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Performance of legume-based annual forage crops in three semiarid Mediterranean environments

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Abstract. Legume-based annual forages could be pivotal for the sustainable intensification of forage production in drought-prone Mediterranean cereal-livestock systems. This study aimed to optimise the composition of these crops for three climatically contrasting areas. Four legumes (field pea of semi-dwarf and tall type; Narbon vetch; common vetch) and two cereals (oat; triticale) were grown in three autumn-sown sites (Sassari, Italy; Sétif, Algeria; Marchouch, Morocco) for 2 years as pure stands and legume-cereal binary and four-component mixtures. We assessed dry matter yield, weed content and farmers' acceptability of the crops, and legume content and Land Equivalent Ratio of the mixtures. Legumes' competitive disadvantage ranged from very high in Sétif to nearly nil in Sassari. Pea- and common vetch-based mixtures out-performed Narbon vetch-based ones in terms of yield, legume content and farmers' acceptability. The tall pea, featuring greatest competitive ability against cereals, maximised the yield and legume content of legume-cereal crops. Vetch-cereal mixtures exhibited lower weed content than the average of the components' pure stands. Oat monoculture was top-yielding but modestly appreciated by farmers. Pea provided the only legume monoculture combining good yielding ability and high farmers' appreciation. Greater species diversity as provided by complex mixtures did not display any production advantage over binary mixtures.

Additional keywords: drought stress, farmer participatory approaches, intercropping, *Pisum sativum*, plant competition, *Vicia*.

Introduction

Crop-livestock systems have outstanding importance in the Mediterranean basin, to meet the growing demand for animal products [particularly in North Africa and West Asia: Delgado *et al.* (1999)], to sustain the production of typical animal products with high added-value (particularly in Southern Europe: e.g. the 46 Protected Designation of Origin cheeses in Italy), and to increase the economic stability of smallholders. Extensive livestock systems, which have largely relied upon rangelands, fallow and cereal stubbles, are threatened by overexploitation and risk of desertification of rangelands, insufficiency of feed proteins and high-quality feed, and decreasing and more erratic rainfall predicted from climate change (IPCC 2007; FAO 2010). Cropping of annual forage crops could be pivotal for these systems, to intensify their forage production in a sustainable manner and to alleviate their pressure on natural resources.

Well-adapted small-grain cereals, such as oat (*Avena sativa* L.) or triticale (× *Triticosecale* Wittm.), produce high dry matter (DM) yield, but their forage usually displays unsatisfactory nutritional quality, particularly in terms of protein content. Growing annual legumes, such as common (*Vicia sativa* L.) or Narbon vetch (*V. narbonensis* L.) or field pea (*Pisum sativum* L.), could ensure high forage protein content along with several environmental benefits, such as higher energy and resource efficiency, lower greenhouse gas emissions and greater soil fertility relative to cereal cropping (Nemecek *et al.* 2008; Cellier *et al.* 2015). Intercropping legumes with cereals is another option whose main appeal is represented by possibly higher yield relative to the mean value of its components' monocultures that arises from resource complementarity between associated species (Hauggaard-Nielsen *et al.* 2001; Bedoussac and Justes 2010; Chapagain and Riseman 2014). Better control of weeds and of biotic stresses are other potential advantages of mixed cropping relative to monocultures (Anil *et al.* 1998). Complex mixtures obtained by association of more than two species have shown greater interest than simpler mixtures for grass-forage legume associations (Kirwan *et al.* 2007; Picasso *et al.* 2011; Brophy *et al.* 2017), but their value is unknown for legume-cereal associations.

The exploitation of legume-based annual forages in Mediterranean-climate regions is hindered by insufficient information on the most suitable legume species for cultivation as monoculture or in association with cereals and by limited comparisons of pure stand versus mixed stand cropping. Common vetch is largely grown in Mediterranean environments, often in association with oat (e.g. Caballero *et al.* 1995; Lithourgidis *et al.* 2006). Advantages of vetch-cereal mixed cropping over the respective monocultures in terms of forage production, total nitrogen (N) content and land-use efficiency were reported for Mediterranean dryland conditions (Kurdali *et al.* 1996). Narbon vetch and field pea are other legumes reportedly adapted to Mediterranean environments (Thomson *et al.* 1997; Siddique *et al.* 1999; Annicchiarico and Iannucci 2008; Lithourgidis *et al.* 2011).

When ensuring a balanced proportion of their components, legume-cereal mixtures can provide nutritionally balanced forage (e.g. Chapko *et al.* 1991; Jedel and Helm 1993). But legume species tend to be weaker competitors than cereals and, in the case of pea, frequently showed a marked competitive disadvantage (Corre-Hellou *et al.* 2006; Lithourgidis *et al.* 2011; Neugschwandtner and Kaul 2014; Monti *et al.* 2016). This drawback, which would limit the positive effects of the legume component in the mixture (increased protein content, N fixation, and so on), could be alleviated by legume selection for greater competitive ability *per se* or for traits contributing to it. Pea taller stature, either in material without dwarfing genes or in taller material of the semi-dwarf type, was associated with higher pea competitive ability against cereals (Annicchiarico *et al.* 2012) or weeds (McDonald 2003).

The objective of this study was contributing to optimise annual forage crop production in three climatically contrasting, drought-prone regions of the Mediterranean basin. In particular, we aimed at: (*i*) assessing legume-cereal mixed crops including different legume and cereal species and their respective monocultures for performance in terms of total DM yield, legume content and weed incidence; (*ii*) verifying in terms of Land Equivalent Ratio [LER; Mead and Willey (1980)] the advantage of mixtures relative to monocultures; (*iii*) verifying whether greater complexity of legume-cereal mixture (four associated cultivars) may provide an advantage over binary mixtures; and (*iv*) comparing the overall performance of a semi-dwarf versus a tall pea type. Our study included the farmers' participatory assessment of novel crops and plant types, given its recognised usefulness for ensuring more thorough evaluation of agro-economical aspects and greater end-user acceptance of agricultural techniques (Zandstra *et al.* 1981) and novel germplasm (Ceccarelli *et al.* 2009).

Materials and methods

Plant material and test environments

The experiment was carried out under rainfed conditions during two cropping years (2013–2014 and 2014–2015) in three locations of the western Mediterranean basin, namely, Sassari, Sardinia, Italy (40°45′N, 8°25′E, 24 m above sea level, a.s.l.), Sétif, inland Algeria (36°18′N, 5°25′E, 984 m a.s.l.), and Marchouch, Morocco (33°33′N, 6°41′W, 421 m a.s.l.). The main climatic characteristics of the three locations are reported in Table 1.

Our study comprised 16 forage crops, namely, four legume and two cereal pure stands, eight legume-cereal binary mixtures, and two complex (four-component) mixtures (Table 2). The legume material included the common vetch cultivar Barril, the Narbon vetch cultivar Bozdag, and the contrasting pea plant types represented by the semi-leafless, semi-dwarf cultivar Kaspa and the semi-leafless, tall line 2/38b/7 (bred at CREA). The cereals comprised the oat cultivar Genziana and the triticale cultivar Vivaciò. The complex mixtures included the two cereals with either the two pea types or the two vetch species (Table 2). The pea cultivar Kaspa and the tall pea type were chosen on the basis of their good adaptation to Mediterranean conditions (Annicchiarico and Iannucci 2008) and to mixed cropping (Annicchiarico *et al.* 2012), respectively. The two vetch cultivars were selected for adaptation to rainfed Mediterranean conditions (D. Crespo, H. Ozpinar, pers. comm.). The two cereal cultivars were chosen on the basis of yield and morphophysiological data collected in variety trials performed in Mediterranean environments of Italy (e.g.

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Perenzin and Notario 2014), and were sufficiently early to enable harvesting at a suitable phenological stage for both the cereals and the legumes in mixtures.

The experiments in each location were laid out in a randomised complete block design with four replications. Plots were 4 m long and 3 m wide, and included 12 rows at 0.25-m spacing. The adopted sowing rates were 70 germinating seeds/m^2 for the two pea types and the Narbon vetch, 140 seeds/m^2 for the common vetch, and 280 seeds/m^2 for the cereals. These rates, which were intermediate between those ordinarily adopted for the monocultures of these crops in the three target areas, were halved for binary mixtures, and reduced to one-fourth for complex mixtures, according to a proportional replacement design (Andersen *et al.* 2005). The associations were established by sowing together legume and cereal seed in each row. Sowing took place between mid-November and the first week of December following a cereal crop, at a sowing depth of 4 cm. Pre-sowing fertilisation was 45 kg/ha of P_2O_5 to all plots along with 30 kg/ha of N to cereal monocultures and 15 kg/ha of N to the other crops. Cereal monocultures received 30 kg/ha of N, and mixtures 15 kg/ha of N, at the end of winter.

Observed traits

Plots were harvested at 2 cm above ground in a single harvest performed in late spring, when cereals were at late heading/early milky stage and legumes were at waxy stage. The harvest date was around mid-April in Sassari and Marchouch, and in early May in Sétif. Crop DM yield, and legume and weed proportion on a DM basis, were recorded on a 1-m^2 sampling area in the middle of each plot, by botanical separation of legume, cereal and weed herbage followed by oven drying of each herbage component at 65°C.

The LER, which defines the relative land area under pure stand that is required to produce the yield of the component species in mixed stand, was computed for binary mixtures according to Mead and Willey (1980) as:

$$\mathrm{LER} = L_M / L_P + C_M / C_P$$

where L_M and L_P are legume yields in mixed stand and pure stand, respectively, and C_M and C_P are cereal yields in mixed stand and pure stand, respectively. For complex (four-component) mixtures, where no botanical separation was performed within legume or grass components, L_M and C_M denoted the pooled yields in mixed stand of the two legumes and the two cereals, respectively; whereas L_P and C_P indicated the average yield in pure stand of the two legumes and the two cereals, respectively. For the sake of statistical analysis, LER values of each mixture were computed for each randomised complete block from data of pure stand and mixed stand crops that it included.

Shortly before harvest, a group of at least 20 local farmers visited the trials of Sassari and Marchouch each year and gave a synthetic visual appraisal of the potential value of each crop for their own use on the basis of a nine-level score ranging from 1 = very poor to 5 = excellent that encompassed half units as well. Test years included different groups of farmers. For the appraisal, the farmers were subdivided into groups of at least

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five persons that evaluated by turns each of the experiment replications. Farmer's scores on each plot were averaged before data analysis.

Statistical analysis

An analysis of variance (ANOVA) including the fixed factors 'location' and 'crop' and the random factors 'cropping year' and 'block within location and year' was carried out for DM yield free of weeds and weed proportion of all crops (16 crops) in three sites, farmers' score of all crops in two sites, and legume proportion and LER of mixtures (10 crops) in three sites. Table 3 reports degrees of freedom for these ANOVA models. Also, it reports the expected mean squares (EMS) as obtained by the statement RANDOM of the PROC GLM of the Statistical Analysis Software (SAS Institute Inc., Cary, NC, USA), limitedly to the model including all crops. On the basis of EMS composition, the factors 'crop' and 'location' and the 'crop × location' interaction were tested by *F*-test against their respective interaction with the random factor 'year'. The pooled error acted as the error term for 'crop × location × year' interaction, which, in turn, acted as the error term for 'crop × year' and 'crop × location' interactions. Finally, the 'year' factor was always tested using 'location × year' interaction as the error term, as 'crop × year' interaction (also present in its EMS: Table 3) never achieved significance. We verified that the *F*-test results obtained by using these error terms coincided with those obtained by the option TEST within the statement RANDOM of the PROC GLM. For crop DM yield, weed proportion and farmers' score, the 15 ANOVA degrees of freedom relative to variation among crops were partitioned through the statement CONTRAST of the PROC GLM into as many contrasts aimed to test specific hypotheses: (*i*) each legume species versus the average of cereal crops, for pure stands (three contrasts); (*ii*) the average of legume and cereal pure stands versus the respective binary mixtures, for each legume species (three contrasts); (*iii*) paired comparisons between pea-based, common vetch-based and Narbon vetch-based binary mixtures (three contrasts); (*iv*) oat-based versus triticale-based binary mixtures (one contrast); (*v*) pea-based versus vetch-based complex mixtures (one contrast); (*vi*) binary versus complex mixtures including either pea or vetches (two contrasts); and (*vii*) semi-dwarf versus tall pea type, either in pure stand or in mixture (two contrasts). Contrasts not involving pure stand crops were also performed for legume proportion and LER. We assessed these contrasts over locations, given their general interest for Mediterranean environments. However, we assessed the value of the individual crops in the single sites, for traits that displayed significant 'crop × location' interaction. Crops within sites were compared using the within-site 'crop × year' interaction error term in case this term displayed heterogeneity between sites according to Fisher's bilateral *F*-test at $P < 0.01$, and the global 'crop × year' interaction in case the individual error terms failed to display heterogeneity. In a further ANOVA, pure stands of the four legumes and their relevant binary mixtures (terming as 'crop type' either the pure stand or the binary mixture of the legumes) were included in addition to location, year and block, assessing the 'legume × crop type' interaction on the error term represented by the 'legume × crop type × year' interaction. Likewise, 'grass × crop type' interaction was tested by a final ANOVA including a 'crop type' factor whose variants were the pure stand and mixed stand cropping of the two grass species. All statistical analyses were carried out using the Statistical Analysis Software.

Results

Climatic characteristics and production responses of the sites

As expected from their ordinary climatic features, Sassari received higher rainfall over the cropping cycle than Marchouch and Sétif, whereas the two North African locations were the most contrasting sites in terms of autumn, winter and spring temperatures, (which were much higher in the Moroccan site) (Table 1). Compared with long-term climatic data, test years were characterised by lower rainfall over the crop cycle in both North African sites, and warmer spring temperatures in Sassari and Sétif (Table 1). Frost events in the test years were numerous in the high-elevation site of Sétif (whose minimum absolute temperature attained –4.8°C in the first cropping year and –6.7°C in the second), fairly rare in Sassari, and nearly absent in Marchouch. Marchouch displayed mean crop yield (free of weeds) comparable with that in Sassari despite its lower rainfall (Table 1), owing to much lower incidence of weeds and better ability of the crops, in the presence of milder temperatures in winter and early spring, to exploit the water available (Table 1). The harsh climatic conditions of Sétif contributed to its lower mean crop yield relative to the other sites (Table 1). In addition, this site exhibited much lower mean legume content of the mixtures than the other locations, associated with mean LER value below one (indicating somewhat negative complementarity of the associated species relative to their response in pure stand). On average, the mixed stand/pure stand yield ratios for cereals and legumes (the terms summed up in LER computation) in this site were 0.71 and 0.19, respectively, confirming the marked competitive advantage of cereals over legumes. These ratios were slightly above or ~0.5 in Sassari and Marchouch, (which were characterised by nearly nil and moderate legumes' competitive disadvantage, respectively), resulting in mean LER values of 1.10 and 1.02, respectively. Differences between locations achieved statistical significance only for legume proportion, owing to significance of 'location × year' acting as the interaction error term and/or the paucity of factorial and error term degrees of freedom (Table 3). Likewise, no significant difference emerged between years (Table 3).

Production traits and weed content of the crops

The variation among crops over sites was significant ($P < 0.01$) for crop DM yield, weed proportion on total DM, and legume proportion on mixture DM (Table 3). In contrast, mixed-stand crops did not differ for LER value ($P > 0.05$). Significant ($P < 0.05$) 'crop × location' interaction occurred for weed proportion and legume proportion (Table 3). 'Crop × year' interaction over locations never achieved statistical significance, whereas 'crop × location × year' interaction, (which acted as error term for 'crop × year' interaction) was significant for all traits except LER (Table 3).

Crop mean values for production traits are given in each site for variables subjected to 'crop × location' interaction, and crop values averaged over sites for the other variables (Table 4). The oat monoculture was the top-ranking crop for DM yield over sites, but did not differ significantly ($P < 0.05$) from its binary mixtures with the two pea types or with common vetch, the tall pea type (P2) in pure stand and in mixture with triticale, and the triticale monoculture (Table 4). Low crop yield over sites was displayed by Narbon vetch in pure stand or binary mixtures, and by common vetch in pure stand or in association with triticale. ANOVA linear contrasts reported in Table 5 highlighted the yield superiority ($P < 0.05$) of pea-based or common vetch-based binary mixtures over Narbon vetch-based ones (contrasts 8 and 9), that of oat-based mixtures over triticale-based ones (contrast 11), and the yield advantage of cereal pure stands over pure stands of either vetch species (contrasts 2 and 3). Also, they revealed a trend towards greater crop yield of mixtures with the tall pea relative to those with the semi-dwarf pea (+11%, $P < 0.10$; contrast 15). Pea pure stands did not differ significantly from cereal pure stands for yielding ability (contrast 1).

Both vetch species in Sétif, and Narbon vetch in Sassari, exhibited high proportion of weeds on DM when grown in monoculture (Table 4). No crop difference for weed proportion emerged in Marchouch, characterised by very low weed amounts. ANOVA linear contrasts in Table 5 relative to crop mean responses across locations indicated that cereal pure stands controlled weeds better than pure stands of either vetch species ($P < 0.05$; contrasts 2 and 3) or pea ($P < 0.10$; contrast 1). Also, oat-based mixtures tended to control weeds better than triticale-based ones (contrast 11). Finally, vetch-cereal binary mixtures displayed lower weed proportion than the average value of the components' monocultures (contrast 3), thereby highlighting an intrinsic advantage of mixed cropping in this respect.

In Sétif, where the average legume proportion was very low, the only mixed crops that achieved legume proportions between 15% and 20% were the binary or complex mixtures including the tall pea (Table 4). These mixtures, along with the common vetch-triticale binary mixture, were the only ones capable of ensuring legume proportion above 40% in Sassari and Marchouch. The species ranking pea > common vetch > Narbon vetch for mean legume proportion in mixtures over locations implied significant differences between the three species ($P < 0.05$) according to ANOVA contrasts (contrasts 7, 8 and 9 in Table 5). Also, ANOVA contrasts indicated that triticale-based mixtures had higher legume content (albeit being lower yielding) than oat-based ones (contrast 11 in Table 5), and confirmed the superiority of the tall pea over the semi-dwarf one for legume content of its mixtures ($P < 0.001$; contrast 15).

No differences among crops emerged for mean LER value across locations (Table 4), possibly because of high experiment error for this variable (average error CV = 24.5%). The tall and the semi-dwarf pea types exhibited one of the highest (1.05) and lowest (0.91) LER values, respectively, in association with the more vigorous cereal companion, i.e. oat. The mixture Narbon vetch-triticale was top-ranking for LER value (1.07), but also low yielding (Table 4). No ANOVA contrast for LER reached significance (Table 5). In Sétif, characterised by low LER values, the only binary mixtures that displayed LER >1 were those including the tall pea (data not shown).

The 'legume × crop type' interaction for the four legume cultivars across pure stand and mixed stand crop types showed a trend towards significance ($P < 0.10$) which, because of its practical importance, is graphically shown by mean legume DM yields of the four cultivars in the two cropping conditions in Fig. 1. The yield values for mixed stands were doubled, to report them to the same surface unit as pure stands (as the seeding rate in mixtures was half that in pure stands). Common vetch was the only legume featuring an almost perfect yield correspondence between the two conditions. In contrast, the semi-dwarf pea type suffered of a marked yield disadvantage in mixed stand relative to pure stand (–25% legume yield). Fig. 1 reports as a reference also the mean cereal DM yield in pure and mixed of the two cereal cultivars. The oat cultivar displayed a distinct increase of DM yield in mixed stand relative to pure stand and the triticale cultivar just a slight increase in mixed stand, but the 'cereal × crop type' interaction did not achieve significance ($P > 0.10$).

Farmers' acceptability score of the crops

Crops differed for farmers' score over locations, but appreciation scores were subjected to 'crop × location' interaction ($P < 0.01$; Table 3). Farmers in Sassari tended to express greater appreciation for common vetch-based crops, whereas those in Marchouch tended to prefer pea-based crops (Table 6). Both farmer groups, however, attributed moderate to low interest to cereal monocultures and Narbon vetch-based crops. ANOVA contrasts in Table 5 relative to crop values over sites confirmed the marked farmers' preference for pea-based or common vetch-based mixtures over Narbon vetch-based ones ($P < 0.001$; contrasts 8 and 9), and highlighted that pea-based or common vetch-based mixtures were significantly more appreciated than the mean value of the respective monocultures of their components (contrasts 4 and 5). In addition, the ANOVA contrasts revealed greater appreciation by farmers for oat-based over triticale-based mixtures (contrast 11), and confirmed the farmers' preference for pea over cereals as a pure stand crop (contrast 1) (with a preference, in this context, for the semi-dwarf pea over the tall type: contrast 14). Finally, complex mixtures were significantly more appreciated than the average of the relevant binary mixtures in the case of vetch species (contrast 13), whereas the opposite held true for the complex mixture including the contrasting pea types (contrast 12).

Discussion

The three test locations represented well the diversity of rainfall and temperature patterns that features the semiarid areas of the Western Mediterranean basin. Lower rainfall and/or higher spring temperatures that occurred in the test years relative to long-term data are consistent with the predicted effects of climate change in the region (IPCC 2007; Alessandri *et al.* 2014), and add interest to our results in the perspective of future climate scenarios.

The harsh climatic conditions of Sétif determined not only low crop yield but also very low legume content of mixtures and the difficulty for mixed stands to achieve LER values even just around unity. The marked competitive disadvantage exhibited by legumes in this cold-prone site may partly be due to less favourable temperatures for legume growth than cereal growth during winter and early spring, as cool-season grain legumes have higher base temperature for vegetative growth than cereals [e.g. 3–6°C vs –4–2°C for leaf appearance: Sadras and Dreccer (2015)]. Low temperatures soon after sowing should not be detrimental to legume establishment and competitive ability in very early crop stages, however, given the somewhat lower optimal temperatures for germination of these species relative to winter cereals (Odabaş and Mut 2007).

The occurrence of 'crop × location' interaction was expected as a consequence of the climatic variation between test sites. Nevertheless, the relative value of each crop was consistent across locations for yielding ability (displaying no 'crop × location' interaction), and usually did not vary markedly for legume or weed proportions on DM. One important reason contributing to modest or non-significant 'crop × location' interaction was its inconsistency across years as indicated by significant 'crop × location × year' interaction, (which acted as its error term). Crop performances were more site-specific in terms of farmers' appreciation score in the two sites subjected to the participatory assessment, suggesting that other factors besides crop production or contents of legume and weed (albeit appreciated visually by farmers) may influence farmers' perception of the value of each crop. Even farmers' responses, however, agreed across locations in various respects (e.g. the poor value of Narbon vetch-based crops, and the only modest interest of cereal monocultures).

Our results confirmed the high forage yielding ability of oat monoculture in Mediterranean environments that emerged in earlier studies (Moreira 1989; Caballero *et al.* 1995; Lithourgidis *et al.* 2006). However, binary mixtures of oat with the tall pea type or common vetch yielded comparably well across the three locations, while allowing for savings in N fertilisation and providing forage that is expected to be qualitatively enhanced by the presence of legumes. Farmers were aware of the lower quality of cereal pure stands relative to legume-cereal associations, as reflected by lower appreciation scores attributed to cereal monocultures relative to best-performing legume-cereal mixtures and by comments recorded during their visits. On the whole, production traits and farmers' appreciation scores encourage the cultivation of legume-cereal mixtures and, in the case of pea, even legume monocultures. This conclusion holds true even though the yield advantage of mixed cropping over the mean yield of its components' pure stands was fairly modest even for best legume-cereal combinations, for example, average LER of 1.05 for the tall pea-oat mixture. However, LER values ~1.05 are frequent in N-fertilised pea-based mixtures (while tending to be higher in the absence of N fertilisation) (Hauggaard-Nielsen and Jensen 2001), whereas LER values below unity have already been reported for specific legume-cereal mixtures in Mediterranean environments (Monti *et al.* 2016). The occurrence of highest and lowest mean values of LER in Sassari and Sétif (1.10 vs 0.90), which were the most contrasting sites for mean legume content of the mixtures (~49% vs 10%), is consistent with the expected advantage of more balanced mixture composition for the occurrence of species complementarity effects related to N dynamics, growth pattern or light utilisation (Bedoussac and Justes 2010). In general, the yield efficiency of a mixture is mainly determined by the performance of its weaker partner (Harper 1977).

On average, pea-based and common vetch-based mixtures out-performed Narbon vetch-based ones in terms of DM yield production, legume content, and farmers' appreciation. Pea-based mixtures, relative to common vetch-based ones, exhibited higher legume content over locations. This proved particularly important in the case of the tall pea in the least favourable site for legume growth (Sétif), in order to attain an acceptable legume proportion (on average, 17.5% for the tall pea vs 5.4% for common vetch: Table 4) and LER >1. These findings, and the good response of pea even as a pure stand crop, indicate that pea has much greater potential as a forage crop for Mediterranean-climate environments than hitherto believed. The breeding of annual forage legumes for West Asia and North Africa has essentially focussed on vetch and chickling (*Lathyrus* spp.) species (Ates *et al.* 2014). The current interest of pea as a forage crop has profited of significant breeding progress achieved on this species (albeit targeted mainly to the grain crop), for example, the exploitation of the semi-leafless trait to improve the standing ability of semi-dwarf or tall material. Actually, the semi-dwarf type exhibited visually greater standing ability than the tall type, which may have contributed to the preference granted by farmers' to this pea type for a pure stand crop. The tall pea was clearly preferable to the semi-dwarf one for mixed cropping, though, because of greater competitive ability against cereal companions implied by greater legume proportion in its mixtures and the trend towards higher yield of its mixtures.

Compared with triticale-based mixtures, oat-based ones were higher yielding and more appreciated by farmers (who possibly valued visually their better yielding ability), but exhibited lower legume content. Likewise, Lithourgidis *et al.* (2006) reported higher crop yield for common vetch in mixture with oat than with triticale. Our yield and legume content results for these cereal companions agree with those for pea-cereal mixtures reported by Jedel and Helm (1993), who assessed as well the protein content of the mixtures and confirmed for triticale-based ones the higher protein content expected from their higher legume content. A trade-off between high crop yield and high legume content is well established for N-fertilised white clover-grass mixtures (Harris 1987; Annicchiarico and Piano 1994), whose competition dynamics has been studied extensively in order to achieve sufficient legume content in mown forage crops. Crop yield of those mixtures was maximised by associating a highly vigorous grass cultivar (where vigour is reflected by high yield in pure stand) with a highly competing white clover cultivar, because of the positive relationship of grass vigour with mixture yield on the one hand and grass competitive ability on the other. Likewise, in the current study the top-yielding mixture included oat (intrinsically more vigorous than triticale on the basis of pure stand yield) and the tall pea type, whose outstanding competitive ability against cereals emerged fully in the unfavourable cropping site of Sétif. Crop yield maximisation by the mixture including a vigorous cereal and a highly-competing legume companion may arise from better N status for cereal plants allowed for by somewhat lower intra-species competition for soil inorganic N and greater N transfer from the legume (Jensen 1996; Chapagain and Riseman 2014), as well as from greater opportunity for other complementarity effects.

Taller stature, resulting in better ability to compete for light, is a key trait for greater competitive ability of crops, as confirmed by earlier studies on pea competitive ability against associated cereals (Hauggaard-Nielsen and Jensen 2001; Annicchiarico *et al.* 2012) or competitive ability against weeds by pea (McDonald 2003; Annicchiarico and Filippi 2007) and cereals (Lemerle *et al.* 2001). In legumes, shading by cereal companions affects also the ability to fix atmospheric N, which is essential for plant survival because of the greater ability by cereals to compete for soil N (Jensen 1996; Corre-Hellou *et al.* 2006). A semi-dwarf pea was preferable to a tall pea only in one study of pea-barley mixtures that showed the infrequent situation of barley at competitive disadvantage against pea (Hauggaard-Nielsen and Jensen 2001). On the whole, our results confirm also for annual legumes the importance of selecting and growing highly competitive legume companions, particularly for target conditions implying a marked competitive disadvantage for the legume. For a poorly competing legume such as white clover, selection under high competitive stress allowed to reach an acceptable clover content even in associations with extremely vigorous grass companions (Annicchiarico and Proietti 2010).

Intercropping has repeatedly proved to reduce weed density and biomass (Liebman and Dyck 1993). We found better weed control by mixed stand than by the average of the components' pure stands for vetch species, in agreement with results by Mariotti *et al*. (2006) in central Italy under organic conditions.

Greater species diversity as represented by the complex mixtures provided no significant increase in crop yield or legume content relative to the mean performance of the relevant binary mixtures. Likewise, Carita *et al*. (2016) reported no advantage of three-species mixtures over two-species ones for annual legume-cereal crops in Portugal. Farmers granted a slight preference to the complex mixture including both vetch species with the two cereals relative to the average of the relevant binary mixtures, but their appreciation of the complex mixture remained somewhat lower than that of the best vetch-based binary mixture, namely, common vetch-oat (Table 6). Our results contrast with the yield advantage provided by greater species diversity in perennial forages evaluated as monocultures and mixtures of varying complexity (Kirwan *et al.* 2007; Picasso *et al.* 2011; Brophy *et al.* 2017). However, the longer cycle of perennials is expected to provide greater opportunities for the display of complementarity effects associated with greater mixture diversity. Indeed, a recent 3-year comparison of binary versus complex mixtures of legume-based annuals and perennials in Morocco has revealed distinctly greater advantage from greater species diversity (e.g. in terms of LER value) in perennials than in annuals (Annicchiarico *et al.* 2017). Actually, the longer cycle of perennials allows as well to achieve higher LER values than annuals for binary mixtures, as shown by comparisons in Schipanski and Drinkwater (2012) and Annicchiarico *et al.* (2017), partly because of distinctly greater N transfer from legume to non-legume companions (Ehrmann and Ritz 2014).

Our results are likely to be of wide interest for semiarid Mediterranean environments, when considering that they were generated from three climatically contrasting locations, were characterised by fairly high consistency of crop value for production traits across sites, and included a farmer participatory assessment (which is expected to ensure greater end-user acceptance). They encourage the cultivation of legume-cereal mixtures, and support the adoption of a semi-leafless, tall pea type or, to a lesser extent, common vetch or a semi-dwarf pea, as a legume companion. Also, they indicated some advantage of oat over triticale as a cereal companion. Our findings have important implications also for the choice of target species that ought to be prioritised by regional breeding efforts.

Conflicts of interest

The authors declare no conflicts of interest.

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Table 1. Rainfall and temperature variables across two cropping years and the long-term (30 years), and mean values of crop dry matter (DM) yield, weed proportion on total aboveground DM, legume proportion on legume-cereal DM and Land Equivalent Ratio averaged across 16 evaluated forage crops, for three Mediterranean-climate locations

Variable	Sassari, Italy	Sétif, Algeria	Marchouch, Morocco
Rainfall November–February, test years (mm)	334	159	177
Rainfall November–February, long-term (mm)	254	199	244
Rainfall March–April, test years (mm)	102	75	48
Rainfall March–April, long-term (mm)	94	99	94
Average daily mean temp. November–February, test years (°C)	10.5	7.0	12.6
Average daily mean temp. November–February, long-term (°C)	11.0	7.4	13.0
Average daily mean temp. March–April, test years (°C)	12.0	10.8	16.0
Average daily mean temp. March–April, long-term (°C)	12.3	11.1	15.2
Average daily max. temp. March–April, test years (°C)	18.5	17.2	20.7
Average daily max. temp. March–April, long-term (°C)	16.9	15.8	20.8
Average dry-matter yield of all crops, test years (t/ha)	5.55	3.87	6.44
Average weed proportion of all crops, test years	0.140	0.123	0.021
Average legume proportion of mixtures, test years	0.490	0.097	0.376
Average Land Equivalent Ratio of mixtures, test years	1.10	0.90	1.02

Table 2. Acronym and composition of 16 forage crops evaluated in three Mediterranean-climate locations

Crop acronym	Composition
P1	Semi-dwarf pea (semi-leafless; cv. Kaspa)
P2	Tall pea (semi-leafless; line 2/38b/7)
N	Narbon vetch (cv. Bozdag)
V	Common vetch (cv. Barril)
O	Oat (cv. Genziana)
T	Triticale (cv. Vivaciò)
P1-O	Semi-dwarf pea – Oat
P1-T	Semi-dwarf pea – Triticale
P2-O	Tall pea – Oat
P2-T	Tall pea – Triticale
N-O	Narbon vetch – Oat
N-T	Narbon vetch – Triticale
V-O	Common vetch – Oat
V-T	Common vetch – Triticale
N-V-O-T	Narbon vetch – Common vetch – Oat – Triticale
P1-P2-O-T	Semi-dwarf pea – Tall pea – Oat – Triticale

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Table 3. Analysis of variance degrees of freedom (d.f.), expected mean squares and *F*-test results for crop dry matter (DM) yield and weed proportion on total aboveground DM assessed on pure stand (PS) and mixed stand (MS) crops in three locations; DF and F test results for visual appraisal score attributed by local farmers to PS and MS crops in three locations; and DF and F test results for legume proportion on legume-cereal DM and Land Equivalent Ratio (LER) assessed on PS crops in three locations

Acronyms for sources of variation are: C, crop (fixed factor); L, location (fixed factor); Y, year (random factor); B, block; E, experimental error. **P* < 0.05; ***P* < 0.01; n.s., not significant

		Expected mean squares									*F*-test			*F*-test		*F*-test	
Source of variation	d.f.	σ_E^2	σ_{CLY}^2	σ_{LY}^2	σ_{CY}^2	CL_{ij}	$\sigma_{B(LY)}^2$	σ_Y^2	L_j	C_i	Crop DM	Weed prop.	d.f.	Farmers' score	d.f.	Legume prop.	LER
C	15	1	4	–	12	–	–	–	–	+	**	**	15	**	9	**	n.s.
L	2	1	4	64	–	–	16	–	+	–	n.s.	n.s.	1	n.s.	2	*	n.s.
Y	1	1	4	64	12	–	16	192	–	–	n.s.	n.s.	1	n.s.	1	n.s.	n.s.
B (L Y)	18	1	–	–	–	–	16	–	–	–	–	–	12	–	18	–	–
C × L	30	1	4	–	–	+	–	–	–	–	n.s.	*	15	**	18	*	n.s.
C × Y	15	1	4	–	12	–	–	–	–	–	n.s.	n.s.	15	n.s.	9	n.s.	n.s.
L × Y	2	1	4	64	–	–	16	–	–	–	**	**	1	n.s.	2	**	**
C × L × Y	30	1	4	–	–	–	–	–	–	–	**	**	15	**	18	**	n.s.
Pooled E	270	1	–	–	–	–	–	–	–	–	–	–	180	–	162	–	–

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Table 4. Mean values of crop dry matter (DM) yield, weed proportion on total aboveground DM, legume proportion on legume-cereal DM yield and Land Equivalent Ratio (LER) of 16 forage crops across two cropping years in three Mediterranean-climate locations (crop mean value is reported when the 'crop × location' interaction was not significant)

See Table 2 for crop acronyms. s.e., standard error of mean (error term: 'crop × year' interaction); d.f., degrees of freedom; l.s.d., least significant difference (*P* < 0.05)

Crop	DM yield (t/ha)	Weed proportion			Legume proportion			LER
		Sassari	Sétif	Marchouch	Sassari	Sétif	Marchouch	
O	6.72	0.093	0.060	0.011	–	–	–	–
P2-O	6.67	0.106	0.080	0.014	0.447	0.151	0.454	1.05
V-O	6.06	0.046	0.067	0.025	0.488	0.030	0.207	1.01
P2	5.85	0.106	0.138	0.014	–	–	–	–
T	5.80	0.143	0.059	0.038	–	–	–	–
P2-T	5.79	0.132	0.082	0.020	0.714	0.199	0.458	1.01
P1-O	5.71	0.075	0.091	0.032	0.482	0.068	0.374	0.91
P1-T	5.49	0.227	0.107	0.023	0.543	0.125	0.381	1.03
P1-P2-O-T	5.45	0.084	0.115	0.013	0.535	0.145	0.438	0.92
P1	5.29	0.165	0.205	0.016	–	–	–	–
N-V-O-T	5.09	0.148	0.109	0.004	0.511	0.047	0.327	1.04
V-T	5.07	0.074	0.116	0.009	0.746	0.079	0.443	1.03
N-O	4.97	0.127	0.089	0.005	0.180	0.050	0.250	0.98
N-T	4.22	0.207	0.054	0.038	0.250	0.070	0.432	1.07
V	3.82	0.020	0.336	0.031	–	–	–	–
N	2.58	0.482	0.262	0.045	–	–	–	–
s.e. (d.f.)	0.36 (15)	0.041 (15)	0.065 (15)	0.014 (15)	0.065 (9)	0.018 (9)	0.056 (9)	0.05 (9)
l.s.d.	1.08	0.124	0.196	n.s.	0.209	0.057	0.181	n.s.

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Table 5. Analysis of variance contrasts for crop dry matter (DM) yield, weed proportion on total aboveground DM, farmers' visual appraisal score, legume proportion on legume-cereal DM yield and Land Equivalent Ratio (LER) across three Mediterranean-climate locations and two cropping

†$P < 0.10$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; n.s., not significant. Error term: 'crop × year' interaction

Contrast	d.f.	DM yield (t/ha)	Weed proportion	Farmers' score (1 = min.; 5 = max.)	Legume proportion	LER
1. Pea vs cereals, pure stands	1	5.67 vs 6.26 n.s.	0.107 vs 0.062†	4.1 vs 3.5***	–	–
2. Common vetch vs cereals, pure stands	1	3.82 vs 6.26***	0.129 vs 0.062*	3.6 vs 3.5 n.s.	–	–
3. Narbon vetch vs cereals, pure stands	1	2.58 vs 6.26***	0.263 vs 0.062***	3.5 vs 3.5 n.s.	–	–
4. (Mean pea + cereals, pure stand) vs corresponding binary mixtures	1	5.91 vs 5.91 n.s.	0.087 vs 0.082 n.s.	3.8 vs 4.0*	–	–
5. (Mean common vetch + cereals, pure stand) vs corresponding binary mixtures	1	5.45 vs 5.56 n.s.	0.088 vs 0.056†	3.5 vs 4.0***	–	–
6. (Mean Narbon vetch + cereals, pure stand) vs corresponding binary mixtures	1	5.03 vs 4.59 n.s.	0.133 vs 0.087**	3.5 vs 3.4 n.s.	–	–
7. Pea-based vs common vetch-based binary mixtures	1	5.91 vs 5.56 n.s.	0.082 vs 0.056 n.s.	4.0 vs 3.9 n.s.	0.366 vs 0.332*	1.00 vs 0.99 n.s.
8. Pea-based vs Narbon vetch-based binary mixtures	1	5.91 vs 4.59***	0.082 vs 0.087 n.s.	4.0 vs 3.4***	0.366 vs 0.205***	1.00 vs 1.02 n.s.
9. Common vetch-based vs Narbon vetch-based binary mixtures	1	5.56 vs 4.59*	0.056 vs 0.087 n.s.	3.9 vs 3.4***	0.332 vs 0.205***	0.99 vs 1.02 n.s.
10. Pea-based vs vetch-based complex mixtures	1	5.45 vs 5.09 n.s.	0.070 vs 0.087 n.s.	3.6 vs 4.0*	0.373 *v.* 0.295**	0.92 vs 1.04 n.s.
11. Oat-based vs triticale-based binary mixtures	1	5.85 vs 5.14*	0.063 vs 0.091†	4.0 vs 3.7*	0.265 *v.* 0.370***	0.99 vs 1.03 n.s.
12. Pea-based binary vs complex mixtures	1	5.91 vs 5.45 n.s.	0.082 vs 0.070 n.s.	4.0 vs 3.6**	0.366 *v.* 0.373 n.s.	1.00 vs 0.92 n.s.
13. Vetch-based binary vs complex mixtures	1	5.08 vs 5.09 n.s.	0.071 vs 0.087 n.s.	3.7 vs 4.0*	0.269 *v.* 0.295 n.s.	1.02 vs 1.04 n.s.
14. Semi-dwarf vs tall pea type, pure stands	1	5.29 vs 5.85 n.s.	0.129 vs 0.086 n.s.	4.4 vs 3.8*	–	–
15. Semi-dwarf vs tall pea type, mixtures	1	5.60 vs 6.23†	0.092 vs 0.072 n.s.	4.0 vs 3.9 n.s.	0.329 *v.* 0.404 ***	0.97 vs 1.02 n.s.

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Table 6. Mean value across two cropping years of a visual appraisal score attributed by local farmers to 16 forage crops shortly before harvest, for two Mediterranean-climate locations

See Table 2 for crop acronyms. s.e., standard error (error term: 'crop × year' interaction); d.f., degrees of freedom; l.s.d., least significant difference ($P < 0.05$)

Crop	Farmers' score (1 = min.; 5 = max.)	
	Sassari	Marchouch
V-O	4.25	4.15
P1	4.15	4.63
V	4.15	3.06
V-T	4.11	3.54
N-V-O-T	4.02	3.91
O	3.85	3.28
P1-T	3.81	4.16
P1-P2-O-T	3.75	3.39
P2-O	3.67	4.44
P1-O	3.60	4.57
P2	3.57	3.96
P2-T	3.52	4.10
N-O	3.36	3.87
T	3.17	3.70
N	3.10	3.92
N-T	2.94	3.44
s.e. (d.f.)	0.17 (15)	0.17 (15)
l.s.d.	0.53	0.53

Fig. 1. Mean legume dry matter (DM) yield of four legume cultivars, and mean cereal DM yield of two cereal cultivars, in pure stand and in legume-cereal binary mixtures across three Mediterranean locations and two cropping years. Yield reported to same area between conditions by doubling its value in mixed stand (○ = tall pea line 2/38b/7; Δ = semi-dwarf pea cv. Kaspa; □ = common vetch cv. Barril; ◊ = Narbon vetch cv. Bozdag; ▲ = oat cv. Genziana; ■ = triticale cv. Vivaciò; the line represents the theoretical relationship $y = x$).