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Abstract

Weeds are often solely considered with a negative viewpoint, but they may also provide services for agroecosystems. Especially, the residual weed flora that is tolerated by integrated crop protection may contribute to a reduction of nitrate leaching and soil erosion during the summer and autumn fallow. To date, the determinants underlying these environmental weed benefits are largely unknown. The present study developed new indicators to account for the potential beneficial role of annual weed flora to reduce nitrate leaching and soil erosion at the field scale, and then calculated them from the outputs of a weed dynamics model. The aim was to analyse which cropping systems facilitate residual weed flora to reduce nitrate leaching and soil erosion, while minimizing negative weed impacts on crop production. When developing the indicators, the potential weed-based reduction of nitrate leaching was considered to increase with both the growth of the weed flora and the weed species potential to take up nitrogen; the potential weed-based reduction of soil erosion was assumed to increase with soil cover by weeds when soil cover by cash crops was low. Our simulation study included 259 arable cropping systems (covering a wide range of herbicide and tillage intensity, with each cropping system simulated over 28 years and repeated 10 times with 10 different weather series) in which the dynamics of 25 annual weed species was simulated. Simulations showed that the cropping systems promoting a high potential weed-based reduction of nitrate leaching were generally also those with a high potential weed-based reduction of soil erosion, pointing to a compatibility between these benefits provided by the weed flora. However, the cropping systems promoting these environmental benefits were generally also those that presented the highest crop yield losses. Tillage and crop rotation were identified as the cultural techniques with the greatest influence on the potential weed-based reduction of nitrate leaching and soil erosion, while herbicides had a more limited effect. Most of the studied cropping systems (representing “real situations” in which farmers or experimenters make the decisions about crop rotations and cultural techniques) tended to favour low crop yield losses rather than high weed-based environmental benefits. Interestingly, a few systems achieved both objectives. Systems that achieved relatively low crop yield losses and high weed-based environmental benefits mainly combined infrequent superficial tillage operations, with a low proportion of winter crops in the rotation and a very low tillage depth. Finally, only a few weed traits determined the role of the weed flora to potentially reduce nitrate leaching and soil erosion. They were seed traits (seed lipid content, seed area per weight and seed coat thickness), driving the early and fast appearance of the weed canopy after weed seed shed. This suggests that, for annual weed species, a high weed flora potential to reduce nitrate leaching and soil erosion is not restricted to specific weed species able to take up nitrogen and cover soil. Thus, our simulation study indicates that such a high potential to reduce nitrate leaching and soil erosion could therefore be reached in very different agroecosystems in terms of weed seed bank.

Keywords

Cultural techniques; tillage; crop rotation; trait; indicator; simulation model.

1. Introduction

As competitors for resources and/or hosts for crop diseases, weeds can cause severe crop yield losses in agricultural systems (Wisler and Norris, 2005; Oerke, 2006). For this reason and because they may also pollute harvests by weed seed debris and cause harvesting problems, weeds are often considered a major pest. However, weeds also provide services for agroecosystems, promoting plant biodiversity and feeding other organisms potentially valuable to crop production (e.g pollinators, beneficial predators such as carabid beetles) (Petit *et al.*, 2011; Kulkarni *et al.*, 2015; Rollin *et al.*, 2016). Among these benefits, the role of the residual weed flora to reduce nitrate leaching, especially during the summer and autumn fallow period, has rarely been highlighted and assessed (Blaix *et al.*, 2018; Huang *et al.*, 2018b).

Yet, some weed species are known for their high potential to take up soil inorganic nitrogen (Moreau *et al.*, 2013; Moreau *et al.*, 2014). A recent meta-analysis of 17 field studies showed potential nitrogen losses from croplands to be 60% greater in bare soil compared to weedy-fallow fields (Wortman, 2016). Moreover, by comparing (1) a maize monoculture vs a maize-weed (i.e. pigweed) mixture in Iran (Gholamhoseini *et al.*, 2013a; Gholamhoseini *et al.*, 2013b) and (2) a system with no tillage and weed cover mulching vs conventional tillage (Yagioka *et al.*, 2015), other field studies also found that weed communities reduce nitrate leaching. Weeds may also contribute to regulate soil erosion by wind or water, but studies on this topic are scarce (Blavet *et al.*, 2009; Lenka *et al.*, 2017; Blaix *et al.*, 2018; Neyret *et al.*, 2018; Liu *et al.*, 2019). Indeed, similarly to crop plants, the leaves of weed plants intercept raindrops thereby reducing splash erosion, their stems may reduce runoff velocity, and their roots may enhance soil shear strength and stability while favouring water infiltration (Kervroëdan *et al.*, 2018; Neyret *et al.*, 2018). These positive side effects of weeds in agricultural systems remain to be assessed in more details, and their determinants to be analysed.

For many years now, nitrate leaching and soil erosion have been reported to threaten the sustainability and productive capacity of cropping systems (Pimentel *et al.*, 1995; Sutton *et al.*, 2011; Cameron *et al.*, 2013). Better understanding the role of weed flora in reducing environmental threats is essential, particularly in the context of integrated crop protection. An integrated crop protection approach tolerates residual weeds if they do not harm crop production. Identifying how farm management choices influence the weed community is an important part of better protecting soil.

Simulation models are powerful tools to evaluate cropping systems (Bergez *et al.*, 2010; Ould-Sidi and Lescourret, 2011; Jeuffroy *et al.*, 2012; Colnenne-David and Dore, 2015). Indeed, they can be used to assess many and diverse cropping systems, in the long term, and with various weather scenarios for their effect on weed flora (Colbach *et al.*, 2014a). Coupling such models to indicators was shown to be a relevant approach to assess both negative and positive impacts of the residual weed flora on agroecosystem functioning (Mézière *et al.*, 2015b). Indicators aggregate existing knowledge and aim to provide information about a variable that is difficult to access in order to help management decisions (Bockstaller *et al.*, 2008; Bockstaller *et al.*, 2015). They can be built from expert opinion and available literature. The advantage of indicators is twofold: they transform multiple and complex model outputs into scores that are easier to analyse, and add new outputs without making the structure of the model more complex. Coupling a simulation model to indicators was successfully used to evaluate a large range of existing cropping systems, in order to determine management rules for reconciling weed-related biodiversity and weed harmfulness (Mézière *et al.*, 2015a; Colbach *et al.*, 2017a).

Using this approach, the present study aimed to (1) develop indicators to account for the potential role of weed flora to reduce nitrate leaching and soil erosion at the field scale, and (2) calculate these indicators from the outputs of a weed dynamics model in order to analyse which cultural techniques and weed traits may favour the potential of the residual weed flora to reduce nitrate leaching and soil erosion, while limiting negative impacts on crop production. The weed dynamics model used in the present study was FLORSYS which is a process-based cropping system model that predicts the dynamics of multi-species annual weed flora and its impact on crop production and biodiversity (Colbach *et al.*, 2014a).

2. Materials and methods

2.1. A short presentation of FLORSYS

2.1.1. Weed and crop life-cycle

FLORSYS is a virtual field on which cropping systems can be experimented while estimating a large range of crop, weed and environmental measurements (Gardarin *et al.*, 2012; Munier-Jolain *et al.*, 2013; Colbach *et al.*, 2014b; Colbach *et al.*, 2014d; Munier-Jolain *et al.*, 2014; Mézière *et al.*, 2015b). The input variables of FLORSYS consist of (1) a description of the simulated field (daily weather, latitude and soil characteristics); (2) all the simulated crop management operations in the field, with dates, tools and options; and (3) the initial weed seed bank. These input variables influence the annual life-cycle which applies to annual weeds and crops, with a daily time-step. Pre-emergent stages (surviving, dormant and germinating seeds, emerging seedlings) are driven by soil structure, temperature and water potential. Post-emergent processes (e.g. photosynthesis, respiration, growth, shade avoidance) are driven by light intercepted by each plant depending on its leaf area and shading by neighbours as well as air temperature. Nitrogen uptake and use by plants (and therefore competition for nitrogen) are not simulated by the model, i.e. FLORSYS assumes that soil nitrogen is always sufficient to fulfil the requirements of all crop and weed plants in the simulated field. At plant maturity, weed seeds are added to the soil seed bank; crop seeds are harvested to determine crop yield (in T/ha and in MJ/ha). Life-cycle processes also depend on cultural techniques, in interaction with weather and soil conditions on the day the operations are carried out. FLORSYS parameters are currently available for 25 frequent and contrasting weed species and 21 crop species (Section A.3 online). Further details on FLORSYS can be found in Section A online.

2.1.2. Domain of validity

FLORSYS was evaluated with independent field data from four regions (Colbach *et al.*, 2016). The evaluation showed that daily plant and seed densities and, particularly, densities averaged over the years were generally well predicted and ranked depending on the weed species and cropping systems in the model's original region, i.e. Burgundy. At more southern latitudes, a corrective function was used to keep weeds from flowering during winter (Section A.5 online). To be noted that only annual weeds are included in the model, so that perennial and biennial weeds are not included in our study.

2.2. Designing indicators of the potential weed-based reduction of leaching and erosion

2.2.1. Principle

FLORSYS already includes several indicators that depict the weed flora impact on crop production and biodiversity (**Table 1**). These indicators are based on the following principles: (1) identification of the relevant weed state variable, e.g. seed density on soil surface for the bird-food indicator, (2) identification of the relevant impact period, e.g. winter for bird food, as the season with the highest famine risk, (3) choice of the relevant species traits, e.g. seed lipid content for the carabid-food indicator (Mézière *et al.*, 2015b; Colbach *et al.*, 2017a). Food-offer indicators reflect a potential weed impact, i.e. a potential food offer for fauna; they do not assess an actual service, i.e. whether the target organisms are actually present and benefit from the food offer. Conversely, indicators of plant biodiversity and weed harmfulness illustrate an actual effect, e.g. crop yield is reduced by the weed presence.

In the following sections, these principles were used to design new indicators of weed impacts. They assess the weed floras' potential (and not an actual service) on reducing nitrate leaching and soil erosion.

Even if FLORSYS, as such, does not simulate the processes underlying nitrate leaching and soil erosion, the connection of these indicators to FLORSYS makes it relevant to account for the potential of the weed flora to take up nitrogen and therefore to lower nitrate leaching during the fallow period.

2.2.2. Indicator conceptualisation

2.2.2.1. Potential impact of weed flora on nitrate leaching

The potential impact of the weed flora on nitrate leaching is calculated during the period when the risk of nitrate leaching is the highest, i.e. during the summer and autumn fallow period in-between two cash crops. That is the reason why the calculation period started at the harvest of the previous crop. The calculation period ended at the beginning of water drainage assuming that, the more weeds take up nitrogen before the beginning of water drainage, the lower the amount of nitrogen available for leaching.

To focus on the fallow period, the indicator is calculated only if water drainage begins before whichever of the following two events occurs earliest, i.e. (1) crop covers > 20% of soil or (2) sowing date + 30 days for spring crops or sowing date + 90 days for winter crops (Equation 1 in **Table 2**). Afterwards, the role of the weed flora to reduce nitrate leaching is supposed to be lower than that of the crop and no value is calculated for the indicator in these situations. Water drainage is considered to begin when the moisture of the top soil layer (30-cm depth) reaches field capacity. The beginning of water drainage is calculated by the soil submodel of STICS model (Brisson *et al.*, 1998) coupled to the FLORSYS model (Gardarin *et al.*, 2012).

In a given field, a weed community is considered to have a high potential to reduce nitrate leaching if (1) it grows strongly and/or (2) it contains species with a high ability to take up soil inorganic nitrogen. So, the relevant weed variables are the plant leaf area - as a driver of plant nitrogen demand (Lemaire *et al.*, 2005; Lemaire *et al.*, 2007) - and the species Ellenberg-N index - as an indicator of the species potential to take up inorganic nitrogen (Ellenberg, 1974; Moreau *et al.*, 2013; Moreau *et al.*, 2014). Indeed, the potential of weed species to take up nitrogen by roots was shown to increase with Ellenberg-N index, and this relationship was shown to be valid for different weed species (Moreau *et al.*, 2014). It is probably not applicable to legume species, due to symbiotic nitrogen fixation. However, there are no legume weed species in the studied agroecosystems, and thus in the simulated agroecosystems (Section A.3 online). If the Ellenberg-N index for a given species is missing, it is estimated from Landolt (Landolt, 1977) as both indicators are correlated (Section C.1 online). Based on this, the daily potential impact of weed flora on nitrate leaching (IN_d) is calculated according to Equation 2 (**Table 2**), for each day (d) of the period of calculation and over all the species (s) present in the weed flora in a given field. To calculate the mean potential impact of the weed flora on nitrate leaching over the period (IN), the daily values are summed over all the days of the period of calculation (D_N), and then divided by the length of this period to make it easier to compare cropping systems (Equation 3; **Table 2**). The higher the indicator value, the higher the potential of the residual weed flora to reduce nitrogen leaching.

2.2.2.2. Potential impact of weed flora on soil erosion

The potential impact of weed flora on soil-erosion reduction is calculated during the period running from the harvest date of the preceding crop until the date when the cash crop is sufficiently dense to cut off soil erosion (proportion of covered soil = 20%), or else at cash-crop harvest date (Equation 4 in **Table 2**). During this period, a weed community in a given field has a high potential to reduce soil erosion if soil cover by weeds is high, while soil cover by cash crops is low. So, the relevant weed state variable is the proportion of light absorbed by the weed community (PLW_d) as a proxy of droplet penetration into the canopy (Kim *et al.*, 2011) . For a given day (d), PLW_d is summed over all individuals (i) of each weed species (s) (Equation 5 in **Table 2**). The indicator of soil erosion (IE) is calculated as the number of days when the light interception by the weed community is higher than 10% (Equation 6 in **Table 2**). The higher the indicator value, the higher the potential of the residual weed flora to reduce soil erosion.

2.3. Simulation study

A simulation study was run with many contrasting cropping systems to assess the effect of cultural techniques on weed-mediated reduction of nitrate leaching and soil erosion.

2.3.1. Cropping systems

A total of 259 arable cropping systems was simulated with FLORSYS (Section B.1 online). These systems were used in previous simulation studies (Colbach *et al.*, 2017a) and originated from cropping system trials (Colbach *et al.*, 2016), farm surveys (Mézière *et al.*, 2015b), the Biovigilance-Flore network (Fried *et al.*, 2008; Colbach *et al.*, 2014e; Colbach *et al.*, 2016) and expert opinion (Ballot, 2009; Colbach *et al.*, 2010; Colbach *et al.*, 2014e; Bürger *et al.*, 2015).

They covered six French regions (Burgundy, the Paris region, Aquitaine, Poitou-Charentes, Lorraine, Picardie) and one Spanish region (Catalonia) (Section B.2 online). They included both intensive and organic systems, with a tillage intensity varying from no-till to annual mouldboard ploughing. Rotations were mainly based on cereals (wheat, barley, maize) and oilseed rape, with a smaller proportion of legumes (lucerne, faba bean, etc), non-legume broadleaved crops (sunflower, flax, etc.) and temporary grassland, with proportions and crop species depending on regions.

2.3.2. Simulation plan

Each cropping system was simulated over 28 years, repeating the basic rotational pattern (e.g. oilseed rape/wheat/barley) over time. Simulations were initialized with a weed seed bank consisting of the 25 weed species currently included in FLORSYS (Section A.3 online). For each region, a typical seed bank was determined from the relative species densities observed in the regional flora (Colbach *et al.*, 2016) (Section B.3 online). Soil parameters were based on soil analyses from the cropping system trials or from locations inside the simulated regions (Section B.2 online). Soil textures included loam, sandy loam and clay loam textures. Daily weather variables (minimum, mean and maximum temperature, precipitation, radiation, evapotranspiration) were recorded by INRA weather stations in the different regions (INRA Climatik platform) (Section B.2 online). Each cropping system was repeated 10 times with 10 different weather series consisting of 28 randomly chosen weather years from its region of origin, using the same 10 series for each system of a given region.

2.3.3. Weed impact indicators and cropping system descriptors

All weed-impact indicators simulated by FLORSYS (**Table 1**) were averaged over the 28 simulated years for each cropping system and weather repetition. The cropping systems were characterized with a series of descriptors of cultural techniques averaged over the 28-year simulation. For example, the number of superficial tillage operations per year is a descriptor. It reflects the number of operations prior to cash crop sowing with diverse tools (e.g. spring tine, power harrow, disks etc), excluding mouldboard plough (which tills deeply and inverts soil layers), roll (which does not mix soil layers) and mechanical weeding (i.e. tillage carried post sowing to destroy weeds in crops). The descriptors used in the present study were already used in previous studies (Bürger *et al.*, 2015; Colbach *et al.*, 2017a; Colbach *et al.*, 2017b; Colbach *et al.*, 2017c). In addition to region and weather repetition (nested within region), a total of 644 descriptors were used in the analysis. Ninety-two were practices averaged over the rotation, concerning crop rotation, sowing and harvesting dates, tillage, herbicides, mechanical weeding and manure. A further set of 46 descriptors was computed for each crop (sugar beet, wheat, oilseed rape, field bean, flax, maize, mustard, barley, pea, soybean, sunflower, triticale).

2.4. Statistical analysis

Antagonisms and synergies between weed impacts were analysed using indicator values averaged over the rotation. Pearson correlation coefficients were calculated between our new indicators quantifying the role of the weed flora to potentially reduce nitrate leaching and soil erosion on the one hand, and the other FLORSYS indicators on the other hand.

The effect of cropping system descriptors on the potential weed-based reduction of nitrate leaching and soil erosion was analyzed with linear models with the LASSO (Least Absolute Shrinkage and Selection Operator) method, using PROC GLMSELECT of SAS (version 9.4). This stepwise selection arises from a constrained form of ordinary least squares regression where the sum of the absolute values of the regression coefficients is constrained to be smaller than a specified parameter. It produces sparser model than the conventional stepwise selection. Descriptors were added sequentially, by adding effects that at each step produce the smallest value of the Schwarz Bayesian information criterion (SBC) statistic and stopping when adding any effect increased the SBC statistic again. Descriptors could also be removed again if this reduced the SBC. The final model was chosen among the successive models as the one that yielded the lowest predicted residual sum of square with cross validation.

This analysis was completed with multivariate regression trees in order to analyse how combinations of cultural techniques (i.e. management strategies) affect simultaneously potential weed-based reduction of nitrate leaching and soil erosion, and crop yield losses due to weeds. Regression trees were computed, using the R software version 3.4.3 (R Core Team, 2014) with the library mvpart (De'Ath, 2002). A multivariate regression tree predicts a set of continuous response variables based on a set of discrete or continuous predictors. The data set is recursively split into two subsets along a threshold value of the predictor in order to maximize the difference between subsets with respect to the multivariate response. Branches are combinations of predictor values that lead to multivariate predictions contained in leaf nodes. Here, weed-mediated reduction of nitrate leaching and soil erosion, as well as crop yield variations due to weeds, were the response variables while cultural techniques were predictors. Variable importance (VIP) was used to rank predictors based on the contribution predictors make to the construction of the tree, i.e. according to their impact on the response variables.

Finally, RLQ analyses were used to identify pertinent relationships between potential weed-mediated reduction of nitrate leaching and soil erosion on the one hand, and weed species traits on the other hand, using the R software version 3.4.3 (R Core Team, 2014) with the library ade4 (Chessel *et al.*, 2004). RLQ analyses perform a double inertia analysis of two arrays, R and Q, with a link expressed by a contingency table L. The method used here was based on Colbach *et al.* (2017a) and Colbach *et al.* (2017b), using indicator values per system and repetition as R matrix, densities per weed species, system and repetition (corresponding to maximum biomass densities per species during crop cycle, averaged over the 28 years of the simulation) as L matrix, and traits per weed species as Q matrix. Only trait-indicator relationships significant at $P = 0.05$ when permutating lines and columns were considered. The species traits used were taken from Colbach *et al.* (2017a) and Colbach *et al.* (2017b). In total, 30 traits were used in the analysis (Section A.3 online).

For all the analyses including the nitrate-leaching indicator, situations (i.e. cropping system × weather repetition) without indicator value (see 2.2.2.1) were disregarded.

3. Results

3.1. Trade-offs and synergies among indicators

Our new indicators of potential weed-mediated reduction of nitrate leaching and soil erosion were highly correlated with each other (**Figure 1**). So, the cropping systems promoting a high weed-based reduction of nitrate leaching were generally also those with high weed-based reduction of soil erosion. This result suggested that the same cultural techniques drove these weed-based environmental benefits, both occurring mainly during the summer and autumn fallow periods.

Both indicators were highly correlated with the pre-existing FLORSYS indicators reflecting weed-based benefits and harmfulness ($P < 0.001$; **Table 1**; Sections C.2 and C.3 online). The positive correlations with species richness indicated that cropping systems promoting potential weed-based reduction of nitrate leaching and soil erosion were generally also those promoting a species-rich weed flora. To a lesser extent, the negative correlations with species equitability suggested that cropping systems promoting these potential weed-based environmental benefits during the fallow period were also those promoting the abundance of a small number of weed species within weed biodiversity. Interestingly, cropping systems promoting the potential weed-based reduction of nitrate leaching and soil erosion were also those providing trophic resources for other organisms (birds, carabids, bees). However, they were generally those that were the most harmful for crop production, causing for instance high crop yield losses due to weeds. The weak correlations with the herbicide Treatment Frequency Index (TFI) showed that the weed-based reduction of nitrate leaching and soil erosion could occur in cropping systems with different intensities of herbicide use.

All these correlation coefficients showed general trends, but the correlation graphs plotting one indicator vs another (Sections C.2 and C3. online) showed that some situations (i.e. cropping systems × weather repetitions) allowed to reconcile contradictory objectives, for instance high potential weed-based reduction of nitrate leaching and moderate crop yield losses due to weeds. The specificities of these situations in terms of cultural techniques and weed flora are analysed in the following sections.

3.2. Which cultural techniques drive weed-based reduction of nitrate leaching and soil erosion?

At the rotation scale, tillage and crop rotation characteristics were the main drivers of both indicators of potential weed-based reduction of nitrate leaching and soil erosion (**Table 3**). Globally, increasing tillage intensity (i.e. number of operations per year and/or tillage depth) adversely affected the role of the weed to reduce nitrate leaching and soil erosion. Interestingly, five tillage variables adversely affected both indicators concomitantly (in bold in **Table 3**). Thus, the same tillage strategies should achieve these two weed services during the fallow period.

The effects of crop rotation characteristics depended on the indicator. Potential weed-based reduction of nitrate leaching was decreased by pea, spring crops and cover crops in the rotation. Moreover, it was decreased when spring crops were harvested later. The potential weed-based reduction of soil erosion increased the later crops were sown after winter and, therefore, with increasing use of summer crops. It also increased with the rotation diversity in terms of cropping seasons, especially with the proportion of cover crops, flax and triticale, but it decreased with the proportion of oilseed rape.

Herbicide choices only affected the nitrate-leaching indicator, with the potential role of weeds generally decreasing with the number of applications of herbicides entering via roots only or with multiple entry modes. Conversely, pseudo-root only herbicides (entering via the shoot tip during seedling emergence) promoted the potential weed-mediated reduction of nitrate leaching.

In addition to the effect of cultural techniques, region had a significant effect on both indicators of weed-mediated environmental benefits (Section C.4 online).

When descriptors accounting for cultural techniques at the crop (annual) scale were added to the analyses, tillage variables were still the key drivers of both indicators (Section C.5 online). Techniques related to seven different crops affected our environmental indicators (barley, flax, maize, oilseed rape, pea, sunflower and wheat). However, the variability explained by these analyses (i.e. their coefficients of determination) were lower than with cultural techniques at the rotation scale only (**Table 3**).

3.3. How to combine cultural techniques to promote the weed-based reduction of nitrate leaching and soil erosion, while minimizing crop yield losses?

None of the studied situations (i.e. cropping system × weather repetition) allowed to both maximize our new environmental indicators and minimize crop yield losses (**Figure 2**). With descriptors of cultural techniques expressed at the rotation scale only, the management strategies (i.e. combinations of cultural techniques) that the best reconciled the three indicators are in green in the regression tree of **Figure 2**. They included no till and a low proportion of winter crops in the rotation ($\leq 21\%$). This combination promoted both low crop yield losses and high potential reduction of soil erosion, while potential leaching reduction was moderate in Aquitaine (green box in the left terminal leaf of the green path). In Catalonia, this combination promoted potential reduction of nitrate leaching more than the two other indicators (green box in the right terminal leaf).

All the other management strategies resulted in at least one indicator lower than the mean performance calculated over all the 2327 situations. For example, one of the management strategy (in orange on **Figure 2**) promoted both nitrate-leaching and soil-erosion potential reduction, but it strongly increased crop yield losses. It included early winter crop harvest ($\leqslant$ 12 July), no-till or infrequent superficial tillage operations in summer ($\leqslant$ 1.5/year), a significant proportion of winter crops in the rotation (> 21%) and rare disking operations ($\leqslant$ 1.1/year). Another management strategy (in purple on **Figure 2**) promoted potential soil-erosion reduction and low crop yield losses, but not potential nitrate-leaching reduction. It included late-sown cash crops (⩾ 13 May), superficial tillage operations (but not necessarily frequently, ⩾ 0.5/year), a low proportion of winter crops in the rotation (⩽ 21%), and finally infrequent or no disking operations (⩽ 1.1/year).

The most frequent management strategy in our database (in red on **Figure 2**, with 22% of the analyzed situations) limited crop yield losses, but it was the most unfavorable to weed-based environmental benefits. It included a moderate frequency of foliar-only herbicide use (⩽ 2.0 /year), frequent superficial tillage operations in winter (⩾ 1.0/year), and finally frequent superficial tillage operation with disks (> 1.1/year).

When cultural techniques expressed at the crop (annual) scale were included to the analysis, in addition to the cultural techniques expressed at the rotation scale, the management strategies that discriminated the different situations were slightly modified (Section C.7 online). The right-hand branch of the regression tree, with most of the analyzed situations (n = 1631 out of 2327), was similar to the analysis when cultural techniques were expressed at the rotation scale only (**Figure 2**), in terms of splitting and number of situations. Only the two branches on the left of the regression tree (n = 696 out of 2327) were modified. Indeed, one descriptor related to the management of a single crop, i.e. wheat, replaced rotation-related descriptors. With the crop-related descriptors, the most unfavorable management strategy for both environmental indicators (in red in Section C.7 online) included frequent use of herbicides for wheat (> 0.5 multi-entry herbicides/year) and frequent disking operations (> 1.1/year).

3.4. Which species traits affect the weed-based reduction of nitrate leaching and soil erosion?

Correlations between weed species traits and the environmental indicators were identified with an RLQ analysis (**Table 4**). Only a few correlations were significant and, among the studied traits, only seed traits had a significant effect. The potential of the weed flora to reduce nitrate leaching increased with seed lipid content and seed area/mass ratio, while the potential to reduce soil erosion decreased with seed coat thickness. No other correlations were identified, including with the Ellenberg-N index which was included in the calculation of the nitrate-leaching indicator.

4. Discussion

4.1. Novelty and limits

Until now, the few studies on this topic only aimed at determining whether the weed flora can significantly contribute to reduce nitrate leaching and soil erosion during the summer and autumn fallow period (Yagioka *et al.*, 2015; Wortman, 2016; Blaix *et al.*, 2018; Neyret *et al.*, 2018). To our knowledge, the present study is the first attempt to analyse the underlying determinants. Our findings are conditioned by the prediction quality of the FLORSYS model, as previously discussed (Bürger *et al.*, 2015; Mézière *et al.*, 2015a; Mézière *et al.*, 2015b; Colbach *et al.*, 2017a), and by the processes included in the model (e.g. only annual weeds are simulated). They also depend on the indicators' conceptualisation, e.g. the threshold values used for determining the periods for the calculation of the indicators, or the proxys that were used (Ellenberg-N index as a proxy of species affinity for nitrogen, the proportion of light absorbed by the weed community as a proxy of droplet penetration into the canopy). Moreover, our indicators only reflect potential roles of the weed flora to reduce nitrate leaching and soil erosion, independently of the risks. For example, neither the FLORSYS model nor the indicator of nitrate leaching take into account nitrogen fertilization techniques. Yet, the role of the residual weed flora to reduce nitrate leaching is expected to increase with the amount of soil mineral nitrogen, which was not considered in the present study. Similarly, our model and indicators do not account for plant nitrogen uptake, herbivory, or plant-microbe interactions, processes that influence plant community dynamics. Nonetheless, the validity of our approach is supported by the fact that the indicators proposed in the present paper are based on the same principle as the other FLORSYS indicators (notably food offer for honey bees, carabids and farmland birds) whose prediction ability was judged reasonable based in view of literature and field observations (Mézière *et al.*, 2015b; Colbach *et al.*, 2017a). Moreover, our results are in good agreement with the well-known effects of cultural techniques and weed traits, as discussed below.

4.2. Ranking the impacts of key cultural techniques on the weed-based environmental benefits

Our study ranked the cultural techniques according to their respective effects on the potential weed-based reduction of nitrate leaching and soil erosion. Tillage intensity was the most influential driver irrespective of whether environmental indicators and cultural techniques were considered individually or in combination. Globally, tillage frequency and depth decreased the potential weed-based reduction of nitrate leaching and soil erosion. This is consistent with the well-reported effects of tillage on weed dynamics: tillage reduces weed seed banks by stimulating germinations during fallow, eliminates weed seedlings and plants before sowing cash crops (Pekrun and Claupein, 2006), and buries weed seeds (Roger-Estrade *et al.*, 2001; Colbach *et al.*, 2014c). The latter decreases seed germination (Gardarin *et al.*, 2012) and increases pre-emergent seedling mortality due to insufficient seed reserve (Gardarin *et al.*, 2010). As tillage contributes *in fine* to reduce the growth of the weed community (Légère *et al.*, 2008; Santín-Montanyá *et al.*, 2016), the reduction of nitrate leaching and soil erosion is logically decreased. Our results are in good agreement with a recent field study showing that nitrogen uptake by fallow weeds is much higher under no-tillage than under conventional tillage systems (Huang *et al.*, 2018a).

Considering crop rotation, the proportions of different crops in the rotation were identified as a key driver when cultural techniques were analysed individually. Potential weed-based nitrate-leaching reduction was the most decreased by choices that penalized the growth of the weed community during summer and autumn fallow, such as the use of cover crops which compete with weeds for light and other resources (Tardy *et al.*, 2015). Spring crops also decreased potential weed-based nitrate-leaching reduction. Indeed, spring crops generally contribute to control weeds (Lutman *et al.*, 2013; Fried *et al.*, 2015), because their short cycle both limits weed growth and seed production inside the crop and lengthens the fallow period, leaving more time for tillage operations. Potential weed-based reduction of soil erosion was mainly driven by choices that favored long periods with a low soil cover by cash crops. This was the case when cash crop sowing was delayed (especially of spring crops), when rotation diversity was increased in terms of cropping seasons (which often meant more spring crops) and when cover crops were grown (which are most frequent before spring crops and late-sown winter crops).

Finally, herbicides decreased the potential weed-based reduction of nitrate leaching, in accordance with the negative effect of herbicides on weed growth. Surprisingly, the frequency of pseudo-root herbicides increased this weed-based benefit. As these herbicides penetrate weeds via the shoot tip during emergence, they only target a small proportion of the actual weed flora, missing any plants emerging before the treatment or once the active ingredient has disappeared from soil surface (Colbach *et al.*, 2017d). Conversely, foliar herbicides entering via the leaves particularly target weeds with a large leaf area, which are also those with the highest potential to catch nitrate.

Note that our analysis of the effects of cultural techniques on the two indicators of potential weed-based environmental benefits was performed twice: once using descriptors accounting for cultural techniques at the rotation scale only, and again using descriptors accounting for cultural techniques both at the rotation and the crop (annual) scales. Both approaches concluded to a similar ranking of cultural techniques, but rotation-scale descriptors were more influential and better at explaining the variability in weed services. The only significant crop-scale descriptors referred to wheat, which was a main crop in the studied cropping systems. The dominant role of the rotation-scale descriptors is consistent with the ability of weed seeds to survive for several years in the soil (Lewis, 1973), thus carrying over the effect of cultural techniques.

4.3. A minor impact of individual weed traits on the weed-based environmental benefits

Our analysis of the key weed traits affecting the potential role of the weed community to reduce nitrate leaching and soil erosion showed that only a few traits, exclusively related to seeds, were influential. The potential reduction of nitrate leaching increased with seed lipid content and seed area/mass ratio which are both known to increase earliness of germination (Gardarin *et al.*, 2011). The potential weed-based reduction of soil erosion decreased with seed coat thickness which is known to promote dormancy (Gardarin and Colbach, 2015). These findings suggest that traits driving the early and fast appearance of the weed canopy after weed seed shed (generally in summer and early autumn) are much more relevant for environmental benefits than the species ability to cover soil and take up mineral nitrogen. The small number of significant traits suggests that weed impacts depended more on the growth of the weed community (determined by soil, climate, and cropping system) than on individual species characteristics. This would explain the global positive correlation between the potential weed-based reduction of nitrate leaching and soil erosion on the one hand, and crop yield losses on the other hand: the faster the weed community grows, the higher its potential is to reduce nitrate leaching and soil erosion, and the more harmful the weed community is to crop production. It is also possible that trait combinations, rather than individual traits as analyzed in our study, were the main driver of weed impacts, and/or the potential role of the weed flora to reduce nitrate leaching and soil erosion resulted from a weed community of interacting species, and not simply from individual weed species or trait combinations as we already observed for weed impacts on parasitic plants (Colbach *et al.*, 2017a).

4.4. Practical implications

The analysis of the role of weed species traits showed that the species ability to cover soil and/or take up mineral nitrogen was not crucial to promote the potential weed-mediated reduction of nitrate leaching and soil erosion, meaning that these environmental benefits depend less upon the weed species identity (provided that they are able to germinate early and fast, as discussed above) than upon the leaf area dynamics of the weed flora as a whole. So, the potential of the weed flora to promote these environmental benefits is not restricted to specific weed seed pools. Moreover, results show that environmental indicators and the herbicide Treatment Frequency Index (TFI) are weakly correlated. So, the potential of the weed flora to promote environmental benefits depends little on the intensity of herbicide use. Altogether, these results indicate that these weed-based services may be achieved in very different cropping systems.

Our results showed that the situations promoting a high potential weed-based reduction of nitrate leaching were generally also those with a high potential reduction of soil erosion, pointing to a compatibility between these environmental benefits provided by the weed flora. Moreover, these situations were also those promoting other weed-based services (such as trophic resource for other organisms, plant biodiversity), pointing to a compatibility among very different weed-services. However, our results showed the difficulty to both maximize these weed-based environmental benefits (especially reduction of nitrate leaching) and minimize weed-mediated crop yield losses. Most of the analyzed farming situations favor low crop yield losses rather than high environmental benefits. This is in accordance with the key challenge for farmers to minimize weed harmfulness, such as crop yield losses, while maximizing the weed-based environmental benefits is generally a minor objective for them (recent French survey of 980 farming actors in Schwartz, 2018; Colas *et al.*, in revision). Interestingly, some cropping systems partly reconciled these contradictory objectives. These systems combined no or rare shallow tillage with a low proportion of winter crops in the rotation, transferring the protective role from those winter crops to naturally occurring residual weeds instead.

5. Conclusions

This study analyzed for the first time the determinants of the weed-based reduction of nitrate leaching and soil erosion, using a simulation model of weed dynamics coupled with new indicators of weed benefits. It identified a compatibility between both environmental benefits provided by the weed flora mainly during summer and autumn fallow. Reconciling these environmental benefits with low crop yield losses due to weeds in agroecosystems was identified as a challenge that may partly be addressed by combining rare tillage with frequent spring crops in the rotation. The next step will be to check our indicators accounting for the potential role of the weed flora to reduce nitrate leaching and soil erosion with field observations, according to recommendations of Bockstaller *et al.* (Bockstaller and Girardin, 2003; Bockstaller *et al.*, 2008). In the future, plant nitrogen uptake will be included into the mechanistic FLORSYS model, in order to quantify the actual rather than the potential role of the weed flora to reduce nitrate leaching.

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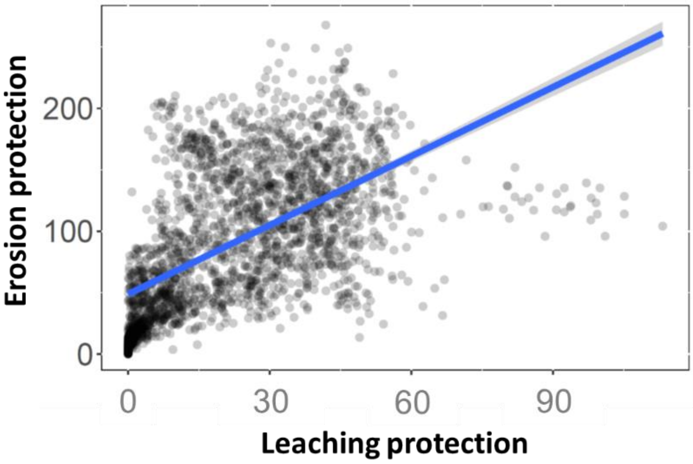

Figure 1. Correlation between the weed-based reduction of nitrate leaching and soil erosion (r = 0.59; P < 0.001; n = 2346**).** The larger the indicator value, the larger the potential of the residual weed flora to reduce nitrogen leaching and soil erosion. Both indicators are dimensionless. Each symbol shows a situation (i.e. cropping system × weather repetition).

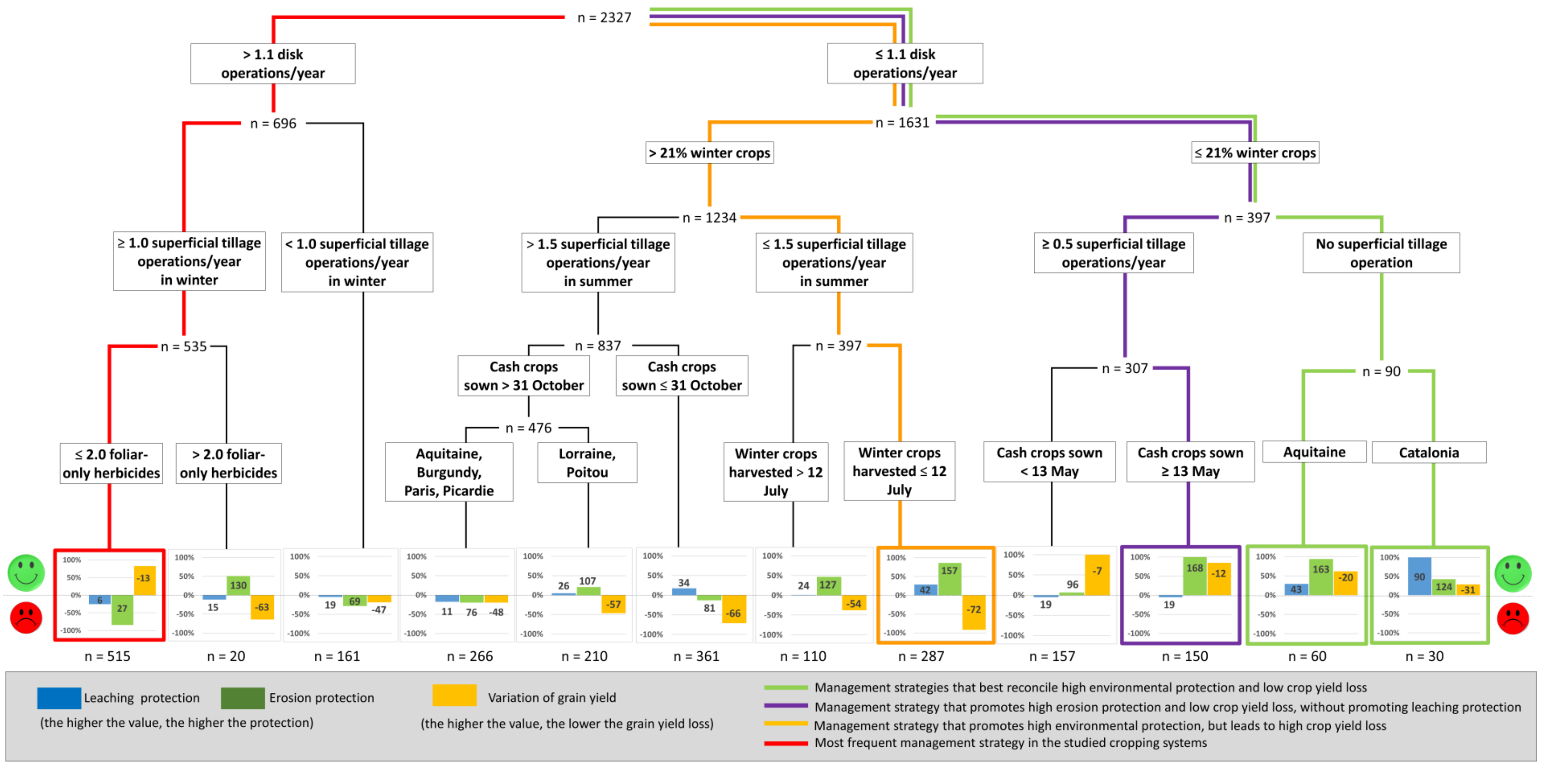

Figure 2. Multivariate regression tree identifying combinations of cultural techniques (at the rotation scale) and their performances in terms of weed-based environmental protection and impacts on crop yield. Tree branches (segments) are combinations of cultural techniques. Terminal nodes ("leaves") show the corresponding performance in terms of weed-based reduction of nitrate leaching and soil erosion, and crop yield variation relative to a weed-free control. On the graphs, the y values are, for each indicator, the standardized values expressed as a percentage of the highest value obtained for the 12 final groups. The y values are at zero for performances equal to the mean performance over all the 2327 situations. The higher the environmental indicator values,

the higher the protection. The higher the value of the indicator of grain yield variation, the lower the grain yield loss due to weeds. For each indicator, the number on each bar is the mean absolute value for the group of situations. Environmental indicators are dimensionless, while the indicator of grain yield variation is in 100T/T.

Table 1: **Pearson correlation coefficients between indicators accounting for the role of the residual weed flora in reducing nitrate leaching and soil erosion on the one hand, and the other FlorSys indicators reflecting weed-based benefits and harmfulness on the other hand.** Green (respectively red) values show indicators that vary favorably (respectively unfavorably) with increasing the weed-based environmental protection. All the correlations were significant at $P < 0.001$.

		Weed-based reduction of	
		Nitrate leaching	Soil erosion
Weed-based benefits	Plant biodiversity:		
	- Species richness (number of species)	0.50	0.46
	- Species equitability (Pielou)	-0.25	-0.30
	Weed-based trophic resource for:		
	- Birds	0.43	0.66
	- Carabids	0.68	0.61
	- Honey bees	0.52	0.47
Weed-based harmfulness	Crop yield loss	0.54	0.49
	Harvest pollution by weed seeds and debris	0.48	0.38
	Harvesting problems due to green weed biomass blocking the combine	0.51	0.39
	Field infestation by weed biomass during crop growth	0.57	0.60
	Additional take-all disease in cereals	-0.12	-0.14
	Additional broomrape risk	0.40	0.39
	Treatment Frequency Index for herbicides	0.11	0.10

Table 2: Equations for the indicators of weed-mediated benefits in cropping systems translating weed variables predicted by FLORSYS into scores illustrating potential weed-mediated reduction of nitrate leaching and soil erosion. With s, the weed species; p, the plant; d, the day.

	Meaning	Abbreviation	Equation
[1]	Period of calculation of the nitrate leaching indicator	D_N	d ∈ [Harvest date$_{\text{previous crop}}$, date$_{\text{beginning water drainage}}$] only if the beginning of water drainage occurs before: - For spring crops: minimum (Date$_{\text{Crop soil cover>20\%}}$; Sowing date$_{\text{current crop}}$ + 30)] - For winter crops: minimum (Date$_{\text{Crop soil cover>20\%}}$; Sowing date$_{\text{current crop}}$ + 90)] Else, no indicator value is calculated.
[2]	Daily impact of weed flora on nitrate leaching	IN_d	$\sum_{s=1}^{n} \text{Leaf area}_{sd} \times \text{Ellenberg N}_s$
[3]	Mean impact of the weed flora on nitrate leaching over the period of calculation	IN	$\frac{1}{D_N}\sum_{d=1}^{D} IN_d$
[4]	Period of calculation of the soil erosion indicator	D_E	d ∈ [Harvest date$_{\text{previous crop}}$, minimum(Date$_{\text{Soil cash crop cover>20\%}}$; Harvest date$_{\text{current cash crop}}$]
[5]	Proportion of light absorbed by the weed community	PLW_d	$\sum_{s}\sum_{p} \text{Light interception}_{spd}$
	Intercepting day	ID_d	1 if If PLW_d > 10%, 0 otherwise
[6]	Impact of weed flora on soil erosion	IE	$\sum_{d=1}^{D} ID_d$

Table 3. Effect of cultural techniques (at the rotation scale) on the potential weed-based reduction of nitrate leaching and soil erosion, using LASSO regressions. Only techniques with a significant effect are shown ($P < 0.05$). Green (respectively red) cells indicate that an increase in the cultural technique descriptor increases (respectively decreases) the indicator value. Techniques with a similar effect on both indicators are in bold. For the nitrate-leaching indicator, n = 2306 and $R^2 = 0.69$. For the soil-erosion indicator, n = 2590 and $R^2 = 0.61$.

		Regression parameter value	
	Cultural technique descriptor	**Nitrate leaching**	**Soil erosion**
Tillage	Number of mouldboard ploughing operations in winter/year	-1.0388	.
	Number of operations with a chisel/year	-4.4943	-15.781
	Number of operations with disks/year	-9.9126	-28.005
	Number of operations with a power harrow /year	-0.4690	-23.951
	Number of rotavator operations/year	.	-30.793
	Number of superficial tillage operations in winter/year	-1.1224	-12.333
	Number of superficial tillage operations/year	-1.2431	.
	Shredding height	-0.1084	0.5589
	Tillage depth	-0.7171	.
	Time from harvest to first till	.	0.0109
	Time from last rolling to sowing	-0.0040	-0.0630
	Years between successive direct sowings	-0.2730	-0.3566
Crop	Proportion of barley	6.5645	.
	Proportion of flax	.	128.95
	Proportion of oilseed rape	.	-30.457
	Proportion of pea	-10.189	.
	Proportion of time with crop cover by cover crops	-21.255	.
	Proportion of triticale	.	35.835
	Proportion of years with cover crops	-4.5737	58.360
	Proportion of spring crops in the rotation	-2.4310	.
	Sowing date of spring crops	.	0.0784
	Harvest date of spring crops	-0.0340	.
	Cropping-season diversity[§]	.	16.173
Herbicide [&]	Number of multi-entry herbicides/year	-0.5072	.
	Number of pseudo-root-only herbicides/year	8.2455	.
	Number of root only herbicides/year	-0.0853	.

[§]Proportion of crop years where previous and current cash crops differ in terms of winter, summer and multiannual crops

[&]Herbicides can enter plants via leaves ("foliar"), shoot tips during emergence ("pseudo-root") or roots ("root"). Multiple entry modes are possible ("multi-mode").

Table 4. Relationships between weed species traits and indicators of weed-based reduction from nitrate leaching and soil erosion identified by fourth-corner analyses preceded by the RLQ analysis. Pearson correlation coefficients (r) between indicators and traits, and tests of the null hypothesis that species are distributed independently of their preferences for scenarios and of their traits (highest P values of permutation models permuting scenarios or species, with 999 permutations). Green (respectively red) cells indicate that an increase in the trait value increases (respectively decreases) the indicator value. Only species traits significantly correlated to at least one indicator at p = 0.05 are listed here.

Weed species trait	**Weed-based reduction from**	
	Nitrate leaching	Soil erosion
Seed lipid content	0.36	
Seed area per weight	0.39	
Seed coat thickness		-0.40