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Introducing and expanding cover crops at the watershed scale: impact on water flows

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Abstract

Cover crops have multiple benefits, such as improving water quality, providing a green manure effect, and storing carbon in the soil. They can, however, reduce drainage significantly during key periods of hydrosystem recharge, especially in winter. The objective of this study was to evaluate the influence of cover crops and/or crop diversification at the watershed scale on water in the downstream watershed of the Aveyron River, based on three scenarios with different management practices. It is an illustrative case study of situations of water imbalance involving 1150 farms, with agricultural fields covering 40,000 ha, of which ca. 40% may be irrigated. The MAELIA model was used to simulate 10 years (2007-2016) of dynamics to estimate the influence of cover crops on water flows. Simulations showed that short-duration cover crops terminated in autumn generally had little influence on water: they decreased drainage slightly in autumn, but the recharge in winter compensated for this decrease and thus did not influence the water dynamics or yields of the succeeding cash crops. Although long-duration cover crops grow for a longer period and are sown more frequently in fields, they also had relatively little influence on water in the region, except for decreasing drainage. A scenario with long-duration cover crops and diversification of rotations was a good compromise for quantitative water management. Diversifying rotations, notably by replacing maize with crops that required less water, compensated for potential negative effects of long-duration cover crops. Although this scenario increased variability depending on the weather year and reduced autumn drainage, it influenced irrigation withdrawals and river flows little over the 10-year period. However, greater variability occurred at the field scale, where cover crops can have more influence. Thus, it is important to adapt the management practices for cover crops in rotations to decrease negative effects, particularly on water availability, which could increase withdrawals in an area that already has a water deficit, and not to decrease yields and thus farmers' profits. Our results are valid for the study area, but these scenarios should be extrapolated to other soil and climate conditions and other rotations and management systems.

1. Introduction

Cover crops are commonly grown during the fallow period between two main cash crops to provide ecosystem services, such as i) water quality regulation by reducing nitrate leaching (Abdalla et al., 2019; Ascott et al., 2017; Justes et al., 2012), ii) nitrogen supply through the “green manure” effect (Thorup-Kristensen et al., 2003; Tonitto et al., 2006), iii) climate change regulation by storing soil carbon (Launay et al., 2021; Poeplau and Don, 2015) and reducing greenhouse gas emissions (Kaye and Quemada, 2017; Plaza-Bonilla et al., 2017; Tribouillois et al., 2018a), v) erosion regulation due to continuous protection of soil in winter (Dabney et al., 2001; Langdale et al., 1991; Ryder and Fares, 2008), and vi) pest, disease, and weed regulation and biodiversity maintenance (Schipanski et al., 2014). However, Meyer et al. (2019) highlighted that the influence of these multiple services of cover crops on water-balance components remains little studied.

Water resources in ecosystems are usually classified into two categories: blue water (from lakes, rivers, oceans, and groundwater) and green water (precipitation stored in the soil and returned to the atmosphere through evapotranspiration) (Falkenmark and Rockström, 2006). Rainfed agriculture uses only green water, while irrigated agriculture uses both green and blue water (Liu et al., 2009). The review of Meyer et al. (2019) highlighted that cover crops may have reduced drainage compared to that under bare soil in 90% of the cases studied (by a mean of 27 mm), but with high variability among soils, climates, and cropping systems. Accordingly, introducing cover crops during the fallow period can create an antagonism between the increase in evapotranspiration (green water) due to the cover crops and a decrease in drainage and groundwater recharge (blue water). An intrinsic biophysical relation exists between evapotranspiration and drainage: when the amount of water evapotranspired by plants increases, the amount of water drained decreases. Cover crops can also reduce the water content of the soil and thus the water available for the succeeding crop (Meyer et al., 2019). Thus, even though cover crops provide multiple services, introducing them in a watershed that has a strong water deficit could negatively impact water resources and the water available for succeeding cash crops, and potentially increase irrigation withdrawals, thus placing more strain on water management in the watershed. Thus, introducing cover crops could yield serious disservices for water cycles at the watershed scale, particularly if applied to a large area. To our knowledge, no study has focused on the influence of cover crops on water cycles at the watershed scale, even though it is the relevant scale at which to assess their interactions with water resources. Due to the difficulty in performing experiments at such a large scale, model-based assessment is the main way to investigate the complexity of these interactions (e.g. Alcamo et al., 2003; Letcher et al., 2006; Murgue et al., 2014b; Zhang and Guo, 2016). The present study combined scenarios and an integrated modelling approach to evaluate the influence of introducing cover crops on drainage, irrigation of cash crops, river water flows, and cash crop yields at the watershed scale. Our case study was the downstream Aveyron watershed, located in south-western France. The watershed experiences strong, recurring water deficits (Martin et al. 2016) that are due in particular to large withdrawals to irrigate maize, a predominant crop in the watershed. We used MAELIA (Therond et al., 2014), an integrated assessment and modelling platform that can represent fine-scale spatiotemporal interactions among crop management, the hydrology of different water resources, and water-resource management (i.e. dam releases and regulations) within watersheds (Gaudou et al., 2014; Murgue et al., 2014). The model represents daily water withdrawals and crop management at the field scale. We used MAELIA to assess three contrasting scenarios: introducing short-duration cover crops, long-duration cover cops, or long-duration cover crops combined with diversified rotations.

The overall objective of this work is to assess the impact of the introduction of cover crops on the main water flows in the investigated watershed: water withdrawals for irrigation, drainage and river flows. Our hypothesis is that the introduction of long-cover crops with spring termination should have a greater effect on these variables than the scenario with short-cover crop and autumn termination. Another objective of this study is to assess effects of a scenario integrating more agroecological practices i.e. the combination of long-cover crops and diversified rotations.

2. Materials and methods

2.1 Case study overview

The downstream Aveyron watershed is an illustrative case study of situations of water imbalance in which low water inputs combine with high agricultural demand for irrigation water. The watershed is located in the Adour-Garonne basin, which has the largest structural deficit of water in France (7 $hm^3.yr^{-1}$, on average). The study watershed area is part of this basin; it covers ca. 800 km^2 and contains many irrigated farming systems, which account for up to 80% of total water consumption during the low-flow period (June-September) (Mazzega et al., 2014). For Aveyron withdrawal, annual irrigation withdrawals are observed in the order of 13 $hm^3.yr^{-1}$. The watershed contains 1150 farms, with agricultural fields covering 40,000 ha, of which ca. 40% is irrigated (according to the French Land Parcel Identification System, 2014). The main cash crops are maize (*Zea mays* L.) (six cultivars, from very early to very late precocity), wheat (*Triticum aestivum* L.), oilseeds with mainly sunflower (*Helianthus annuus* L.), and a few protein crops as pea (*Pisum sativum* L.). The watershed also contains fields of fruit crops and seed maize, which has a high added value. Two main rivers cross the watershed: the Aveyron and Lère. They have a measured annual flow of 35 $m^3.s^{-1}$ and 2 $m^3.s^{-1}$ respectively, falling to around 7 $m^3.s^{-1}$ and 0.7 $m^3.s^{-1}$ in average during the low-flow period. Moreover, their flow rates frequently drop below the target regulatory thresholds (4.0 and 0.1 $m^3.s^{-1}$, respectively) established to ensure aquatic ecosystem health. Irrigation demand and the resulting withdrawals strongly influence river flow dynamics. When a flow rate drops below the threshold, water managers use two main mechanisms: restrictions on irrigation withdrawals and flow-support releases from large collective reservoirs (Murgue et al., 2015). The number of days with flow rates below the low-flow target thus indicates the degree of potential restriction of irrigation.

We studied a 10-year period (2007-2016) using daily SAFRAN climate data (8 × 8 km grid) (Vidal et al., 2010) that covered the entire watershed. Over the study period, mean cumulative annual precipitation and potential evapotranspiration were 757 and 849 mm, respectively, with a mean annual water deficit of 91 mm. The daily mean minimum and maximum temperatures were 9.0 and 17.2°C, respectively. The years 2011 and 2015 were the driest (547 and 673 mm of precipitation, respectively), with an annual water deficit of more than 300 mm. For the low-flow period from June to September, 2009, 2012, and 2016 were the driest, with a water deficit of more than 300 mm.

2.2 MAELIA model overview

MAELIA was developed to study environmental and socioeconomic impacts of water-management strategies (Martin et al., 2016; Murgue et al., 2015, 2014). It was developed in an open-source generic modelling and simulation environment: GAMA® (Grignard et al., 2013). MAELIA simulates, at a daily time step, multi-scale interactions among the following:

1) agriculture, i.e. soil-crop dynamics (crop growth, yield, irrigation, and soil water dynamics), at the field scale using the AqYield model (Constantin et al., 2015; Tribouillois et al., 2018b), and farmer behaviour using a farmer-as-agent model to represent crop management (Murgue et al., 2014)
2) hydrology of rivers, reservoirs, and groundwater using SWAT (Arnold et al., 2010) algorithms (Martin et al., 2016)
3) domestic and industrial water uses using econometric equations (Therond et al., 2014)
4) water-management practices such as withdrawal restrictions and water-release decisions (Mazzega et al., 2014; Olivier Therond et al., 2014)

In the agriculture module, AqYield simulates crop growth based on cumulative mean daily effective temperature, and soil water content is predicted daily as the balance of water inputs and outputs. All cash crops currently in the study watershed have been calibrated in AqYield, which is considered sufficiently accurate to represent the dynamics of soil water content and evapotranspiration well for a wide range of situations (Constantin et al., 2015; Tribouillois et al., 2018b). Detailed description and equations of AqYield can be found in previous studies (Constantin et al., 2015; Tribouillois et al., 2018b). Five cover crop species were simulated in MAELIA to construct alternative scenarios: vetch (*Vicia sativa* L.), faba bean (*Vicia faba* L.), rapeseed (*Brassica napus* L.), white mustard (*Sinapis alba L.*), and Italian ryegrass (*Lolium multiflorum* Lam.). These cover crop species were calibrated in AqYield based on several experimental databases for sites with contrasting soil and climate across France. The calibration ensured that AqYield accurately predicted soil water dynamics under the five cover crops for different soils and climates.

In MAELIA, AqYield simulates interactions between soil water content and crop growth in each field by considering the crop rotation identified in the French Land Parcel Identification System (Murgue et al., 2016; Martin et al., 2016). The farmer's behaviour for each field of each farm is represented through

IF-THEN decision rules that describe the conditions that trigger tillage, seeding, irrigation, and harvest. In addition, a temporal window that defines early and late dates for triggers is defined for each technical operation. Irrigation decision rules, based on the climate, soil type, irrigation equipment, and available workforce, determine the amounts and dates of water supplied to each irrigated field on each irrigated farm. The decision rules for this case study were collected in a previous study using a dedicated farm survey (Murgue et al., 2015). Based on local databases, expert knowledge, and geographic information system analysis, each irrigated field is connected to one or more water sources (i.e. river(s) or reservoir(s)) (Murgue et al., 2015).

The hydrology of the watershed's surface water and groundwater was simulated using the soil and routing phases of SWAT (Arnold et al., 2010), which have been recoded in MAELIA. In the water-management module, IF-THEN decision rules are used to simulate daily management of dam releases and withdrawal restrictions (Mayor et al., 2012; Mazzega et al., 2014). These decision rules were determined using information from regional authorities about current practices. Four dams are available in the watershed to increase river flow rates during the low-flow period. More information about MAELIA can be found in previous studies (Martin et al., 2016; Murgue et al., 2016; Therond et al., 2014).

2.3 The reference scenario

The current situation was considered the reference scenario. Specific modules of MAELIA, as well as the entire model, were calibrated and validated in previous studies of the Aveyron watershed, using quantitative and qualitative expert-based approaches (Constantin et al., 2015; Martin et al., 2016; Murgue et al., 2016; Tribouillois et al., 2018b; Tribouillois et al., 2022). Results of these studies highlighted the model's ability to simulate water-related variables accurately at the field scale (i.e. soil water content, evapotranspiration, and drainage) and the watershed scale (i.e. irrigation withdrawals and river flows) as a function of the climate. More specifically, the predictive quality of MAELIA was previously assessed from measured data as satisfactory for estimating the volume of irrigation withdrawals and the flow of the two rivers of the same watershed (Tribouillois et al., 2022). Local experts also validated the results of simulated crop-management practices (e.g. sowing dates, first and last dates of irrigation) (Murgue et al., 2016).

2.4 Alternative scenarios

We developed three alternative scenarios at the watershed scale to investigate the influence of cover crops on water cycles (Fig. 1). Some management rules for cover crops were applied to all three scenarios:

1) Cover crops were sown as early as possible beginning from 1 August to promote emergence and development (due to the potential for thunderstorms in August) or from 7 days after harvesting the previous crop.
2) Cover crops were terminated three days before beginning tillage or, at the latest, 14 days before beginning sowing of the succeeding cash crop in order to avoid a pre-emptive effect on water, as recommended by Justes et al. (2012) and Meyer et al. (2022).
3) Cover crops were not irrigated or fertilised.

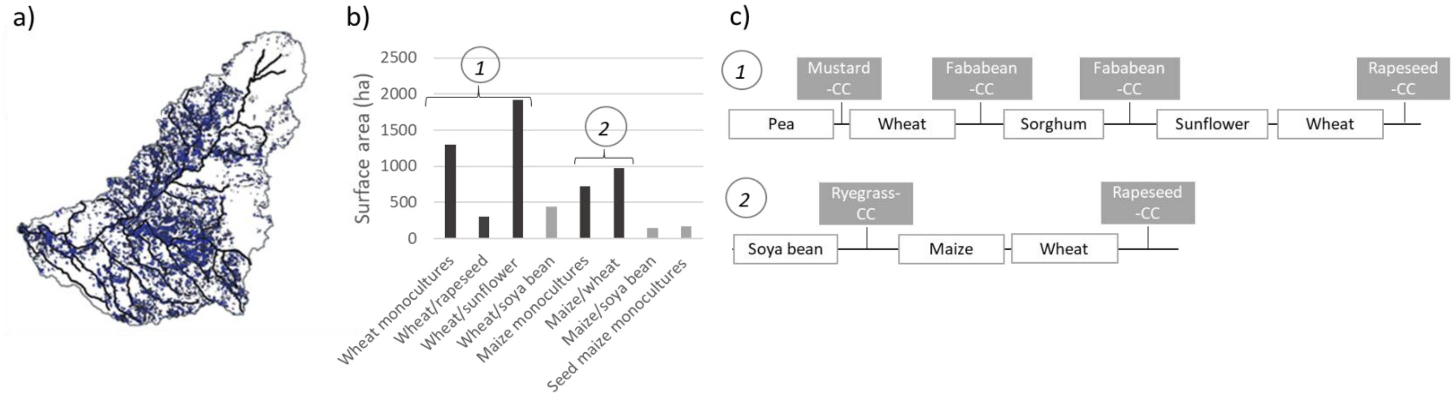

Figure 1. Graphic description of the alternative scenario with long-duration cover crops and diversified rotations (Long-CC&Div) with a) map of the watershed with the affected fields identified, b) areas of the reference rotations affected by the scenario and timelines of new crop rotations replacing some of the reference rotations.

Note: The fields identified on the map are the same as those involved in the long-CC scenario, and include those involved in the short-CC scenario (fewer parcels).

2.4.1 Short duration cover crop scenario

In the short-duration cover crop scenario (Short-CC), all cover crops grew for at least two months and were terminated before winter. The objective was to reproduce the current regulatory situation in nitrate vulnerable zones, where the main objective is to reduce nitrate leaching to aquifers. Like under current management practices, only non-leguminous cover crops were sown in order to maximise nitrate capture before winter and reduce the risk of leaching during the drainage period (especially in winter). Nearly 90% of the cover crops sown were white mustard, as it develops rapidly, which makes it suitable for a short growing period. The other ca. 10% of cover crops were Italian ryegrass, which was sown after rapeseed cash crops to avoid a cruciferous cover crop and its associated risk of diseases or pests. Cover crops were sown only after rapeseed, wheat, and winter pea, and only before spring cash crops and winter pea. Cover crops were not sown after cash crops with a late harvest (i.e. sunflower, maize, or soya bean) because the interval between this harvest and the tillage and/or sowing of the succeeding cash crop (< 2 months) was too short. In this scenario, 8000 ha of the 19,300 ha of agricultural land in the watershed (i.e. ca. 41%) was sown with a cover crop each year.

2.4.2 Long-duration cover crop scenario

In the long-duration cover crop scenario (Long-CC), the objective was to maximise the influence of the multiple services provided by cover crops. Accordingly, cover crops were sown in every fallow period possible, with termination at the end of winter or in spring, as close as possible to the sowing of the succeeding cash crop to provide the cover crops with a longer growing period and promote their development. At the field scale, leguminous cover crops were introduced before non-leguminous cash crops, and vice-versa. For non-leguminous cover crops, rapeseed was sown instead of white mustard when possible because it maintains its cover during the winter under the study conditions and continues to grow in spring before termination. Due to these allocation rules, at the watershed scale the main cover crops were rapeseed, faba bean, and vetch (ca. 30% each), followed by white mustard and Italian ryegrass. In total, 13,300 ha of agricultural land in the watershed (i.e. ca. 69%) was sown with a cover crop each year.

2.4.3 Scenario with long-duration cover crops and diversified rotations

Cover crops and diversification of rotations are two key pillars of an agroecological transition (Duru et al., 2015), and the latter has been studied as one way to limit the water deficit in the Aveyron watershed (Allain et al., 2018). Consequently, we developed a third alternative scenario (Long-CC&div) to explore potential effects of combining long-duration cover crops with diversification of the main crop rotations in the watershed (Figure 1a). It was designed in two steps: 1) legumes were introduced to diversify the crop rotations, and then 2) cover crops were introduced. We chose diversified crop rotations from those recommended by Tribouillois et al. (2018b) to diversify the main cropping systems in south-western France, developed in consultation with experts in the region. Because rotations that already included a legume (soya bean) every two years (wheat/soya bean or maize/soya bean) benefitted from its presence, they were not modified. Seed maize monocultures were not modified either due to their high added value for the region. The other rotations were modified as follows (Figure 1 b-c):

- Maize monocultures and maize/wheat rotations were replaced with a soya bean/maize/wheat rotation.
- Cereal monocultures, wheat/rapeseed, and wheat/sunflower rotations were replaced with a pea/wheat/sorghum/sunflower/wheat rotation.

The beginning of the new rotations was established in a spatially homogeneous way between the different crops. This means that for a given year, there was a homogeneous distribution between the different crops, and not a single crop. In the new rotations, maize was always a mid-late cultivar to ensure that it could be harvested before sowing the succeeding crop. The rotations were modified by alternating the first species in the rotation in order to distribute all species evenly over the watershed each year. Thus, diversification of the rotations reduced the area of maize by ca. 2500 ha (from 6000 to 3500 ha), wheat by ca. 1200 ha (from 9000 to 7800 ha), sunflower by ca. 700 ha (from 3100 to 2400 ha), rapeseed by ca. 500 ha (from 560 to 60 ha), temporary grassland by ca. 400 ha (from 7600 to 7200 ha), and fallow land by ca. 300 ha (from 2300 to 2000 ha). Conversely, it increased the area of sorghum by ca. 1900 ha (from 0 to 1900 ha), pea by ca. 1900 ha (from 100 to 2,000 ha), and soya bean by ca. 1700 ha (700 to 2400 ha). Thus, the area of leguminous crops in the watershed increased greatly, which resulted in more equal crop areas in the watershed.

Next, cover crops were introduced into the new rotations, following the rules applied in the Long-CC scenario. The cover crop species were rapeseed (35%), faba bean (30%), Italian ryegrass (16%), white mustard (14%), and vetch (5%). Similar to the Long-CC scenario, 13,400 ha of agricultural land in the watershed (ca. 70%) was sown with a cover crop each year.

2.4.4 Modifying crop-management practices to introduce cover crops

To attempt to maximise the development of the new cover crops as a farmer might, the management practices used in the reference scenario were modified in the alternative scenarios. The latest possible maize harvest date was advanced by 10 days so that the succeeding cover crop could be sown earlier. In the Long-CC and Long-CC&div scenarios, tillage on clay soils (hillsides) was moved from autumn to spring to terminate the cover crop later. This spring tillage often delayed the sowing of spring crops by a few days to a few weeks.

2.5 Data analysis

As MAELIA had already been largely validated for this study area (Allain et al., 2018; Martin et al., 2016; Murgue et al., 2016; Tribouillois et al., 2018b), we calculated most results as a difference of the alternative scenarios from the reference scenario in order to highlight the influence of cover crops. We focused on irrigation withdrawals, drainage, river flow, and yields at the watershed scale. For irrigation withdrawals and drainage, we calculated totals for each of the 10 years simulated, as well as mean annual dynamics (i.e. mean of the 10 years simulated). For yields, we excluded the Long-CC&div scenario because its diversification of crop rotations changed the relative areas of cash crops in the watershed, which would have biased mean yields of all fields in the watershed.

3. Results

3.1 Little influence of cover crops on irrigation withdrawals

The mean annual irrigation withdrawals simulated for the reference scenario were 10.5 hm^3 (range: 9.6 hm^3 in 2014 to 11.5 hm^3 in 2009). Compared to the reference scenario, the Short-CC scenario had little influence on mean annual irrigation withdrawals, which increased by only 0.6% (i.e. 0.06 hm^3) (range: 0.0% to +1.2%) (Figure 2a) over the study period. The Long-CC scenario had more influence on mean annual irrigation withdrawals, which increased by 1.8% (i.e. 0.18 hm^3) (range: +0.7% to +4.2%).

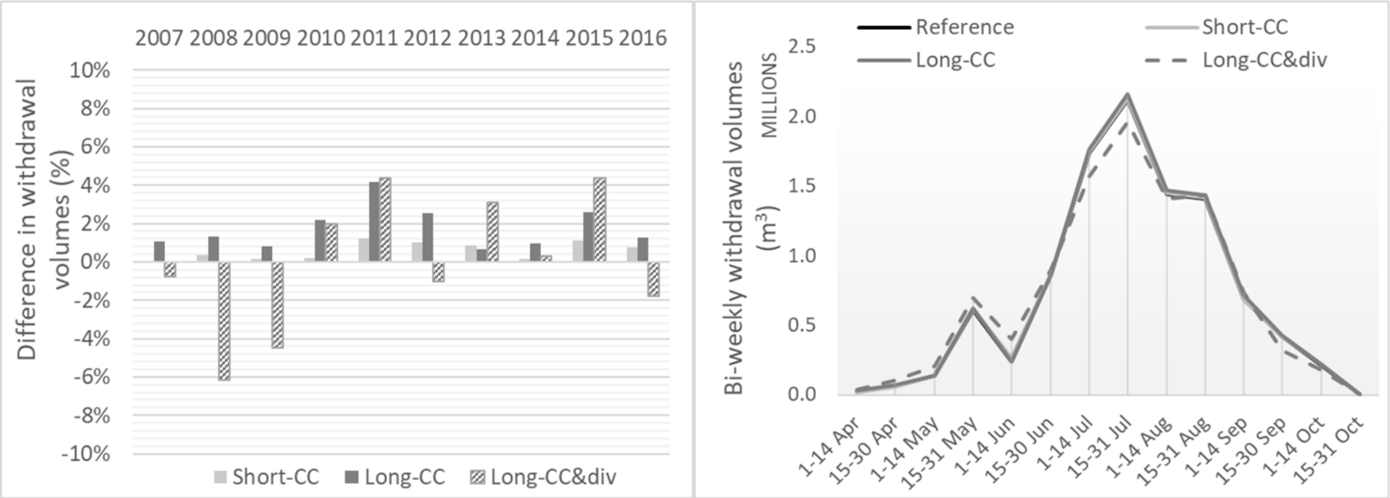

Figure 2. Relative difference in irrigation withdrawals from the reference scenario simulated for the three alternative scenarios with cover crops (CC) from 2007-2016: a) annual withdrawals and b) mean biweekly withdrawals during the irrigation period simulated over the 10-year period.

For both scenarios, withdrawals increased the most in 2011, which had a particularly dry spring. The influence of cover crops on withdrawals in the Long-CC&div scenario varied much more among years, ranging from a large decrease (-6.2%, i.e. -0.65 hm^3) in 2008 to a relatively large increase (+4.4%, i.e. +0.46 hm^3) in 2011. However, mean withdrawals over the study period did not differ from those in reference scenario (0.0%). Withdrawals decreased during years with the smallest water deficit, especially outside of summer. Conversely, withdrawals increased the most in 2011 and 2015, which had the largest annual water deficits. Compared to the Short-CC and Long-CC scenarios, withdrawal dynamics differed in the Long-CC&div scenario: withdrawals were higher at the beginning of summer and then lower in July, early August, and, to a lesser extent, autumn (Figure 2b).

3.2 Decrease in drainage due to cover crops

Over the study period, mean annual drainage of the reference scenario was 368 mm.yr^{-1} (range: 176 mm.yr^{-1} in 2011 to 580 mm.yr^{-1} in 2013). Cover crops in the three alternative scenarios decreased annual drainage (Figure 3a) due to higher evapotranspiration during the fallow period. Compared to the reference scenario, mean annual drainage in the Short-CC scenario decreased less (-1.7%, i.e. -5.8 mm.yr^{-1}; range: -2.9% to 0.1%) than that in the Long-CC scenario (-2.4%, i.e. -8.3 mm.yr^{-1}; range: -3.6% to -1.1%) (Figure 3a). The Long-CC&div scenario decreased mean annual drainage the most (3.1%, i.e. 11 mm.yr^{-1}; range: -4.2% to -1.6%).

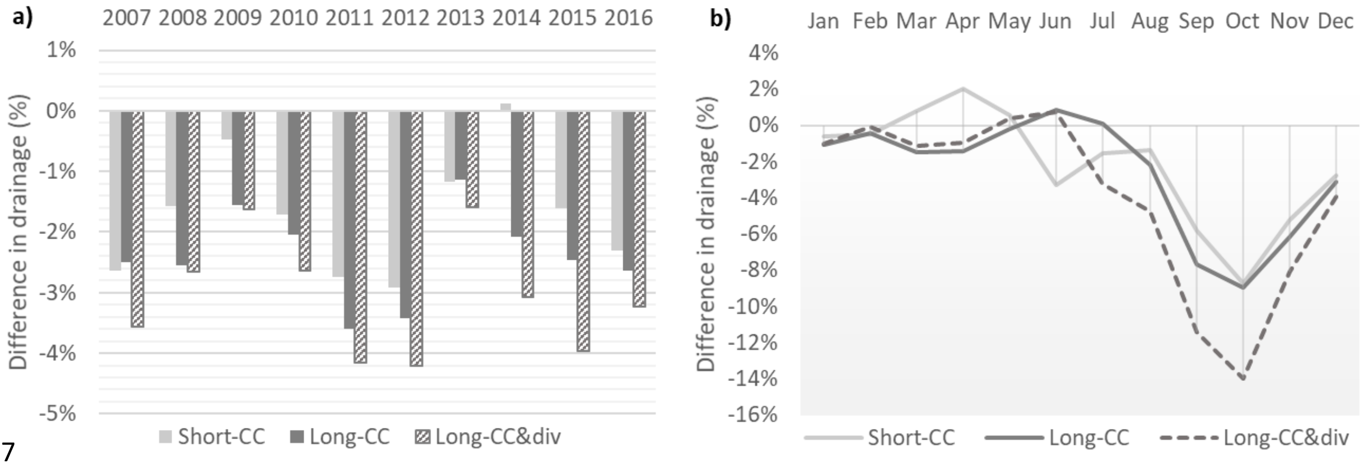

Figure 3. Relative differences in drainage (%) from the reference scenario for the three alternative scenarios with cover crops (CC) calculated from the mean of all agricultural fields in the lower Aveyron watershed in a) annual drainage and b) mean monthly drainage simulated over the 10-year period.

Monthly drainage decreased mainly in autumn, reaching -8.7% and -9.0% in October in the Short-CC and Long-CC scenarios, respectively (i.e. -1.4 mm in both) (Figure 3b). This decrease was due to the cover crop being sown in late summer and growing in autumn. The Long-CC&div scenario decreased drainage even more in autumn (-14.0%, i.e. -2.2 mm in October) because the maize area decreased; consequently, less irrigation was used in late summer, which resulted in drier soil at the end of summer and thus less drainage in autumn. The Short-CC scenario increased drainage slightly in March and April.

Overall, annual drainage did not change or barely decreased in ca. 60% of the fields in each of the alternative scenarios (Figure 4). In comparison, annual drainage decreased by 0-30 mm.yr^{-1} in 24-30% of the fields, depending on the alternative scenario. Thus, drainage at the watershed scale decreased slightly overall. This decrease in drainage varied slightly among years, but remained relatively small. Drainage decreased the most in 2012 and 2007 and the least in 2009 and to a lesser extent, 2011 and, for Short-CC, 2014.

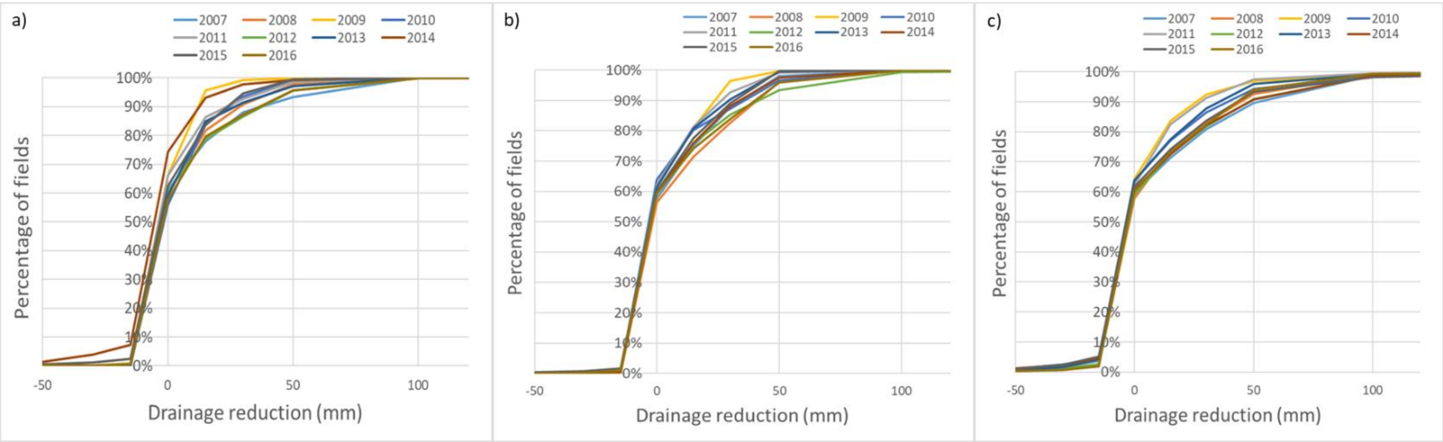

Figure 4. Cumulative frequencies of the simulated decrease in annual drainage each year from 2007-2016, calculated in comparison to the reference scenario, in the lower Aveyron watershed for the scenarios with a) short-duration cover crops (CC), b) long-duration CC or c) long-duration CC plus more diversified rotations.

3.3 Little influence of cover crops on river flows

In the Aveyron River, the mean annual flow was 30.6 m.s^{-1} (range: 15.1-45.1 m.s^{-1}), and the mean flow during the low-flow period (June-September) was 12.2 m.s^{-1} (range: 4.6-24.1 m.s^{-1}). The flow was much lower in the Lère River, with a mean annual flow of 0.95 m.s^{-1} (range: 0.57-1.25 m.s^{-1}) and mean flow during the low-flow period of 0.73 m.s^{-1} (range: 0.43-1.25 m.s^{-1}). Cover crops in the alternative scenarios did not influence mean river flows during the low-flow period: 12.2 m.s^{-1} in the Aveyron and 0.73 m.s^{-1} in the Lère. Flow during the low-flow period varied among months, although the differences were negligible for the Aveyron and small for the Lère (Figure 5). Flow decreased slightly from July-September in both rivers in the Long-CC scenario. Monthly flows changed the most in the Long-CC&div scenario, either increasing or decreasing depending on the month, especially in the Lère. Flows tended to decrease slightly in spring, increase in summer, and then decrease again in late summer (by up to -3.1% in the Lère).

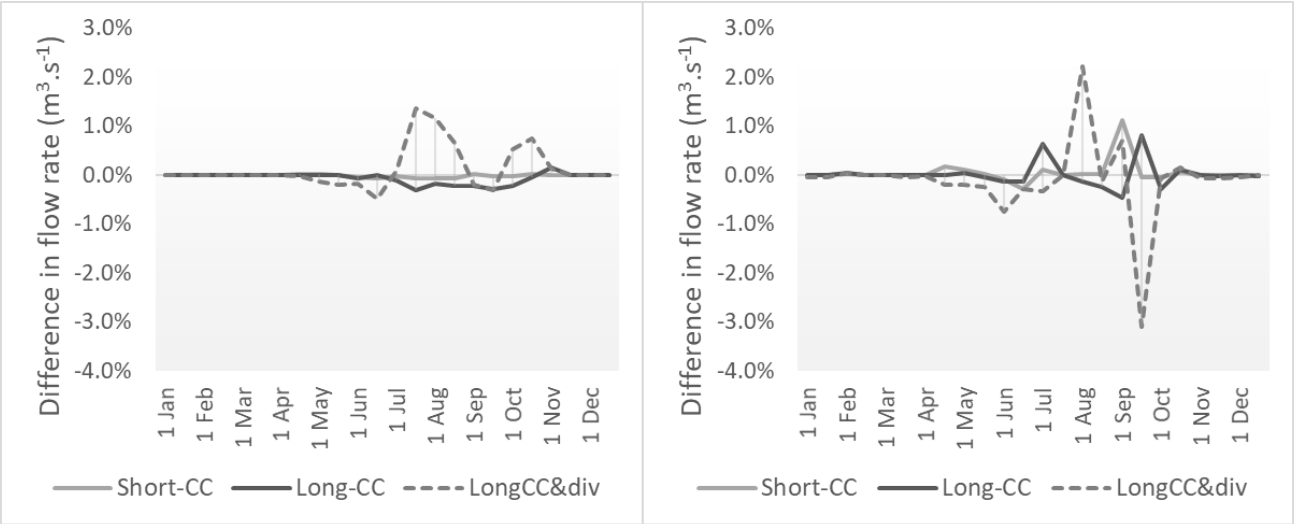

Figure 5. Relative differences in simulated biweekly flow rates between the reference scenario and each alternative scenario for the a) Aveyron River and b) Lère River.

As introducing cover crops had little influence on flows, it also had little influence on the number of days with flow rates below the low-flow target from 15 June to 15 September: no more than 4 days per year (Table 1). The Long-CC&div scenario had slightly more influence on the number of days per year: from -22% to +11% for the Aveyron (mean: -3%) and from -6% to +18% for the Lère (mean: +3%), depending on the year. Thus, introducing cover crops would have little influence on summer irrigation restrictions.

Table 1. Number of days from 15 June to 15 September with simulated flow rates below the low-flow target, for the two rivers of the downstream Aveyron watershed, for the reference scenario and the three alternative scenarios with short-duration cover crops (Short-CC), long-duration (Long-CC), or long-duration plus diversified rotations (Long-CC&div). The values shown for the alternative scenarios are differences from the reference scenario.

Year	**Aveyron**					**Lère**				
	Reference		**Short-CC**	**Long-CC**	**Long-CC&div**	**Reference**		**Short-CC**	**Long-CC**	**Long-CC&div**
2007	0	**vs.**	0	0	0	35	**vs.**	0	0	-2
2008	18		0	0	-2	23		0	2	2
2009	50		0	0	-3	53		0	0	3
2010	54		0	1	2	46		1	0	-2
2011	59		0	0	0	38		0	0	1
2012	55		0	1	-3	43		0	0	1
2013	9		-1	0	-2	26		0	1	0
2014	1		0	0	0	11		1	1	2
2015	37		0	0	4	26		0	1	1
2016	25		0	0	0	46		0	0	-1
Total	**308**		**-1**	**2**	**-4**	**347**		**2**	**5**	**5**

3.4 Little influence of cover crops on crop yields

In Short-CC, introducing cover crops had relatively little influence on cash crop yields: the mean difference from the reference scenario was -0.02 t.ha^{-1} (i.e. -0.3%) for all species combined (Table 2), ranging from -0.09 t.ha^{-1} (i.e. -2.0%) for early maize to +0.05 t.ha^{-1} (i.e. +0.6%) for very late maize. In Long-CC, mean crop yields decreased by 0.10 t.ha^{-1} (i.e. 1.7%) for all species combined (Table 2), ranging from -0.2 t.ha^{-1} (i.e. -6.6%) for sunflower to +0.07 t (i.e. +0.8%) for very late maize. Along with sunflower, yields of the earlier maize cultivars (very to mid-early) decreased the most (-0.3 t ha^{-1}, i.e. -5.2%). The mean decrease in yield varied greatly among years, mainly for earlier maize cultivars, especially during the 3 driest years of the 10 years simulated (i.e. 2009, 2012, and 2015 with -23% to -

41% for early maize in the Long-CC scenario). The impact of cover crops on the following crops led to a slight decrease in the total production at the watershed scale by 1 900 to 2 500 t yr^{-1}, corresponding to 1.5 and 2.0% in the Short-CC and Long-CC respectively. In accordance with yield impacts, the highest decrease in total production were found in sunflower (-10%), mid-early and early maize (5.9 and 5.0%) and soybean (-4.8%) in Long-CC.

Table 2. Yield, area and production estimated for all crops of the downstream Aveyron watershed, for the reference scenario (Ref.) and the three alternative scenarios with short-duration cover crops (Short-CC), long-duration (Long-CC) or long-duration plus diversified rotations (Long-CC&div).

	Yield (t/ha/year)				Area (ha/year)				Production (10^3 t/year)			
	Ref.	Short-CC	Long-CC	Long-CC&div	Ref.	Short-CC	Long-CC	Long-CC&div	Ref.	Short-CC	Long-CC	Long-CC&div
Wheat	7.0	7.0	7.0	7.1	9 043	8 925	8 915	7 787	63.7	62.3	62.8	54.9
Very early maize	6.1	6.0	5.8	0.0	53	53	53	0	0.3	0.3	0.3	0.0
Early maize	4.5	4.4	4.3	0.0	170	170	170	0	0.8	0.7	0.7	0.0
Mid-early maize	5.3	5.2	5.0	0.0	297	297	297	0	1.6	1.5	1.5	0.0
Mid-late maize	7.0	7.0	6.9	7.4	1 374	1 373	1 373	1 239	9.5	9.5	9.4	9.0
Late maize	9.7	9.7	9.7	8.5	1 052	1 051	1 051	75	10.2	10.2	10.2	0.7
Very late maize	9.1	9.1	9.1	7.5	324	324	324	28	2.9	3.0	3.0	0.2
Silage maize	12.2	12.1	11.9	11.5	1 441	1 439	1 439	1 064	17.7	17.6	17.3	12.5
Seed maize	3.4	3.4	3.4	3.6	1 322	1 319	1 319	1 095	4.5	4.5	4.5	3.9
Sunflower	2.8	2.8	2.6	2.6	3 157	3 053	3 046	2 437	8.8	8.5	8.0	6.3
Soybean	2.8	2.7	2.6	2.8	681	680	679	2 428	1.9	1.9	1.8	6.9
Rapeseed	3.8	3.8	3.8	3.8	557	552	538	61	2.1	2.1	2.1	0.2
Pea	3.8	3.8	3.8	3.8	125	124	124	1 968	0.5	0.5	0.5	7.5
Sorghum	0.0	0.0	0.0	5.0	0	0	0	1 926	0.0	0.0	0.0	9.6

The div-CC modified deeply the crop acreages at the regional scale, leading to a difference in total production of 12 800 t yr^{-1}, corresponding to 10% of the total production in the reference scenario. Among the three main annual crops in the reference scenario, wheat production was decreased by 8 800 t yr^{-1}, grain maize by 15 350 t yr^{-1} and sunflower by 2 600 t yr^{-1}. On the contrary, legume production, including pea and soybean was increased by 12 000 t yr^{-1} and sorghum, the new crop introduced in the rotation, produced 9 600 t yr^{-1}.

3.5 Processes' illustration at the field scale

At the field scale, we illustrate the influence of cover crops on simulated drainage and soil water content of a specific field over ca. 3 years to better understand the results and changes in the processes. In this field with a wheat/sunflower rotation, white mustard or rapeseed was sown in the Short-CC and Long-CC scenario, respectively, between wheat harvest and sunflower sowing (Figure 6).

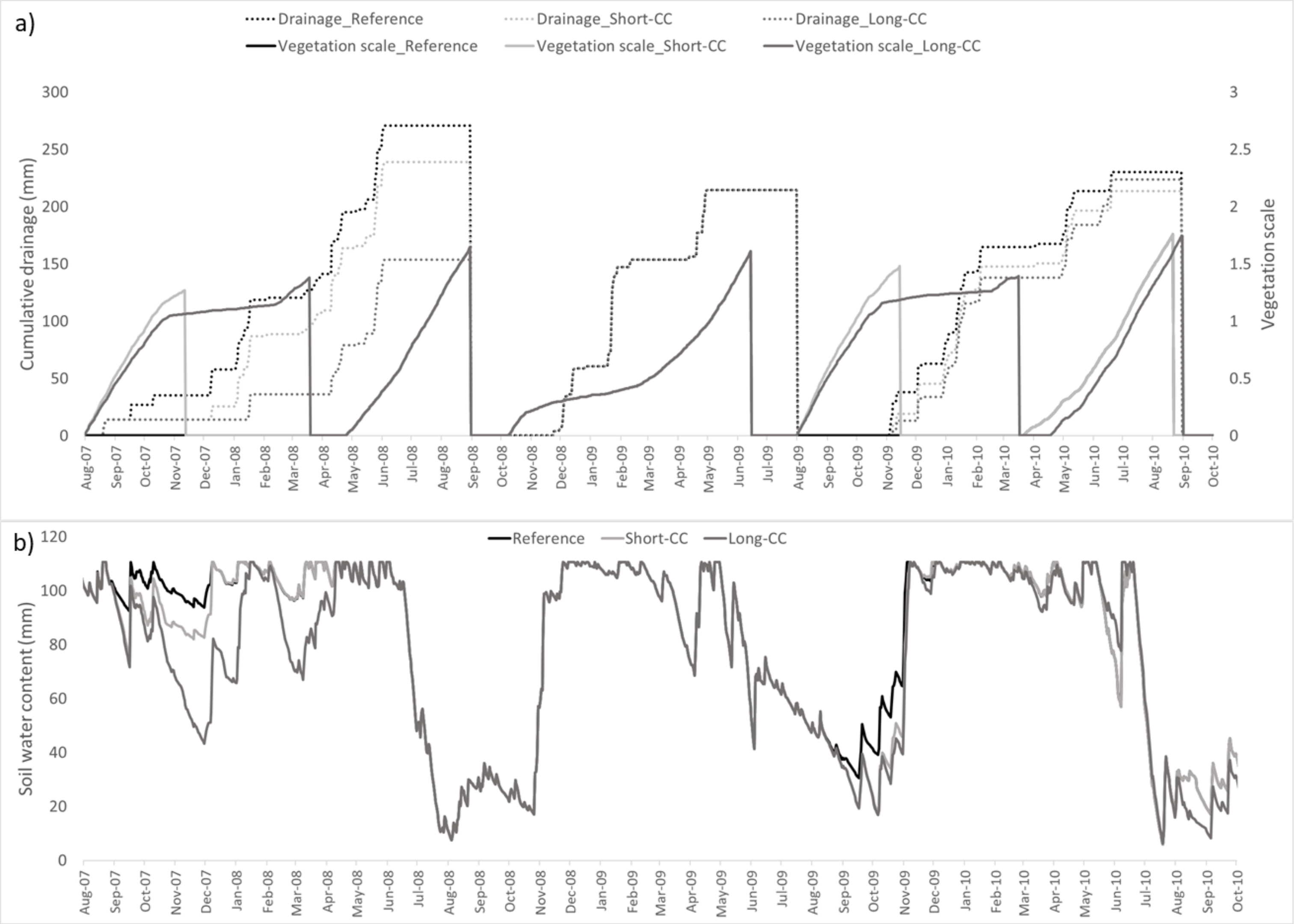

Figure 6. Simulated water-balance dynamics of an example field in the lower Aveyron watershed without irrigation sown with a sunflower/wheat rotation in the reference scenario and, in alternative scenarios, also with a short-duration cover crop (CC) or long-duration CC (i.e. white mustard or rapeseed, respectively) sown after

wheat. a) Cumulative drainage and the vegetation scale (level of crop development based on phenology, 1 is flowering) from sowing to harvest of crops and CC and b) soil water content.

Compared to the reference scenario, the cover crop in the Long-CC scenario decreased drainage more (-116 mm from cover crop sowing to sunflower harvest in 2008 and -17 mm in 2010) than it did in the Short-CC scenario with termination in the autumn (-31 mm in 2008 and -6 mm in 2010), due to having more time to grow. The soil water content under the cover crop was thus lower in the Long-CC scenario than the Short-CC scenario. For example, on 1 December 2007 (maximum effect), soil water content decreased by 11 mm in Short-CC and 51 mm in Long-CC compared to that in the reference scenario. Despite the decrease in drainage in both alternative scenarios, cover crops were terminated long enough before sunflower to allow the soil water content to recharge before sowing. In the Long-CC scenario, however, sunflower sowing was delayed by nearly four weeks due to soil tillage management before sowing. This delay in the sowing date of spring crops, which was frequently observed in other fields, resulted in different crop water requirements and soil water dynamics than those in the reference and Short-CC scenarios. In this example, compared to the reference scenario, drainage decreased greatly in 2007-2008 (-12% in Short-CC and -43% in Long-CC) but decreased less in 2009-2010 (-3% in Short-CC and -7% in Long-CC), which illustrates the high variability in soil water and drainage dynamics among years. Water dynamics under the wheat crop in 2008-2009 differed little among the three scenarios, as they simulated the same crop growing conditions.

4. Discussion

4.1 Cover crops have little influence on water withdrawals and water resources at the watershed scale

The simulations of the downstream Aveyron watershed indicated that widespread introduction of cover crops with autumn termination would have little influence on water withdrawals, river flows, or water-resource management. Even though cover crops decrease autumn drainage, terminating them before winter provides sufficient time for soil water to recharge during winter and thus has no influence on water availability for the succeeding cash crop or its yield, and thus little influence on irrigation withdrawals.

The simulations indicated slightly more influence when cover crops are sown over a larger area and for longer durations to maximise their production of ecosystem services. Mean irrigation withdrawals over the 10 years increased by only 2%. The influence on decreasing drainage was larger, however, which is consistent with many studies (Meyer et al., 2019, 2022). Although river flows decreased sharply during the summer in the reference scenario, cover crops in the Short-CC and Long-CC scenarios did not decrease river flows because they had little influence on withdrawals, and they influenced drainage especially in winter.

Finally, combining long-duration cover crops with crop diversification seems to be a good compromise for quantitative water management. Diversifying crops, notably by replacing maize with crops that require less water, reduces the total water demand and compensates for potential negative effects of cover crops with late termination. Diversifying the crop rotation increased withdrawals in early summer due to more crops with greater water requirements in early summer (especially wheat), which increased irrigation. However, irrigation withdrawals decreased in July, early August, and the autumn, due to less area with maize, which requires more water than the crops introduced in the diversified rotations (i.e. wheat, soya bean, and sorghum). Cover crops had little influence on mean withdrawals, river flows, or the number of days with flow below the low-flow target over the 10 years simulated. However, the Long-CC&div scenario increased variability among years, with some dry years having a stronger influence, which can become a problem for water management in these years. Finally, drainage decreased mainly in autumn because irrigation of the crops introduced into the rotations stopped earlier in the summer that it had for maize, resulting in drier soil at the end of summer and thus less drainage in autumn.

4.2 Adapting management to limit the negative influence of cover crops

Although cover crops have little influence at the watershed scale, their influence does depend on the production situation (i.e. soil, climate, and cropping system). At the field scale, cover crops before non-irrigated maize on shallow soils (hillsides) tends to have more influence on maize's yield. In the Aveyron watershed, these earlier maize cultivars are sown in shallow soils on hillsides and are irrigated less than later maize cultivars sown along the rivers because irrigation water is more difficult to obtain. In the Aveyron watershed, approximately 55% of fields of earlier maize cultivars (1-3) are irrigated, compared to 70-80% of those of later maize cultivars (4-6). However, the early cultivars cover less area in the watershed: 50, 170, and 300 ha for maize 1, 2, and 3, respectively, compared to 1400, 1000, and 100 ha for maize 4, 5, and 6, respectively. Thus, for most of the years simulated, introducing cover crops during fallow periods decreased yields only slightly. Thus, the negative influence on yields occurred mainly in particularly dry years for non-irrigated maize on shallow soils, which covers a relatively small area of the watershed. From an economic viewpoint, as shown by Bergtold et al. (2019) and Cai et al. (2019), the costs of cover crops need to be balanced against the benefits to properly assess their economic interest. Accordingly, the benefits (e.g. green manure effect) and costs of introducing cover crops (e.g. purchase of seeds, additional tillage) must be considered for complete evaluation of the influence of cover crops at the regional scale. Also, for more integrated assessment of the influence of cover crops, indicators related to nitrogen cycles, carbon cycles, and greenhouse gas emissions should also be assessed. A version of MAELIA that simulates water, nitrogen, carbon, and economic indicators at the watershed scale is under development to perform this kind of multi-criteria evaluation.

A previous study highlighted that cover crops with late termination are strongly discouraged in dry regions to avoid the risk of water (and nitrogen) pre-emption, which could decrease the yield of the succeeding cash crop (Alonso-Ayuso et al., 2014). As recommended in the literature (Ewing et al., 1991; Justes et al., 2012), care was taken in the Long-CC scenario to select a termination date long enough before the sowing date of the succeeding cash crop to avoid influencing soil water availability at sowing. Analysis at the watershed scale indicated that, given the trend for rainy springs in this region, the mean termination date was early enough to allow soil water to recharge before sowing the spring crop. However, for non-irrigated maize on shallow soils, the termination dates chosen did not seem conservative enough to ensure adequate yields. Shorter-duration cover crops should be planted in these production situations.

In the Long-CC scenario, late termination of cover crops required changing management practices, notably by delaying tillage (i.e. autumn ploughing postponed to spring) for clay soils. Doing so can be difficult due to the positive influence of frost on soil structure after tillage in some soils (Leuther and Schlüter, 2021), however the beneficial effects of cover crops on the soil and the reduction of erosion (Blanco-Canqui and Ruis, 2020) can counterbalance this effect. More generally, terminating cover crops in late winter delayed spring tillage dates slightly, which then delayed the sowing of spring crops, sometimes by several weeks, particularly on shallow soils. Indeed, in MAELIA, the termination of cover crops in late winter implies additional technical management to be carried out at this time, and which are also conditioned by a sufficient bearing capacity of the ground (IF-THEN decision rules). Thus, some years, the bearing capacity may not be sufficient and thus delay the technical managements (cover crop termination, soil tillage and/or sowing of spring crop), in addition to the time also necessary for their realization. This later sowing of spring crops often shifted crop growth and its associated water requirements to a period with less precipitation (e.g. August), which explains the increased irrigation withdrawals, slightly decreased river flows, and decreased yields, especially for early cultivars in dry years.

Long-duration cover crops tend to influence management practices by delaying sowing of spring crops and decreasing yields locally. In our scenarios, management practices were assumed to be the same for the entire watershed, but they should be adapted for each farm to limit potential negative effects of long-duration cover crops on irrigation withdrawals and yield for succeeding cash crops. Delayed sowing is common in conservation agriculture and remains compatible with crop temperature requirements. A compromise exists to be found among a cover crop’s duration, the ecosystem services it provides (e.g. carbon storage), and optimal dates for the succeeding cash crop, knowing that the final weeks of a cover crop strongly influence the amount of biomass it produces.

4.3 Integrated assessment of the influence of cover crops

Well-managed cover crops (i.e. with the species and sowing and termination dates adapted to the location) could be an effective way to provide many ecosystem services such as reducing nitrate leaching, green manure effect, increasing carbon storage in soil or decreasing erosion risks... Our results show that long-duration cover crops have little influence on water at the watershed scale, but a more negative influence in certain production situations. However, given the many services that cover crops can provide in these situations, multi-criteria assessment could be useful for assessing costs and benefits of introducing them. From an economic viewpoint, the benefits of ecosystem services for farmers (e.g. green manure effect) could outweigh potential negative effects. Accordingly, economic impacts on cash crop yields and the additional costs of introducing cover crops (e.g. purchase of seeds, additional tractor passes) must be considered for complete evaluation of the influence of cover crops at the regional scale. Also, for more integrated assessment of the influence of cover crops, indicators related to nitrogen cycles, carbon cycles, and greenhouse gas emissions should also be assessed. A version of MAELIA that simulate water, nitrogen, carbon, and economic indicators at the watershed scale is under development to perform this kind of multi-criteria evaluation.

4.4 Additional scenarios

Allain et al. (2018) and Tribouillois et al. (in revision) highlight that optimising irrigation has the most influence on decreasing irrigation withdrawals. Accordingly, simultaneously introducing long-duration cover crops, diversifying rotations, and optimising irrigation could be a promising way to meet objectives for ecosystem services, yields, and conservation of water resources. As Obiang Ndong et al. (2020) suggested, it would be interesting to define and simulate new scenarios of cover crop management that could reduce their negative impacts on water drainage (blue water) and available water for succeeding crops, such as harvesting cover crop biomass before the termination date. As a step further, Therond et al. (2017) recommended designing scenarios that combine optimisation, diversification, and management-based mechanisms to explore the ability to maximise the supply a balanced bundle of ecosystem services under current and future climate conditions.

Finally, our results and conclusions are valid under the specific conditions of the downstream Aveyron watershed: climate (e.g. precipitation, evapotranspiration), soil types, cropping systems, and management practices. The conclusions could differ for regions with different soils and climate, farming systems, and/or specific constraints (e.g. little or no access to water). It would be interesting to investigate these scenarios for contrasting sites to see how the influence of cover crops, diversified rotations, and other key mechanisms differ among regions.

5. Conclusion

The MAELIA model showed that cover crops, even with late termination, generally had relatively few negative effects on water at the watershed scale. Even introducing long-duration cover crops to maximise ecosystem services had little influence on mean irrigation withdrawals (+2%) or irrigation restrictions, and decreases in yields were generally small and occurred only in dry years. However, soil water availability for non-irrigated maize on shallow soils can be more sensitive to cover crops. In these situations, it is important to adapt the management practices of long-duration cover crops to avoid impacting succeeding cash crops.

Finally, simultaneously introducing long-duration cover crops and diversifying crop rotations, as a stronger pathway of agroecological transition, can compensate for the potentially negative influence of long-duration cover crops on water flows. The results of the associated scenario illustrate that an agroecological transition can generate solutions that improve water resource conservation in regions with a strong water imbalance due to irrigation. This integrated assessment and modelling study can be extended by exploring more ambitious scenarios based on combining optimisation, management, and agroecological changes to develop a balanced bundle of ecosystem services to farmers and society.

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