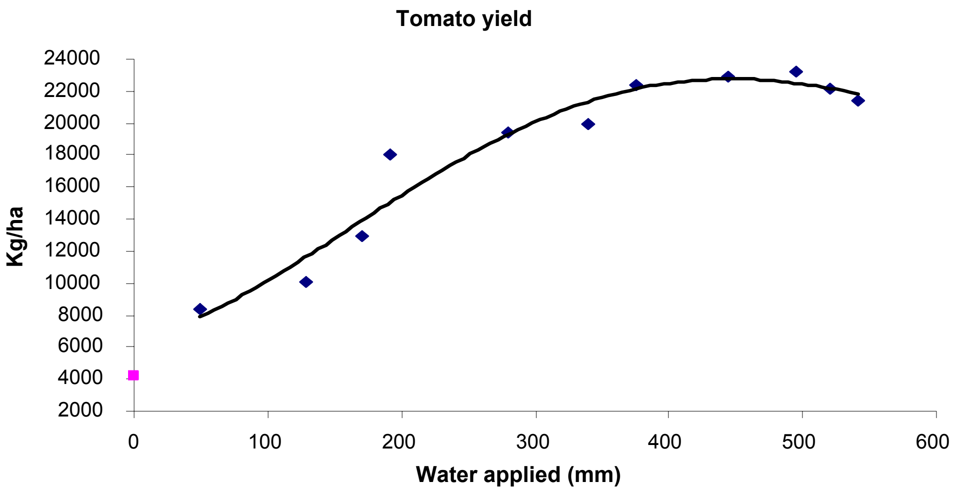


6. Tomato

The curve for the overall yield response of tomato to water applied is shown in Figure 25.

The yield varies from 4200 $kg.ha^{-1}$ under rainfed conditions to 10,100 $kg.ha^{-1}$ with the application of 130 mm irrigation water. Yield increased to 16,700 $kg.ha^{-1}$, with increase in water application to 300 mm to reach the value of and was 23,300 $kg.ha^{-1}$ with 496 mm. It then remained even when water application was increased and finally decreased when very large amounts of water were applied.

Fig. 25. General pattern of tomato yield response to water

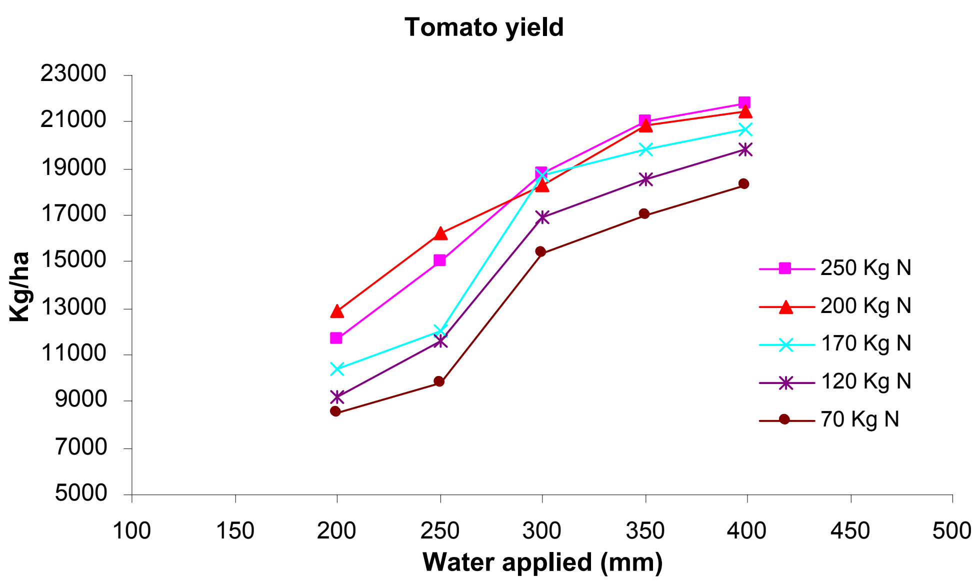


Tomato yield response to water for each level of nitrate application and the five levels of water applied is shown in Figure 26. Here, yield increases with increased water amount nitrate. For the first level of deficit irrigation (200 mm), the variation of yield from low nitrate application to high applications is large, increasing from 8,500 to 11,700 kg.ha^{-1}, representing 24% variation.

This increased to 30% with 300 mm water. It is clear that for the two highest levels of nitrate application (200 and 250 kg.ha^{-1}), yields cease to increase with water application greater than 350 mm but increase steadily with the three other lower levels.

Application of 200 kg.ha^{-1} nitrate is therefore quite sufficient for full crop development with water application of 400 mm. A reduction in the amount of nitrate applied shows a delay in crop maturity and hence a reduction in yield. Application of 70 kg.ha^{-1} nitrate gives the lowest yield for all the different amounts of water applied

Fig. 26. Tomato yield variation with the variation of water and nitrate application

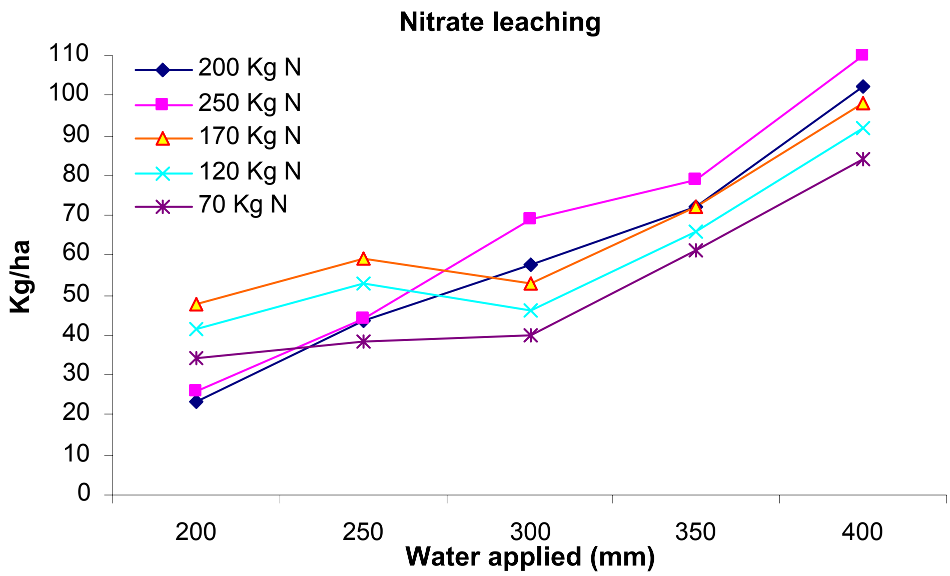


Nitrate percolation under tomato for the five levels of irrigation and the five levels of nitrate is shown in Figure 26. Nitrate leaching increases with increased water. It can be seen that for the first level of water applied, the two highest nitrate applications show the lowest nitrate percolation, explaining why the difference between these two levels of nitrate application and the others is high in terms of yield in figure 27.

This continues to 250 mm water applied and then at 300 mm the three lowest amounts of nitrate application show an expected reduction in nitrate leaching. Nitrate leaching at 200 mm of water applied varies from 23 to 48 $kg.ha^{-1}$.These values increase to 38 and 59 $kg.ha^{-1}$ at 250 mm water, continue to increase at 300 mm to 40 to 69 $kg.ha^{-1}$, 61 to 79 $kg.ha^{-1}$ at 350 mm and 84 to 110 $kg.ha^{-1}$ at 400 mm water.

At 170 kg nitrate applied, percolation is almost the same as the two highest levels and yield is lower, making the environmental pollution cost of this combination very high.

Fig. 27. Nitrate percolation in response to different amounts of water and nitrate applied to tomato

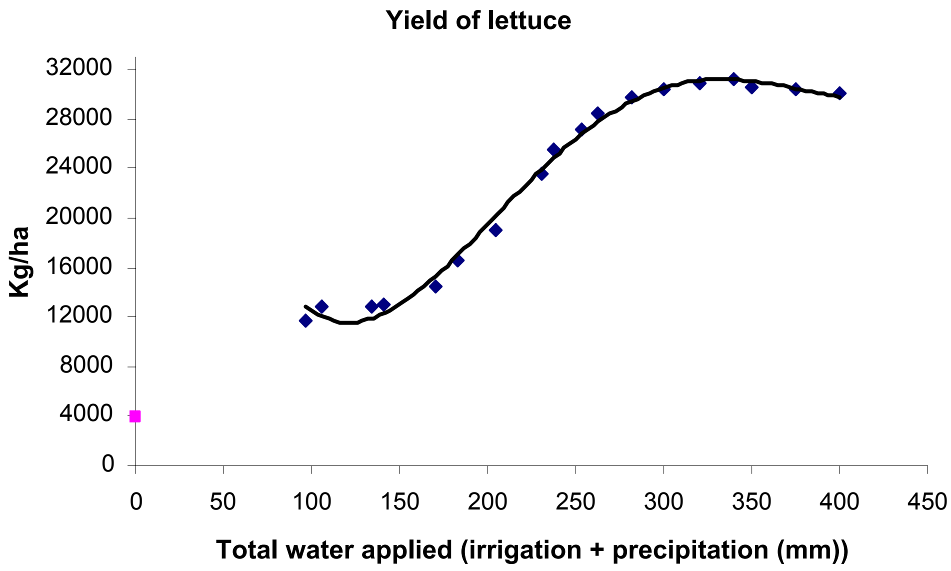


7. Lettuce

It can be seen in Figure 28 that the lettuce yield rises with the increase in the amount of water applied. It starts at about 4,000 $kg.ha^{-1}$ under rainfed conditions, rises to 12,830 $kg.ha^{-1}$ at 100 mm water applied and continues to increase to a maximum at 340 mm, when yield is about 31,200 $kg.ha^{-1}$.

Yield then decreases with each amount of water applied in excess of 340 mm and is 30,000 $kg.ha^{-1}$ at 400 mm. This is the result of the distinct effect of high soil moisture content on production. Yield stops increasing when large amounts of water are applied (irrigation + precipitation). Precipitation was about 175 mm during the lettuce cycle and so irrigation should be controlled to prevent waterlogging of the root zone

Fig. 28. General pattern of lettuce yield response to water applied



The yield response to the water applied in different scenarios is shown in Figure 28. The yield obtained with 200 mm water is about 14,130 kg.ha^{-1} for 100 kg nitrate per hectare. Yield rises with the increase in water applied until it reaches a maximum of 29,500 kg.ha^{-1} with 350 mm water. Yield decreases with the application of 100 kg nitrate and more than 350 mm water. However, the four other highest nitrate applications (150 to 300 kg.ha^{-1}) are accompanied by yield stability with a slight decrease.

Fig. 29. Lettuce yield variation with the variation in water and nitrate applied

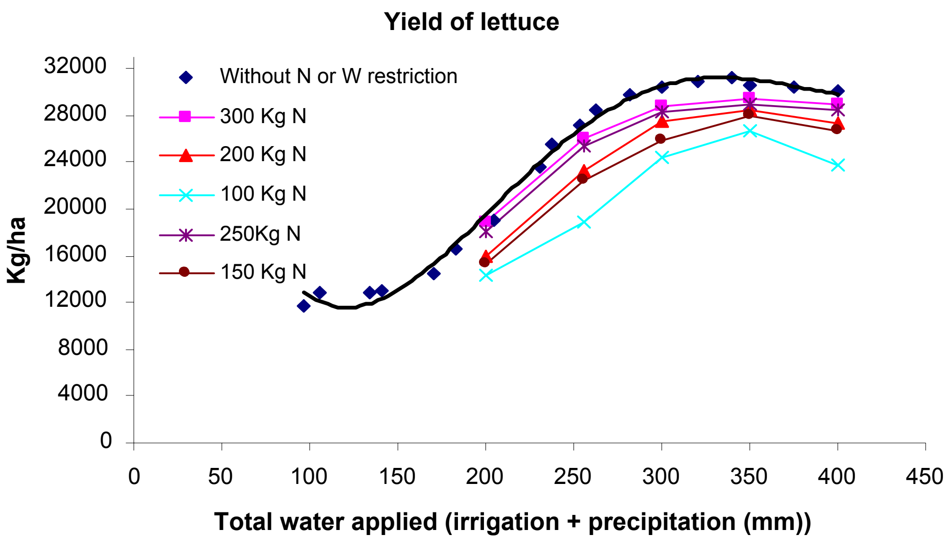
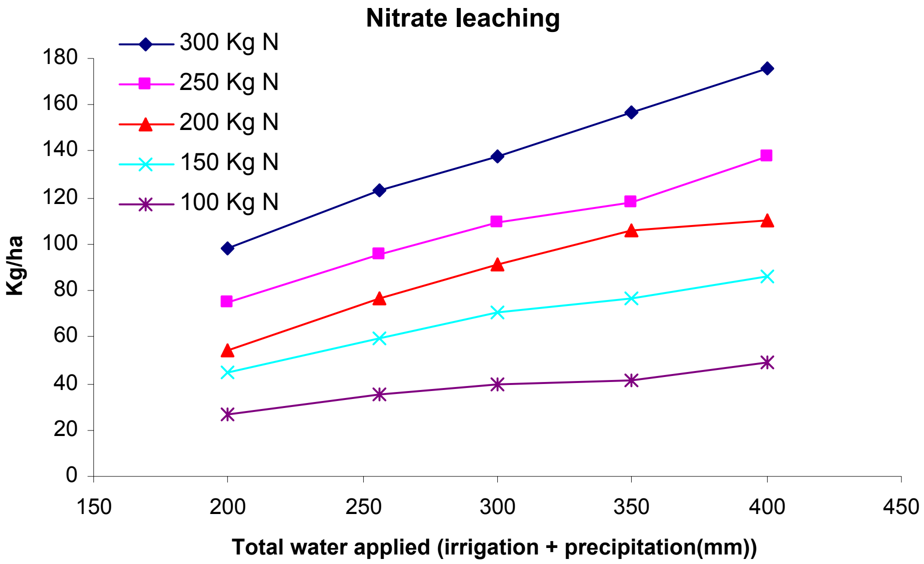


Fig. 29. The difference between lettuce yields at full nitrate and water application and in scenarios

A plot of the yield curve in Figure 29 against the yield curve in Figure 28 is shown in Figure 29. This shows that yields are not the same with the same amount of water applied and under the same climatic conditions because of the effect of the different levels of nitrate applied per hectare and differences in farm management. The highest yield is obtained with no restrictions in terms of water and nitrate applications. Yields decrease with the decrease in nitrate application to a low of 23,700 kg.ha^{-1} at 100 kg nitrate per hectare and 400 mm water.

Fig. 30. Nitrate percolation in response to different amounts of water and nitrate applied to lettuce



In Figure 30, nitrate percolation under lettuce is shown for different amounts of water. This highlights the fact that the nitrate leaching increases with the amount of water applied. The amounts leached vary between 27 and 98 kg.ha^{-1} at 200 mm. It is clear that the quantity of nitrate leached at 300 kg nitrate applied is the maximum and is three times that leached with 100 mm. Leaching under the three highest nitrate application levels of 200, 250 and 300 kg.ha^{-1} shows variation between 56 and 172 kg.ha for the 5 levels of water applied. Comparison of these values with those for the other crops shows that more nitrate is leached. The nitrate leached with application of 300 kg shows a steadily rising curve similar to a straight line. The yield at 250 kg nitrate applied is almost the same as that obtained at 300 kg nitrate with the difference that less nitrate is leached when 250 kg nitrate is applied.

II. Economic results

The results of simulations of yield response to several levels of nitrate, water application and nitrate percolation under the seven crops in the agronomic model were introduced in the economic model with the economic inputs. The economic model is in GAMS language and is an optimisation positive model aimed at maximising the farmer's net revenue with minimum risk.

The optimum solutions given by this model for every simulation show the cropping pattern, the farmer's net revenue, total water consumption and total nitrate percolation. It is noted that all these variables change in every optimal solution.

Three policies were simulated:

- water pricing: the effects of different levels of water pricing (volumetric pricing) on pollution and on all the other variables are shown;
- flat-rate taxation and block-rate taxation of the inputs that cause pollution; these are nitrogen fertilisers;
- cross compliance subsidies enabling farmers to receive agricultural support by undertaking specific environmental activities.

1. Water pricing

After the construction of the economic model, many simulations were performed for observation of the effect of changing the price of water.

The model gave one optimum solution for each water price. Each solution is characterised by a certain cropping pattern and irrigation methods inducing corresponding levels of water consumption, nitrate pollution and farmer's net revenue.

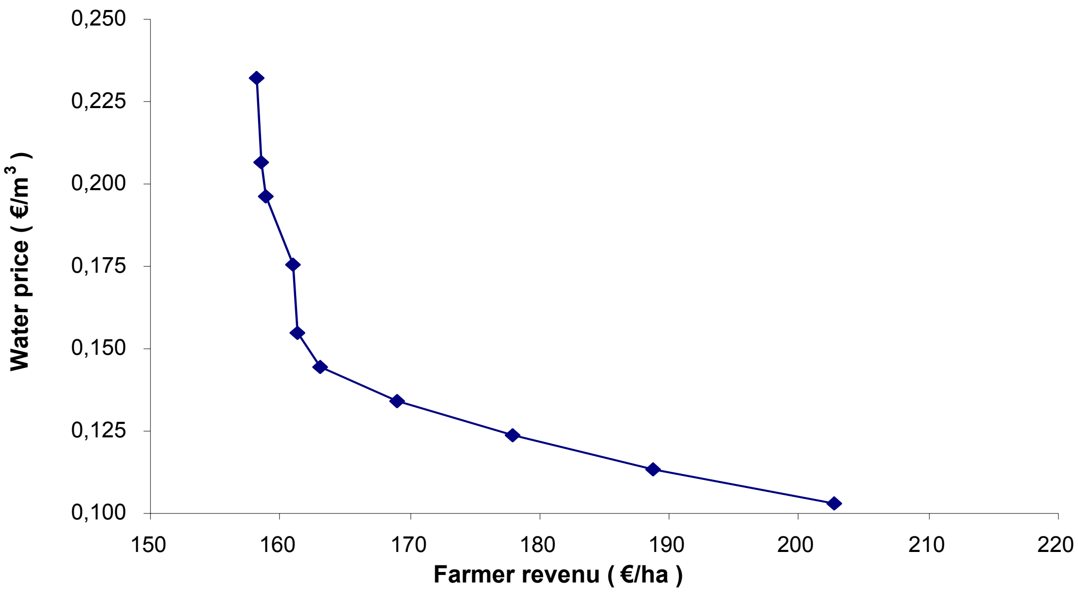
A. The effect of water pricing on cereal farms

Ten simulations were performed to observe the effect of water pricing on cereal farms, with the price ranging from € 0.104 per m^{-3} to € 0.234 per m^{-3}, with a stepwise increase of € 0.010.

a] Net revenue

The results show a decreasing response of the farmer's net revenue with the increase in the price of water. Figure 31 shows a certain elasticity in price variation at high water prices. The slope of the curve is negative with a decreasing rate. The net revenue decreases from € 203 per ha^{-1} to € 158 per ha^{-1}, forming a decrease in income of about 22%.

Fig. 31. Farmer's revenue variation with the variation of water pricing



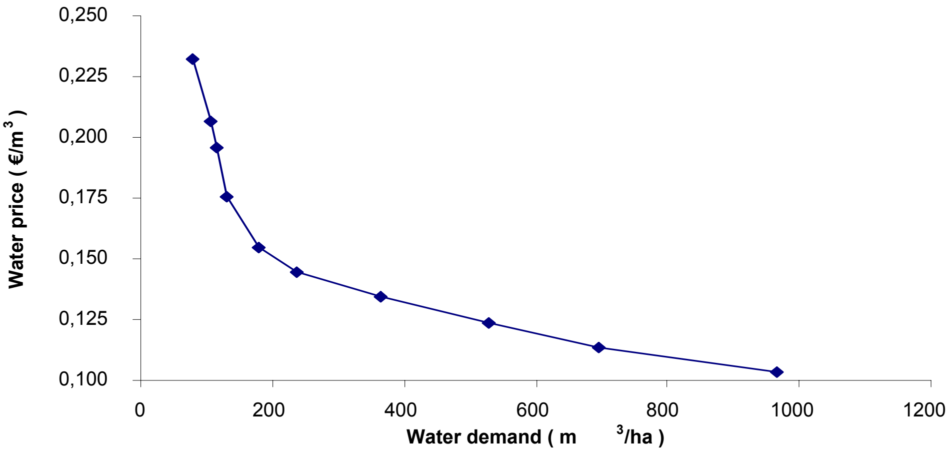
b] Water use

It can be seen that irrigation volume is still high when the price of water is high (Figure 32).As the price of water increases, the volume decreases to 185 $m^3.ha^{-1}$ and then decreases slowly to 79 $m^3.ha^{-1}$. Nitrate pollution is reduced by half when the price of water is 0.154€.m^{-3} and 785 $m^3.ha^{-1}$ water is economised The curve is in three parts:

- the rate decreases sharply at first, indicating higher elasticity, (this is for the first 4 iterations to a water price of € 0.134 per m^{-3});

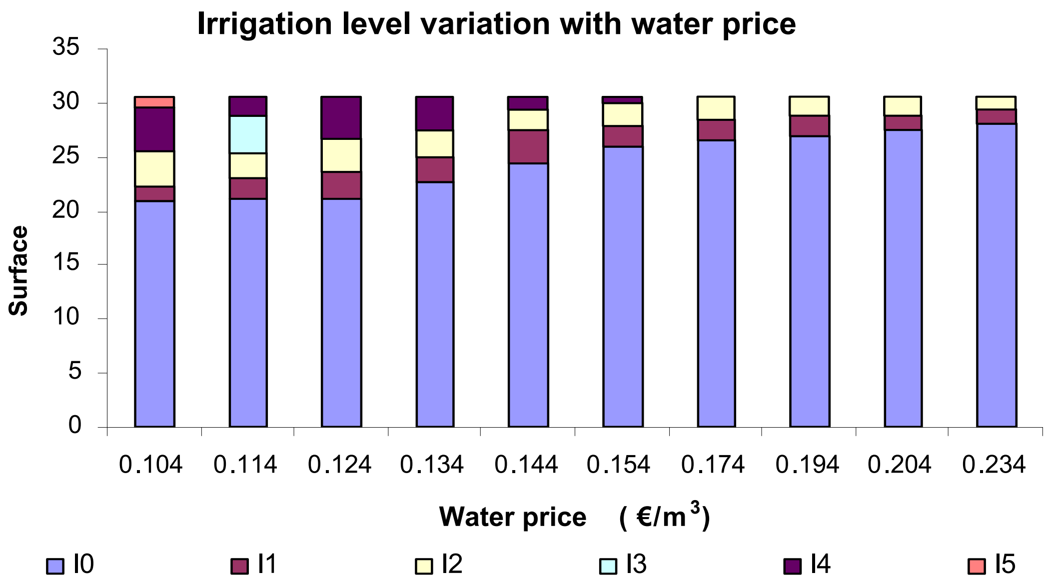
- the second part has little elasticity, and falls slowly from € 0.134 per m^{-3} to € 0.174 per m^{-3}),
- the last part of the curve from € 0.194 per m^{-3} is inelastic. Water consumption remains constant when the price increases.

Fig. 32. Water demand variation with variation in water pricing



The amount of water used corresponding to each cropping pattern and thus to each water price is shown in Figure 33. Here, it is clear that water short level I0 increases with the price of water. When water costs € 0.114 per m^{-3}, I5 disappears and I4 remains present until the price of water reaches € 0.154. I3 only appears at the second iteration.

Fig. 33. The effect of water pricing on the amount of water applied

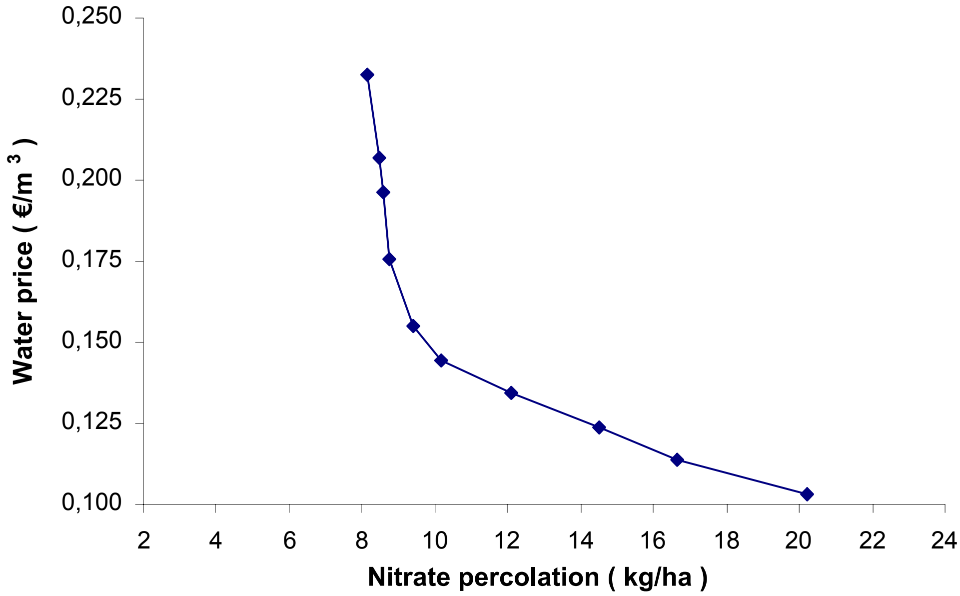


c] Nitrate percolation

As for water consumption, the nitrate pollution occurring at each level of water pricing and each related optimum solution given by the model is shown in Figure 34. Percolation varies from 20 $kg.ha^{-1}$ when water costs € 0.104 per m^{-3} to 8 $kg.ha^{-1}$ at € 0.154 per m^{-3} and then remains practically constant.

It is clear that nitrate percolation remains constant at water prices higher than € 0.154 per m^{-3}. Our target is to reduce nitrate percolation by half and so the water price should be pegged at € 0.154 per m^{-3}.

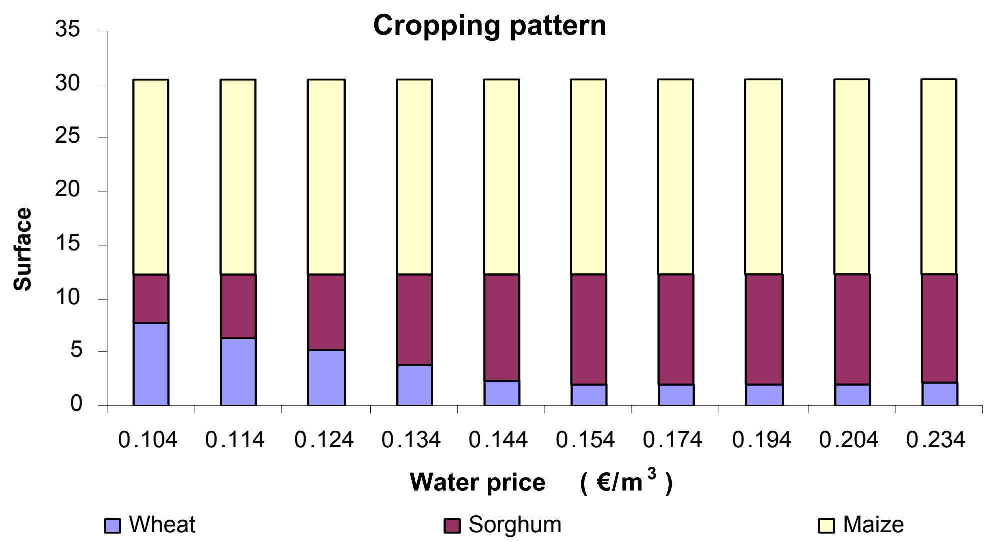
Fig. 34. Nitrate percolation variation with the variation of water pricing



d] Cropping pattern

With regard to the cropping pattern, it can be seen in Figure 35 that the maize crop remains the same even when the price of water is increased. The change is noticeable for wheat and sorghum. When the price of water is increased, the area under wheat decreases and wheat is replaced by sorghum because of its high return. Crop distribution is also shown with the columns representing the area under each crop. It can be seen that the area under maize is always constant, that under sorghum increases with the price of water the area under wheat surface decreases as the price of water rises.

Fig. 35. The effect of water pricing on the cropping pattern



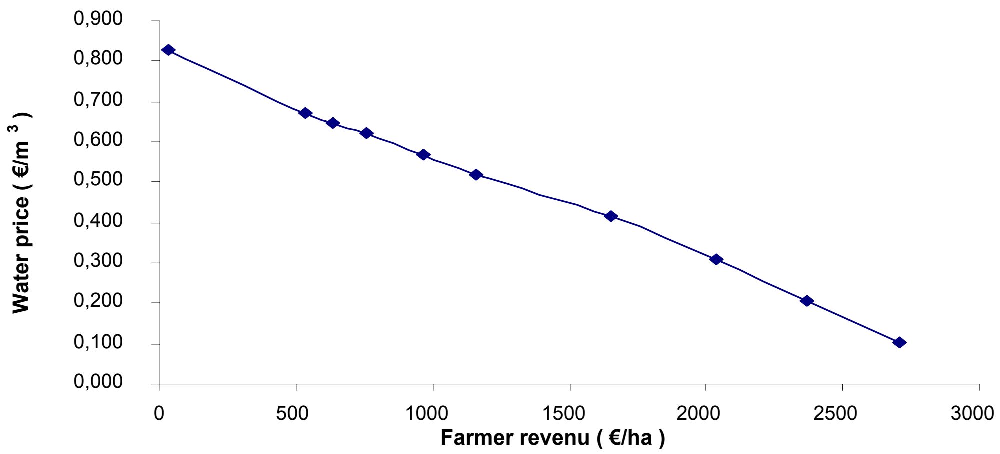
B. Effect of water pricing on horticultural farms

Ten simulations were performed from € 0.104 to € 0.826 per m^{-3} with a stepwise increase of € 0.104 per m^{-3} to observe the effect of water pricing on horticultural farms.

a] Net revenue

The results of running the program results are shown in Figure 36. It is clear that the curve displays a steady slope as the price of water rises. At € 0.826 per m^{-3}, the farmer's income is about € 35 per ha^{-1} while at € 0.670 per m^{-3} its is € 533 per ha^{-1}. Income was initially € 2707 per ha^{-1} and decreased steadily and rapidly as the price of water increased.

Fig. 36. Variation in the farmer's revenue with the variation in water pricing

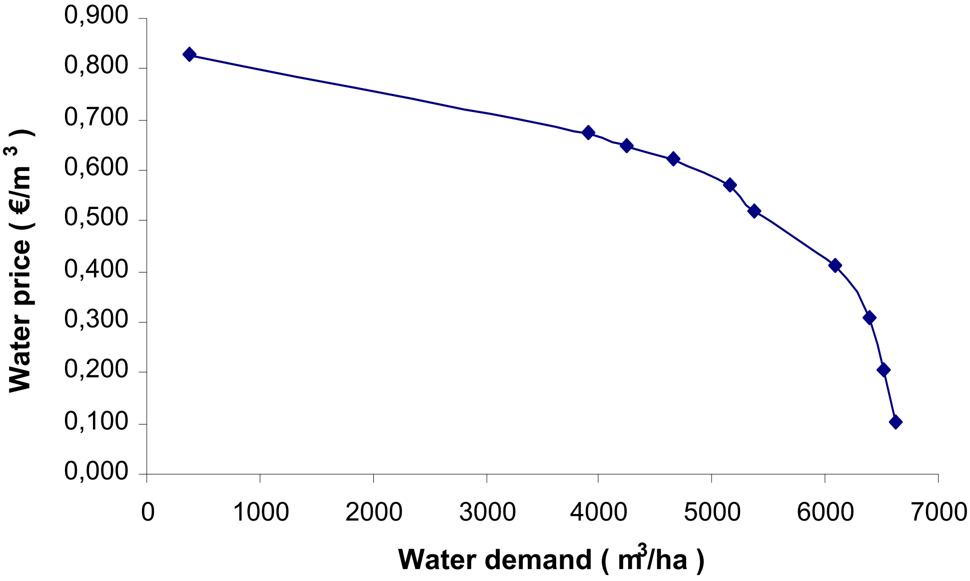


b] Water use

The results of the introduction of different water prices shown in Figure 37 demonstrate that farmers' water use tends to be more efficient as the price rises. The volume used is reduced to save expensive water.

For a water price of between € 0.104 and € 0.416, the volume decreases slowly from 6600 $m^3.ha^{-1}$ to 6100 $m^3.ha^{-1}$ and water use continues to decrease until irrigation ceases when the price of water is high. The water demand curve is inelastic because high value crops cannot be grown under rainfed conditions and so production depends on the water applied.

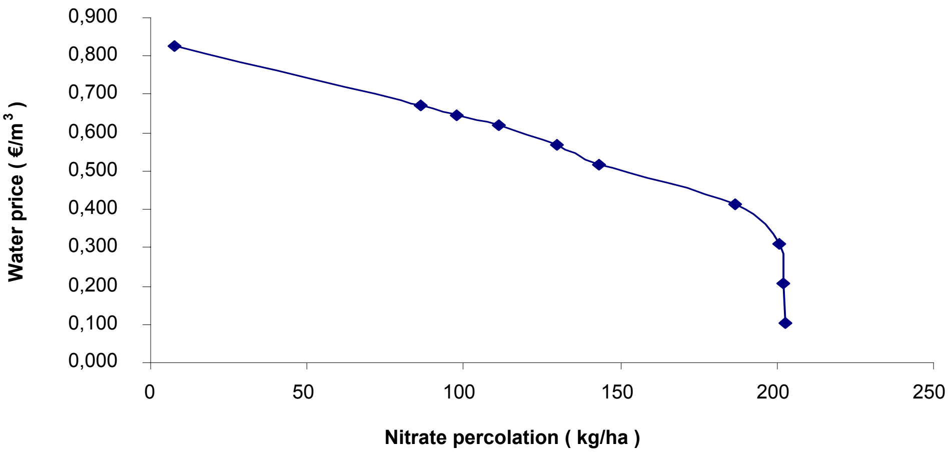
Fig. 37. Water demand variation with the variation of water pricing (summer and winter activities)



c] Nitrate percolation

The nitrate percolation trend with an increase in the price of water is shown in Figure 38. Starting with 200 kg.ha^{-1}, and with the objective of reducing pollution by 50%, it is better to apply a water price of € 0.645 per m^{-3} and achieve 98 kg of nitrate percolated per hectare. At prices higher than € 0.645 per m^{-3} , there is a risk of reducing farmers' revenue to point at which they cease to operate.

Fig. 38. Nitrate percolation variation with the variation of water pricing

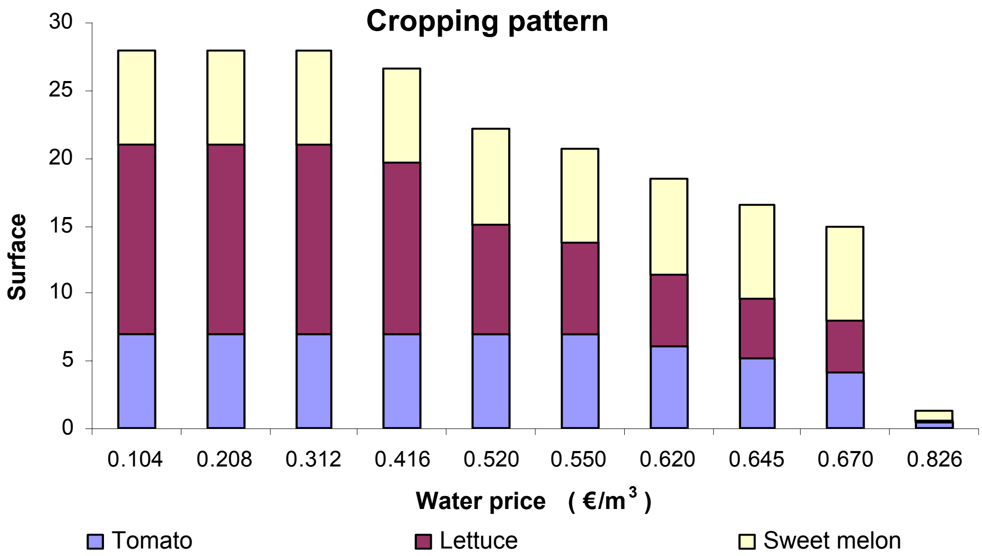


d] Cropping pattern

With regard to the' cropping pattern, Figure 39 shows that in the first iterations (with he water price lower than € 0.416 per m^{-3}), almost all the area was used and then the cultivated area decreased to reach 15 ha at € 0.670 per m^{-3}. With a high water price of € 0.826 per m^{-3}, farmers ceased operations with only 1.4 ha.

The area devoted to lettuce decreases with the increase of water price, whereas tomato and melon remain constant because of the higher income generated.

Fig. 39. The effect of water pricing on the cropping pattern



2. Nitrogen taxes

Another way to decrease pollution is to set taxes on the inputs that in general cause this pollution. Several simulations were performed with taxes applied per kg N-used.

A. Nitrogen taxes applied to cereal farms

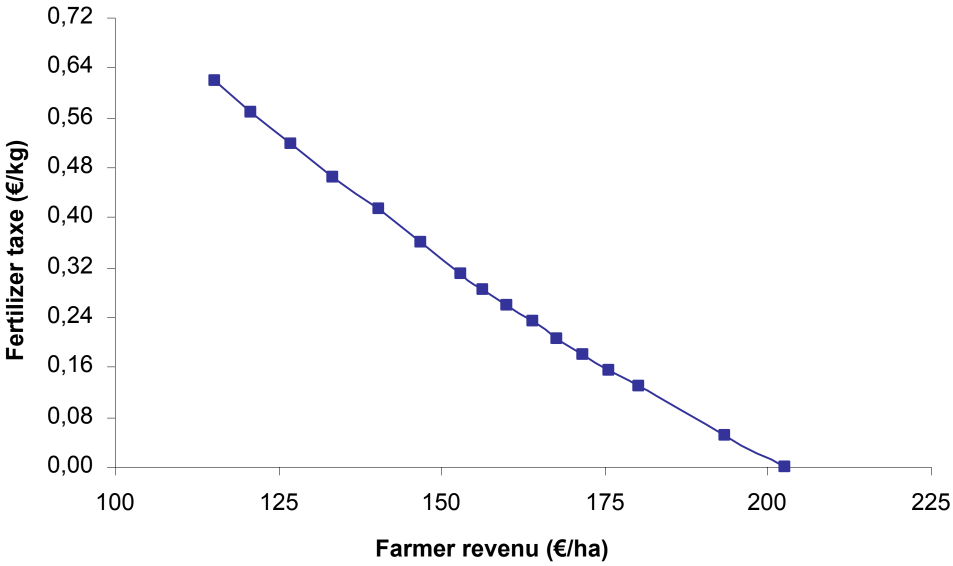
Sixteen levels were applied to test the effectiveness of reducing nitrate pollution by applying taxes on nitrogen. They ranged from € 0 to € 0.620 per kg^{-1} with a stepwise increase of € 0.051 per kg^{-1}.

a] Farmers' revenue

The results are shown in Figure 40.

The social cost is calculated in this case as the sum of the private cost (farmer's loss of income) and the public cost, which is as follows for example in the case of a fertiliser tax: (initial tax)*(initial quantity of fertiliser used) – (tax for the 50% reduction)*(reduced quantity of fertiliser used). Here, with the aim of reducing nitrate percolation by 50%, the farmer's income is reduced by about 37.5 % (from € 203 per ha^{-1} to € 127 per ha^{-1}).

Fig. 40. The effect of nitrogen taxes on farmers' revenue

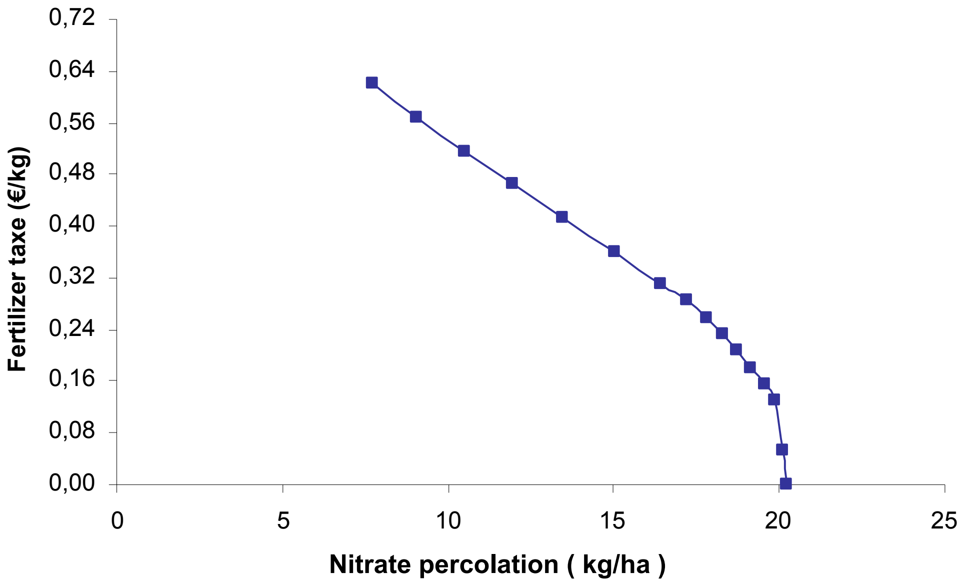


When pollution is decreased by about 25% (from 20 kg.ha^{-1} to 15 kg.ha^{-1}), farmers' losses are about 27.5% (from € 203 per ha^{-1} to € 147 per ha^{-1} with a tax of € 0.362 per kg^{-1} N.

b] Nitrate percolation

The results of the taxes are shown in Figure 41. In this policy, reducing nitrate percolation by 50% from 20 kg.ha^{-1} to 10 kg.ha^{-1}, the farmer's income decreases and the tax should be € 0.516 per kg^{-1}. This tax represents 220% of the price of N.

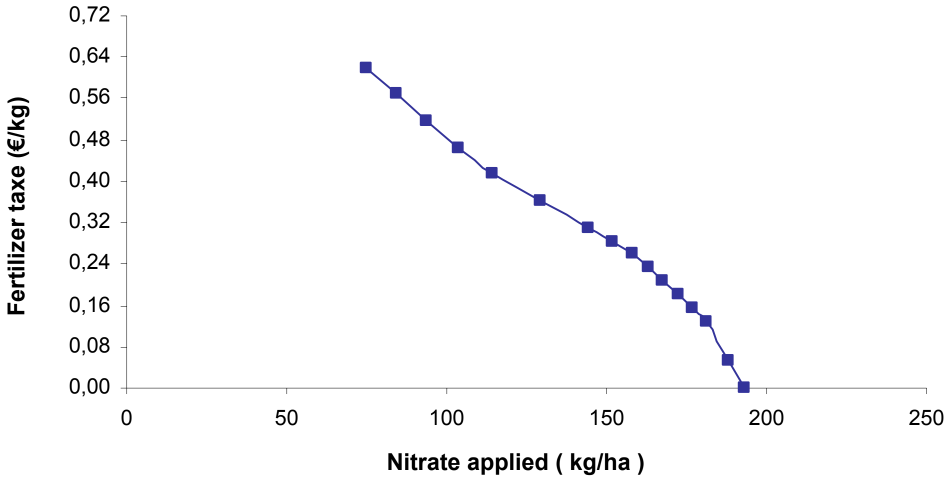
Fig. 41. The effect of taxes on nitrate percolation



c] Fertiliser application rate

Aiming at reducing nitrate pollution by 50% nitrate pollution, Figure 42 shows that the quantity applied decreases from 193 kg.ha^{-1} to 94 kg.ha^{-1} with a tax of € 0.516 per ha^{-1}; percolated nitrate is reduced by 50%

Fig. 42. The effect of nitrogen taxes on the rate of application



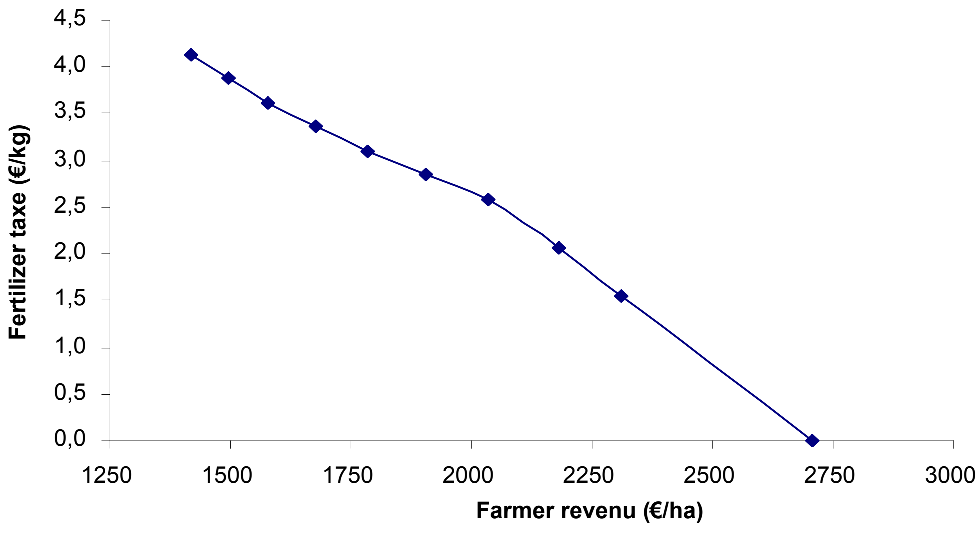
B. Nitrogen taxes applied to horticultural farms

A tax of from € 0 to € 4.13 per kg^{-1} with a stepwise increase of € 0.25 per kg^{-1} was applied to fertiliser application on horticultural farms to attempt to reduce nitrogen pollution by 50%

a] Farmer's revenue

Shown in the same way as nitrate pollution, the reduction in the farmer's revenue at each level of tax applied is presented in Figure 43. The curve has a single trend.

Fig. 43. The effect of nitrogen taxes on farmers' revenue

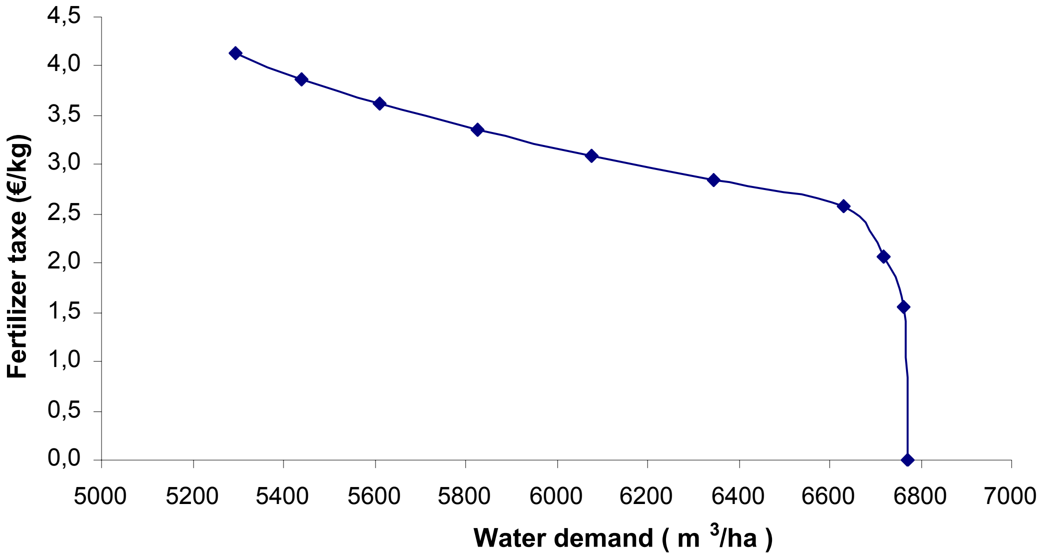


The tax has little effect on the curve from zero to € 2.84 per kg^{-1} and revenue decreased from € 2707 per ha^{-1} to € 1905 per ha^{-1}. For values higher than € 2.84 per kg^{-1}, the curve displays the same decrease and reached € 1418 per ha^{-1} at a tax of € 4.13 per kg^{-1}, at which point a 50% reduction of pollution is achieved.

b] Water consumption

The water consumption corresponding to each water price is shown in Figure 44. In this figure, the water is calculated in $m^3.ha^{-1}$, this being the average for the whole area. Consumption varies between 6770 $m^3.ha^{-1}$ with no nitrogen tax and 5293 $m^3.ha^{-1}$ with a nitrogen tax of € 4.13 per m^{-3}.

Fig. 44. The effect of nitrogen tax on the demand



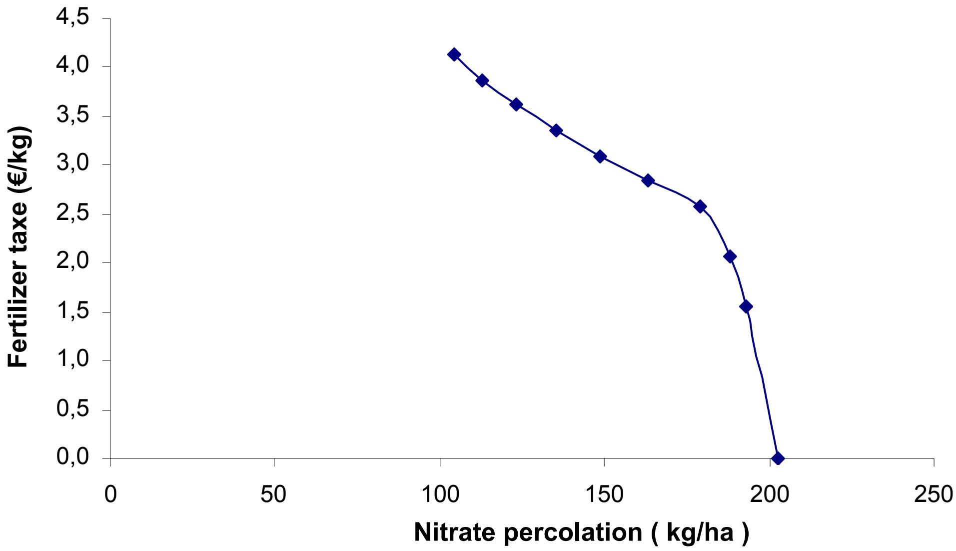
c] Nitrate percolation

Applying a flat-rate tax to nitrogen application causes a reduction in percolation is noticed and. This is illustrated in Figure 45, starting with 203Kg kg.ha-1 at zero tax and decreasing to 104 $kg.ha^{-1}$ at € 4.13 per kg-1. It is clear that at low values a low tax on inputs has no effect.

When the tax is increased from zero to € 2.58 per kg^{-1}, nitrate pollution decreases to 179 $kg.ha^{-1}$, an 18% reduction. The slope of the curve is steeper and the reduction in nitrate pollution more noticeable at values higher than € 2.58 per kg^{-1}.

With a nitrogen tax of € 4.13 per kg^{-1}, pollution is reduced by 50% and at this rate our objective of reducing pollution by 50% is attained.

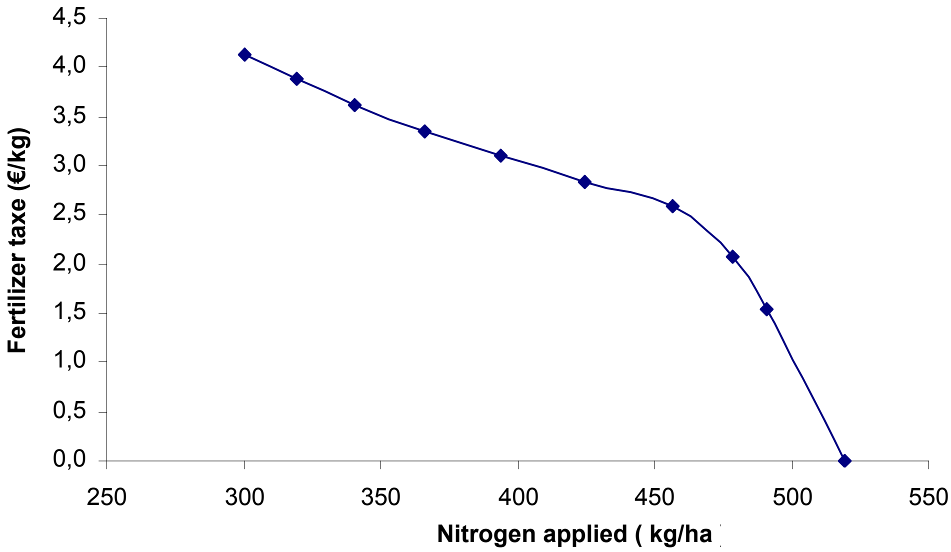
Fig. 45. The effect of taxes on nitrate percolation



d] Application rate of fertiliser

Figure 46 shows application starting at 520 $kg.ha^{-1}$ and decreasing with the tax increase to 491 $kg.ha^{-1}$ at € 1.55 per kg^{-1}, 478 $kg.ha^{-1}$ at € 2.07 per kg^{-1} and 457 $kg.ha^{-1}$ at € 2.58 per kg^{-1}. It then continues to decrease with a steeper slope for values higher than € 2.58€ per kg^{-1}, starting at 424 $kg.ha^{-1}$ at € 2.84 per kg^{-1} and reaching 300 $kg.ha^{-1}$ at € 4.13 per kg^{-1}. Application rate is reduced by 41% and the farmer's income by 48% to reduce nitrate percolation by 50%.

Fig. 46. The effect of nitrogen tax on the rate of application



3. Nitrogen block-rate tax

Another way of taxing input is a block-rate tax. Here, several blocks are chosen and each block has its own quantity limit and price level.

A. Nitrogen block-rate tax tested on cereal farms

The tax consists of costs according to the amount of fertiliser used and is charged on a rising block-rate basis from € 0 per m^{-3} to € 1.03 per m^{-3} (Table 15).

a] Revenue, fertiliser applied and percolated and water consumption

The results of the application of block-rate taxes on cereal farms are shown in Table 15. The farmer's revenue is € 141 per ha^{-1}, nitrate leaching is reduced by up to 50% to 10 $kg.ha^{-1}$ percolated and the amount of fertiliser applied is 74 $kg.ha^{-1}$

Table 15. Revenue, nitrate leaching and fertiliser applied (cereals)

	€/ha	kg/ha
Revenue	141	
Nitrate percolation		10
Fertiliser applied		74

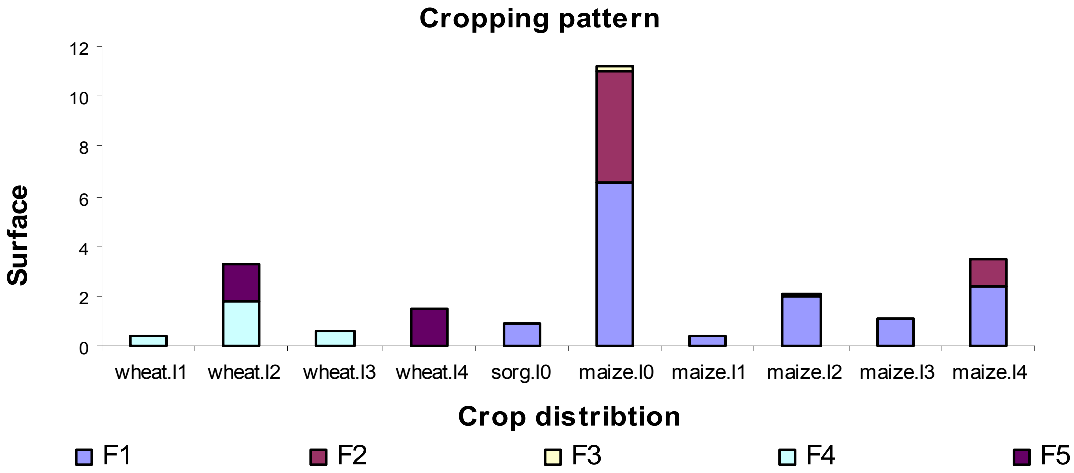
b] Cropping pattern

In order to reduce nitrogen percolation by 50%, the cropping patterns shown in Table 16 and Figure 47 show that wheat is still cultivated with different deficit water levels and the two highest fertiliser applications while sorghum appears to be grown under rainfed conditions and the first level of fertiliser deficit. Maize is grown under rainfed conditions and different deficit water levels coupled with the use of the lowest two levels of fertiliser deficit.

Table 16. Area distribution (ha) of the different crops associated with different amounts of water (I) and fertiliser applied (F).

	F1	F2	F3	F4	F5
wheat.I1				0.4	
wheat.I2				1.8	1.5
wheat.I3				0.6	
wheat.I4					1.5
sorgum.I0	0.9				
maize.I0	6.5	4.5	0.2		
maize.I1	0.4				
maize.I2	2	0.1			
maize.I3	1.1				
maize.I4	2.4	1.1			

Fig 47. Crop distribution associated with different amounts of water (I) and fertiliser (F) applied.



B. Nitrogen block-rate taxes tested on horticultural farms

Three blocks of taxes on fertilisers were applied, varying from 0 to € 6.20 per kg^{-1} (Table 17)

a] Revenue and fertilisers

Block-rate taxes on horticultural farms are shown in Table 17.

Farmer's revenue is reduced from € 2707 per ha^{-1} to € 1956 per ha^{-1}, nitrate leaching by as much as 50% to 52 $kg.ha^{-1}$ percolated and the amount of fertiliser applied is 284 $kg.ha^{-1}$.

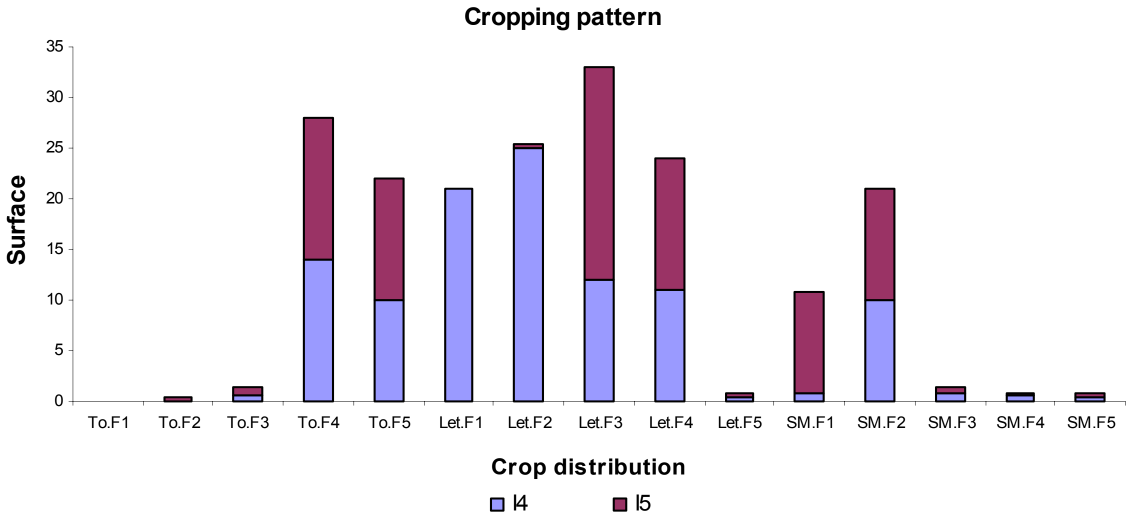
Table 17. Revenue, nitrate leaching and fertiliser (horticulture)

	€/ha	kg/ha
Revenue	1956	
Nitrate percolation		52
Fertiliser		284

b] Cropping pattern

Figure 48 shows the distribution of the different crops for each amount of water and fertiliser applied.

Fig 48. Crop distribution for different amounts of water (I) and fertiliser (F). To=tomato, Let=lettuce and SM=sweet melon



4. Cross compliance subsidies

The results of the application of cross-compliance subsidies are illustrated in Table 18, where € 27 per ha^{-1} is awarded to cereal farms and € 652 per ha^{-1} to horticultural farms to reduce pollution by 50%.

Table 18. Subsidies per hectare for each type of farm

	Fertilizer applied kg/ha	Subsidies €/ha
Cereal farms	100	27
Horticultural farms	160	652

5. Comparison of policies.

After analysis of each policy alone, the social cost of these policies is now analysed on a comparative basis. The results are shown in Tables 19a and 19b for a 50% reduction of nitrate pollution and show the social cost of each policy.

The social costs were calculated as the difference between the losses and the gains of the different economic agents of society as a result of the implementation of each policy. It can be seen that for a 50% reduction of pollution on horticultural farms, the policy of a block-rate tax on inputs has a social cost of € 337 per ha^{-1}. This is followed by water pricing which has a social cost of € 509 per ha^{-1}, while cross compliance subsidies have a social cost of € 652 per ha^{-1} and the flat-rate tax policy on nitrogen fertilisers is ranked last and has a social cost of € 1227 per ha^{-1}. The block-rate tax has the lowest social cost, followed by water pricing, cross compliance and finally the flat-rate tax on nitrogen.

It can be seen that the private cost of water pricing is too high (€ 1954 per ha^{-1}). This means that the loss of farmer's revenue is significant, even if this solution has a better social cost and better public income than cross compliance, which has no public income and less private cost.

An example of social calculation of nitrogen tax on cereals is as follows:

i) private cost: 2707-1418 = € 1289 per ha^{-1} (loss of farmers' revenue)
ii) public income: 0.413 (tax for obtaining a 50% reduction of N fertiliser) *150 (quantity of fertiliser used) = 62
iii) social cost: 1289 – 62 = € 1227 per ha^{-1}
In the other cases, the social cost is calculated as farmers' loss caused by the policy minus the public gain through taxes or water prices.

The results of policies are shown in Tables 19a and 19b.

Table 19 a. Comparison of policies for horticultural farms

(policy ranking)	Policies (50% pollution reduction)	Baseline revenue (€.ha^{-1})	After policy revenue (€.ha^{-1})	Private cost (€.ha^{-1})	Public income (€.ha^{-1})	Social cost (€.ha^{-1})
1	Nitrogen block-rate taxes	2707	1956	751	414	337
2	Water pricing	2707	753	1954	1445	509
3	Cross compliance	2707	2055	652	0	652
4	Nitrogen taxes	2707	1418	1289	62	1227

Table 19 b. Comparison of policies for cereals

(policy ranking)	Policies (50% pollution reduction)	Baseline revenue (€.ha^{-1})	After policy revenue (€.ha^{-1})	Private cost (€.ha^{-1})	Public income (€.ha^{-1})	Social cost (€.ha^{-1})
1	Water pricing	203	163	40	34	5
2	Cross compliance	203	175	27	0	27
3	Nitrogen taxes	203	127	76	48	27
4	Nitrogen block-rate taxes	203	163	40	9	31

For cereal farms, increasing the price of water has the lowest social cost at € 5 per ha^{-1}, followed by the cross compliance and flat-rate policies, both of which have a social cost of € 27 per ha^{-1}. The nitrogen block-rate tax policy is ranked last and has a social cost of € 31 per ha^{-1}. In addition to this cost, other costs should be taken into consideration such as the private and public income. The private cost of water pricing, with the lowest social cost, is higher than cross compliance and equal to the nitrogen block-rate tax that is ranked last. Nitrogen flat-rate tax has the highest private cost, with a dramatic decrease in farmer's revenue.

However, the effectiveness of the implementation of each policy must be taken into account. Water pricing and taxes are easy to implement, but they are less well accepted by farmers. The subsidies policy is better accepted by farmers but is more difficult to control.

This can show the importance of the introduction of high irrigation efficiency levels and high levels of farm management for the reduction of nitrate pollution.

Conclusion

Efforts have been made during the past decade to reconcile agricultural and environmental policies. At the European level, agricultural policy is increasing subsidies for less intensive and less pollutant methods of production and environmental policy has begun to target the agricultural pollution of water directly. Policies for controlling agricultural water pollution have gradually been extended to incorporate a mix of voluntary, regulatory, and incentive-based measures. However, there has been great reluctance to use measures other than voluntary ones. In cases where regulatory or incentive-based measures have been used, they have usually been in violation of the "polluter pays" principle by payments to farmers. The implicit assumption seems to have been that farmers have a property right to use land as they think fit and if the public wants less intensive land use, it must pay compensation. The irony is that the public also pays for the agricultural support prices that encourage intensification.

In recent years, it has become obvious that this state of affairs is no longer sustainable. In particular, direct income support is expected to increasingly replace agricultural price support, which should provide effective incentives for agricultural pollution abatement. Environmental policies will increasingly address agricultural water pollution problems by imposing mandatory "codes of good agricultural practice". Monitoring and enforcement will be facilitated by more sophisticated administration and information systems for registering land use and other activities of a shrinking population of full time farmers. There is still much to be learned about agricultural pollution control and the effectiveness of various mixes of measures. Empirical work on alternative control policies is too limited today for it to be possible to devise informed "packages of good control measures". It is therefore important for many control approaches to be pursued in greater detail and to be more closely evaluated.

Results in terms of social cost were defined to compare policies used. The social cost of a 50% reduction of nitrate pollution by cereal farms was € 5 per ha^{-1} for a water pricing policy, € 27 per ha^{-1} for the application of flat-rate tax on fertilisers and for cross-compliance subsidies and € 31 ha^{-1} for block-rate taxes. For horticultural farms, the block-rate tax had a social cost of € 337 per ha^{-1}, water pricing € 509 per ha^{-1}, cross-compliance € 652 per ha^{-1} and flat-rate tax € 1127 per ha^{-1}, with the latter having the highest social cost.

This shows that control by water price has the lowest social cost, followed by cross-compliance, flat-rate tax and block-rate tax for cereals. Block-rate tax comes first for horticulture, followed by water prices, cross-compliance and then flat-rate tax.

Implementation effectiveness should also be taken into account, because taxes and water pricing are fairly easy to implement and control but they are not readily accepted by farmers. While subsidies might gain more acceptance from farmers, implementation and the control of the results are more difficult.

This was a simplified approach in which only field crops were studied for one environmental impact (nitrate pollution). Further studies can be developed to focus on other environmental impacts or other possible agricultural policies.

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