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Does intercropping winter wheat with red fescue as a cover crop improve agronomic and environmental performance?

A modeling approach

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Abstract

The introduction of a living cover crop during a cash crop growth cycle (relay intercropping) and its maintenance after the cash crop harvest may help to preserve biodiversity, increase soil organic matter content and carbon sequestration and provide other ecosystem services, such as increasing useful biotic interactions within the agroecosystem. We studied the impact of various approaches to managing a red fescue cover crop in a winter wheat crop in terms of light, water and nitrogen competition, using the STICS crop model adapted for intercropping. The STICS model for wheat/fescue intercropping was first evaluated on two years of experimental data obtained in the field. It gave satisfactory statistical results for the prediction of dry matter, leaf area index (LAI) and nitrogen accumulation in the two species, and for

nitrogen and water dynamics in the soil. By providing access to unmeasured variables, such as transpiration, the results of simulations with this model improve our understanding of the performance of the intercrop in the field. For example, we showed that the intercropping system was more efficient than the wheat crop grown as a monoculture in terms of nitrogen accumulation and decreasing soil nitrogen levels before the leaching period. However, it also resulted in lower wheat yields. We then used the STICS model to compare four intercropping management scenarios differing in terms of the date of red fescue emergence, over 35 climatic years. We found that, in most climatic scenarios, the emergence of the fescue crop during the late tillering phase of the wheat crop gave the best compromise between wheat yield overall nitrogen accumulation and radiation interception.

Keywords: Competition; Facilitation; Relay intercropping; Yield; Biomass; Light; Water; Nitrogen

1. Introduction

A cover crop, grown between two main crops, changes the physical ([Zibilske and Makus, 2009](#)), chemical ([Rinnofner et al., 2008](#)) and biological ([Isik et al., 2009](#)) conditions of both the soil and the crop. The use of cover crops in cropping systems therefore has interesting agronomic and environmental effects, including protecting the soil against erosion, contributing to the control of weeds and diseases, providing the next crop with nitrogen and preventing nitrate leaching ([Hartwig and Ammon, 2002](#)). Cover crops are frequently managed by sowing after the harvest of the main crop, with subsequent destruction by chemical or

mechanical techniques. The introduction of a living cover crop during the cash crop growth cycle (intercropping) and its maintenance after the cash crop harvest are less frequently observed. However, this approach has several advantages, including the preservation of biodiversity, increasing soil organic matter content and carbon sequestration ([Scopel et al., 2005](#); [Lahmar et al., 2006](#); [Teasdale et al., 2007](#)), and increasing biotic interactions within the agroecosystem ([Hartwig and Ammon, 2002](#)). Direct and indirect interactions between the cash crop and the cover crop generate opposing facilitative and competitive effects. A facilitative effect is a positive interspecific interaction between the intercropping species ([Vandermeer, 1989](#)). Such effects occur when one crop increases the availability of resources to the other crop. For example, a living cover crop can decrease weed growth in the cash crop ([Brandsaeter et al., 1998](#); [den Hollander et al., 2007](#)), improve soil structure regeneration and provide nitrogen to the following cash crop (if the cover crop is a legume). However, when the cash crop and the cover crop are intercropped during the cash crop growth cycle, they generally have to compete for the same resources, which may decrease cash crop yields ([Carof et al., 2007a, b](#)). The success of the intercropping system, which may be combined with reduced or no-tillage systems ([Holland, 2004](#)), therefore depends on maximizing facilitation and minimizing competition between the two crops, in terms of light, water, and nutrients. Little is currently known about these aspects, particularly for temperate crops.

Modeling can be used to simulate and to improve our understanding of the partitioning of resources in these complex systems. It is therefore a useful tool for identifying ways to increase facilitation or to curb competition. Most of the agronomic intercropping models studied to date are used as tools for achieving three main objectives. The first one of these objectives is the analysis of biotic interactions and resource partitioning in an intercropping system ([Berntsen et al., 2004](#); [Tsubo et al., 2005a](#); [Corre-Hellou et al., 2007](#)). In this case,

modeling provides a straightforward quantification of the processes involved in facilitative and competitive relationships, through the explicit representation of fundamental physical and biological processes, such as photosynthesis, dry matter partitioning, leaf area growth, root growth, plant development, the nutrient cycle and energy balance. It is also possible to fine-tune interactions between light, water, and nitrogen on the basis of analyses of the relationships between supply and demand and between related indicators, such as NNI or interception efficiency. The second objective of these models is to assess intercropping performances ([Baumann et al., 2002a](#); [Jensen, 2006](#); [Whitmore and Schröder, 2007](#)). In this case, modeling provides access to intermediate variables that are of considerable importance for assessment but difficult to measure, such as nitrogen and water fluxes between different compartments of the system. The third objective is to use modeling to explore scenarios defined in terms of climate or management strategy ([Tsubo, 2005b](#); [Baumann et al., 2002b](#)).

In this study, we used a modeling approach to investigate facilitation and competition for resources in terms of light, water and nitrogen, in a cropping system based on the intercropping of winter wheat and red fescue. We investigated the extent to which the STICS model ([Brisson et al., 2009](#)) accurately reflected the functioning of the intercropping system over a two-year period of experimentation ([Picard et al., submitted](#)), and used this model to test various cover crop management strategies in terms of competition for light, water and nitrogen, with the aim of enhancing the agronomic and environmental performances of the system.

2. Materials and methods

2.1. Model overview

The model used was an intercropping extension of the sole crop model STICS (Brisson et al., 2009) considering the system to consist of two species rather than one (Brisson et al., 2004). This model is based on a daily time-step that integrates input variables related to climate, soil properties and cropping system, to calculate both agricultural and environmental variables (Brisson et al., 2009). STICS is a generic model that can readily be adapted to various crop types and is known to be robust, based on parameterizations in various soil and weather conditions; this model also has a high level of plasticity, based on options in terms of formalism for both physiology and management (Brisson et al., 2009). The crop is characterized by its aerial biomass and leaf area index and in terms of the number and biomass of harvested organs. The soil is divided into a succession of horizontal layers, each of which is characterized by its water and mineral N content. The soil environment is assumed to be identical for both crops in the intercropping system. Soil and crop interact through the roots, via the root density distribution in the soil profile.

STICS simulates daily biomass accumulation in the canopy and the water and nitrogen balances of the system. Crop development is driven by thermal time and is used principally to calculate leaf area and to define the filling phase of the harvested organ. The corresponding phenological stages depend on the species and variety. Crop growth is driven by plant carbon accumulation, through the interception of solar radiation by the canopy and its transformation into biomass. This biomass is thus the net result of the processes of photosynthesis, respiration, and root/shoot partitioning. The STICS intercropping model simulates the sharing of light between the two crops, by calculating radiation transfer as a function of the volume of the canopy (height and width) of each species (Brisson et al., 2004). The fraction of the photosynthetically active radiation (PAR) actually absorbed by the two crops depends greatly

on their respective heights, which depend in turn on both the characteristics of the plants concerned and the growth conditions. Crop nitrogen content depends on carbon accumulation and soil nitrogen availability. The amount of nitrogen taken up by each species depends on root depth penetration, root distribution in the soil layers, and N demand. Daily absorption of N by each species is determined by the smaller of two quantities: the amount of N available through the soil-root system or crop N requirements. Crop requirements are calculated with the N concentration/biomass relationship established from the upper limit of N dilution curves. The possible existence of water stress and N stress is taken into account with indices decreasing leaf growth and biomass accumulation in conditions of water or nutrient limitation (Brisson et al., 2009). Water is transported downwards in the soil when water content exceeds field capacity in a particular layer. For nitrate, transport within the soil profile is simulated with the “mixing cells” concept, which accounts for convection and dispersion.

2.2. Experimental data

The results used for model parameterization and evaluation were obtained in two field experiments carried out in the 1999-2000 (referred to as the 1999 experiment) and 2000-2001 (referred to as 2000) growing seasons at the INRA Grignon experimental station, located in northern France (48°50'N, 1°56'E). The soil was an orthic luvisol (FAO-UNESCO, 1974) containing 281 g.kg⁻¹ clay, 599 g.kg⁻¹ silt, and 120 g.kg⁻¹ sand in the 0-90 cm soil layer, in the 1999 experiment, and 261 g.kg⁻¹ clay, 649 g.kg⁻¹ silt, and 90 g.kg⁻¹ sand in the 0-90 cm soil layer, in the 2000 experiment. Weather conditions during the experimental period are shown in Fig.1. Cumulative daily mean temperature and cumulative solar radiation were similar in 1999 and 2000 (4895 and 4891 degree days, respectively, for temperature and 4259 and 4319 Mj.m⁻², respectively, for solar radiation), whereas cumulative rainfall was greater in 1999 than

in 2000 (1164 and 867 mm, respectively; Fig.1). The preceding crop was barley in 1999 and rapeseed in 2000. The experimental treatments were winter wheat grown as a monoculture (*Triticum aestivum*, cv Isengrain), red fescue grown as a monoculture (*Festuca rubra*, cv Sunset) and winter wheat intercropped with red fescue. The intercropped crops and sole crops were sown at the same time and at the same sites. Plant densities were 18 kg seed.ha⁻¹ for fescue and 150 plants.m⁻² for wheat. These crops were grown in mixtures with an additive design in 1999 and 2000 (identical sowing densities were used for wheat grown as a monoculture and for intercropped wheat). A split-plot design was used for both experiments, with four replicates in 1999 and six replicates in 2000. Nitrogen fertilizer applications were similar for all treatments of the two experiments, including red fescue grown as a monoculture. The total amount of N fertilizer applied was 166 kg N.ha⁻¹ in 1999 and 160 kg N.ha⁻¹ in 2000. These amounts were applied in two applications, between tillering and anthesis, in each year. Weeds, pests and diseases were controlled with appropriate pesticides. Wheat (both sole-crop and intercropped wheat) was harvested on 18 July 2000 for the 1999 experiment and on 23 July 2001 for the 2000 experiment.

In each year, measurements were taken during two periods: the intercropping period (referred to hereafter as ϕ 1) and after the harvest of the wheat crop, when the fescue was growing as a monoculture (ϕ 2), until the end of the year. For these two periods, we collected the following data: aerial dry matter, leaf area index (LAI) and nitrogen accumulation in crops, together with soil mineral nitrogen and soil water content. The experiments are described in detail elsewhere Picard *et al.* (submitted).

2.3. Calibration and evaluation of the model

The parameters of STICS defined by [Brisson et al. \(2009\)](#) were used to simulate the wheat-fescue intercrops. Only varietal parameters, site-specific soil parameters and radiative transfer parameters for fescue (not available in the paper by [Brisson et al., 2009](#)) were calibrated, using experimental data for sole crops only (Table 1). The model was then evaluated with intercrop data.

Varietal parameter calibration was carried out in two steps for wheat and fescue. We first forced leaf area index with the measured values and then calibrated the other modules closely related to this variable, such as aerial biomass and nitrogen accumulation. In the second step, we calibrated the parameters determining LAI, without forcing LAI, on the same data set. For site-specific soil parameters, we calibrated potential soil evaporation (q_0), by optimizing water content dynamics for sole-crop data. Soil water content was estimated at field capacity ($WC_{pF2.0}$) and at wilting point ($WC_{pF4.2}$), together with bulk density, for each year, on the basis of observed soil data. For fescue, we also calibrated the “radiative transfers” module in two steps, using data for fescue grown as a monoculture (1999, 2000). First, leaf area index (LAI) parameters used to simulate changes in LAI in STICS were optimized on the basis of observed LAI data. We then used observed LAI and biomass data for fescue grown as a monoculture to optimize the various parameters of the “radiative transfer” module (Table 1).

We used several criteria to compare simulated and experimental results in intercrops ([Wallach and Goffinet, 1987](#)). The root mean square error (RMSE) was used to evaluate the prediction error of the model, by heavily weighting large errors. We assessed the predictive ability of the model by calculating the root mean square error of prediction (RMSEP) and model efficiency (EF). A detailed description of the estimation of these criteria was provided by [Wallach et al. \(2006\)](#).

2.4. The scenarios simulated

Simulations were used to study several management scenarios, to analyze the impact of the timing of the fescue cycle on the agronomic and environmental performance of the system. These simulations were run over 35 years of climatic data (1970-2004) from Versailles (48°48'N, 2°04'E), which is situated close to the Grignon experimental station, to enable us to take climate variability into account in the scenario assessment (Fig. 1). We compared four management scenarios, assessing the performance of the system during the two phases considered (ϕ 1 and ϕ 2). We stopped the simulation on 31 December, because STICS cannot run simulations over more than two consecutive years.

Scenario 0 simulated wheat grown as a sole crop and was treated as the reference scenario against which the performance of the other three scenarios was assessed. In scenario 1, we simulated fescue emergence one week after the harvest of the wheat crop (in July, precise date depending on wheat maturity), corresponding to a rotation: wheat monoculture followed by fescue monoculture. In scenario 2, we simulated fescue emergence in the spring (18 March), corresponding to relay intercropping: wheat grown as a monoculture from October to March and then intercropped with fescue. In scenario 3, we simulated the simultaneous emergence of wheat and fescue (10 October), corresponding to full intercropping. In scenarios 2 and 3, fescue was not destroyed after wheat harvest, therefore remaining alive during ϕ 2.

Some of the other simulated cropping practices and initial data for state variables were similar over the 35 years for the four scenarios. Three applications of N fertilizer were carried out, on 25 February, 25 March and 30 April. The amounts of N fertilizer applied during the first and

third applications were fixed at 50 and 40 kg.ha⁻¹, respectively. The amount of N fertilizer applied during the second application was estimated with the balance-sheet method (Rémy and Hébert, 1977), with a target yield of 9 t.ha⁻¹ for each climatic year.

3. Results

3.1. Evaluation of the model

Good agreement was found between the observed and simulated data obtained for wheat-fescue intercrops, for both years (Fig. 2 and 3), as indicated by the RMSE value and the efficiency (EF) of the model (Table 2). In both years of experimentation, the model reproduced the marked predominance of wheat over fescue. Dry matter levels were much lower for fescue than for wheat (Fig. 2a): at harvest, mean observed wheat dry matter content was about 17.6 t.ha⁻¹ and mean observed fescue dry matter content was about 0.42 t.ha⁻¹, in both years. The capacity of wheat to develop leaf area more quickly than fescue during ϕ 1 (Figure 2b) probably played a key role in this predominance. Just before the wheat harvest, wheat LAI decreased due to senescence, leading to an increase in fescue LAI, which was overestimated by the model but with no effect on the simulation of dry matter and N accumulation.

Wheat absorbed much more nitrogen than fescue during ϕ 1 (Fig. 2c). At harvest, the mean amount of nitrogen absorbed was 190.7 kg N.ha⁻¹ for wheat and 6.5 kg N.ha⁻¹ for fescue. However, the fescue absorbed the residual nitrogen just after wheat harvest. The simulations for this variable were of better quality for ϕ 1 than for ϕ 2. The model overestimated nitrogen accumulation by fescue during this period. However, the differences between the observed

and simulated values remained small. The observed and simulated yield values were 8.47 and 10.7 t.ha⁻¹, respectively, in 1999 and 8.9 and 8.57 t.ha⁻¹, respectively, in 2000, giving a RMSEP of 2.27 t.ha⁻¹ (n =2).

The agreement between the observed and simulated data for inorganic N in the soil (Fig. 3a) was less satisfactory than for the results presented above, as indicated by the RMSE and the EF of the model (Table 2). Nevertheless, the model reproduced the principal changes in soil inorganic N and water content well until the wheat harvest. The model simulated overall changes in soil water content well during the two contrasting experimental years (Fig. 3b). The model also simulated accurately a dry period observed at the end of the summer of 1999 and at the end of the growth cycle in 2000. However, for 2000, the model tended to overestimate soil water content just after a dry period (beginning of June until October). However, the amount of water involved in this overestimate was not very large: the difference between observed and simulated soil water contents varied between 20 and 40 mm during this period. After the dry period, the model accurately simulated the reconstitution of soil water stores.

3.2. Performance of wheat-fescue intercropping, as assessed by the model

Simulation results showed that wheat yield was not overly affected by fescue development in the intercropping system (table 3): yield differences between sole-crop and intercropped wheat were about 0.43 t.ha⁻¹ in 1999 and 0.39 t.ha⁻¹ in 2000, corresponding to a difference of less than 5%. The modeling results provide an explanation for this difference, through analyses of the partitioning of resources between the two crops. The model provides insight into the contribution of each species to dry matter production, light interception, water

consumption and N acquisition in the intercropping system. The comparison between simulated aerial dry matter for intercropped wheat and sole-crop wheat showed that dry matter levels were slightly lower (about 2%) for intercropped than for sole-crop wheat in both years. However, dry matter levels for wheat plus fescue were 11% and a 9% higher than for sole-crop wheat, in both 1999 and 2000, due to the growth of fescue during ϕ 1 and, particularly, ϕ 2. PAR interception by intercropped wheat was similar to that for sole-crop wheat in both years (Table 3). Nevertheless, over the complete cycle (ϕ 1 and ϕ 2), the model simulates 27% and a 21% higher levels of total absorbed radiation in 1999 and 2000, respectively, due to the greater LAI of the fescue. Indeed, fescue intercepted 51 and 35 Mj.m^{-2} of light, respectively, in 1999 and 2000 during ϕ 1, and about 178 and 119 Mj.m^{-2} , respectively, in 1999 and 2000 during ϕ 2 (Fig. 4). Thus, 19% and 15% less radiation reached the soil in the intercropped system in 1999 and 2000.

Simulation showed that the intercropped wheat absorbed 2% less nitrogen in 1999 and 2000 than did sole-crop wheat (Table 3). However, overall nitrogen absorption by wheat plus fescue in the intercropped system was greater than nitrogen absorption by wheat grown as a monoculture. Indeed, an additional 43 and 46 kg of nitrogen per hectare was absorbed by the fescue in 1999 and 2000, respectively, during ϕ 1 and ϕ 2. The nitrogen absorbed by the two crops reduced residual soil nitrogen levels by 8 and 9 units after harvest in 1999 and 2000, respectively, and by 39 and 42 units by 31 December, in 1999 and 2000, respectively (Table 3). This decrease in soil nitrogen stores before the end of December decreased the amounts of nitrogen likely to be leached during January-April leaching period.

The simulated transpiration for intercropped wheat was slightly lower (about 1%) than that for sole-crop wheat, in both years (Table 3). Nevertheless, the total water transpired by the

two crops over the whole cycle (ϕ 1 and ϕ 2) was 22% in 1999 and 15% higher in 2000 than that transpired by sole-crop wheat. This had a direct effect on evaporation from the soil: in both years, intercropping wheat and fescue resulted in 12% less evaporation from the soil than growing wheat as a sole crop. This difference results mostly from the presence of the fescue during ϕ 2, which limits water loss by evaporation from the soil (Table 3). The simulated amount of below-ground water drainage differed considerably between the two experimental years (Table 3), due to climatic differences. Drainage levels were 11% lower in 1999 and about 4% lower in 2000 in intercropped wheat and fescue than in wheat grown as a monoculture.

Soil water content was slightly lower at harvest (5 mm) in 2000 and complete replenishment occurred by the end of December in both years (Table 3). Overall, the intercropping of fescue with wheat did not decrease the availability of water resources for the following crop.

3.3. Analysis of four simulated scenarios for emergence dates over 35 climatic years

The simulated yield for wheat grown as a monoculture (scenario 0) varied from 7.60 to 10.9 t.ha⁻¹ (Fig. 5a), and simulated aerial dry matter varied from 18.0 to 22.5 t.ha⁻¹ (Fig. 5b), depending on the year considered. Yield (5.70 t.ha⁻¹) and dry matter (15.8 t.ha⁻¹) levels were exceptionally low in 1975, due to the occurrence of a very dry season with mean rainfall levels of 277 mm over the simulated period, whereas mean rainfall over the 35 years was 540 mm. Over the 35 years considered, intercropping fescue with wheat was predicted to result in a 0.52 t.ha⁻¹ lower wheat yield, on average, in scenario 3 than obtained for wheat as a sole

crop (scenario 0), with a high level of variability between years (Fig. 5a). If the fescue emerged in spring (scenario 2), wheat yield losses did not exceed 0.5 t.ha⁻¹ (0.18 t.ha⁻¹ on average). No difference in wheat yield was predicted for scenario 1, in which the fescue was sown after wheat harvest and could therefore not affect wheat growth. Yield variability over time was similar for all four scenarios. Aerial dry matter levels for intercropped wheat were systematically lower in scenarios 2 and 3 than for scenario 0: with a 0.5 to 1.75 t.ha⁻¹ yield loss in scenario 3 and a loss of no more than 1 t.ha⁻¹ in scenario 2 (results not shown). By contrast, overall dry matter production (wheat plus fescue) was greater than for wheat as a monoculture, by 1.26, 1.84 and 2.19 t.ha⁻¹ on average for scenarios 1, 2 and 3, respectively (Fig. 5b), due to the production of 1.26, 2.30, 3.36 t.ha⁻¹ dry matter, on average, by fescue for scenarios 1, 2 and 3, respectively (results not shown). The variability of dry matter production over time was slightly higher for earlier fescue emergence dates.

The difference between the scenarios is linked to differences in the timing of fescue dry matter production, which varied from 0.8 to 1.9 t.ha⁻¹ in scenario 1, from 0.5 to 1 t.ha⁻¹ in scenario 2 and from 1.5 to 2.5 t.ha⁻¹ in scenario 3, depending on the year (results not shown). Analyses of intermediate variables related to resource capture (indices of nitrogen and water stress, radiation interception efficiency) identified no single major factor explaining the effect of intercropping with fescue on wheat growth and yield. This effect resulted from complex interactions between competition for light, water and nitrogen, which differed from year to year over the 35-year period.

The simulated PAR intercepted by wheat grown as a sole crop varied from 636 to 892 Mj.m⁻², as a function of the year considered. Regardless of the year considered, intercropping fescue with wheat had no effect on the capacity of wheat to intercept light radiation (data not

shown), but increased light interception by the whole canopy over the two phases considered (ϕ 1 and ϕ 2), with only low levels of variability over the 35 years (Fig. 5c). Overall light interception was a mean of 101, 234 and 398 Mj.m^{-2} higher, on average in scenarios 1, 2 and 3, respectively. Mean PAR interception over the 35 years was 13%, 31% and 52% higher in scenarios 1, 2 and 3, respectively, than for wheat grown as a monoculture. The simulated PAR reaching ground level over the entire simulated period varied with the year, from 2339 to 3119 Mj.m^{-2} for wheat grown as a monoculture. Adding fescue to the system decreased radiation transmission by a mean of 201, 497 and 839 Mj.m^{-2} , for scenarios 1, 2 and 3, respectively, corresponding to decreases of 7%, 18% and 31% of radiation available for weed growth, respectively (Fig. 5d).

Simulated transpiration levels from sole-crop wheat (scenario 0) varied over time, from 189 to 265 mm (Fig. 5e). When wheat was intercropped with fescue (scenarios 2 and 3), the wheat crop transpired less water than did wheat grown as a monoculture: from 0 to 15 mm in scenario 2 and from 15 to 35 mm in scenario 3 (results not shown). However, overall canopy transpiration was higher when fescue was also sown, by 17, 50 and 55 mm on average in scenarios 1, 2 and 3, respectively (Fig. 5e). The calculation of water uptake per tone of dry matter for the two crops showed that in scenarios 2 and 3 this variable was similar, for all years, over the 35-year period (11.35 to 13.75 mm/t of dry matter). The longer fescue growth cycle in scenario 3 did not affect this variable. However, in scenario 1, in which fescue emerged after the wheat harvest, this ratio was smaller and varied less (9.92 to 12.91 mm/t of dry matter). The simulated water evaporation from the ground varied between years, from 222 to 400 mm for wheat grown as a monoculture (Fig. 5f). Intercropping with fescue decreased evaporation, by a mean of 13, 68 and 89 mm in scenarios 1, 2 and 3, respectively.

Simulated below-ground water drainage varied from 108 to 652 mm over time for wheat grown as a monoculture (scenario 0). Intercropping with fescue had a very slight effect on water drainage, which decreased in half the situations, and increased in the others (result not shown). In 95% of cases, the impact of intercropping was limited, corresponding to less than 10% of total water drainage in the soil profile. The balance between a higher level of transpiration, a lower level of evaporation and similar levels of drainage when fescue was sown had only a very small effect on water stores at the end of the two phases (ϕ 1 and ϕ 2) in these three scenarios, as shown by comparisons with wheat grown as a monoculture: the differences simulated were less than 10 mm in 90% of cases (results not shown).

Simulated N acquisition by wheat grown as a monoculture varied over time, from 200 to 242 kg N.ha⁻¹, except for 1975, when it was exceptionally low, at 160 kg N.ha⁻¹. Intercropping wheat and fescue (scenarios 2 and 3) decreased N acquisition by the wheat crop, by 10 to 35 kg N.ha⁻¹ in scenario 2 and by 40 to 75 kg N.ha⁻¹ in scenario 3 (data not shown). The difference in N acquisition between scenarios 2 and 3 resulted from the greater nitrogen stress in scenario 3. Over the 35-year period, an increase in N acquisition by both crops was possible only in scenarios 1 and 2 (Fig. 5g), for which intercropping increased total N acquisition by a mean of 30.5 and 21.6 kg N.ha⁻¹, respectively. In scenario 3, intercropping did not systematically increase N acquisition, and the increases observed never exceeded 18 kg N.ha⁻¹. Results showed that, in 50% of cases, N acquisition even decreased, by up to 20 kg N.ha⁻¹. At the end of the simulated period (31 December), regardless of the scenario considered, intercropping with fescue resulted in lower soil inorganic N content than leaving the soil bare after the wheat harvest (Fig. 5h). Mean soil inorganic N content on 31 December was 40.2 kg N.ha⁻¹ for wheat grown as a monoculture (scenario 0) and varied considerably

over the years, reaching a mean of 7.7, 13.1 and 18.9 kg N.ha⁻¹ in scenarios 1, 2 and 3, with lower levels of variability for scenario 3.

4. Discussion

4.1) Model performance

Our approach, based on parameterization of the model with experimental data obtained for monocultures and evaluation of the model with an intercropping system, has been adopted in various studies modeling intercropping ([Baumann et al., 2002b](#); [Berntsen et al., 2004](#); [Corre-Hellou et al., 2007](#)). This approach gave good results in our study, showing that the model essentially used the same processes to describe the functioning of the system for both monocultures and intercropping systems. The changes in state variables observed for the intercropping system in this study therefore resulted essentially from resource sharing and changes in growth conditions (simulated by STICS) rather than processes occurring specifically in the intercropping system and relating to architectural plasticity or specific biotic constraints. Baumann et al. (2002b) showed that, in certain cases, the model makes errors, due to different leaf morphology responses in mixtures and in monocultures. In such cases, models parameterized for monocultures cannot take into account adaptations occurring in mixtures. In our conditions, any morphological adaptations occurring in intercropped plants probably had only a very small effect on the simulated processes, due to the very strong dominance of wheat over fescue. For example, the etiolation of fescue plants would probably have been insufficient to increase their access to radiation.

Evaluation of the STICS model during the cropping cycle ($\phi 1$) indicated that this model accurately simulated biomass production, changes in leaf area and nitrogen accumulation for the two species. It also accurately simulated nitrogen and water fluxes. In other modeling studies based on the use of STICS and focusing on pea/barley intercropping systems (Jensen, 2006; Corre-Hellou et al., 2007), the model accurately reproduced the state variables of the intercropped species, but gave RMSE values slightly lower than those obtained here (Launay et al., 2009). These previous results were obtained for production levels well below ours (7 t.ha⁻¹ total biomass, versus 24 t ha⁻¹ in our study), indicating that our results were better. Corre-Hellou et al. (2007) attributed the differences between observed and simulated data to poor simulation of the partitioning of radiation between the two species in cases in which the dominance relationship between the species was inversed at the end of the cropping cycle. For our intercropping system, no such inversion occurred, with wheat continuing to dominate over fescue from sowing until harvest. Nitrogen and biotic stresses were also weaker in our experimental conditions, which were not subject to the constraints of organic farming. This may account for the differences in the level of production and the better performance of the model (as STICS models cannot take biotic stresses into account) in our study.

During the intercropping period, the model tended to overestimate the amount of mineral nitrogen taken up by the fescue after the wheat had been harvested ($\phi 2$). This decreases the quality of the model's predictions for the variable "plant nitrogen" for fescue during this period. It also implies a possible underestimation of the amount of mineral nitrogen remaining in the soil during the winter period and therefore likely to be leached. The results obtained for simulations with the model indicate that the model allowed the uptake of nitrogen by fescue roots when nitrogen levels in the soil were very low. Dorsainvil (2002) modeled intermediate

crops and attributed the overestimation of nitrogen uptake by crops in the STICS model during the intercropping period to this factor, which is a generic parameter of the model that we did not modify (we modified only site-specific parameters). The performance of the STICS model could be improved by more complete parameterization, but we feel that the error in the estimation of nitrogen absorption by fescue inherent to the STICS model is acceptable given the intended use of this model.

4.2. Effects of intercropping on plant growth

Although we simulated a strong domination of wheat over fescue, intercropping decreased wheat yields by about 5%. This yield-decreasing effect of intercropping on wheat has been reported in studies of other types of mixed cultures involving wheat and legumes, or on competition between wheat and weeds. In studies of competition between wheat and weeds, particularly for grass weeds, decreases in wheat yields of more than 20% have been systematically reported, with yield loss even reaching 90% in some cases, due to competition for environmental resources ([Lemerle et al., 2004](#); [Vandeleur and Gill, 2004](#); [Blackshaw et al., 2005](#)). In studies of wheat-legume intercropping, yield losses generally vary between 10 and 30% with respect to wheat sown as a monoculture at the same density ([Bulson et al., 1997](#); [Haymes and Lee, 1999](#); [Banik et al., 2006](#); [Thorsted et al., 2006 b](#); [Carof et al., 2007a](#)), but may reach 70% in some cases in which there is intense competition for resources ([Haymes and Lee, 1999](#); [Hiltbrunner et al., 2007](#)). This variability may be accounted for principally by the intensity of competition between wheat, the leguminous crop and weeds. In studies in which wheat yields were little affected by intercropping, the authors generally attributed this result to a difference in the use of environmental resource niches by the two crops ([Anil et al., 1998](#)) or to the complementary use of these resources by the two species

([Willey, 1979](#)). For our intercropping system involving two members of the grass family, the small decrease in wheat yields under intercropping cannot be attributed to the use of different niches. Instead, it is due to the strong dominance of wheat over fescue, resulting from an earlier onset of the growth cycle, with fescue emerging four months later than wheat. This difference in emergence times allowed the wheat crop to outcompete the fescue, particularly for the interception of solar radiation.

Intercropping may facilitate the better use of environmental resources, thereby increasing productivity ([Vandermeer, 1989](#); [Willey, 1990](#)). In the situation studied here, intercropping did not increase total yields because the fescue was not harvested. By contrast, intercropping did increase the total amount of biomass produced, consistent with the results of various studies on intercropping ([Hauggaard-Nielsen et al., 2001a](#); [Thorsted et al., 2006c](#)). [Teasdale et al. \(2007\)](#), in a long-term study of the functioning of an intercropping system involving a living cover crop, showed that the biomass produced accumulated in the soil, helping to increase the organic matter content of the soil. We showed that this increase in primary productivity resulted essentially from improvements in radiation interception when crops were grown together, particularly after the wheat harvest, consistent with the results obtained for other combinations of crops ([Tsubo et al., 2001](#); [Carof et al., 2007b](#)). Some of these authors suggested that their results were due to the complementary nature of the aerial architecture of the two species. In our case, this complementarity results primarily from the vertical distribution of the leaves, with the taller wheat crop shading the shorter fescue (simulated data not shown).

The dominance of wheat over fescue results from its genetic characteristics rather than from an adaptation of its aerial architecture during intercropping. The simulation results, confirmed

by experimental observations (Picard et al., submitted), demonstrate that the LAI and height of wheat are similar in monoculture and in the intercropping system. This complementarity is also achieved through the offset of the growth cycles of the two crops, enabling the fescue to intercept solar radiation during wheat senescence and after the wheat harvest (Fig. 4). This greater radiation interception efficiency after the wheat harvest may result in the suppression of weed populations (Bulson et al., 1997; Hauggaard-Nielsen et al., 2001a; Thorsted et al., 2006c; den Hollander et al., 2007; Hilbrunner et al., 2007). However, some studies have attributed this decrease in weed populations to an allelopathic effect observed in some crop combinations (White et al., 1989 cited by Banik et al., 2006).

4.3. Effect of intercropping on water and nitrogen fluxes

The presence of a second crop may also affect water balance, by increasing transpiration by the canopy, as shown by several authors (Thorsted et al., 2006c). Morris and Garrity (1993) showed that intercropping slightly modified water uptake, which varied between -6 and +7% of the levels recorded for monocultures, whereas the intercropping system used water much more efficiently than monocultures. In our intercropping system, the water stress indices obtained with the STICS model showed that, in the trial conditions, neither of the two crops experienced water stress during the intercropping trial. This finding may be accounted for in part by the low levels of biomass production by the fescue during $\phi 1$. Fescue contributed 2.5% of the total biomass produced during intercropping. It may also be accounted for by the decrease in evaporation and drainage due to the presence of the fescue, resulting in an absence of water deficiency in the climatic conditions occurring during the experiments. Consistent with this finding, Carof et al. (2007b) showed that intercropping did not affect water availability to cultures in this type of climate.

The dominance of wheat at the start of the growth cycle limited both nitrogen availability to the fescue and the fescue's nitrogen demand. [Corre-Hellou \(2005\)](#) showed, for the pea-barley combination, that a species with a rapid growth rate at the start of the cycle could rapidly come to dominate in competition for this resource. This is due to a difference in access to nitrogen, due to the difference in rooting patterns between the two species. In our situation, the dominance of wheat over fescue was also due to a difference in root architecture. Simulation results showed that the wheat roots penetrated the soil to a depth of 120 cm, whereas the fescue roots remained in the first 30 cm of soil. [Hauggaard-Nielsen et al. \(2001b\)](#) also observed, for a combination of pea and barley, that the barley root system penetrated to greater depths in intercropping conditions than in monocultures. This difference in rooting pattern allows the barley crop to use resources more effectively, by exploring the soil more efficiently than barley grown as a monoculture. In our conditions, the simulation data, confirmed by experimentation (not shown) showed no difference in root length between intercropped wheat and wheat monocultures. Maintenance of the living fescue crop immediately after the wheat harvest significantly decreased nitrogen levels in the soil on December 31 (Table 4). Fescue is thus an effective catch crop during this period, like other members of the grass family ([Dorsainvil, 2002](#); [Känkänen and Eriksson, 2007](#)).

4.4. Impact of the timing of the fescue growth cycle on the performance of the system

Simulation results demonstrated that the system was highly sensitive to the timing of the fescue growth cycle, particularly in terms of dry matter production, the interception of radiation and nitrogen capture (Fig. 7). Effects on yield were more limited and there was almost no effect on water balance in this study. These results are consistent with studies on

the impact of the sowing date of a cover crop after the main crop (Vos and van der Putten, 1997; Dorsainvil, 2002) or of an intercrop (Whitmore and Schöder, 2007; Launay et al., 2009). In the case of a cover crop introduced into the rotation (our scenario 1), Dorsainvil (2002) showed that the establishment of grasses (ryegrass in the studied concerned) was very slow if they were sown just after the cereal harvest, resulting in low levels of biomass production, principally due to water stress. We may have overestimated the emergence rate of fescue sown after the wheat harvest (scenario 1). Indeed, the simulation conditions for the emergence of a spring- or summer-sown crop are poorly described in the model: STICS takes into account only the mean water content of the soil layer containing the seeds, but large gradients in water content are often observed in the first few centimeters of the soil in summer. This might lead to the overestimation of fescue growth and resource uptake. In intercropping situations (our scenarios 2 and 3) Launay et al. (2009) obtained results similar to ours for a pea-barley system, in which barley yields were 30% higher if barley was sown two weeks before pea.

Advancing the sowing date of the fescue increases both competition effects (decreasing wheat biomass and yield) and facilitation effects (increasing total biomass and soil cover, decreasing the amount of solar radiation reaching the soil). It also increases the efficiency of radiation and nitrogen use. The sowing date for the fescue is therefore a key technical choice determining the balance between competition and facilitation. Other canopy management techniques can also be used to adjust this balance. These techniques include the mechanical (Thorsted et al., 2006a) or chemical (Carof et al., 2007a) control of the cover crop during the growth cycle. We studied this balance over only one cropping and intercropping cycle. However, certain facilitation processes may occur more slowly. For example, the nitrogen absorbed by the fescue during the intercropping period may be supplied to the next crop,

thereby reducing its nitrogen fertilizer requirements. Similarly, the increase in biomass production due to the fescue may increase the organic matter content of the soil in the medium term, thereby improving its fertility. Longer term experimental and modeling studies are required to determine the consequences of these processes for agronomic and environmental performance.

5. Conclusion

The inclusion of a fescue as a cover crop in a wheat intercropping system may therefore favor certain biotic processes, such as the production of primary biomass, the interception of radiation that might otherwise reach weeds and the recycling of nutrient elements. A comparison of the simulated and observed results showed that the “STICS intercropping” model accurately simulated these processes and could be used to evaluate their impact on the agronomic and environmental performance of the system for different climatic and technical scenarios. The simulated results show that the use of fescue as a cover crop increases the efficiency of radiation interception by up to 50%, thereby resulting in higher levels of biomass production and a decrease, by up to 30%, in the amount of radiation reaching the ground and available to weeds. This makes it possible to recycle mineral nitrogen efficiently during the intercropping period, with no effect on water balance in the climatic conditions of the Parisian Basin. Despite the strong dominance of wheat over fescue, the simulation data nonetheless showed mean yield losses of 2 to 6%, depending on the sowing date for the fescue. The timing of the fescue growth cycle is thus a key technical choice for control of the balance between competition and facilitation and for improving the agronomic and environmental performance of the system.

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Table 1. Results of calibration of the STICS model for varietal parameters (wheat and fescue), for specific site context and radiative transfer parameters, based on experimental data for monocultures

Description of the parameters		Units	Wheat	Fescue	Site context
Varietal parameters					
Croirac	Growth rate of root front	cm degree.days ⁻¹	0.12	0.06	
JVC	Number of vernalizing days	day	55	-	
stlevamf	Sum of development units between the stage of emergence and maximal leaf growth (end of juvenile phase)	degree.days	245	116	
stamflax	Sum of development units between the stage of juvenile phase and maximal LAI	degree.days	375	-	
stlevdrp	Sum of development units between the stage of emergence and beginning of grain filling	degree.days	878	1000	
stdrpmat	Sum of development units between the stage of beginning of grain filling and physiological grain maturity	degree.days	780	600	
nbgrmax	Maximum number of grain	grains m ⁻²	41.5	-	
durvieF	Maximal lifespan of an adult leaf	Q10	236	303	
sea	Specifique surface of fruit envelops	cm ² g ⁻¹	142	-	
adens	Interplant competition parameter	non dimentional	-	-3.30E-04	
adilmax	Parameter of the maximum curve of nitrogen needs [Nplante]=adilmax MS ^A (-bdilmax)	N%	-	3.003	
bdilmax	Parameter of the maximum curve of nitrogen needs [Nplante]=adilmax MS ^A (-bdilmax)	N%	-	3.02E-01	
Site-specific soil parameters					
q0	End of maximum evaporation stage parameter	mm	-	-	2.21
Hcc	Soil water content at field capacity	%	-	-	(22 - 27)*
Hmin	Soil water content at the wilting point	%	-	-	(11 - 12)*
da	Bulk density	g.cm ⁻³	-	-	(1.14 - 1.54)*
Radiative transfer parameters					
ktrou	Extinction Coefficient of PAR through the crop (radiation transfer)	cm ⁻¹	-	0.50	
Rapforme	Ratio thickness/width of the crop form (negative when the base of the form < top)	non dimentional	-	0.85	

* Minimum and maximum values for the site-specific soil parameters obtained for the two experimental years (1999 and 2000).

Table.2. Root mean square error (RMSE) and efficiency (EF) of the model obtained for the plant and soil variables for wheat-fescue intercrops, for the two experimental years (1999 and 2000).

Variables	Experiment	RMSE	EF
Plant variables			
Wheat dry matter	1999	1.28 (t.ha ⁻¹)	0.97
	2000	0.98 (t.ha ⁻¹)	0.97
Fescue dry matter	1999	0.40 (t.ha ⁻¹)	0.56
	2000	0.35 (t.ha ⁻¹)	0.72
Wheat LAI	1999	0.47 (m.m ⁻²)	0.91
	2000	0.86 (m.m ⁻²)	0.75
Fescue LAI	1999	0.15 (m.m ⁻²)	0.72
	2000	0.37 (m.m ⁻²)	0.12
Wheat N acquisition	1999	20.6 (kg.ha ⁻¹)	0.94
	2000	18.4 (kg.ha ⁻¹)	0.91
Fescue N acquisition	1999	7.44 (kg.ha ⁻¹)	0.46
	2000	9.71 (kg.ha ⁻¹)	0.49
Soil variables			
Soil inorganic N (0-120 cm)	1999	17.8 (kg.ha ⁻¹)	0.59
	2000	38.0 (kg.ha ⁻¹)	-0.34
Soil water (0-120 cm)	1999	105 (mm)	0.12
	2000	255 (mm)	-0.02

Table.3. Simulated results for the performance criteria of wheat monocultures and wheat-fescue intercrops during the crop growth period and the interculture period for the two experimental years.

Period System Crops	Experiment	Crop period (ϕ 1)			Interculture (ϕ 2)		Variation *
		Monoculture	Intercrop		Monoculture	Intercrop	
		Wheat	Wheat	Fescue	None	Fescue	
Crop production							
Yield (t.ha ⁻¹)	1999	10.7	10.3	0	0	0	-4%
	2000	8.57	8.18	0	0	0	-5%
Dry matter (t.ha ⁻¹)	1999	21.8	21.4	0.59	0	2.19	11%
	2000	18.6	18.2	0.49	0	1.69	10%
Light							
PAR intercepted by the canopy (Mj.m ⁻²)	1999	854	854	51	0	178	27%
	2000	729	764	35	0	119	21%
PAR transmitted to the soil (Mj.m ⁻²)	1999	1556	1372		1596	1174	-19%
	2000	1206	1121		1526	1204	-15%
Water							
Transpiration by the crop (mm)	1999	226	225	13	0	38	22%
	2000	215	213	11	0	24	15%
Soil water evaporation (mm)	1999	269	266		184	139	-11%
	2000	185	186		163	120	-12%
Drainage (mm)	1999	247	245		126	88	-11%
	2000	325	320		14	4	-4%
Soil water (mm) 0-120 cm at harvest (ϕ 1) and at 31 December (ϕ 2)	1999	293	293		293	293	0%
	2000	282	277		299	299	-1%
Nitrogen							
N acquisition (kg .ha ⁻¹)	1999	223	218	15	0	28	17%
	2000	183	179	15	0	31	23%
Soil inorganic N (kg.ha ⁻¹) 0-120 cm at harvest (ϕ 1) and at 31 December (ϕ 2)	1999	13	5		47	8	-78%
	2000	17	8		65	23	-63%

* Difference between the results obtained for the wheat plus fescue intercrop and wheat monoculture during the simulation period (φ1 and φ2)

Fig. 1. Weather data (cumulative daily mean temperature, cumulative rainfall and cumulative solar radiation) calculated over the total period of simulation (10 October (year n) until 31 December (year n+1)) for each climatic year (35 years from 1970 to 2004) at Versailles, northern France. Open symbols correspond to the two experimental years (1999 and 2000)

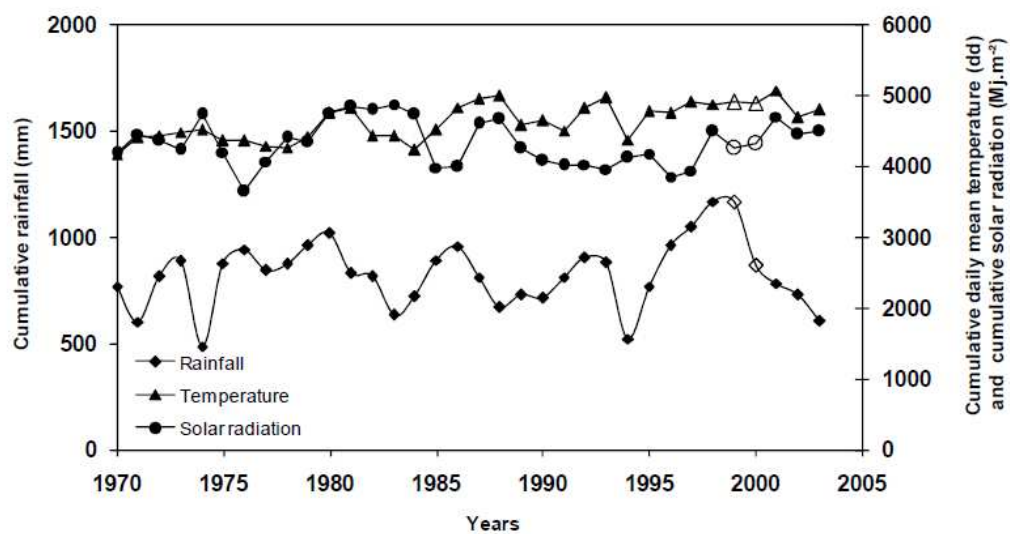


Fig. 2. Observed (obs) and simulated (sim) aerial dry matter accumulation (a), leaf area index (LAI) (b) and nitrogen (N) acquisition (c) in intercropped wheat plus fescue for the two experimental years (1999 and 2000). Vertical bars indicate the least squares difference (0.05) and the dashed vertical line shows the date of wheat harvest.

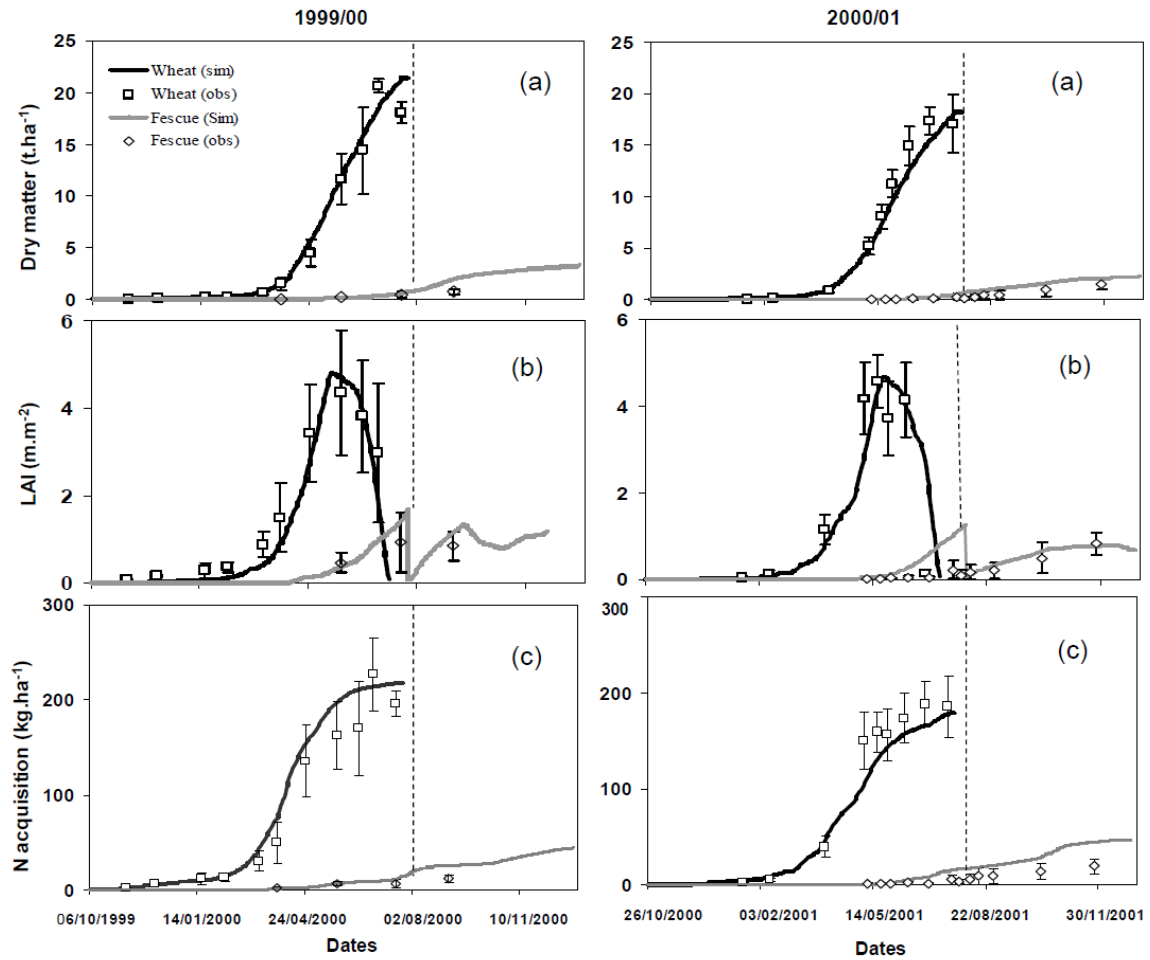


Fig. 3. Observed (line) and simulated (symbols) inorganic nitrogen in the soil (a) and soil water content (b) in wheat-fescue intercropts for the two experimental years. Vertical bars are least squares differences (0.05) and the dashed vertical line shows the date of harvest

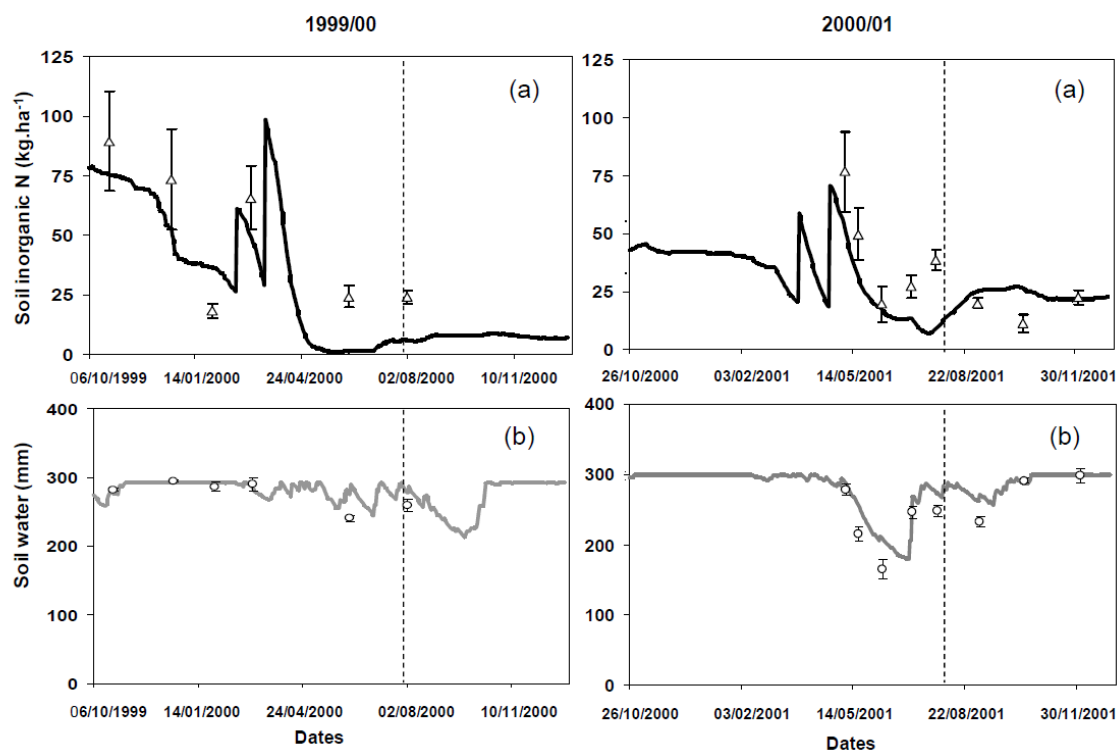


Fig.4. Simulated daily proportion of PAR intercepted by the wheat monoculture (a) and wheat plus fescue intercrop (b) in 2000. The pattern of change in the proportion of light intercepted was observed in 1999.

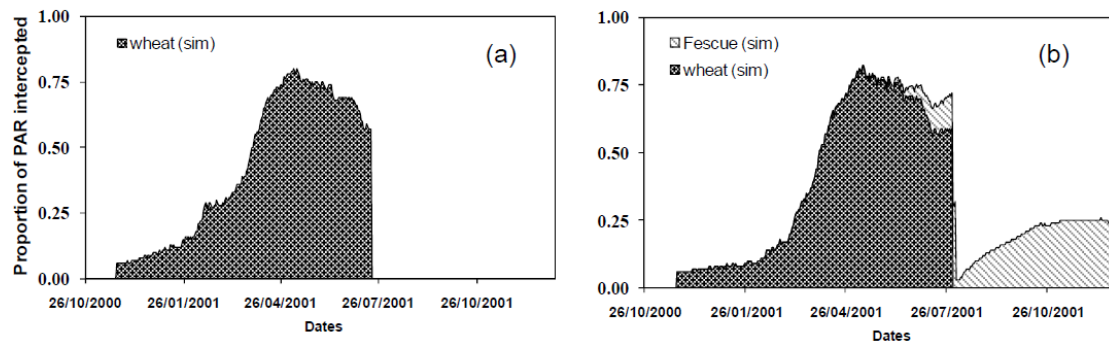


Fig. 5. Frequency analysis for managing scenario 0 (wheat monoculture), 1 (wheat-fescue rotation), 2 (relay intercropping) and 3 (full intercropping) over the 35 climatic years, for wheat yield (a), wheat-fescue aerial dry matter (b), PAR interception by crops (c), PAR transmitted to the soil (d), crop transpiration (e), soil evaporation (f), N acquisition by crops (g), mineral nitrogen in the soil in the end of the simulation on 31 December (h).

