HAL open science

The use of cover crops to reduce nitrate leaching: Effect on the water and nitrogen balance and other ecosystem services

Eric E. Justes, Olivier Rechauchère, Philippe Chemineau

To cite this version:

Eric E. Justes, Olivier Rechauchère, Philippe Chemineau. The use of cover crops to reduce nitrate leaching: Effect on the water and nitrogen balance and other ecosystem services. [0] INRA. 2012, 8 p. ⟨hal-03231464⟩

HAL Id: hal-03231464

https://hal.science/hal-03231464v1

Submitted on 20 May 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Distributed under a Creative Commons CC BY-NC-ND 4.0 - Attribution - Non-commercial use - No Derivative Works - International License

The use of cover crops to reduce nitrate leaching

Effect on the water and nitrogen balance and other ecosystem services

The presence of excess nitrate in surface water and groundwater is a double challenge, both in terms of public health (WHO standard for drinking water < 50 mg NO_3/L) and environmental protection (eutrophication of coastal zones). It is the subject of a European public policy that has been adapted by each Member State at national level and includes action plans for reducing nitrate as part of the "Nitrate Directive".

High nitrate levels are due to the excessive use of nitrogen fertilizers, and the natural production of nitrate by the mineralization of soil organic matter. Cover crops as catch crops trap the residual mineral nitrogen in the soil before the drainage period, thereby reducing nitrogen leaching and the nitrate concentration in the drainage water.

As part of the preparation for the fifth action program (beginning in 2013), the public authorities have requested an updated set of information and agronomic data relating to the effectiveness of cover crops. To this end, the Ministries of Ecology and Agriculture have asked the INRA to conduct a study whose objective is to take stock of the knowledge and research, as well as the uncertainties and questions requiring further investigation on this issue.

The main objective of this study is therefore to review the available knowledge on nitrogen management during fallow periods for arable crop systems in each of the different agricultural French regions, as well as the conditions influencing the effectiveness of catch crops in reducing nitrate leaching. As there is insufficient scientific literature available when it comes to understanding the diversity of situations in mainland France, the contracting body accepted INRA's proposal to supplement this corpus of knowledge by a simulation study. Moreover, the examination of the effects of catch crops was also extended to other potential ecosystem services, i.e. protecting the soil against water erosion, carbon sequestration in soils, contributing to the control of weeds, pests and diseases, etc. In addition, the study also examined other plant covers such as oilseed rape and winter wheat volunteers, as well as other fallow period practices such as mulch residues from the previous crop, either buried or left on the surface of the soil. In this document, the term "cover crops" refers both to catch crops and volunteers. When examining specifically the function of trapping nitrate, the term "catch crops" is used; when referring to other functions, the term "cover crop" is used.

1. The functions of cover crops

In crop rotation, the fallow period is the period between the harvest of the main crop and the sowing of the next. It can last from several days to several months.

The characteristics of cover crops are the following: **they are planted during the fallow period but they are not harvested**. They are instead destroyed or buried *in situ*, in contrast to crops producing forage or grain as a second cash crop which are also planted between two main crops. From an agronomic perspective, such plant covers may include **sown cover crops** (mustard, rye-grass, Phacelia, etc.) **or volunteers** from the previous crop (oilseed rape, winter wheat or barley, etc.).

The "nitrate trapping" effect of cover crops

Preventing nitrate leaching: the role of catch crops

Nitrate comes from the use of nitrogen fertilizers and the mineralization of soil organic matter (humus, crop residues, organic inputs). It is absorbed by plants (main crops, cover crops or weeds) and by soil micro-organisms (which collect the mineral nitrogen from the soil during the decomposition of organic matter, in a process known as nitrogen "immobilization").

Nitrate is a highly soluble form of nitrogen, particularly prone to leaching. This occurs when the **soluble nitrate ions** are transported by drainage (water transfer) beyond the root zone. Water transfer and the associated leaching are particularly

Juin 2012

common in the autumn, when precipitation often exceeds the water storage capacity of the soil. Nitrate leaching can contribute to the pollution of surface and groundwater and also results in a loss of the nitrogen essential for agriculture, requiring the production of nitrogen fertilizers in order to offset losses.

In order to control nitrate leaching it is necessary to minimize the quantity of mineral nitrogen in the soil at the beginning of the drainage period. The first requirement is to adjust or adapt the amount of nitrogen fertilizer used so that the quantity of mineral nitrogen in the soil at the time of harvesting the previous crop is minimal. This step is a necessary one but it is not sufficient in itself: the previous crop does not absorb all of the mineral nitrogen present, and the continuing mineralization of soil organic matter adds to the pool of mineral nitrogen in the soil.

One solution is to absorb mineral nitrogen using a plant cover in order to temporarily fix the nitrogen in an organic form (plant nitrogen). The function of catch crops is twofold: to absorb soil mineral nitrogen to prevent the loss of nitrogen through leaching and to return this nitrogen to the next crop via the mineralization of the catch crop residue.

Two variables can be used to estimate the extent of leaching and the effectiveness of catch crops:
- the amount of nitrate leached (expressed in kg N/ha): The effectiveness of catch crops is measured by comparing the soil nitrogen levels under catch crops to those in bare soil;
- the nitrate concentration of the drainage water (expressed in mg NO_3/L): The effectiveness of catch crops is measured by its ability to reduce the nitrate content (% reduction compared to bare soil) resulting in water that satisfies regulatory potability standards (50 mg NO_3/L).

Questions about the effectiveness of catch crops and their feasibility as a crop management practice

Under certain conditions, the question of the effectiveness of catch crops may arise. This is particularly the case:
- after a late harvest of the previous crop, especially of grain maize, leaving too little time for the growth of a catch crop before the resumption of drainage;
- in the case of a short fallow period between a summer harvest of the previous crop and the planting of a winter crop;
- for the use of legumes, because they cover part of their needs through the symbiotic fixation of atmospheric nitrogen, therefore absorbing less mineral nitrogen from the soil;
- when manure or residual organic matter is applied in the autumn, likely to result in nitrate quantities greater than the absorption capacity of catch crops.

Catch crops can also pose compatibility problems when it comes to:

- tillage in the autumn, particularly clay soils;

- the “stale seedbed” technique (whereby a seed-bed is prepared but not sown, in order to promote germination and emergence of weed seeds, which are subsequently destroyed by mechanical means) notably in organic farming.

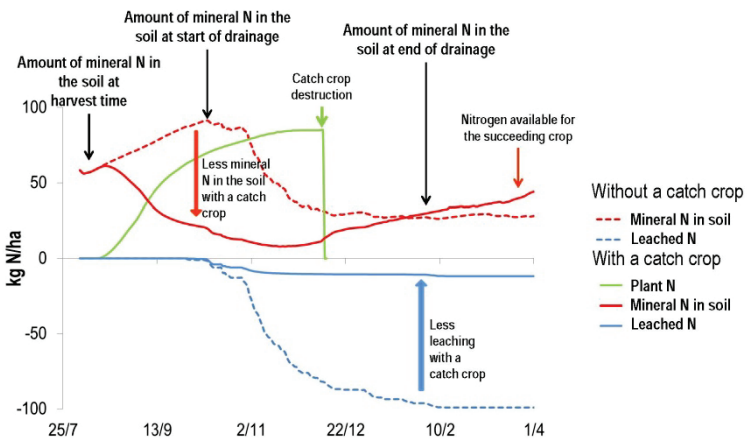
The potential difficulties involved in establishing a catch crop system should encourage further study of the effectiveness of alternative practices such as the development of previous crop volunteers, the burial of chopped residues from the previous crop or crop residues that remain on the soil surface as mulch.

Data analysis (768 scientific publications and 27 technical documents) prove that catch crops are effective in most of the situations tested, in the reduction of leaching and the nitrate concentration of drainage water, with a reduction generally of more than 50% with, in most cases, a drainage water content of < 50 mg NO_3/L. However, the effects are variable depending on the soil and climate, the weather conditions of the year and the cropping system.

The data from the various experimental studies, carried out unevenly throughout France, would appear to be insufficient to establish quantitative benchmarks that would allow us to predict the relative effectiveness of catch crops compared to other forms of fallow period management in given local conditions. In such a context, the relevance of carrying out a simulation study becomes apparent.

Finally, putting in place a catch crop system can be costly and may result in certain restrictions in terms of the farmer’s organization of labour. Analysis of the data has shown that such questions have not been the subject of many studies. A calculation on the basis of the benchmarks available estimates this cost to be in the region of €54-110/ha (incl. labour costs), depending on the cost of implementation and seeds (cf. summary and report).

Nitrogen management in fallow periods, with and without catch crops



Several factors/mechanisms explain the development over time of an "amount of mineral nitrogen in the soil" (nitrate available for plants but also exposed to leaching) after the harvest of the previous crop.

Before the beginning of drainage, the high mineralization rate of organic matter at the end of the summer and in the autumn increases the amount of mineral nitrogen in the soil. During the drainage period, this amount decreases due to nitrate leaching and a lower rate of mineralization at the end of the autumn and during the winter.

The levels of mineral nitrogen in the soil will be influenced by catch crops. By absorbing mineral nitrogen from the soil before the start of drainage, catch crops can prevent the increase of mineral nitrogen levels in soils at risk from leaching.

The effects of catch crops on the succeeding main crop and on groundwater recharge

By avoiding leaching and returning mineral nitrogen via the mineralization of residues, catch crops should, in theory, have a positive effect on the succeeding crop (a "green manure" effect). However, their consumption of water and nitrogen may result in a reduction of these resources for the subsequent crop (pre-emptive competition).

The published results of experimental studies show that the effect of catch crops on the succeeding crop is generally positive. However, the reasons for the variability of the results of these experimental studies remain unclear, except for legumes which always have a positive effect. In our temperate climates, the harmful effects are not usually due to their absorption of water, but of nitrogen (pre-emptive competition for N). The levels of available nitrate after catch crops may be lower if there is little drainage (the nitrogen absorbed by the catch crops was not leached), or if the return of nitrogen takes place too late, or too early (the released nitrate is leached before the spring). This nitrogen return by the mineralization of catch crop residue depends on its date of destruction, as well as its biochemical composition, notably its C/N ratio.

Finally, although the catch crop's consumption of water does not usually result in a reduced supply for the succeeding crop, it does result in a reduction in the amount of drained water, which has an impact on groundwater recharge

Fallow period management practices

The latest available data in France (pending 2011 results) are those from the "Cropping Practices" survey from 2006. At that time, less than 8% of the arable crop systems surveyed grew catch crops, 20% used previous crop volunteers; 28% of plots of arable land had been spread with ***organic manure.***

The other functions of cover/catch crops

In addition to their nitrogen-trapping function, cover crops offer other ecosystem services.

Protection against erosion and improving soil structure

The biomass and roots of cover crops protect the soil from the impact of raindrops, hold moisture and slow down run-off, thereby reducing water erosion.

Through their contribution to soil organic matter in particular, cover crops can also improve the structural and physical properties of soil (provided that it has not suffered mechanical damage during the destruction of the cover crop). However, these effects are minor than those caused by tillage or weather variability.

Carbon sequestration and the greenhouse gas balance

Cover crops significantly contribute to the sequestration of carbon (on average 300 ± 150 kg C/ha/yr) and mineral nitrogen in the soil; recent experiments have tended to overestimate this storage amount, which tends to decrease after a few years. On the other hand, non-leguminous cover crops may bring about a slight increase in N_2O emissions. In total, the greenhouse gas balance of cover crops appears to be positive, with an average reduction of the equivalent of one tonne of CO_2/ha the year the cover crop system is put in place, but with a high degree of variability depending on the biomass produced by the cover crops. There is little experimental data available and in particular on legumes (cf. report and summary, as well as the ESCo report entitled "Increasing carbon stocks in French agricultural soils?").

Weed control

Due to competition from cover crops, there is likely a reduction in weed emergence, development and bolting, accompanied in some cases by an allelopathic effect (toxicity of PCB metabolites released by root exudation or during the decomposition of the chopped and buried residues). These effects however, depend on the biology of the weeds. The impact on weeds is significant, but it is not a complete substitute for other methods of weed control, in particular for the perennial weeds.

The introduction of a cover crop system is compatible with the "stale seedbed" technique, but requires some changes in crop management practices at the time of its implantation and/or destruction. Moreover, the cover crop system should be adjusted in the case of no-tillage practices, which often lead to the chemical destruction of cover crops and weeds even though mechanical destruction would be feasible.

The effects on diseases, pests and beneficial fauna

The effect may be direct, by breaking the cycle of the pest or pathogen if the cover crop is not a host crop, or indirect, by the addition of organic matter which stimulates biological activity and natural regulation. Moreover, several botanical families (Brassicaceae, Poaceae, Alliaceae) have an allelopathic potential. These effects have been proved for Brassicaceae and are used against soil-borne diseases or pests, including sugar beet or vegetable crop nematodes. Their effectiveness however, is variable and demonstrates a high specificity (effectiveness depends upon the species or even the variety of cover crop, the species or even the breed of the pest), making their use particularly complex.

The biological activity of the soil, increased by cover crops, can also reduce pests through antagonistic regulation – the implementation of which takes several years however, and is not guaranteed. Cover crops and their residue promote beneficial invertebrates such as earthworms (especially in cases of reduced tillage), mesoarthropods, predators of nematodes, or even pollinators if the cover crop comes into bloom.

Conversely, pests may be attracted by certain cover crops and their residues, as is the case with slugs or phytophagous larvae of certain Coleopteran, Dipteran and Lepidopteran species.

In total, the balance of the effects of cover crops on pests and diseases would appear to be positive overall, although we need to better characterize their potential and behavior in order to enhance the positive effects demonstrated in experiments and to minimize possible adverse effects.

2. Simulation study

The simulation study carried out in parallel with the data analysis covers the period from the harvest of the previous crop to that of the succeeding crop. Its aim is to evaluate the effectiveness of catch crops and to quantify their effects on the water and

nitrogen balance, in comparison to volunteers and residues, for a wide ranges of soils, climates and French arable crop systems. The simulation study consists of 3 parts.

Part 1: Simulations of the impact of fallow period management practices on the water and nitrogen balance and yield of the succeeding crop

This study uses the soil-crop model STICS, a dynamic model that simulates the development of the crop and processes such as water, carbon and nitrogen cycles in the cultivated field. Developed by the INRA in the 1990s, the STICS model makes use of parameters that have been validated for numerous cropping systems, as well as the most common catch crops grown in France, and the fate of crop residues. The simulated processes are relevant and applicable to the main French soils.

The simulation study consists of selecting a range of weather, soil and crop situations and a set of fallow period management practices (see below). The combinations of these contexts and practices tested over a 20-year period of weather records have made it possible to simulate ca. 1.3 million fallow period management situations.

Using the STICS model, continuous simulations were performed over a 20-year time course, thereby allowing for frequency analysis (probability) of the occurrence of any given result. It was also possible to quantify the "risk" of a reduced efficacy of catch crops, or of adverse effects, depending on conditions and practices.

Parts 2 and 3: Additional simulations on the emergence and destruction phases of cover crops

The 2nd part of the simulation study looks at the **sowing-emergence phase** of catch crops, upon which the effectiveness of the nitrate trapping depends. The simulations were carried out with the aid of a specific model, SIMPLE, which allows us to evaluate the effects of different factors (sowing date, planting method, soil type and weather) on the germination and emergence percentages of catch crops.

The 3rd part focuses on the **destruction phase** of catch crops and aims to evaluate the "potentially available days" in autumn during which it is possible to mechanically destroy the crops without risk of damaging the soil (by compaction) in the process. The simulation is carried out based on soil type, levels of soil moisture (simulated using the STICS model), without taking into account restrictions on the organization of labour.

Prior to conducting this simulation study, the predictive quality of the STICS and SIMPLE models were assessed and their domain of validity determined in order to simulate both for arable crop systems and cover crops, and to ensure that the dynamics of the predominant processes were correctly represented. The results were satisfactory and "numerical modelling" was therefore carried out. However, certain conditions, beyond the models' validity domain, were not included in the simulations in order to avoid a potentially uncertain result: this was the case with undersown catch crop, mixed catch crops (legumes and non-legumes), and soils with a clay content higher than 45%. Finally, biotic factors (effects of diseases and pests on catch crops) were not taken into account in the simulations.

3. The main findings

In general, the findings of these simulations confirm those of the published literature in terms of crop growth, the absorption of nitrogen, the dynamics of water and nitrogen in the soil and its effects on the succeeding crop. The simulations also specify the effects of cover crops for a wide range of French soils and climates, and cropping systems.

The effectiveness of catch crops in "trapping nitrate"

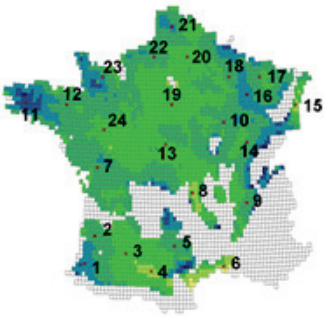
- Catch crops are effective in reducing nitrate leaching and concentration in drainage water (except for long fallow periods after a late harvest)

Despite the year-to-year variability due to climate, simulations have demonstrated the incontestable effectiveness of non-legume catch crops in reducing leaching and soil water nitrate levels in both short fallow periods e.g. an oilseed rape-wheat rotation) and long fallow periods (e.g. a wheat-maize rotation). However, this is not the case for long fallow periods after a late harvest (a grain-grain rotation) (cf. report).

Situations and management of the fallow period simulation models

*The selected **situations** allow us to simulate a wide range of soil and agronomic contexts. They include a choice of:*
- 24 sites in a "Nitrate-vulnerable" zone, over a 20-year time course simulation (using Météo-France [French weather service] data) ;
- different soil types (wide variability in sandy, loamy and clay soils), representative of each of the sites chosen;
- 3 crop rotations, corresponding to the different types of intercropping: Wheat-maize (long fallow period), Oilseed rape-wheat (short fallow period) and Maize-maize (long fallow period after a late harvest). These 3 crop successions are practised all over the country - with regional variations (common or durum wheat, and grain maize or silage).

*The **fallow period management practices** simulated are as follows:*
- bare soil (without catch crops) during the fallow period, with different management practices of the residue from the previous crop (left on the surface of the soil, exported or buried);
- 5 plant cover types: 3 species of seeded catch crops (Brassicaceae: Yellow mustard, Poaceae: Italian rye-grass and a legume: vetch); oilseed rape or wheat volunteers (with 2 crop densities);
- different crop management practices: several planting and destruction dates for catch crops ; 3 different levels of mineral nitrogen in the soil at the time of harvesting the previous crop (20, 60 and 100 kg N/ha); application of organic fertilizer (pig manure).



Localization of the 24 climatic sites

From light green to dark blue: increasing potential drainage classes such as [Rain - PET] from August to March.
In grey: area outside the "Nitrate" vulnerable zone.

The effectiveness of catch crops:
- is proved for the three simulated initial nitrogen levels, even when there is a low level of mineral nitrogen in the soil (because even in this theoretically favourable context, high levels of nitrogen can be produced during mineralization in the summer and autumn). The effectiveness of catch crops is reduced if the initial amount of mineral nitrogen in the soil is high: despite their capacity to trap a lot of nitrate, catch crops cannot completely correct high levels of mineral nitrogen initially present in the soil;
- is more marked in sites with high precipitation, and hence increased drainage and leaching, during long fallow periods (where the lifespan of the catch crop is longer than that of the main crop), in shallow and sandy soils, which are more sensitive to drainage and therefore to leaching, and if the catch crop develops early;
- depends more on the emergence date than on the destruction date, except if the growth period is shorter than two months. For short fallow periods, the catch crops are effective when they can absorb nitrogen in September and October, a period of intense mineralization due to warm, damp soil.

For non-leguminous catch crops and across all of the sites, the reduction of the nitrate concentration in drained water was generally more than 50% (or 75% for a large number of sites with high precipitation) on the optimum emergence and destruction dates (dates differ depending on the soil and weather). As a result, the nitrate concentration in drainage water was below 50 mg NO_3/L in the majority of situations.

- Legumes can be useful in reducing nitrate leaching, although they are only half as effective as non-leguminous species (Brassicaceae and Poaceae)

Simulations show that mustard (Brassicaceae) and Italian rye-grass (Poaceae) are equally efficient in reducing the nitrate content of drained water for the same emergence dates. Mustard however, due to its rapid growth and its greater rooting depth, is more effective when the growth period is short (short fallow period or late sowing in September), or in deep soil.

Vetch (a legume) is only ca. half as effective in reducing leaching as mustard or ryegrass – although its water consumption is equally high. Vetch obtains its nitrogen through symbiotic fixation and this legume therefore absorbs less of the available mineral nitrogen in the soil. Despite their reduced efficiency, legume crops are nevertheless useful for reducing the nitrate leaching and concentration, and are therefore preferable to bare soil.

As demonstrated in the published literature, a mixture of leguminous and non-leguminous species could be effective as a catch crop, less effective than a catch crop made up solely of non-legumes but more effective than a purely leguminous one, and then largely better than bare soil.

- Oilseed rape and winter wheat volunteers are effective in reducing the nitrate concentration in drainage water, provided that the plant cover is dense and uniform.

Simulations show that oilseed rape and winter wheat volunteers are effective in reducing the nitrate concentration in drainage water if the plant cover is sufficiently dense and uniform. When this is the case, oilseed rape volunteers are just as efficient as sown mustard, and wheat volunteers are as efficient as Italian ryegrass. However, when the volunteers are sparse and unevenly distributed in space (e.g. in "strips", under the passage of the combine harvester, alternating with bare soil) the result is on average only half as efficient as dense, uniform volunteers.

The ground cover, upon which the effectiveness of volunteers depends, is determined by the size and spatial distribution of grain losses at the time of harvesting the oilseed rape or winter wheat. There is no available statistical information on the characteristics of volunteer covers on agricultural land. Volunteer oilseed rape, due to the amount of seeds that fall before harvest, is often dense and covers the entire surface area. The density and coverage are more variable for cereals.
Volunteers are the least expensive crop management option. However, they are inconvenient in that one cannot choose the emergence date, which may coincide with an unfavourable period, e.g. too dry. This technique may also result in plant health risks: volunteers are a host crop for pests and are especially susceptible to the diseases that affect crop rotation systems.

Fallow period after maize (in rotation or monocropped)

- The ineffectiveness of catch crops after grain maize requires very strict management of the use of nitrogen fertilizers in order to avoid nitrate leaching

After **silage maize** (harvested mid- to late-September), catch crops are only partially effective: the median reduction in nitrate concentration in drained water is ca. 35% for mustard and 25% for ryegrass; this figure is close to 50% in the southern half of the country, where the catch crop growth can be rapid in the autumn.

After **grain maize** (harvested mid- to late-October), catch crops are inefficient (the reduction in nitrate concentration is less than 10%) because their growth is slow and late in the autumn due to late sowing. However, in regions with a Mediterranean climate, the long growth period and higher mean temperature allows mustard a significant reduction in nitrate concentrations, with a median of 30%. **The ineffectiveness of catch crops in this context requires very strict management of the use of nitrogen fertilizers**; *another option, not studied here and yet to be optimized, would be to undersow the catch crop before harvesting the maize*. Another option may be to sow early varieties of maize.

- A mulch of chopped maize stover left on the surface of the soil does not reduce nitrate concentration in drained water after grain maize, so it is preferable to bury the mulch, even though this technique has a limited efficacy

Since catch crops are inefficient after grain maize, crop residue management may be a potential alternative. Simulations show that chopped maize stover mulch has no effect on leaching but buried mulch may cause a slight reduction in leaching (by 5 kg N/ha) and in the nitrate concentration in drained water (in the range of 5 to 10%) due to net nitrogen immobilization in the soil.

In terms of leaching, even though the effect may be modest, the incorporation of chopped maize stover into the soil just after harvesting is preferable to mulching. It is also preferable in terms of plant health. In contrast, mulching is favourable in terms of carbon sequestration (because the decomposition of residue is less rapid and has higher humification levels). It also provides soil protection.

Similar results have been obtained for wheat residues. Straw mulch has no effect on leaching, but burying the chopped straw

brings about a moderate reduction in nitrogen losses (ca. 20 kg N/ha on average) and in nitrate concentration (in the order of 20 mg NO_3/L). Furthermore, the nitrogen immobilization effect is greater than for maize as the C/N balance of straw is higher than that of maize stover.

The case of clay soils

- The number of potentially available days for the destruction of catch crops in the autumn is not a seriously limiting factor in carrying out this action, except for clay soils (> 37% clay)

The number of potentially available days (determined solely on the basis of the soil water content) to carry out mechanical destruction in the autumn is hardly, or not at all, limiting for sandy or loam soils. However, the number of possible days decreases as the season progresses for clay loam soils.

For clay soils (clay content between 37 and 43%), less than a third of the days are available from the beginning of November; catch crop destruction at the end of October is therefore preferable. Soils with a clay content above 45% were not included in simulations because their physical behaviour is harder to model. Indeed, this type of soil is not common in arable crop systems as it is not very suited to arable cultivation.

- On clay soils tilled in the autumn, even those catch crops destroyed early still prove to be generally effective in reducing nitrate leaching

Early destruction (mid- to late-October) of catch crops, whether it is done to allow the tillage of clay soils or the sowing of a winter crop (short fallow period), is not incompatible: a rapidly growing catch crop (Brassicaceae) is effective if it remains in place for at least two months (emergence late July or August).

This effectiveness is generally lower when the amount of mineral nitrogen in the soil is high, but the reduction in the drained water nitrate concentration however, is often significant (often >50%), making catch crops very useful.

Adapting to the climate, particularly Mediterranean climates

- For a catch crop planting to be successful, the sowing date should be adapted in order to reduce establishment failures.

Simulations with the SIMPLE model demonstrate that in general, the emergence of catch crops is potentially sufficient (seed emergence rate > 75%) for a successful planting, whatever the species and sowing technique used. Poor emergence (< 50%) happens in various weather conditions, but rarely (in less than one year in ten for northern sites, and two years in ten in the south-west. In regions with a Mediterranean climate) emergence varies greatly from year to year, with failures (< 25%) approx. two years in ten and low emergence (< 50%) approx. four years in ten. Poor emergence typically occurs with early sowing. Later sowing, around September 15, is generally more efficient.

It is worth noting that the model used does not take into account any potential damage caused by pests. Pests and diseases may occasionally cause significant losses, particularly when seeds are not treated.

- In Mediterranean regions, emergence problems do not detract from the important role played by catch crops in the reduction of nitrate leaching in years of excessive drainage.

In these regions, sowing in early or mid-September avoids the high water stresses that occur earlier in the summer and increase the likelihood of successful emergence of catch crops and their subsequent ability to absorb nitrogen. Simulations also show that early destruction (before mid-December) reduces the crop's consumption of water and nitrogen, thereby avoiding harm to the succeeding crop and limiting the reduction of drainage and consequently, groundwater recharge.

In Mediterranean zones, the regular planting of catch crops, particularly during long fallow periods, would appear to be an interesting option for preventing nitrogen pollution. It could prove to be of limited use in years with no or little drainage (approx. one year in two) but extremely useful (reduction of <75% in nitrate concentration) in wet years, with drainage > 100 mm.

The effect on the succeeding main crop and on groundwater recharge

- Catch crops reduce drainage but have no effect on the water consumption and status of the succeeding crop if their destruction date is well chosen

Catch crops usually reduce annual drainage by about 30 mm on average (from 0 to 80 mm according years), due to their consumption of water and despite the fact that less water is evaporated from soils with plant cover. This reduction in drainage is greater when the weather is dry because approx. the same actual evapotranspiration occurs despite a lower winter/spring rainfall. Catch crops do not generally affect the water absorption of the succeeding crop; rainfall recharges the soil water, except in dry conditions when the catch crop is destroyed shortly before the sowing of the succeeding crop.

This reduction in drainage is less than 10% of the water drained in the majority of soil/climate sites, but can reach 25% in some years at sites with low winter rainfall. The extensive use of catch crops in a given region may therefore reduce the groundwater recharge in hydro-geological situations where this depends mostly on under crop-based drainage.

- The impact of Brassicaceae and Poaceae on the yield of the succeeding main crop is slightly positive or null, except in situations of short fallow periods when it can be negative. The impact is always positive with vetch.

Comparisons of simulated yields of the succeeding crop with or without catch crops shows that overall, the impact on the succeeding crop is positive following a long fallow period, but also after silage maize, with a long fallow period after a fairly late harvest. However, the yield increase is moderate (on average 1 to 8% depending on the climatic site). The effect is almost zero after grain maize due to the small amounts of nitrogen absorbed by the catch crop.

For short fallow periods with mustard and rye-grass, simulations have demonstrated a depressive effect on wheat yields, especially when the initial amount of nitrogen in the soil is low (pre-emptive competition). The poor results shown in simulations are even lower when the initial amount of mineral nitrogen in the soil is high, if the site is wet or the catch crop destruction date is late.

In contrast to the two other non-leguminous species studied, vetch has an almost-invariable positive effect on the yield of the succeeding crop. In situations with a short fallow period and a low initial amount of mineral nitrogen in the soil, vetch allows exogenous nitrogen "to enter" through symbiotic fixation and has a positive effect in 75% of the models simulated. As a result, sowing a mixture of species of catch crop including a legume,

even a pure legume cover, could be an efficient solution to reduce the cases where a depressive effect would occur to the succeeding main crop.

Catch crops and fertilizer management

- Catch crops are only fully efficient if the nitrogen fertilizer used for the previous main crop was correctly calculated, leaving a small to moderate quantity of mineral nitrogen in the soil at the time of harvesting.

Catch crops are effective in correcting small to moderate quantities of mineral nitrogen in the soil at harvest time (in situations where the initial amount of mineral nitrogen was 60 kg N/ha), in short and long fallow periods. They are not effective however, after grain maize. Despite their high nitrogen trapping ability, non-leguminous catch crops, and particularly legumes, do not always reduce the nitrate in the drainage water to less than 50 mg NO_3/l in situations where there was a high initial quantity of mineral nitrogen in the soil (>100 kg N/ha).

These results are a reminder, as if we needed one, of the necessity of adjusting, on the basis of a provisional nitrogen balance, the nitrogen fertilization of main crops as a prerequisite in the control of nitrate leaching. Furthermore, this adjustment is a means of avoiding excessively high mineral nitrogen quantities in the soil at harvest time, particularly situated deep in the soil, beyond the root zone of catch crops or previous crop volunteers. Catch crops are a complementary step in the management of nitrogen during fallow periods in order to efficiently trap soil mineral nitrogen (coming from residual nitrogen at harvest and soil organic matter mineralization) and to recover drainage water with markedly lower nitrate concentration levels.

- The application of livestock manure at catch crop sowing is compatible with the reduction of nitrate leaching, as long as certain rules are followed.

The application of pig manure (a manure used in simulation models because of its high mineral nitrogen content and its easily mineralizable organic fraction) markedly increases nitrate concentrations in bare soil situations.

Catch crops are **only effective** in reducing the nitrate concentration in drained water **if the following four conditions are met**: 1) there is a small initial quantity of mineral nitrogen in the soil (about 20 kg N/ha over 90 cm); 2) preferably, a rapidly-growing Brassica catch crop is sown; 3) the chances of obtaining good uniform emergence have been maximized, or the catch crop has been checked for emergence before spreading the manure; 4) the amount of manure applied is limited so that the total amount of nitrogen applied does not exceed 75 kg N/ha.

The compatibility or compromise between trapping nitrogen and other ecosystem services

Several ecosystem functions can be fulfilled in conjunction with catch crops, with more or less efficiency, depending on the species and the crop management practice. However, in certain situations, it is necessary to choose between the desired services and local priorities, particularly by adapting planting dates and the dates and methods of destruction.

Therefore for example, **stale seedbed technique** has been shown to be compatible with a catch crop providing that sowing occurs 2 to 3 weeks later than usual, allowing the soil to be tilled beforehand. With emergence at the end of August or even mid-September - in southern regions, catch crops retain their effectiveness - certainly sub-maximal - in reducing the nitrate concentration in drained water. Destruction of the catch crop in the autumn also destroys any late-germinating weeds before they seed.

On **sloping land** however, it may be necessary to choose between the "nitrogen-trapping" and particularly the "anti-erosion" functions of catch/cover crops on the one hand, which would require the destruction of the cover after the winter, and favouring groundwater recharge on the other (catch crops may also help in reducing run-off in favour of water infiltration).

Optimizing catch crop management techniques

It is possible to determine optimum crop management techniques based on the results of the simulations, by putting them through a multi-criteria analysis, combining several parameters of the efficiency of catch crops, or of other effects selected, based on local issues or factors. The objective was to establish ***pairs of emergence and destruction dates*** *allowing us to achieve the best possible combined performance over a 20-year simulation. This was done by selecting dates that have successfully met with the successive applied criteria:*

1. *The high efficiency of catch crops, characterized by an interannual average, over the 20-year period simulated, nitrate concentration in drained water of < 50 mg NO_3/l and a reduction of >75% in the maximal rate achieved for the most effective pair of emergence and destruction dates,*

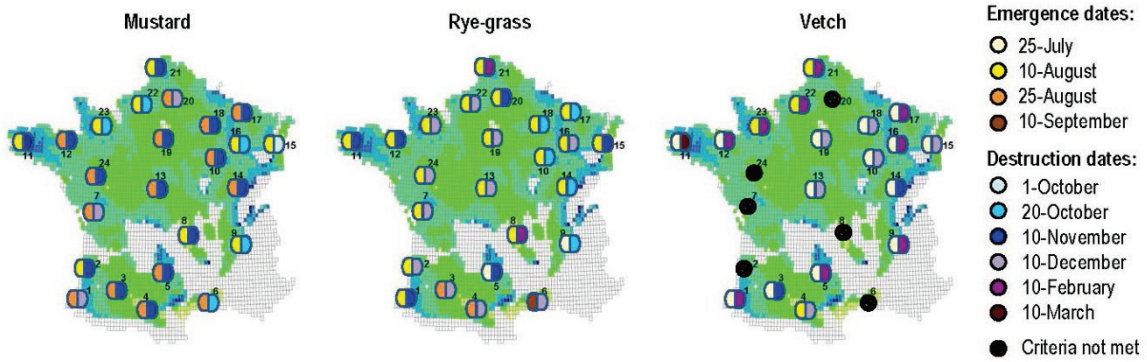
2. *No reduction in the yield of the succeeding main crop,*

3. Reliability *of catch crop efficacy, defined as regular efficacy between years characterised a low probability of obtaining a reduction in nitrate concentration of less than 50%,*

4. *The lowest possible reduction in drainage so as to minimize the impact on groundwater recharge.*

With the above criteria and the stringent choice of efficacy thresholds:
- vetch does not meet the criteria for nitrate concentration in drained water when the initial nitrate level in soil is high,
- the optimum emergence dates, over a 20-year period, are August 10 or 25 (for this specific analysis),
- the optimum destruction time is early autumn

The pairs of optimum dates selected therefore highlight the importance of weather conditions, of the species or variety of catch crop and the quantity of mineral nitrogen in the soil.



Optimum emergence and destruction dates for catch crops with a mineral nitrogen baseline of level 2

Conclusion and outlook

This simulation study has added new knowledge for local French situations and allowed to quantify the effects of catch crops on a wide range of arable crop systems, soil and climatic conditions and fallow period management practices, thereby adding to the existing experimental data. The objective was to produce additional data to the literature and it is now the role of stakeholders, public authorities and “extension workers” to use this data in their decision-making processes and to apply these to local contexts and to advise farmers.

The efficacy of catch crops has been confirmed and the conditions for their implementation clarified

- **Catch crops are necessary**, even when there remains little mineral nitrogen in the soil after the previous crop due to judicious fertilization, because the mineralization of organic matter in the soil continues to produce high levels of nitrate, which can then be leached. Applying synthetic nitrogen fertilizer to catch crops does not increase the effectiveness of catch crops in "trapping nitrate" and only increases the stock of nitrogen that can be leached.
- **Non-leguminous catch crops are effective to trap nitrate in soil**, in very many of the simulated conditions. This effectiveness applies to both long and short fallow periods and for early destruction dates (in October). Leguminous such as vetch are less effective in this regard. Non-leguminous catch crops are also effective if organic manure is applied, as long as the initial quantity of mineral nitrogen in the soil is low and the amount of manure spread low. They are not effective after grain maize, where nitrogen fertilizer management is vital.
- **Crop management techniques should be adapted** to the local soil and climatic conditions and to the crop system to jointly maximize the effectiveness of "nitrogen trapping" and to minimize the potential adverse effects on the succeeding crop. This adaptation of catch crop management should also take into account the other "ecosystem services" rendered by catch crops, depending on the local context (preventing erosion, restoring the water supply, etc.). On a broader scale, fallow period management is one of the components of the (re) design of cropping systems that are more environmentally friendly, attributing a value to ecosystem services.

Research needs - development

Whilst the study has confirmed the effectiveness of catch crops and their major determinants, it has also highlighted the need for better knowledge and the need to develop coordinated research, particularly on:
- the properties of the available catch crop species and cultivars, their effect on the pests and diseases of primary crops, their diversification and their improvement by targeted genetic selection;
- the diversification and optimization of catch crop management techniques: the use of legumes or a mixture of species to jointly optimize the "nitrogen catching" and "green manure" effects, the practice of undersowing, the adaptation of no-tillage systems, and the development of decision-making tools in order to optimize crop management practices;
- the impact of the generalized use of catch crops on water resources;
- the effects of climate change on the effectiveness of catch crops;
- a risk-benefit analysis of cover crops, taking into account all of their functions, as well as a study of the most efficient public policies for their implementation.

Study conducted by the INRA at the request of the Ministries of Ecology and Agriculture

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE
Ministère de l'Écologie, du Développement durable et de l'Énergie

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE
MINISTÈRE DE L'AGRICULTURE ET DE L'AGROALIMENTAIRE

The studies conducted by the Delegation of Scientific Expertise, Foresight and Advanced Studies (DEPE) of the INRA are exercises derived from collective scientific expertise and are guided by professional standards. These studies are carried out at the request of public commissioning bodies, under the responsibility of the INRA, and are conducted by a multidisciplinary group of scientific experts, responsible for collectively analyzing the international bibliographical references in order to find useful information to respond to any questions raised by public managers. In this study, the analysis of the bibliographical references has been enlarged by an original approach to data and/or simulation work. These studies do not formulate opinions or recommendations.

For this study, the group of experts was made up of 16 researchers from various disciplines (soil sciences, agronomy, crop protection, law, etc.), belonging to research bodies or the following higher education establishments: INRA, IRSTEA, ENSAT, University of Toulouse, Agroscope (Switzerland). Field experts from Technical Institutes and Chambers of Agriculture were consulted for the simulation work of the study.

For more information:

Justes E., Beaudoin N., Bertuzzi P., Charles R., Constantin J., Dürr C., Hermon C., Joannon A., Le Bas C., Mary B., Mignolet C., Montfort F., Ruiz L., Sarthou J.P., Souchère V., Tournebize J., Savini I., Réchauchère O., 2012. The use of cover crops in the reduction of nitrate leaching: Impact on the water and nitrogen balance and other ecosystem services. Summary of the study report, INRA (France), 60 pgs.

This short memo, the summary, as well as the complete study report can be consulted free of charge on the INRA website (www.inra.fr).

Contacts:

Eric Justes, INRA, Scientific Director for the study:
Eric.Justes@toulouse.inra.fr

Olivier Réchauchère, INRA-DEPE, Project Manager for the study:
Olivier.Rechauchere@paris.inra.fr

Philippe Chemineau, INRA, Director of the DEPE:
Philippe.Chemineau@paris.inra.fr