Decomposition of mulched versus incorporated crop residues: Modelling with PASTIS clarifies interactions between residue quality and location

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Abstract

Crop residue management has been shown to significantly affect the decomposition process of plant debris in soil. In previous studies examining this influence, the extrapolation of laboratory data of carbon and/or nitrogen mineralization to field conditions was often limited by a number of interactions that could not be taken into account by a mere experimental approach. Therefore, we demonstrated the interactive effect between crop residue location in soil (mulch vs. incorporation) and its biochemical and physical quality, in repacked soil columns under artificial rain. Decomposition of ^{13}C and ^{15}N labelled rape and rye residues, with associated C and N fluxes, was analysed using the mechanistic model PASTIS, which turned out to be necessary to understand the interacting factors on the C and N fluxes. The influence of soil and residue water content on decomposition and nitrification was evaluated by the moisture limitation factor of PASTIS. This factor strongly depended on residue location and to a smaller extent on physical residue properties, resulting in a lower decomposition rate of about 35% for surface placed compared to incorporated residues. Irrespective of its placement, the biochemical residue quality (e.g. N availability for decomposition, amount of soluble compounds and lignin) was responsible for a faster and more advanced decomposition of about 15% in favour of rye compared to rape, suggesting only a limited interaction between residue quality and its location. Net N mineralization after nine weeks was larger for rye than for rape, equivalent to 59 and 10 kg NO_3^-–N ha^{-1} with incorporation, and 71 and 34 kg NO_3^-–N ha^{-1} with mulch, respectively. This net N mineralization in soil resulted from the interaction between soil water content, depending on residue placement, and N availability, which was determined by the biochemical residue quality. Moisture limitation appeared more important than N limitation in the decomposition of mulched residues. Modelling of gross N mineralization and immobilization also revealed that leaving crop residues at the soil surface may increase the risk of nitrate leaching compared to residue incorporation, if (i) soil water content under mulch is larger than with residue incorporation (more gross N mineralization), and (ii) availability to the applied C-source is limited (less gross N immobilization). Scenario analyses with PASTIS confirmed the importance of moisture conditions on the decomposition of mulched residues and the small interaction between biochemical crop residue quality and its location in soil.
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1. Introduction

Crop residue management in agricultural soils has received much attention to control soil erosion and in carbon sequestration studies (e.g. Blevins and Frye, 1993; Guérif et al., 2001). Adapted tillage practices also determine the initial location and distribution of crop residues in soil that, in turn, act directly on soil physical

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properties such as soil water characteristics and structural properties (Franzluebbers, 2002). In addition, crop residue location and/or distribution pre-determines gradients in the organic matter content of the soil, in the decomposing microbial biomass and their activity (Dominy and Haynes, 2002). At a small scale, i.e. at the soil/residue interface and the detritusphere, the presence of residue particles leads to strong gradients of residue-derived C, residue- and soil-N, microbial biomass and enzymatic activities (Gaillard et al., 1999). The characteristics and size of the so-called detritusphere have been shown to be influenced by the biochemical quality of the decomposing residues and by the nature and intensity of water fluxes (Gaillard et al., 2003; Poll et al., 2006). Limited availability of mineral N to the decomposer communities has been assumed to be the main reason for the slower decomposition of crop residues with limited contact with the soil. The combined effect of: (i) distance from soil (either due to residue particle size or distribution) and (ii) low residue N content (e.g. Angers and Recous, 1997; Magid et al., 2006) accounts for this. At a larger scale, e.g. in the field, the combined effect of limited soil-residue contact and N limitation generally results in a slower decomposition rate for mulched than for incorporated residues (e.g. Douglas et al., 1980). However, the effect of residue location on decomposition interacts with residue quality and soil water dynamics (Schomberg et al., 1994). Those interactions should be taken into account when translating laboratory results to field conditions and require the use of models allowing this.

In a modelled soil profile subjected to water infiltration due to artificial rain, we previously investigated the interaction between water dynamics and biological processes (C and N biotransformation) as a result of the initial location of rape residues. We showed the major impact of water dynamics both on mulch residue decomposition and on the distribution and fate of residue-C and soil- and residue-N in a soil column (Coppens et al., 2006a, b), confirming the earlier conclusions of Schomberg et al. (1994). In order to account for the earlier mentioned interactions, the model PASTIS (Garnier et al., 2003; Findeling et al., 2007) was developed and parameterized to simulate water, carbon and nitrogen fluxes in soil with incorporated and mulched residues. The submodel 'mulch' adopts the concept of two stacked mulch layers, where only the layer in contact with the soil is subject to decomposition (Thorburn et al., 2001; Berkenkamp et al., 2002).

The main aim of this work was to examine the interactions between crop residue quality and residue placement on C and N fluxes in soil and, more in particular: (i) the effect of residue location and quality on water transport and subsequent decomposition due to redistribution of C and N in soil, and (ii) the interaction between residue placement and soil water dynamics on mineralization–immobilization of N and net N availability. Key in this paper is that modelling allows calculation of cumulative carbon mineralization, gross fluxes of nitrogen mineralization and nitrate transport in soil—processes that

otherwise are not accessible with our experimental set-up. In addition, scenario analyses were performed to confirm the importance of water availability in the decomposition process of mulched residues and to further explore the interaction with crop residue quality.

2. Materials and methods

2.1. Experimental set-up

The soil used in this study was sampled from the experimental site of INRA, Mons-en-Chaussée, Northern France (Orthic Luvisol). Selected soil parameters are given in Table 1. We sampled the 0–25 cm soil layer, sieved it at field moisture content to pass 2 mm and stored the fine earth in plastic bags at 4 °C prior to use. The soil was pre-incubated for two weeks at 20 °C before the start of the experiment. The initial microbial biomass C was determined by a modified fumigation–extraction method proposed by Vance et al. (1987).

The fresh organic matter added to the soil was mature oilseed rape (*Brassica napus* L., referred to as RAPE) and young rye (*Secale cereale*, referred to as RYE), both labelled ^{13}C and ^{15}N. The oilseed rape residue consisted of a mixture of leaves (25%), stalks (41%), branches (8%) and pods (26%). For the rye residue, only the green leaves were used. Both residues were chopped at 1 cm before application to the soil. The C content and C:N ratio of the residues and the biochemical composition determined by proximate analysis (Van Soest, 1963) are given in Table 2. Residue properties are described in more detail by Coppens et al. (2006b) and Findeling et al. (2007).

Plastic cylinders (PVC, 15.4 cm inner diameter, 30 cm high) with perforated bases were used to contain 25 cm of soil compacted at $1.3 \, \text{g cm}^{-3}$. Oilseed rape or rye residues were applied at the soil surface (referred to as SURF) or homogeneously mixed in the 0–10 cm soil layer before compaction (referred to as INC) at a rate of 13.8 g dry matter per column, equivalent to a return of $7.4 \, \text{t ha}^{-1}$. Control columns without addition of fresh organic matter (referred to as CTRL) were prepared. At the start of a nine-week incubation period, rain with an intensity of $12 \, \text{mm h}^{-1}$ was applied with a rainfall simulator on all of

Table 1
Selected characteristics of the soil from Mons-en-Chaussée, France

Parameter	
Clay (%)	13.4
Silt (%)	81.6
Sand (%)	5.0
pH (in H_2O)	8.2
Total C content (%)	0.85
Total N content (%)	0.09
C:N ratio	9.5
Microbial biomass-C (mg C kg^{-1} soil)	128.3
Humified organic matter (mg C kg^{-1} soil)	8372.0
Soluble organic matter (mg C kg^{-1} soil)	31.2

Table 2
Selected chemical and biochemical properties of the RAPE and RYE residues

	RAPE			RYE		
	Dry mass (%)	C (%)[a]	C:N	Dry mass (%)	C (%)[a]	C:N
Total residue	100.0	100.0	29	100.0	100.0	16
Soluble fraction (CWE)[b]	25.8	17.8	14	45.0	36.2	16
Soluble fraction (NDS)	45.6	39.1	20	52.5	47.4	15
Hemicellulose	14.4	12.6	49	24.9	28.2	11
Cellulose	33.2	38.7	125	21.2	22.7	101
Lignin + ash	6.7	9.6	44	1.4	1.7	12

[a] % C of total residue-C in biochemical fractions.
[b] Cold-water extractible (CWE) fraction, part of the fraction extracted with neutral detergent solution (NDS).

the soil columns to raise the volumetric soil water content to $0.34 \, cm^3 \, cm^{-3}$. No drainage was observed. Subsequently, the soil columns were transferred to a climate chamber and left uncovered at $20 \, ^\circ C$ and 70% relative air humidity to allow evaporation. After three, six and nine weeks of incubation, soil columns were placed again under the rainfall simulator until the water lost by evaporation was replenished.

Carbon dioxide fluxes from the soil surface to the atmosphere were calculated from the accumulation rate of CO_2 in the headspace of the columns. Soil volumetric water content (measured by TDR) and soil water potential (measured with a tensiometer) were determined at 6 and 14 cm depth. Mass loss of the columns was used to calculate daily evaporation rates. Soil solution was sampled at 2, 10 and 18 cm depth for mineral nitrogen measurement by colorimetry, 12 h after each rain. Destructive measurements were carried out on specific columns after three, six and nine weeks. Mulch dry mass was measured after oven drying. The mineral nitrogen content in layers of 0–5, 5–10, 10–17.5 and 17.5–25 cm was extracted with KCl before each rain and measured by colorimetry. The total C content of the soil and the recovered plant residues, with their isotopic excess, were determined using an elemental analyser coupled to a mass spectrometer. Details of the experimental conditions and performed measurements are extensively described by Coppens et al. (2006b). Table 3 summarizes the initial experimental conditions.

2.2. Model description

Transport of water and nitrate in soil was simulated with the one-dimensional mechanistic model PASTIS (Prediction of Agricultural Solute Transport In Soil: Lafolie, 1991; Garnier et al., 2001). The submodel CANTIS (Carbon and Nitrogen Transformations In Soil) simulated the biotransformations of carbon and nitrogen in soil. The PASTIS model, originally designed for incorporated residues, was adapted to take into account the physical effects of mulch on rain interception and evaporation (Findeling et al., 2003) and the specific dynamics of mulch decomposition (Findeling et al., 2007), resulting in the extended model PASTIS$_{mulch}$. In contrast to models used for prediction,

Table 3
Description of initial conditions for the RAPE and RYE experiment

Parameter	RAPE	RYE
Amount of residues added (g column^{-1})[a]	13.78	13.78
Initial mulch thickness for SURF (cm)	1	2
Depth of incorporation for INC treatment	from 0 to 10 cm	from 0 to 10 cm
N added by residue (g column^{-1})	0.12	0.37
C added by residue (g column^{-1})	5.82	5.98
Amount of soil (kg column^{-1})[a]	6.02	6.02
Initial N–NO$_3^-$ in soil (mg kg^{-1} soil)	9.80	29.85
Temperature ($^\circ$C)	20	20
Incubation time (d)	64	64
Days for rain application (d)	0, 21, 42, 63	0, 21, 42, 63

[a] Dry weight.

e.g. Roth-C (Coleman and Jenkinson, 1996), PASTIS$_{mulch}$ is considered as a research tool to study mechanisms in residue decomposition and transport processes.

The PASTIS model has been previously calibrated for incorporated residues (Garnier et al., 2003). The present data for incorporated RAPE and RYE were used for model validation. Only soil-specific hydraulic parameters and soil- and residue-dependent biological parameters were optimized on experimental data, while all other model parameters were used from Garnier et al. (2003). Calibration of the mulch specific parameters for RAPE and RYE was done by Findeling et al. (2007). In the PASTIS model, the decomposition process can be affected by limitation factors linked to temperature, moisture and nitrogen (Garnier et al., 2001). The moisture limitation factor is derived from Andrén et al. (1992) using the matric potential of water h (cm of water):

$$f_W = \frac{\ln(h/h')}{\ln(h_{ref}/h')} \tag{1}$$

for $h' \leqslant h \leqslant h_{ref}$ where h_{ref} is the 'reference' potential (-100 cm of water or field capacity) and h' is the potential at which microbial activity ceases ($-75\,800$ cm of water). When $h \leqslant h'$, f_W equals to 0 and when $h_{ref} \leqslant h$, f_W equals to 1.

2.3. Modelling conditions

2.3.1. Boundary and initial conditions

The PASTIS$_{mulch}$ model was applied to the 25-cm monoliths of the SURF and INC treatment for RAPE and RYE. Boundary conditions for water fluxes and temperature, and the initial conditions for water content and soil solutes were previously defined by Findeling et al. (2007). The initial conditions for organic pools and microbial biomass in the CANTIS submodel are derived from Tables 1 and 2.

2.3.2. Parameter optimization

The soil water retention curve $h(\theta)$ was obtained for each soil treatment using TDR and tensiometer measurements in the columns (matric potential in the range of -50 to -300 cm of water) and by the pressure extractor method (Klute and Dirksen, 1986) for lower matric potentials (-500, -1000, -3000 and -15000 cm of water). The experimental data were fitted with the model of Van Genuchten (1980). The hydraulic conductivity curve $K(\theta)$ was obtained by inverse modelling with PASTIS, also using the Van Genuchten (1980) equation. The fitted parameters are given in Table 4. Soil- and residue-specific biological parameters of the CANTIS submodel were acquired by fitting the model to experimentally obtained mineralization curves of C and N. Details of the fitting procedures are given by Findeling et al. (2007).

2.3.3. Model efficiency coefficient

The model was evaluated graphically and statistically. Simulated soil matric potential, residual ^{13}C and the amount of $NO_3^- $-N in the different soil layers were compared with measured data. The efficiency, E_f ($-$), was used to assess model performance (Smith et al., 1996):

$$E_f = \frac{\sum_{i=1}^{n}(m_i - \bar{m})^2 - \sum_{i=1}^{n}(s_i - m_i)^2}{\sum_{i=1}^{n}(m_i - \bar{m})^2}, \qquad (2)$$

where m_i and s_i are the measured and simulated results, and $\bar{m}$ is the average of the n measured results.

Table 4
Hydraulic parameters of soil retention and soil conductivity curves for RAPE and RYE used in PASTIS$_{mulch}$

Function	Hydraulic parameters	Soil columns			
		RAPE		RYE	
		INC	SURF	INC	SURF
$h(\theta)$	θ_s (cm^3 cm^{-3})	0.420	0.535	0.530	0.500
	θ_r (cm^3 cm^{-3})	0.000	0.000	0.000	0.000
	α (cm^{-1})	0.258	0.259	0.107	0.107
	N ($-$)	1.142	1.185	1.228	1.228
$K(\theta)$	Ks (cm h^{-1})	3.20	6.00	30.00	15.00
	M ($-$)	1.25	1.29	1.25	1.25

2.4. Scenario analysis

2.4.1. Influence of water dynamics

To test the hypothesis that water availability is the main factor driving surface residue decomposition, a scenario analysis for RAPE was performed with PASTIS$_{mulch}$ where the same amount of water as added by the three rain events in the experimental design was homogenously distributed over the nine-week incubation period. For INC and SURF, a daily rain of respectively 0.118 and 0.080 cm was simulated. All other model parameters were held constant.

2.4.2. Influence of residue quality

The PASTIS$_{mulch}$ model was also used to evaluate the interaction of residue quality with residue location. Therefore, a scenario was set-up to simulate decomposition of incorporated and surface placed wheat straw (referred to as WHEAT), with differing physical and biochemical properties compared to RAPE and RYE. Physical and biochemical properties of WHEAT were taken from Oorts K. (Ph.D. Thesis, 2006). The C:N ratio of WHEAT was 88. The carbon content of the Van Soest fractions was: 5.2% in the soluble fraction (NDS), 34.0% in the hemicellulose, 51.7% in the cellulose and 9.1% in the lignin fraction. The percentage distribution of residue carbon in the cold water extractable fraction was 1.77% of the total. The addition of a same amount of C as in the RAPE and RYE experiment was simulated. Decomposition parameters and some of the physical parameters of WHEAT mulch were taken from Oorts K. (Ph.D. Thesis, 2006). Some other physical parameters of the mulch, like the maximal and residual water content and the retention curve of straw, were measured and described in Garnier et al. (2004). All other model parameters were held constant compared to RAPE and RYE simulations.

3. Results

3.1. Water dynamics and moisture limitation factor

The water dynamics data were already described by Coppens et al. (2006b) when the comparison between SURF and INC treatments was made for RAPE. Findeling et al. (2007) compared model and experimental data of RAPE and RYE for the SURF treatments. In the present study, we observed for both residues a decreased evaporation within the SURF treatment compared to the INC treatment ($P < 0.001$). The gravimetric water content of mulch quickly increased during rain applications and then decreased gradually during the evaporation period. The model simulated well the water dynamics of mulch (Findeling et al., 2007, Table 5).

The moisture limitation factor f_W of PASTIS$_{mulch}$ (Eq. (1)) which affects the decomposition, was calculated from the simulated water potential in soil and mulch (Fig. 1A and B). For the INC treatment, f_W was calculated at 5 cm soil depth, as an average value for the residues

Table 5
Model efficiency coefficients (E_f) for evaluation of PASTIS$_{mulch}$

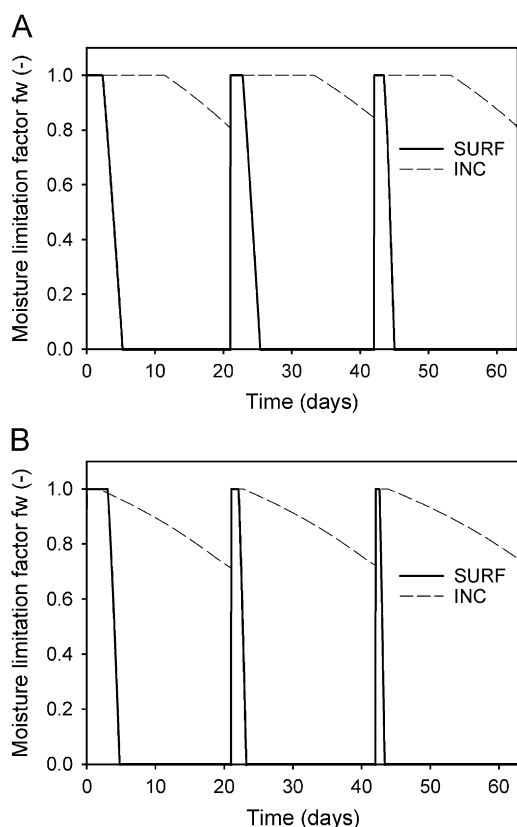|	Soil matric potential	Residual ^{13}C	NO$_3^-$-N (0–5 cm)
RAPE INC	0.876	0.978	−0.813
RAPE SURF	0.963	0.813	0.795
RYE INC	0.897	0.974	−5.351
RYE SURF	0.915	0.924	0.725

Fig. 1. Change of the moisture limitation factor f_W over time, with incorporation (INC, dashed line) and surface application (solid line) of: (A) RAPE residues; and (B) RYE residues.

incorporated in the 0–10 cm soil layer. For the SURF treatment, f_W was calculated in the mulch layer. The factor f_W was very sensitive to wetting and drying cycles for SURF while it was more constant for INC. It was always equal or lower for SURF than for INC. For the SURF treatment, f_W dropped to 0 for both residues five days after the initial rainfall (= decomposition ceased). The factor f_W increased again to 1 with the subsequent rain applications (= no limitation). However, the time elapsed for the factor f_W before dropping to 0 shortened with every wetting–drying cycle and was smaller for RYE than for RAPE. For the INC treatment of RAPE, f_W started to decrease 11 days after rainfall and reached an average value of 0.82 at the end of each evaporation period. For RYE, f_W decreased immediately after a rainfall event to arrive at 0.73 after three weeks of evaporation. As a result, the moisture limitation factor strongly depended on residue location and to a smaller extent on residue quality.

3.2. Residue decomposition

Crop residue quality and location both had a strong effect on the kinetics of decomposition and on the subsequent distribution of residual ^{13}C into the soil (Table 6). The total amount of ^{13}C recovered in soil decreased much faster for INC than for SURF ($P < 0.05$), with about half the amount of residual ^{13}C in the 0–25 cm column at week 9, whatever the residue quality. For RYE, a very fast decomposition with INC was obtained at week 3 already (66.3% of the C applied) and the total amount of residual ^{13}C did not change much afterwards, while some redistribution of ^{13}C between soil fractions occurred between week 3 and week 6. For RAPE, decomposition with INC was more regular along the nine-week experiment.

For both residues, the INC treatments resulted in a more homogeneous distribution of ^{13}C along the soil column as expected from the initial location, but also more transfer of ^{13}C from the > 2 mm fraction into the < 2 mm fraction was observed than in the SURF treatment ($P < 0.05$). The differences in distribution of residual ^{13}C at week 9 between the INC treatments of RYE and RAPE resulted mainly from the depletion of the > 2 mm fractions of RYE compared to RAPE, while the amounts of ^{13}C in the < 2 mm fractions were similar for both residues. For the SURF treatments, similar amounts of ^{13}C were accumulated in the fine fractions for RYE (9%) and RAPE (8%) at week 9, although less ^{13}C remained at the surface for RYE (57%) than for RAPE (74%).

The total residual ^{13}C in soil amounted to 82% (SURF) and 45% (INC) of the applied residue-C for RAPE, and 66% (SURF) and 32% (INC) of the applied residue-C for RYE after nine weeks of incubation (Fig. 2A and B). The model simulated well total residual ^{13}C in the soil (Table 5 and Fig. 2A and B). For RYE, although final values of simulated residual ^{13}C were in accordance with measured values, the model was not able to simulate the fast initial residue decomposition with INC.

Modelling with PASTIS$_{mulch}$ revealed that less carbon was emitted as CO_2 from the 'soil + residue' system by leaving crop residues at the soil surface than when incorporated in the soil. Expressed on an area basis, the smaller C-emission for SURF than for INC over the nine-week period was equivalent to −1217 kg C ha^{-1} for RAPE and −1108 kg C ha^{-1} for RYE and this reduction was due to a slower decomposition of the mulch. More carbon was mineralized with RYE than with RAPE: +597 kg C ha^{-1} for surface applied and +489 kg C ha^{-1} for incorporated residues, which was mainly attributed to the effect of residue quality.

During decomposition, the residues were enriched in soil-derived N due to microbial colonization, as shown by the dilution of ^{15}N atom % excess in the residue fraction > 2 mm with unlabelled N. For the SURF treatment, the relative enrichment of the nitrogen content with soil derived N after nine weeks was +4% for RAPE and +2% for RYE. This indicates that fungal translocation

Table 6
Summary of the distribution of total residue-C in the mulch, 0–5, 5–10 and 10–25 cm soil layers, for RAPE and RYE either incorporated (INC) or left as mulch at the surface (SURF)

	Week	SURF (%)				INC (%)			
		0	3	6	9	0	3	6	9
RAPE									
Surface	>2 mm	100.0	84.3°	79.2°	73.8°	ND	ND	ND	ND
0–5 cm	>2 mm	0.0*	0.0*	0.0*	0.0*	50.0*	29.9*,°	15.0*,°	11.2*,°
	<2 mm	0.0	5.0*	6.2*	6.3*,°	0.0	10.7*	13.1*	11.9*
5–10 cm	>2 mm	0.0*	0.0*	0.0*	0.0*	50.0*	15.8*,°	9.9*,°	9.5*,°
	<2 mm	0.0	1.6*	1.6*	1.5*	0.0	10.7*	12.4*	10.5*
10–25 cm	<2 mm	0.0	0.0*	0.1*	0.0*	0.0	1.9*,°	2.4*,°	2.3*,°
Total		100.0	90.9*,°	87.1*,°	81.6*,°	100.0	69.0*,°	52.8*,°	45.4*,°
RYE									
Surface	>2 mm	100.0	68.6°	58.6°	57.0°	ND	ND	ND	ND
0–5 cm	>2 mm	0.0*	0.0*	0.0*	0.0*	50.0*	6.8*,°	0.5*,°	0.2*,°
	<2 mm	0.0	4.7	6.1*	7.6*,°	0.0	5.0	11.7*	12.1*
5–10 cm	>2 mm	0.0*	0.0*	0.0	0.0*	50.0*	2.7*,°	0.2°	0.3*,°
	<2 mm	0.0	1.7*	1.3*	1.2*	0.0	11.4*	12.6*	12.0*
10–25 cm	<2 mm	0.0	0.3*	0.2*	0.2*	0.0	7.8*,°	8.2*,°	7.3*,°
Total		100.0	75.3*,°	66.2*,°	66.0*,°	100.0	33.7*,°	33.2*,°	31.9*,°

Total residue-C is expressed as percent of C added. Values are the means of three measurements. Differences between treatments (SURF vs. INC) and species (RAPE vs. RYE) are indicated by * and °, respectively ($P<0.05$).

of soil N to surface placed residues (Frey et al., 2000) was more important for those residues with a higher C:N ratio. For the INC treatment, the more intimate contact between soil and residues resulted after nine weeks in a relative enrichment of RAPE with 25% of soil derived N. No data are available for RYE, since the more advanced decomposition level did not allow recovering a residue fraction of >2 mm size. The final C:N ratio of the applied residues after nine weeks was 48 (SURF), 39 (INC, 0–5 cm) and 29 (INC, 5–10 cm) for RAPE, and 14 (SURF), 35 (INC, 0–5 cm) and 24 (INC, 5–10 cm) for RYE.

3.3. Nitrogen dynamics

Measurement of nitrate accumulation in the different soil layers is illustrated for the 0–5 cms oil layer (Fig. 2C and D). For RAPE, a strong depletion in the NO_3^-–N content was observed at week 3 for the INC treatment (0.4 mg NO_3^-–N kg^{-1}) compared to SURF (14.3 mg NO_3^-–N kg^{-1}) and this difference persisted over the nine-week incubation period ($P<0.001$). For RYE, in contrast, larger amounts of nitrate were measured in the 0–5 cm soil layer of INC (30.5 mg NO_3^-–N kg^{-1}) compared to SURF (16.2 mg NO_3^-–N kg^{-1}). The general evolution in nitrogen dynamics was well simulated with PASTIS$_{mulch}$, although the model efficiency coefficients were quite low for the INC treatment (Table 5). Model efficiency was better for SURF than for INC, because in the SURF treatment additional optimizations were performed on the observed data to obtain specific parameters for mulch decomposition in PASTIS$_{mulch}$ (Findeling et al., 2007).

Crop residue location had a significant effect on the nitrogen fluxes in soil, which largely depended on biochem-

ical residue quality (Fig. 3). In general, larger gross N fluxes were simulated for INC than for SURF, which is in accordance with the faster residue decomposition observed for INC. The net N mineralization measured after nine weeks was larger for RYE than for RAPE for both treatments, equivalent to 59.4 and 10.0 kg NO_3^-–N ha^{-1} for INC and 70.5 and 34.1 kg NO_3^-–N ha^{-1} for SURF, respectively. Simulation of N fluxes in the RYE treatment did not correspond well with the experimental net N mineralization, particularly for the INC treatment where the model overestimated the experimental data.

The nitrate concentration in the soil profile depended both on residue location and quality, as illustrated from simulated results for the first wetting–drying cycle (Fig. 4). The model showed large differences in the nitrate concentration between day 1 and 21. The decreased nitrate concentrations measured in the upper layer at day 1 were mainly due to nitrate dilution with the rainwater and its transport with water to deeper layers. The simulated increase in nitrate concentrations in the upper layer from day 1 to 21 (except for INC-RAPE) was mainly due to its concentration because of water evaporation, its transport with the water up-flow and its net mineralization as it is shown in Fig. 3. For the INC-RAPE treatment, the low nitrate concentration in the upper layer at day 21 resulted from the large immobilization of nitrogen due to the decomposition of the RAPE residue. The PASTIS model tended to underestimate the measured nitrate concentration in the intermediate and deep layers for SURF treatments. The "Rhizon" probes that sample intermediate or macro sized pores might have overestimated the nitrate concentration, because equilibrium with immobile water might not be reached at day 1 (Garnier et al., 2001; Beulke et al., 2004).
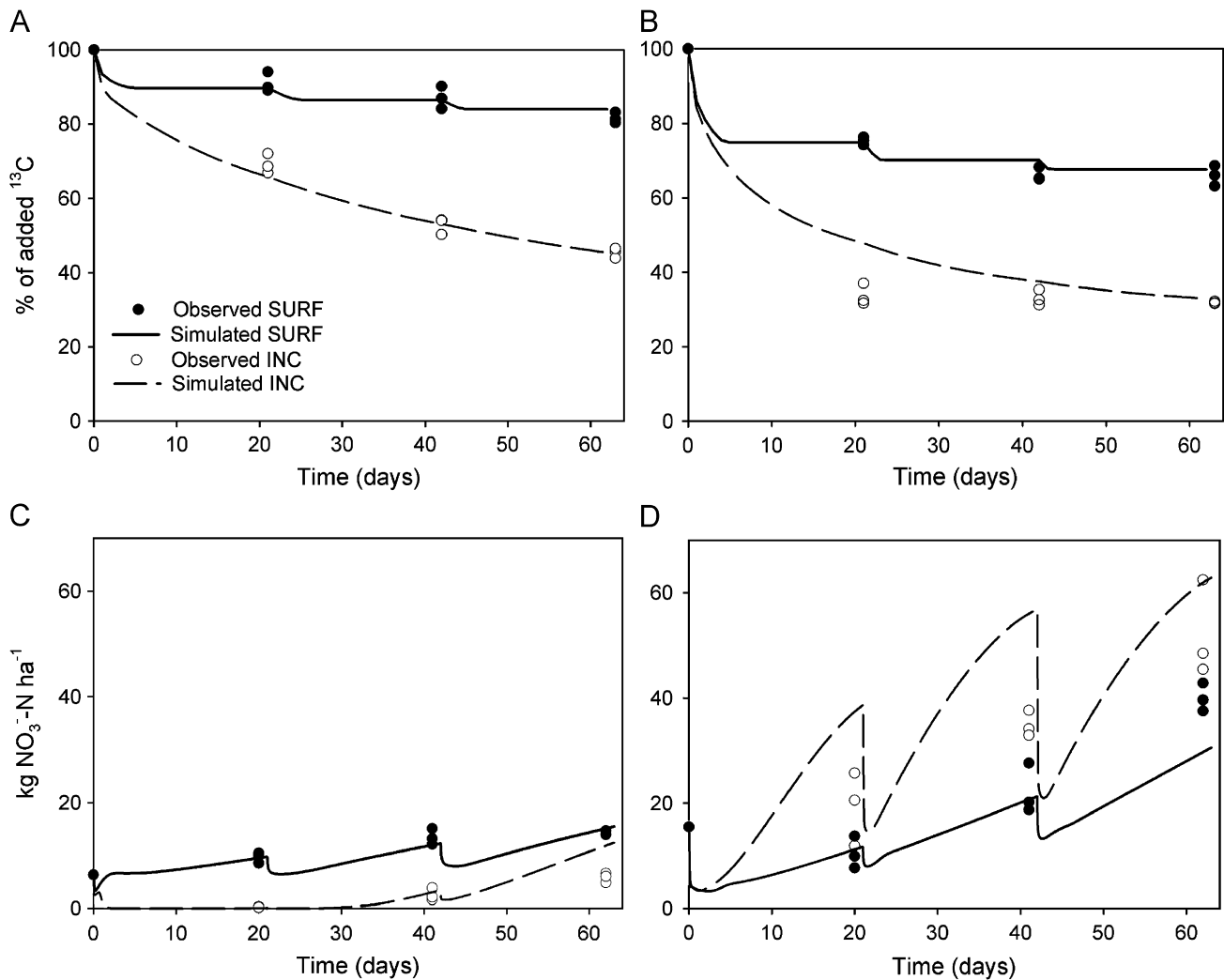
Fig. 2. Comparison between the observed and simulated change in total remaining ^{13}C over time, with incorporation (INC, dashed line) and surface application (SURF, solid line) of: (A) RAPE; and (B) RYE residues; and comparison between the observed and simulated change in mineral nitrogen content of the 0–5 cm soil layer, with incorporation (INC, dashed line) and surface application (SURF, solid line) of (C) RAPE; and (D) RYE residues.

The cumulative gross nitrogen immobilization after nine weeks, estimated from modelling and expressed per gram of applied residue-C, was 39 mg N immobilized g^{-1} added C for RAPE-SURF, 90 mg N g^{-1} added C for RAPE-INC, 59 mg N g^{-1} added C for RYE-SURF and 156 mg N g^{-1} added C for RYE-INC, in accordance with the more advanced decomposition for RYE than for RAPE and for INC than for SURF at week 9. Expressed on the basis of cumulative C mineralized for each treatment, the gross immobilization was 246 mg N immobilized g^{-1} mineralized C for RAPE-SURF, 164 mg N g^{-1} C for RAPE-INC, 186 mg N g^{-1} C for RYE-SURF and 240 mg N g^{-1} C for RYE-INC.

3.4. Scenario analysis

3.4.1. Influence of water dynamics

For INC, decomposition of RAPE was slightly affected by the modified water regime (Fig. 5A). After nine weeks, the simulated amount of mineralized C with a homogenous distribution of the rain was only 3% less than observed with three rain events. For SURF, in contrast, 31% more residue-C mineralization was simulated than observed in the RAPE experiment (Fig. 5B). With this homogenous distribution of rain, the RAPE decomposition was then quite similar for INC and SURF with 49% and 53% of C decomposition at day 62, respectively.

3.4.2. Influence of residue quality

For INC, only 50% of the added WHEAT was simulated decomposed after nine weeks, while it was 55% and 68% for RAPE and RYE respectively (Fig. 6A). For SURF, 12% of the added WHEAT was simulated decomposed, compared to 18% and 34% for RAPE and RYE, respectively (Fig. 6B). The moisture limitation factor f_W dropped to 0 later for WHEAT than for the other residues, for the three cycles. (Fig. 6C). This result was explained by a delay in decomposition of WHEAT mulch compared to RYE and RAPE mulch. For both INC and SURF, a significant negative correlation was found
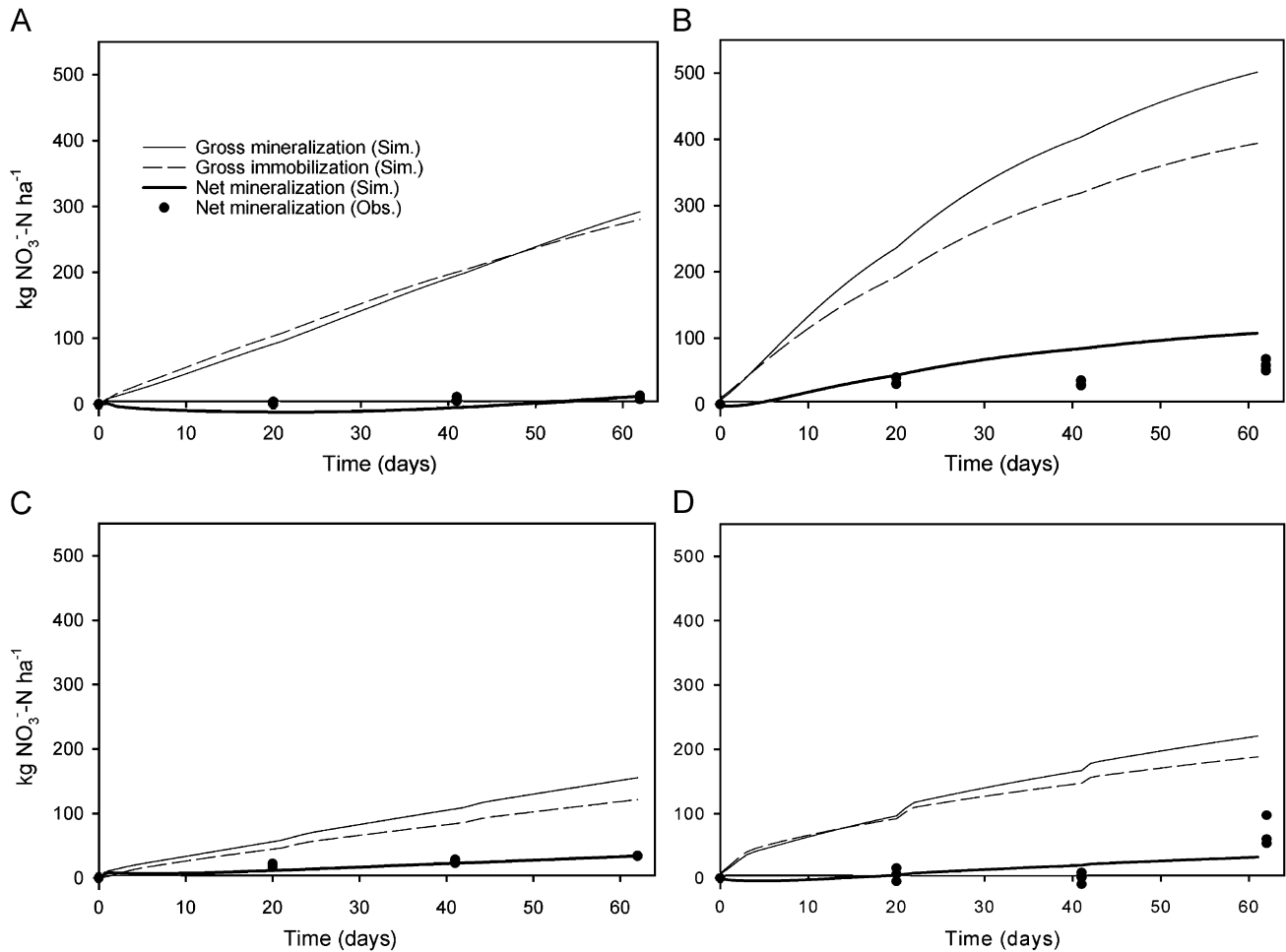
Fig. 3. Evolution of the simulated gross fluxes of nitrogen mineralization and immobilization, and comparison between simulated and observed net nitrogen mineralization in the 0–25 cm soil layer with: (A) incorporation (INC) of RAPE; (B) incorporation (INC) of RYE; (C) surface application (SURF) of RAPE; and (D) surface application (SURF) of RYE.

between the lignin content of the residues and the amount of C decomposed after nine weeks (Fig. 6D). The slope of the regression was similar for both treatments: -2.43 ± 0.45 for INC and -2.88 ± 0.71 for SURF (slope $\pm 95\%$ confidence interval).

4. Discussion

4.1. Interactions between water dynamics and residue placement

The observed pulses in mulch decomposition after rainfall resulted from a flush of microbial activity, stimulated by the rewetting of the residue particles. In our simulations, this effect was taken into account by the water limitation factor f_W of PASTIS$_{mulch}$, calculated from the volumetric water content of the mulch layer. For RYE mulch, the periods without moisture limitation for decomposition ($f_W = 1$) were shorter after the second and third rain than for RAPE mulch, which can be explained by the more advanced decomposition level of RYE mulch. Indeed, the faster decrease in volume

of RYE mulch implied that less water was stored in the mulch particles, inducing a faster drying of the particles of RYE compared to RAPE at the same sampling dates.

We used scenario analysis with PASTIS to examine the influence of rain distribution on RAPE decomposition. The model simulated that the even distribution of rain reduced the decomposition of incorporated residues (INC) slightly, which may be explained by the on average dryer soil conditions induced by the new rain events. However, the most remarkable impact of rain distribution was observed with surface placed residues. By adjusting only the water regime in the simulation, the difference in RAPE decomposition between SURF and INC was reduced by about 90%. With the three rain events of our experiment, the water content of the mulch rapidly decreased during each evaporation period following rain, resulting in a decrease in the activity of the microbial decomposers. In the present scenario, daily rain applications maximized the water content of the residue mulch during the whole period, which resulted in a stimulated microbial activity and increased decomposition rate. Our scenario analysis so
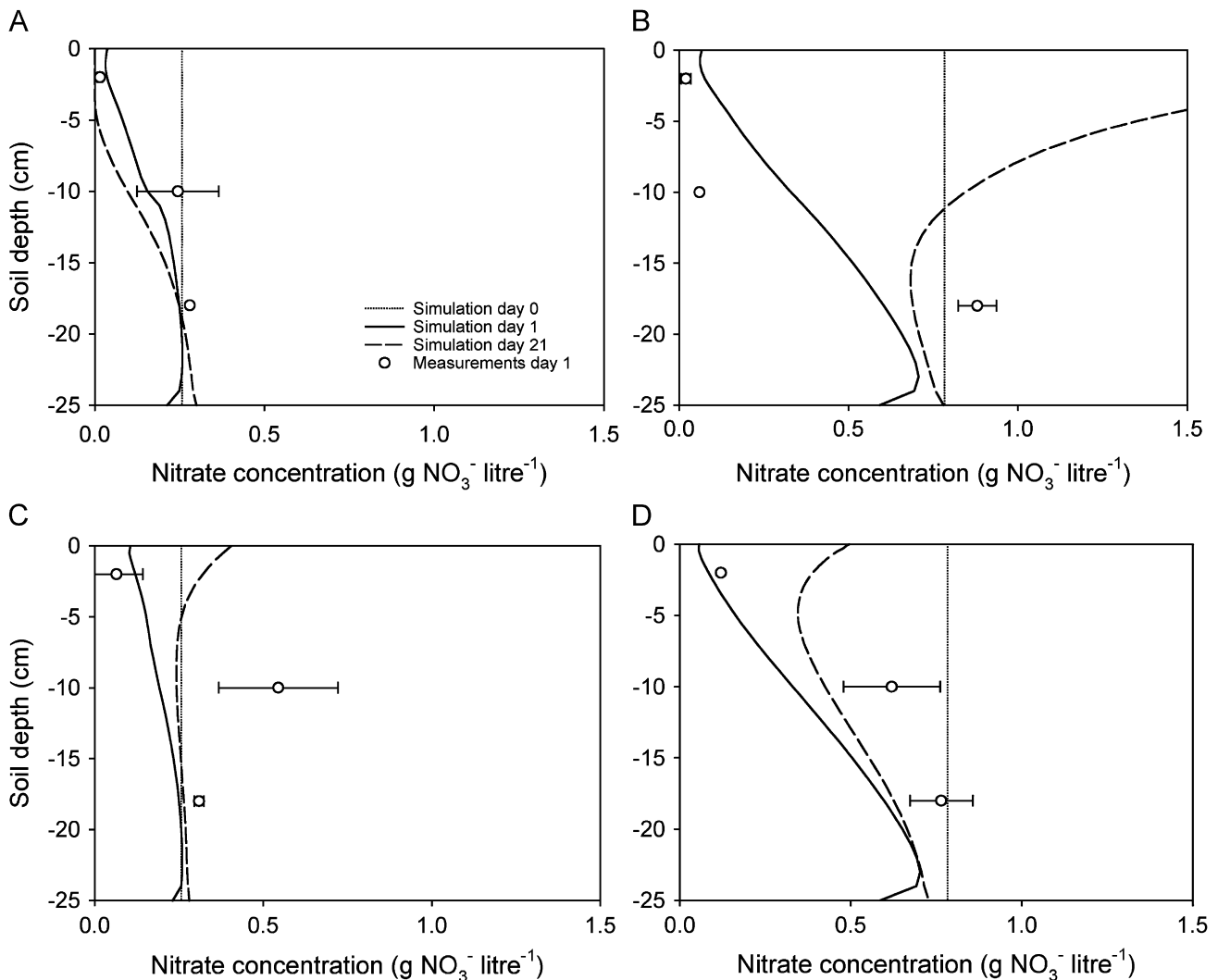
Fig. 4. Simulation and measured values of the nitrate concentration through the soil profile after 0 (dotted line), 1 (solid line) and 21 days of evaporation (dashed line), with: (A) incorporation (INC) of RAPE; (B) incorporation (INC) of RYE; (C) surface application (SURF) of RAPE; and (D) surface application (SURF) of RYE.

seems to corroborate the concepts on which the model is built. Hence it can be asserted that 90% of the effect of residue location on decomposition is explained by mulch water content and that other limiting factors for decomposition such as soil–residue contact, N availability or microbial colonization are of minor importance compared to the water regime.

4.2. Combined effects of residue location and quality on decomposition

In general, decomposition was faster for young rye residues than for mature oilseed rape and for incorporated than for surface placed residues. Firstly, differences in carbon mineralization when comparing incorporation of RAPE with incorporation of RYE, or surface application of RAPE with surface application of RYE were attributed to the biochemical quality of residues (Trinsoutrot et al.,

2000). The larger N availability of RYE (C:N = 16) compared to RAPE residues (C:N = 29), the larger content in soluble fraction and the smaller lignin content of RYE compared to RAPE, favoured a faster decomposition of RYE (about + 15% of added C in nine weeks), irrespective of the residue placement. Also the scenario analysis performed with PASTIS including WHEAT residues having a larger lignin fraction, confirmed the negative correlation between residue decomposition and lignin content as observed by several authors (e.g. Cortez et al., 1996; Sariyildiz and Anderson, 2003). Secondly, the faster decomposition rate with incorporated compared to surface placed residues was mainly explained by more favourable moisture conditions, which is in agreement with previous studies (e.g. Schomberg et al., 1994; Curtin et al., 1998) and corroborated by our scenario analysis concerning water dynamics. The difference between the intercepts of both regression lines in the scenario analysis with
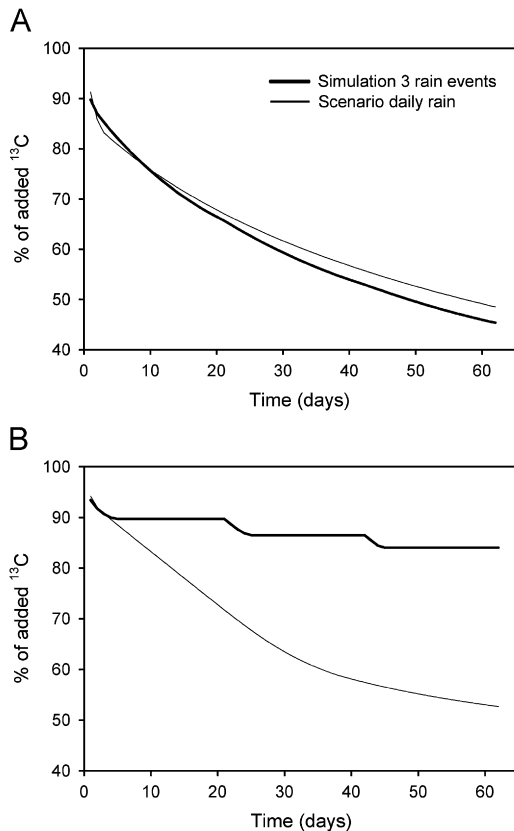
Fig. 5. Results of the simulation with $PASTIS_{mulch}$ of the experimental design with three rain events (bold line) and the theoretical scenario with daily rain application (thin line): (A) simulated ^{13}C remaining for INC; and (B) simulated ^{13}C remaining for SURF.

WHEAT expressed the observed relative difference in C decomposition of about 34% due to moisture limitation. The similarity of the slopes for incorporated residues (INC) and surface placed residues (SURF) indicated that for a given placement the residue decomposition rates were mainly driven by the biochemical quality, and that there was no interaction between the biochemical quality of residues and their location in soil regarding to decomposition.

4.3. Combined effects of residue location and quality on N availability in soil

One major effect of residue location was its influence on N distribution into the soil column and the net N mineralization, that consequently: (i) may create nutrient limitation to micro-organisms during decomposition, and (ii) may influence significantly the subsequent availability of nitrate, particularly for leaching.

For all treatments, the nitrate concentration in the upper soil layer was significantly reduced after rainfall, due to nitrate leaching into deeper layers and to dilution by the increase in soil water content due to rain application. Thereafter, nitrate concentration in soil was first depending on residue quality. As expected (e.g. Trinsoutrot et al.,

2000), the RAPE residue having the higher C:N ratio induced a larger gross immobilization of N and a lower gross N mineralization than RYE, inducing a larger net N mineralization. Nitrate concentration also depended on residue location. The absence of residues decomposing in the soil layer itself (SURF treatments), induced a relatively smaller gross N immobilization, which resulted in a larger net nitrogen accumulation in soil under mulch than when the same amount of residues were incorporated.

Consequently, leaving crop residues at the soil surface could increase the risk on nitrate leaching in soil compared to residue incorporation, mainly by increasing the water content of the top soil in situations of reduced evaporation, which in turn enhances gross N mineralization of native organic matter, but also by increasing the distance between C substrates and soil N that limits the availability of N to decomposers and therefore decreases the gross N immobilization, again resulting in larger mineral N pools. In addition, with the larger water content under mulch less rainfall would be required before leaching started. Indeed, the amount of N immobilized was lower for RYE as mulch than for incorporated residues (186 vs. 240 mg N immobilized g^{-1} of C mineralized), confirming the data of Magid et al. (2006) who found more N immobilized per unit of respired C with homogeneously distributed (cf. INC) compared to stratified residues (cf. SURF). This was attributed to a higher limitation of available N with stratified (or surface) residues in the active zone of decomposition, which could induce substantially different population dynamics (as discussed by Magid et al., 2006) and reduced N requirements by the decomposing microflora (Recous et al., 1995). The amount of immobilized N was much higher for RYE-INC than for RAPE-INC (240 vs. 164 mg N g^{-1} C mineralized), suggesting a higher N limitation with RAPE residues, which is confirmed by the very low N content of the soil layer in which the RAPE residues were incorporated compared to RYE. Only the large amount of N immobilized with the RAPE residues as mulch contradicts this hypothesis of a strong interaction between residue distribution, residue quality and resulting N availability on gross N immobilization. Water dynamics in our experiment that affect the N content of mulch by initial leaching may explain these contrasting results. Magid et al. (2006) recently discussed with the help of modelling the occurrence of nutrient-limitation conditions for several scenarios of residue distribution and residue quality. In our conditions, we can conclude that the impact of water dynamics on mulch decomposition and nitrogen mineralization is of larger importance than N availability, given the fact that: (i) in the 0–5 cm soil layer under mulch and in the soil solution at 2 cm depth N concentrations were not limiting (Findeling et al., 2007), (ii) stimulated CO_2-fluxes after rain did not suggest that mulch decomposition was reduced by N limitation (Coppens et al., 2006b), and (iii) our scenario analysis showed that mulch water content was the main factor determining its degradation.
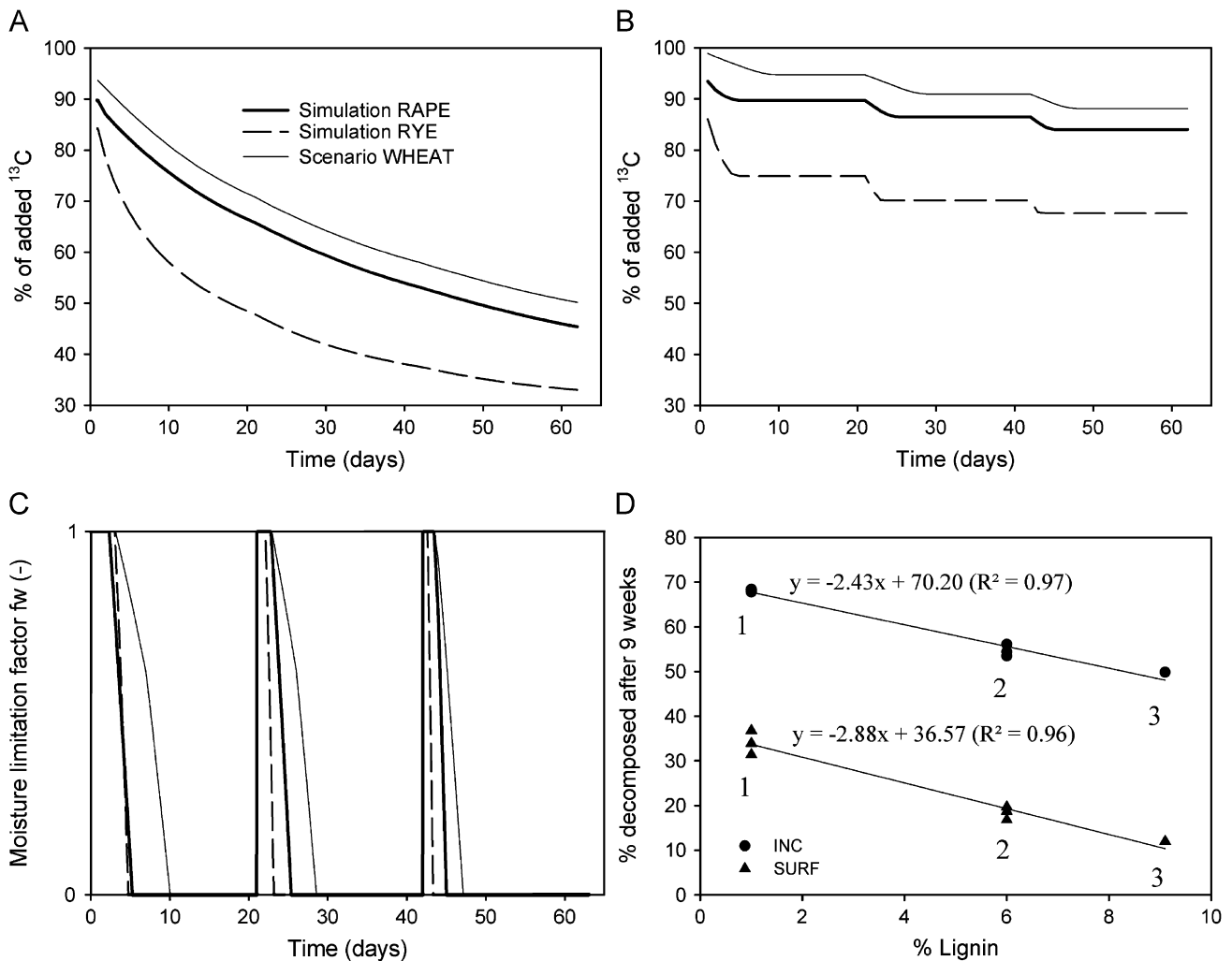
Fig. 6. Results of the simulation with PASTIS$_{mulch}$ of the experimental design with RAPE (bold line), RYE (broken line) and the theoretical scenario with WHEAT (thin line): (A) simulated ^{13}C remaining for INC; (B) simulated ^{13}C remaining for SURF; (C) evolution of the moisture limitation factor for SURF during nine weeks of incubation with three wetting–drying cycles; and (D) relationship between lignin content of the residues and the percent of C decomposed after nine weeks with 1 = RYE, 2 = RAPE, 3 = WHEAT.

5. Conclusions

A change in mulch water content was assumed to be the main factor controlling surface residue decomposition, which to a lesser degree also depended on its physical and biochemical quality. However, when incorporated, C mineralization kinetics were mainly influenced by biochemical residue quality and nitrogen content. The strongest interactions between residue location and quality were observed in the N dynamics: net N mineralization was determined by the interaction between soil water content (depending on residue location) and N availability (depending on residue quality). Modelling allowed to access gross N fluxes, to estimate nitrate transport and potential leaching in the soil profile and to quantify the impact of residue location and quality on C and N mineralization in soil. Simulation results clearly demonstrated that moisture limitation was a more important factor than N limitation in the decomposition of mulched

residues. Under certain conditions, mulching of residues resulted in an increased risk of nitrate leaching compared to residue incorporation.

The present work shows that a mechanistic model such as PASTIS is a valuable tool in the study of carbon and nitrogen dynamics in soil, to elucidate interactions that are not, or not easily accessible by experimental work. Our modelling results are promising in this area of research since the mechanisms they are using are built on well-proven concepts. The good performance hence suggests that a better understanding of crop residue degradation in the field is possible, duly taking into account the many and intricate interactions between residue quality, residue placement and climate conditions.

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