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Alternative crop rotations under Mediterranean no-tillage conditions:

Biomass, grain yield and water-use efficiency

ABSTRACT

In Mediterranean semiarid areas barley (*Hordeum vulgare* L.) and wheat (*Triticum aestivum* L.) are major crops because they are well adapted to limited-water environments. In this study we tested the performance of alternative rotations to the typical barley and wheat monoculture in a rainfed Mediterranean semiarid area of the NE Spain under a no-tillage system. Four rotations were established and maintained over six-year period (1999-2000 to 2004-2005): a wheat monoculture (W-W-W); a barley monoculture (B-B-B); a wheat-barley-rapeseed (*Brassica napus* L.) rotation (W-B-R) and a wheat-barley-vetch (*Vicia sativa* L.) rotation (W-B-V). Above-ground biomass, grain yield, water use and water use efficiency were measured several times every season during the study period. All the parameters studied had a strong dependence on the rainfall variability found between growing seasons. Barley under rotation performed better than barley under monoculture in yield and water use efficiency (WUE) terms. However, wheat performed as well in a monoculture production system as it did in rotation. Rapeseed and vetch failed the 80% and 35% of the growing seasons, respectively. However, in semiarid Mediterranean agroecosystems of northeastern Spain, despite the beneficial rotation effect of theses alternative crops on barley performance economical benefit of the overall rotation is doubtful since vetch failed in 2 out of 6 years and rapeseed failed 5 out of 6 years.

Abbrevations: NT, no-tillage; W-W-W, wheat monoculture; B-B-B, barley monoculture; W-B-R, wheat-barley-rapeseed rotation; W-B-V wheat-barley-vetch rotation; WU, water use; WUE, water use efficiency; WUEb; water use efficiency for above-ground dry biomass; WUEy, water use efficiency for grain yield.

Mediterranean climate is characterized by low and variable rainfall and by high evapotranspiration rates, especially during spring and summer when temperatures are high. Under these conditions, barley and wheat are common crops in these rainfed Mediterranean agroecosystems due to their adaptation to water-limited environments and high temperatures during grain filling (Cantero-Martínez et al., 1995). In these areas, barley and wheat are continuously grown year after year (monoculture) or alternated with a fallow season (cereal-fallow system). Research conducted in some parts of the Mediterranean region has demonstrated the low efficiency of long-fallowing to increase cereal crop yields on an annual basis (López and Arrúe, 1997; Lampurlanés et al., 2002; Moret et al, 2007). At the same time, the instability of monocultures has been well documented because of its effects on nutrient depletion (Campbell et al., 2007), weed and pest proliferation (Liebman and Dick, 1993; Gurr et al., 2003) and low water use efficiency (Pala et al., 2007). Likewise, lower grain yields under cereal monoculture than under rotation have been reported under Mediterranean semiarid conditions (Díaz-Ambrona and Mínguez, 2001). The use of alternative crops such as legumes or cruciferous crops in the rotations has been reported to have beneficial effects not only in the overall grain yield of the rotation but also in the chemical and physical properties of the soils (Hernanz et al., 2002; Álvaro-Fuentes et al., 2008). However, in Mediterranean semiarid areas the success of an alternative crop in a rotation will be determined by its adaptability to water stress situations, its pattern and efficiency to the use of water (Pala et al., 2007), he biotic stresses, and finally by its relative economic return to the farmer.

During the last decade, few rotations experiments have been carried out in semiarid conditions of Spain (López-Bellido et al., 1996; Dorado et al., 1998; Díaz-Ambrona and Mínguez, 2001; Moret et al., 2007; Martín-Rueda et al., 2007). Most of these experiments were set up to study the effects of different crop rotations and tillage on crop yield. At the same time, these experiments focused on the effects on crop growth and grain yield of shifting from a cereal-fallow system to a more intensive cereal-cereal or cereal-legume system under conventional intensive tillage vs. no-tillage.

In the semiarid eastern part of the Ebro valley, dryland farming occupies 75% of the agricultural area (Angás et al., 2006). At present, this Mediterranean area is characterized by significant the production of wheat and barley using conservation tillage practices (more than 30% of the total land area) without the intensive tillage used in similar areas. The introduction of these management practices has led to a more efficient use of soil and water resources by the crop (Cantero-Martínez et al., 2007).

However, the high use of fertilizers by farmers, with nitrogen application rates between 100 and 200 kg ha^{-1} (Cantero-Martínez et al., 2003), the presence of weeds and pests difficult to control by chemical mechanisms and the look for new markets like biofuels have resulted in a need of new alternative crops to the common wheat and barley.

Consequently, the overall objective of this study was to test the performance of potential alternative rotations to the typical barley and wheat monoculture under no-tillage (NT) in a rainfed Mediterranean semiarid area of north-eastern Spain. In order to accomplish the above-mentioned objectives, rotations were established with the typical barley and wheat crops together with a legume (vetch) and a cruciferous (rapeseed) crop.

MATERIAL AND METHODS

Site, crop management and experimental design

This study was conducted over a six-year period (1999-2000 to 2004-2005) at Agramunt, in northeastern Spain (41º48´N, 1º07´E, 330m elevation). The climate is semiarid with an average annual precipitation of 432 mm and an average air temperature of 13.8 ºC. Rainfall is distributed bimodally with peaks in autumn and late spring and little rainfall in winter and summer. This pattern is, however, variable and there is 25% probability of little rainfall in spring (Cantero-Martínez et al. 2007). The soil was a Xerofluvent typic (Soil Survey Staff, 1994) with the following key properties for the 0- to 30-cm layer: pH (soil:H_2O, 1:2.5): 8.3; electrical conductivity: 0.13 dS m^{-1}; organic matter: 7 g kg^{-1}; $CaCO_3$: 420 g kg^{-1}; texture was loam with the sand (2000-50 µm), silt (50-2 µm), and clay (<2 µm) content: 498, 381 and 121 g kg^{-1}, respectively.

The experiment was established the fall of 1999. Previous management of the site consisted of a barley monoculture with intensive tillage. Four 3-year crop rotations were established under no-tillage: a wheat monoculture (W-W-W); a barley monoculture (B-B-B); a wheat-barley-rapeseed rotation (W-B-R) and a wheat-barley-vetch rotation (W-B-V). In the four rotations, weeds were controlled with 1.5 L 36% of glyphosate [N-(phosphonomethyl)-glycine] plus 1 L of 40% MCPA [2-(4-chloro 2-metilfenoxi) acetic acid] per ha before sowing. Nitrogen fertilization consisted of 60 kg N ha^{-1} in the wheat, barley and rapeseed plots and it was broadcast applied as ammonium sulfate (21% N) in January-February. No nitrogen fertilization was applied to the vetch plots. Also, additional 60 kg P ha^{-1} (superphosphate 18% P_2O_5) and 90 kg K ha^{-1} (potassium chloride, 50% K_2O) were applied in all four crops before sowing. Fertilization rates were decided according to soil analyses previous to the establishment of the experiment, crop extractions and response essays made in the same area (Angás et al., 2006). “Soisson” wheat and “Hispanic” barley were sown during early November at a sowing rate of 450 seeds m^{-2}. “Spinelle” vetch and “Silvia” rapeseed were sown during late September-early October at a sowing rate of 150 and 80 seeds m^{-2}, respectively. These wheat and barley cultivars are commonly grown by farmers in the area of study due to their good adaptation to the soil and climate conditions. Sowing was performed with a no-till disc drill with a row spacing of 19 cm. Both sowing and harvest dates for each crop and growing season are shown in Table 1. After the emergence of the crop but before tillering, the wheat and barley crops received a mixture of 2.5 L of 50% chlortoluron [3-(3-chloro p-tolil)1,1-dimetilurea] plus 3 L of 7% terbutrine [2-ter-butilamino-4-etilamino-6-metiltio-1,3,5-triazina] per ha applied for annual grass and broadleaf weed control. Rapeseed was sprayed with 2.5 L of 50 % metazaclor [N-(2,6-dimetilfenil) N-(1 pirazolilmetil) cloroacertamide] per ha for annual grass and broad leaf control before the crop emerged. For grass control, both in rapeseed and vetch, 3 L de 5% quizalofop-p-etil [2-(4-(6 clor 2- quinoxaliniloxi) fenoxi) etil] per ha was applied after emergence (February-March). Harvesting was done with a standard, medium-size combine with the straw chopped and spread.

Individual plots were 50 m x 8 m (400 m^2) in size and arranged in a randomized block design with three blocks. All the different phases from each rotation were represented each growing season. Consequently, each block consisted of 8 plots: one plot for each monoculture and six plots for the three phases of both W-B-R and W-B-V rotations.

Sampling and measurements

Rainfall and air temperature measurements were taken daily using a standard weather station situated 5 km from the experimental field. Soil and crop measurements were taken during the six growing seasons, comprising two complete cycles of every rotation. For above-ground biomass measurements, three randomly selected samples of 0.5 m^2 areas were taken per plot at maturity. Plant samples were dried to constant weight at 65ºC in a forced-air oven. Grain yield for each phase was expressed for growing season and also for the whole rotation, as all phases were annually present in the field. The vetch was harvested as forage, consequently in the result section it was expressed as total forage biomass harvested.

Soil water content was measured four times every year: before sowing, end of tillering, at anthesis and after harvest, except for the 2004-2005 season which harvest sampling was not taken. Soil cores were taken from 0-25, 25-50, 50-75, 75-100 cm depth layers and soil was dried to constant weight in a forced-air oven at 105 ºC for gravimetric water content determination (Campbell and Mulla, 1990).

As runoff and drainage within 100 cm depth was negligible, crop water use (WU), including soil water evaporation and crop transpiration, was calculated from seasonal rainfall and the change in soil water content to a depth of 100 cm. Water use efficiency (WUE), expressed as kg ha^{-1} mm^{-1}, was determined as the respective total above-ground dry biomass (WUEb) or grain dry weight (WUEy) at harvest divided by the water used.

Statistical analyses

Statistical analyses were performed using the SAS software (SAS institute, 1996). In order to test the main effects of year (YEAR) and phase for every rotation (PHASE) and its interaction a PROC GLM was applied. Mean separations were expressed for significant effects with LSD (least significant difference) at P = 0.05. The vetch and rapeseed phases were not considered in the statistical analyses in order to facilitate the interpretation of the statistical results obtained.

RESULTS

Weather conditions

Monthly rainfall and average monthly air temperature are shown in Fig. 1. The total precipitation recorded from crop sowing to harvest (September-June) varied during the studied period. The least precipitation was collected during the 2004-2005 growing season with 194 mm and the greatest during the 2003-2004 season with 547 mm. However, in the basis of the total rainfall, the 2001-2002 and 2004-2005 growing seasons can be considered dry with total precipitation <350 mm (Fig. 1).

Rainfall distribution within growing seasons was also variable. In the 2000-2001, 2002-2003 and 2003-2004 growing seasons, more than 60% of the total seasonal rainfall was collected from September to January, which is considered in these conditions the soil recharge period. However, in the other years, more than 60% of the total seasonal rainfall was collected from March to June period which is important for the performance of the crop in the grain filling period (Fig. 1). Air temperatures followed a similar pattern each year with the lowest monthly temperatures recorded during January and the highest during the summer months (July-August).

Above-ground biomass and crop yield

Above-ground biomass was significantly different (P<0.001) among rotation phases, growing seasons and their interaction. The W-(B)-V phase was the only phase with the greatest above-ground biomass at maturity in all the growing seasons studied (Table 2). In four of the six growing seasons studied, the (W)-B-V and the W-W-W showed higher biomass at maturity compared with the other phases (Table 2). On average, the biomass of barley in monoculture was similar to the barley in rotation and in only two of the six growing seasons the barley phases in rotation were higher than barley in monoculture. In contrast, despite similar average biomass recorded for wheat in monoculture and in rotation in two of the six growing seasons (2002-2003 and 2004-2005), the wheat in rotation showed lower biomass than wheat in monoculture (Table 2). In the 1999-2000, 2000-2001 and 2004-2005 growing seasons, greater biomass at maturity was observed in the W-W-W monoculture compared with the B-B-B monoculture. However, the rapeseed and vetch failed in five and two of the six growing seasons studied, respectively (Table 2).

Grain yields were affected by the rotation phase, the growing season and the interaction of both factors. In 2002-2003, the wheat phases were affected by "Take all fungus"(*Gaeumannomyces graminis*), which restricted crop yields (Table 3). In five and four of the six growing seasons studied, the W-(B)-V and W-(B)-R phases had the greatest crop yields (together with other phases, depending on the growing season). In three of the six growing seasons (1999-2000, 2001-2002, 2002-2003) barley in rotation obtained higher yield than barley in monoculture and only in one of the six growing seasons the grain yield of wheat in rotation was greater than wheat in monoculture (Table 3). In the 2003-2004 and 2004-2005 growing seasons, the two monocultures had similar grain yields. However, in the 2000-2001 and 2002-2003 greater crop yields were observed in the B-B-B compared with the W-W-W monocultures. The opposite was observed in the 1999-2000 and 2001-2002 growing seasons (Table 3). Overall experiment the greatest grain yield were observed in the two barley phases, W-(B)-V and W-(B)-R (Table 3).

Water use and water use efficiency

Water use (WU) was different between the rotation phases, growing seasons and the interaction of both factors. WU ranged from 246 to 521 mm (Table 4). The (W)-B-V phase had the greatest WU in the 1999-2000, 2000-2001, 2001-2002 and 2003-2004 growing seasons (Table 4). Also, the W-(B)-V and the W-W-W had the greatest WU in the 1999-2000, 2001-2002 and 2002-2003 growing seasons (Table 4). Overall lower WU was observed in the barley phases compared to the wheat phases.

In all the growing seasons studied the W-(B)-R and W-(B)-V phases showed the greatest WUEb, together with other phases depending on the growing season (Table 5). In the 1999-2000 and 2000-2001 growing seasons, similar WUEb was observed among the different phases. In the 2003-2004 growing season, lower WUEb was measured in the wheat phases compared to the barley phases (Table 5).

Overall, the greatest WUEy was measured in the two barley phases (W-(B)-V, W-(B)-R) and in the barley monoculture (Table 5). The average WUEy was similar in barley monoculture compared with barley in rotation. Further, in three of the six growing seasons WUEy was greater in barley in rotation than barley in monoculture (Table 5). In contrast, the average WUEy in wheat monoculture was higher compared to wheat in rotation; and in only two of the six growing seasons (2000-2001 and 2003-2004) wheat in monoculture was higher than wheat in rotation (Table 5).

DISCUSSION

The use of rotations has been largely related to beneficial effects on soil quality and crop yield (Díaz-Ambrona and Mínguez, 2001; Hernanz et al., 2002). In our study area, where wheat and barley monocultures are common the incorporation of alternative crops like vetch and rapeseed into the rotation was studied. Vetch and rapeseed were chosen for their performance in other semiarid areas (Yau et al., 2003) and for the look for new markets like biofuels, respectively. Our rotation design was established based upon previous knowledge in the area (data no publish), which vetch and rapeseed have several abiotic and biotic limitations. Consequently, theses crops were included every three growing seasons.

Rainfed semiarid Mediterranean agroecosystems are characterized by a low and an erratic rainfall pattern during the growing season. In these systems water content is the most limiting factor to crop development and yield (McAneney and Arrúe, 1993; Lampurlanés et al., 2001; Moret et al., 2007). Consequently, in our study, differences in above-ground biomass and grain yield between growing seasons were the result of the typical rainfall variability of these Mediterranean areas. The lowest grain yield was measured in the 2004-2005 growing season with 399 kg ha^{-1} in which the seasonal rainfall (from September to June) recorded was 194 mm that corresponded 60% of the average seasonal rainfall for the six years of experiment (315 mm). In addition, it has been shown that under these conditions winter cereal grain yield is dependent on the total rainfall accumulated during the soil water recharge period (from September to January) in the 65% of the years and only the 35% of the years is dependent on the total rainfall accumulated during grain filling period (April and May) (Austin et al. 1998; Cantero-

Martínez et al., 2007). In our experiment, we observed that during the growing seasons with a rainfall pattern that promoted soil water accumulation in the recharge period (September to January), barley obtained better grain yields than wheat. In contrast, wheat yield was greater during growing seasons with a spring rainfall pattern (from March to May), especially with significant late May rainfall. In our study, the 1999-2000, 2001-2002 and 2004-2005 growing seasons had high spring rainfall resulting in better grain yields and WUEy in the W-W-W compared to the B-B-B monoculture that performed better in the other growing seasons with autumn rainfall accumulation. However, the rotation phases of wheat, (W)-B-R and (W)-B-V, compared with the barley phases, W-(B)-R and W-(B)-V, did not follow the same pattern because of the effect of the preceding alternative crops which had a very irregular behavior in this experiment. At the same time, the greatest WUEy was observed in the 1999-2000 growing season whereas the lowest WUEy was obtained during the 2002-2003 and 2003-2004 growing seasons when high yield and WU was observed (WUEy was not calculated in the 2004-2005 season). It is remarkable that during the 1999-2000 growing season, more than 65% of the seasonal rainfall was collected during the March-May period (190 mm of rainfall recorded in these three months) compared with the 40% of rainfall recorded in the same spring period during the 2002-2003 and 2003-2004 growing seasons. Consequently, the final yield and WUEy in these Mediterranean semiarid agroecosystems depend not only on the total rainfall during the growing season but also on the pattern of rainfall during the growing season (French and Schultz, 1984; Austin et al., 1998). It is known that plants respond differently to water stress at different growth stages (Fischer, 1985).

The barley phase of the W-B-V and W-B-R rotations showed greater biomass at maturity, grain yield and water use efficiency compared to monoculture during the most part of the experiment. Consequently, data showed that a positive rotational effect was observed in the barley phases of both rotations. Similar studies carried out under Mediterranean conditions also observed greater performance of barley under monoculture rather than following an alternative crop (Díaz-Ambrona and Mínguez, 2001; Yau et al., 2003). However, the wheat phases of the two rotations performed similar (e.g. grain yield) or even worse (e.g. WUEy) than the wheat monoculture. This trend was opposite to the observed by Lopez-Bellido et al. (1996), also in semiarid Spain. These authors observed better performance of wheat under rotation than under monoculture. The lower performance of the wheat under rotation than under monoculture can be explained by the poor performance of the vetch and rapeseed as preceding crop of the wheat. Rapeseed failed the 80% of the growing seasons enhancing subsequent wheat yield during wet growing seasons (e.g. 2003-2004) but did not during dry seasons (e.g. 2001-2002 and 2004-2005). Also, vetch failed in 35% of the growing seasons and had a negative influence on wheat yield during the 2002-2003 growing season. After the failure of the vetch and the rapeseed an herbicide was applied to avoid weed growth. Thus, the amount of crop residue was minimal and so the soil surface kept bare the rest of the growing season. The water stored was evaporated from the soil during summer and it did not contribute to the following wheat growth. In the barley phases did not occur since in both rotations were followed by wheat phases. This reason is also supported by the fact that similar above-ground biomass, yield and WUE were observed between both monocultures. Consequently, under similar precedent conditions, both wheat and barley performed similar in our study.

The failure of the vetch might be attributed to low temperatures and limited soil water content (Abd El Monein et al., 1988; Papastylianou, 1995). Papastylianou (1995) found that both monthly rainfall and monthly minimum temperature accounted for over 99% of the variance of vetch yield in Cyprus. In our study, the 2004-2005 growing season, the period from October to June received the lowest rainfall. During the 2001-2002 season, December was unusually cold with a monthly minimum temperature of -4ºC. Generally the seasons in which the vetch survived and matured, lower grain yields than wheat and barley were measured. In rainfed semiarid Mediterranean areas vetch is mainly used as a forage legume because of its high protein yield (Papastylianou, 1995). The harvest index value was obtained from other studies carried out under Mediterranean conditions (Yau et al., 2003). This harvest index is considerably lower than the typical harvest index for wheat or barley leading to smaller grain yields in the vetch regardless the relative large above-ground biomass achieved at maturity.

The failure of the rapeseed as a viable alternative crop for our conditions might be related to the need for optimum conditions for successful seed germination and seedling emergence. Early growth of the plant is sensitive to low soil temperature, limited soil water availability (Rao and Dao, 1987) and soil structure condition (Diepenbrock, 2000). In our study, the soil water limiting conditions and the absence of seedbed preparation during the whole experiment together with the presence of the stem flea beetle (*Psylliodes chrysocephala* L.) could severely affect the growth of the crop during the first stages. In Mediterranean semiarid conditions, no-tillage has been showed to be a possible option to increase soil water availability due to a reduction in soil evaporation (Moret et al., 2007).

SUMMARY AND CONCLUSIONS

In Mediterranean semiarid agroecosystems of the east Ebro valley (NE Spain), dryland agriculture is usually conducted using conservation agriculture practices. No-tillage has been previously reported as a successful practice to water conservation and erosion control in this area. In this region, cropping systems are mainly continuous cereal systems with barley and wheat as main crops. In this experiment, alternative rotations to the typical cereal monoculture were tested. The data of our study suggest that barley under rotation performed better than barley under monoculture in yield and WUE terms. However, wheat performed similar under monoculture than under rotation. Rapeseed and vetch failed the 80% and 35% of the growing seasons, respectively. However, despite the beneficial rotation effect of theses alternative crops on barley performance, economical benefit of the overall rotation is doubtful since vetch and rapeseed failed nearly during the whole experiment. The poor performance of these two alternative crops has a negative impact not only in the economical benefit for the farmer but also in the soil quality and productivity (e.g. exposure of soil surface to wind and water erosion, increased weed growth and soil carbon loss). Consequently, other crops more adapted to the limited water conditions of the area should be tested. Thus, other small grain cereals either for grain or forage production like rye (*Secale cereale* L.), triticale (*x Triticosecale wittmak*) or oat (*Avena sativa* L.) could be more suitable for these areas and might perform better into the rotation with the typical wheat and barley.

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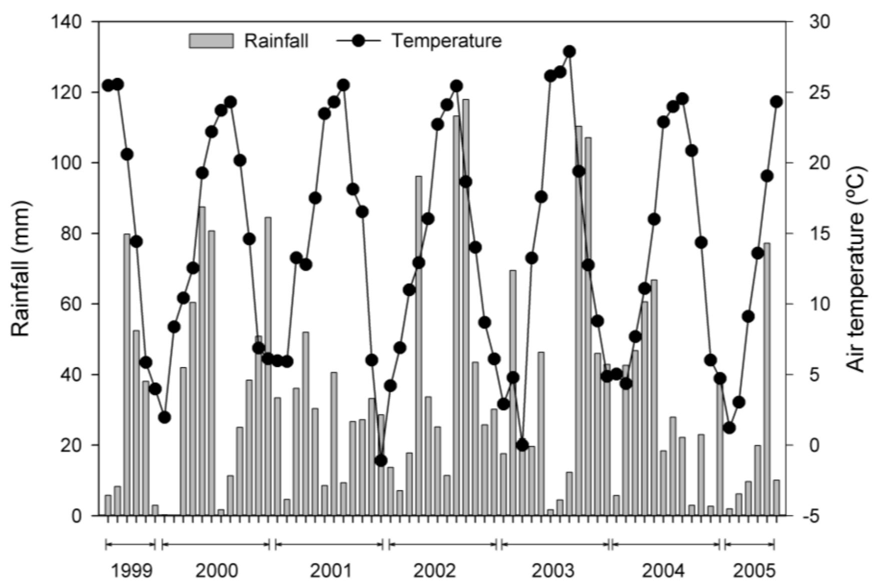
Fig. 1. Monthly rainfall and air temperature for the experimental period (June 1999-June 2005).



TABLES

Table 1. Sowing and harvest dates for the study period (1999-2005).

Growing season	Crop				
	Barley / Wheat		Vetch		Rapeseed†
	Sowing	Harvest	Sowing	Harvest	Harvest
1999-2000	24 Nov.	21 June	29 Sept.	18 May	21 June
2000-2001	29 Nov.	29 June	30 Oct.	22 May	-
2001-2002	2 Nov.	19 June	16 Oct.	15 May	-
2002-2003	6 Nov.	20 June	28 Sept.	15 May	-
2003-2004	29 Nov.	14 July	2 Oct.	30 May	-
2004-2005	15 Nov.	15 June	6 Oct.	25 May	15 June

† Rapeseed sowing in the same dates than vetch.

Table 2. Above-ground biomass at maturity for each rotation phase and growing season.

Growing season	Rotation phase†							
	W-W-W	(W)-B-R‡	(W)-B-V	B-B-B	W-(B)-R	W-(B)-V	W-B-(R)	W-B-(V)
	Dry weight (t ha^{-1})							
1999-2000	9.8a§	7.4b	9.7a	7.1b	8.7ab	9.5a	12.5	9.1
2000-2001	10.7ab	11.5ab	12.2a	8.4b	9.9ab	11.4ab	0.0	4.1
2001-2002	6.9a	4.1a	6.5a	4.3a	5.8a	5.3a	0.0	0.0
2002-2003	9.6ab	5.4c	5.5c	7.4bc	8.6ab	11.0a	0.0	16.3
2003-2004	6.0c	7.1c	7.1c	10.5b	14.0a	11.5ab	0.0	5.2
2004-2005	2.7a	1.3b	1.4b	2.3a	2.1a	2.8a	0.0	0.0
Average	7.6ab	6.1b	7.1ab	6.7ab	8.2a	8.6a	2.1	5.8

† W-W-W, wheat monoculture; B-B-B, barley monoculture; W-B-R, wheat-barley-rapeseed rotation; W-B-V, wheat-barley-vetch rotation.

‡ Parentheses denote rotation phase sampled.

§ Different lower case letters indicate significant differences among rotation phases within the same growing season (P<0.05). The values for rapeseed and vetch phases were not included in the statistical analysis.

Table 3. Grain and forage yields for each rotation phase and growing season.

Growing season	Rotation phase†							
	W-W-W	(W)-B-R‡	(W)-B-V	B-B-B	W-(B)-R	W-(B)-V	W-B-(R)	W-B-(V)
				$kg\ ha^{-1}$				
1999-2000	3678a§	3362a	3352a	2346b	3327a	3204a	1817	9093
2000-2001	2263c	2057cd	1861d	3303b	3110b	3751a	0	4105
2001-2002	2778b	1971c	3007ab	2275c	3036ab	3320a	0	0
2002-2003	1506c	1325c	1183c	2097b	2729a	3104a	0	16336
2003-2004	2549cd	3068ab	3168a	2814bc	2278e	2402de	0	5198
2004-2005	856a	103b	178b	317ab	431ab	512ab	0	0
Average	2272b	1981b	2125b	2192b	2485ab	2716a	303	5789

† W-W-W, wheat monoculture; B-B-B, barley monoculture; W-B-R, wheat-barley-rapeseed rotation; W-B-V, wheat-barley-vetch rotation.

‡ Parentheses denote rotation phase sampled.

§ Different lower case letters indicate significant differences among rotation phases within the same growing season (P<0.05). The values for rapeseed and vetch phases were not included in the statistical analysis.

Table 4. Water use from sowing to harvest for each rotation phase and growing season.

Growing season	Rotation phase†							
	W-W-W	(W)-B-R‡	(W)-B-V	B-B-B	W-(B)-R	W-(B)-V	W-B-(R)	W-B-(V)
				mm				
1999-2000	305ab§	305ab	321a	259c	292b	308ab	407	313
2000-2001	246b	328a	335a	246b	252b	257b	274	258
2001-2002	265ab	249c	272a	266ab	256bc	260abc	283	277
2002-2003	331a	286bc	277c	307ab	294bc	326a	352	346
2003-2004	351d	504b	521a	386c	348de	332e	382	369
2004-2005	-¶	-	-	-	-	-	-	-
Average	300ab	335ab	345a	293b	288b	297b	340	312

† W-W-W, wheat monoculture; B-B-B, barley monoculture; W-B-R, wheat-barley-rapeseed rotation; W-B-V, wheat-barley-vetch rotation.

‡Parentheses denote rotation phase sampled.

§ Different lower case letters indicate significant differences among rotation phases within the same growing season ($P<0.05$). The values for rapeseed and vetch phases were not included in the statistical analysis.

¶ Not determined.

Table 5. Water use efficiency for biomass (WUEb) and for grain yield (WUEy) from sowing to harvest for each rotation phase and growing season.

Growing season	Rotation phase†							
	W-W-W	(W)-B-R‡	(W)-B-V	B-B-B	W-(B)-R	W-(B)-V	W-B-(R)	W-B-(V)
	WUEb (kg mm^{-1} ha^{-1})							
1999-2000	32.5a§	24.0a	30.2a	27.5a	29.7a	31.0a	30.8	29.1
2000-2001	43.1a	35.1a	36.4a	34.0a	39.6a	44.2a	0.0	15.9
2001-2002	25.8a	16.4b	24.0a	16.2b	22.8a	20.2ab	0.0	0.0
2002-2003	29.2abc	19.0c	19.7bc	24.3abc	29.5ab	34.0a	0.0	47.2
2003-2004	17.1c	14.0c	13.7c	27.2b	40.3a	34.7a	0.0	14.1
2004-2005	-¶	-	-	-	-	-	-	-
Average	29.5abc	21.7d	24.8cd	25.8bcd	32.4ab	32.8a	6.2	21.3
	WUEy (kg mm^{-1} ha^{-1})							
1999-2000	12.1a	11.0ab	10.4ab	9.2b	11.4ab	10.4ab	4.5	1.4
2000-2001	9.2c	6.3d	5.6d	13.4ab	12.5b	14.6a	0.0	3.9
2001-2002	10.5b	7.9c	11.1b	8.5c	11.9ab	12.8a	0.0	0.0
2002-2003	4.5c	4.6c	4.3c	6.9b	9.3a	9.5a	0.0	12.0
2003-2004	7.3a	6.1b	6.1b	7.3a	6.6ab	7.2a	0.0	3.7
2004-2005	-	-	-	-	-	-	-	-
Average	8.7b	7.2c	7.5c	9.1ab	10.3ab	10.9a	0.9	4.2

† W-W-W, wheat monoculture; B-B-B, barley monoculture; W-B-R, wheat-barley-rapeseed rotation; W-B-V, wheat-barley-vetch rotation.

‡ Parentheses denote rotation phase sampled.

§ Different lower case letters indicate significant differences among rotation phases within the same growing season ($P<0.05$).). The values for rapeseed and vetch phases were not included in the statistical analysis.

¶ Not determined.