Design of intercrop management plans to fulfil production and environmental objectives in vineyards

Aude Ripoche\textsuperscript{a}, Florian Celette\textsuperscript{b}, Jean-Pierre Cinnac\textsuperscript{c}, Christian Gary\textsuperscript{a,}\textsuperscript{*}

\textsuperscript{a} INRA, UMR SYSTEM (INRA-CIRAD-SupAgro), 2 place Pierre Viala, 34060 Montpellier Cedex 2, France
\textsuperscript{b} ISARA-Lyon, Department of Agroecosystems-Environment-Productions, Agrapole, 23 rue Baldassini, 69364 Lyon Cedex 07, France
\textsuperscript{c} INRA, UR Productions Végétales, 97170 Petit-Bourg, France

\textbf{ABSTRACT}

Designing intercrop management plans (IMP) to meet objectives related to both crop production and environmental impacts is a challenge for farmers. A multiple criteria decision analysis is thus needed to evaluate and rate various cropping systems in different soil and climate conditions. Different intercrop management plans in vineyards were analysed in this study so as to classify them in relation to their ability to fulfil a particular set of objectives and to deal with climatic variability.

The method included five steps. A set of intercrop management plans was defined by combining the type of grass, the covered soil surface ratio, and the intercropping duration. Four evaluation criteria were chosen: grapevine vegetative development, yield, product quality and runoff. Corresponding indicators were identified and the range of values that would be desirable or not were defined. A water balance model designed for row crops was run to simulate the behaviour of the grapevine–intercrop–soil system under different management plans and at various soil depths. The model was used to calculate, for each management plan and soil depth, the four indicators and evaluate the overall agreement and discordance with various weights assigned to the four criteria. A frequency analysis on 30 years of weather data was carried out to estimate the robustness of the most satisfactory intercrop management plans.

The most satisfactory intercrop management plans differed according to the priority given to managing production or reducing environmental impacts and depended on the soil depth. This confirms the conclusions drawn on the basis of various experiments assessing a limited range of intercropping policies. Overall, giving priority to the environmental criterion was favourable for cropping systems with a long intercrop period regardless of the soil type. Few management plans were suitable for all years.

The observed yearly rainfall varied from 330 to 1200 mm during the 1975–2003 period, which generated marked variations in the water balance of the grapevine–intercrop–soil system.

The lack of robustness of the explored intercrop management plans could be a consequence of the poor description of the management plans due to the limited combinations of technical options considered. Strategic or tactical adjustments could be introduced by farmers. We assume that more robust intercrop management plans could be developed by introducing such rules in a decision model combined with the present biophysical model.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Agriculture should fulfil the economic, environmental and social objectives of sustainable development. It is thus necessary to tailor current cropping systems to meet these needs as they are often too intensive and dependent on external inputs. Alternatives such as plurispecific cropping systems are of considerable interest because plant associations can provide environmental benefits in terms of better use of resources (De Costa and Surentham, 2005; Dulormne et al., 2004) and provision of ecological services (Altieri, 1999; Kang et al., 1990; Lal, 1989; Mafongoya et al., 2004). Yet they should also be able to maintain a level of productivity and production stability that fits with farmers’ objectives.

In vineyards, intercrops (grass cover in the inter-rows) are now being introduced to an increasing extent due to the potential positive impacts on grapevines and their environment: increased infiltration rate and decreased runoff due to modified soil surface characteristics (Léonard and Andrieux, 1998), mitigation of soil erosion (Battany and Grismer, 2000), limitation of herbicide use and weed control (Monteiro and Lopes, 2007), better water resource utilisation by grapevine roots (Monteiro and Lopes, 2007; Celette et
al., 2008), and limitation of risks of diseases by reducing vegetative development (Valdés Gomez et al., 2008). However, intercropping also induces competition for soil resources (Celette et al., 2005) and vegetative development and yield can consequently be limited (Chantelot et al., 2004). In Mediterranean regions, the risk of severe drought during spring and/or summer hampers the adoption of these systems by farmers (Gaudel, 2002). Therefore, designing sustainable cropping systems that would provide ecological services while also achieving production objectives is a real challenge for research. These different functions should be promoted through simultaneous adapted management of the two crops of the system (grapevine and grass cover). Hence, multiple criteria decision analysis is suitable for designing such complex cropping systems with respect to a set of contrasted objectives.

Several methods have been developed to evaluate ex ante crop management planning (Gary, 2004; Loyce and Wery, 2006; Sadok et al., 2008). They all involve a set of criteria which are used to assess and rate various management plans. In the Betha system, Loyce et al. (2002a,b) adopted a multiple criteria decision analysis (MCDA) method that combined generation of a range of alternative management plans, calculation for each of these of indicators associated with the various criteria, and aggregation of these criteria in order to determine the candidate management plans that performed well. An outranking method as in this study was to evaluate the ability of a simple water balance model to assess a range of intercrop management plans (IMP). The second aim was to analyse the outputs of these various IMPs regarding farmers’ objectives, while focusing on grapevine production and/or environmental impacts and climate and soil variability.

2. Material and methods

2.1. Definition of criteria and associated indicators

Four criteria were retained for evaluating the IMPs: three related to grapevine production (vegetative growth, yield, product quality) and one to the environmental impact of the cropping system (runoff). The associated indicators were defined. According to the literature (Gary et al., 2005; Pellegrino et al., 2006), three indicators named FTSW1, FTSW2 and FTSW3 were associated with vegetative growth, yield and product quality, respectively. FTSW1 was the mean daily FTSW value during the period between grapevine budbreak and flowering, FTSW2 was the mean value during the period from flowering to veraison, and FTSW3 was the mean value during the period between veraison and grape harvest. For the environmental criterion, the indicator was the ratio between annual runoff (Ra) and annual rainfall (Pa).

2.2. Description of the biophysical model

The water balance model of Lebon et al. (2003) was designed for vineyards with bare soil and could not simulate runoff. To adapt the model to intercropped vineyards, Celette (2007) divided the soil in two compartments: one below the inter-row, corresponding to the volume explored by the intercrop root system (where grass and grapevine roots coexist) and characterized by its total transpirable soil water TTSWIC, and the other corresponding to the rest of the soil volume that is utilised by the grapevine root system only. The whole soil volume is characterized by the total transpirable soil water TTSW (Lacape et al., 1998). These two soil compartments communicate: when the intercrop compartment is replenished, water drainage occurs from this compartment to the other one below, following a tipping bucket principle. Another improvement of the water balance model was the introduction of runoff calculated by the curve number method (USDA, 2004).

Daily changes in available soil water in the two compartments were:

\[
\Delta \text{ASW}_{ic} = P_{ic} - R_{ic} - \text{ETR}_{ic} - T_{v} \times \frac{\text{ASW}_{ic}}{\text{ASW}_{tot}} \\
\text{in the “intercrop” soil compartment, and}
\]

\[
\Delta \text{ASW}_{v} = P_{v} - R_{v} + D_{ic} - D_{v} - T_{v} \times \frac{\text{ASW}_{v}}{\frac{\text{ASW}_{tot} - \text{Es}_{v}}} \\
\text{in the “grapevine” soil compartment,}
\]

where ‘ic’ refers to intercrop and ‘v’ to grapevine, ASW is the available soil water; P, rainfall; R, runoff, ETR, evapotranspiration of the grass strip; D, drainage; T, transpiration of the grapevine row and Es evaporation of bare soil under the grapevine row.

On day i, the total ASW that is available to the grapevine was:

\[\text{ASW}_{tot}(i) = \text{ASW}_{ic}(i) + \text{ASW}_{v}(i)\]

and the corresponding FTSW was:

\[\text{FTSW}(i) = \frac{\text{ASW}_{tot}(i)}{\text{TTSW}}\]

The model was initialised as following:

\[\text{ASW}_{tot}(0) = \text{TTSW} \quad \text{and} \quad \text{ASW}_{ic}(0) = \text{TTSW}_{ic}\]

2.3. Multiple criteria decision analysis

First, rules for calculating the partial agreement and discordance were determined for each criterion according to the methodology
used in the Bemha system (Loyce et al., 2002a). The degrees of agreement $C_j(a)$ and discordance $D_j(a)$ represent the extent to which the value of the indicator of criterion $j$ was favourable or not to the assignment of an IMP 'a' to a "good" or "bad" class. To this end, the ranges of values of the indicator of criterion $j$ which are favourable or not to the assignment of an IMP to a "good" or "bad" class, and the fuzzy region in between, must be determined. Only the "good" class was considered here (Fig. 1). For the three grapevine production criteria, the classes established by Gary et al. (2005) and Pellegrino et al. (2006) were retained. For each of them (Fig. 1a–c), it was considered that a severe drought was not acceptable ($0 < FTSW_1 < 0.05$) and could involve a veto against the candidate IMP ($D_j(a) = 1$). For FTSW$_1$, no water stress or just mild water stress ($0.6 < FTSW_1 < 1$) were required to provide satisfactory vegetative development and an agreement index of 1. If the water stress increased, the agreement index decreased linearly until 0. To achieve a good yield, mild to moderate water stress was required ($0.3 < FTSW_2 < 0.6$) whereas a more severe stress was preferred for quality ($0.1 < FTSW_3 < 0.3$). For the fourth criterion, i.e., runoff, the agreement index increased as the Ra/Pa ratio decreased (Fig. 1d).

Two assessment policies were defined and the four criteria were weighted correspondingly. One assessment focused on grapevine production and the weights ($w_j$) associated with the three first criteria were 0.33 for FTSW$_1$, FTSW$_2$ and FTSW$_3$, and consequently 0 for Ra/Pa. The second assessment focused on the reduction of the environmental impact and the weights were 0.7 for Ra/Pa and 0.1 for FTSW$_1$, FTSW$_2$ and FTSW$_3$. Then, according to the sets of weights, the overall agreement $C(a)$ and discordance $D(a)$ were calculated as well as the degree of overall compatibility $R(a)$:

$$C(a) = \sum_{j=1}^{4} w_j C_j(a)$$
$$D(a) = 1 - \prod_{j=1}^{4} (1 - D_j(a)^{w_j})$$
$$R(a) = C(a)(1 - D(a))$$

where $\sum_{j=1}^{4} w_j = 1$.

To assign a candidate IMP to the "good" class, $R(a)$ was compared to a threshold "s". This latter factor represents the user's requirement of effectiveness (i.e., a high "s" value selects the most competitive IMPs).

Finally, the robustness of candidate IMPs, i.e., their ability to satisfy the different assessment policies and deal with climatic variability, was analysed on the basis of assessments carried out on over 30 years of climatic data from 1974 to 2003 from the St-Gilles weather station (43°71N, 4°39E). For each climatic year, $R(a)$ was compared with a threshold $s = 0.4$ and the frequency of assignment to the "good" class (frequency of success) was calculated over the 30 years.

2.4. Evaluation of the MCDA approach

The approach was evaluated at several levels: relevance of the three production indicators, sensitivity analysis and expert evaluation of the MCDA method. Data from an experiment carried out over 4 years (2003–2006) near Montpellier, France (43°31N, 3°51E) and fully described in Celette et al. (2008) were used for this purpose. Three treatments were compared: bare soil maintained by chemical weed control, a permanent intercrop (mixture of 80% tall fescue Festuca arundinacea L. and 20% perennial rye grass Lolium perenne L.) and a temporary intercrop (spring barley, Hordeum vulgare L.) called BS, PIc and TIc, respectively. Both intercrops were sown in the inter-rows at 1.5 m width. The permanent intercrop was sown in November 2002 whereas the temporary intercrop was sown every year in November and tilled at vine flowering (beginning of June). During the 3-year experiment, the field was used for winemaking, and each year the winegrower used harvests from the three treatments, while changing the proportions according to the quality of the harvest and his personal winemaking objectives.

The observed weight of pruned wood and the yield were related to the simulated FTSW$_1$ and FTSW$_2$ values, respectively. The sugar content in berries, the ratio between sugar and acidity and the N content in must were related to the simulated FTSW$_3$ values. Linear regressions were carried out using Statbox software (v. 6.23) to analyse the significance of the relationship between the observed and simulated variables.

Then a sensitivity analysis of the MCDA outputs was carried out on the threshold values that delineate the agreement and discordance areas of the four criteria (Fig. 1). Since these thresholds are independent, they were tested separately, while increasing or decreasing their value by 5–20%.

Finally, the relevance of the MCDA outputs was evaluated by comparison with an expert assessment. The winegrower promoted production over environmental objectives, as runoff was not a significant problem in this specific field. He sought a good balance between vegetative and fruit growth in relation to grape quality. His weighting of criteria ($w_j$) was 0.3 for vegetative development and yield criteria, 0.4 for quality and 0 for runoff. Thus, the water balance was simulated for the three treatments (BS, PIc and TIc) over the years 2004–2006. The MCDA method was used with the winegrower’s specific set of weights and the outputs were compared to the classification independently drawn up by the winegrower.

2.5. Definition of candidate intercrop management plans

The climate and soil setting of the present study was a grapevine production area in Languedoc-Roussillon (South of France). Three types of soil were considered in terms of soil water reserve in order to take the diversity in the region into account (Guix-Hébrard et al., 2007; Lagacherie et al., 2006). They were characterized by a TTSW value of 100 mm for a shallow soil, 250 mm for a deep soil and 170 mm for an intermediate soil.

Intercropping management plans were assessed in a standard vineyard with a density of 3333 plants/ha (2.5 m between rows × 1.2 m between plants) and vines trained on a vertical shoot positioned trellis with a head height of 1 m, and a canopy height of 1.9 m.

The candidate IMPs were defined by a combination of three variables: (i) the type of grass, (ii) the percentage of covered soil surface area, and (iii) the intercropping period.

(i) Two grass ideotypes were considered, one as very competitive (VC) and another as less competitive (LC) for water resources. It was assumed that their ability to compete with grapevine could be represented by their rooting depth, and soil covering ratio. The VC and LC ideotypes were identified as the permanent tall fescue intercrop and the annual barley intercrop, respectively, which were studied by Celette et al. (2008). Soil cover ratios were estimated as 70% and 40% (Delabays et al., 2000), corresponding to a curve number of 84 and 89, respectively, in the studied climate and soil conditions (USDA, 2004). Their potential TTSWic measured over 4 years (2003–2006) were 95 and 60 mm, respectively for 1.5 m wide intercrop strips (Celette et al., 2008).

(ii) The diversity of management of the vineyard inter-rows was represented by a range of percentages of intercropped soil surface area. Three possibilities were studied: half the inter-rows intercropped over 60% of the total surface area of the inter-row (i.e., 30% of the surface of the field) and all inter-rows intercropped over 50% or 70% of the total surface. As the inter-rows
were 2.5 m wide, these cover ratios corresponded to intercrop strips 1.5, 1.25 and 1.75 m wide, respectively. TTSWc was adapted in proportion to the TTSW and to the width of the intercrop strip.

(iii) Bare soil (BS) and three intercropping periods were studied. For the three intercropping periods, the intercrop growth started in autumn. These periods differed by the date of destruction of the cover which occurred at grapevine budbreak (CB) or flowering (CF). Permanent cover (PC) was also considered.

Finally, 19 combinations were possible for each of the three soil types: bare soil + 2 grass types × 3 covered soil surface areas × 3 covering periods.

In this paper, only the results for 16 IMPs are presented. We first present the frequency of assignment to the “good” category obtained by the four treatments BS, CB, CF and PC in a control situation combining a shallow soil (TTSW = 100 mm) and the VC grass type sown on over 70% of the total surface area. Then we compare these results with those obtained by modifying: (i) the width of the total sown surface area (30%), (ii) the grass type (LC) and (iii) the soil type (TTSW = 250 mm).

Statistical analyses were carried out using Statbox v. 6.23 software to assess differences between IMPs.

3. Results

3.1. Evaluation of the MCDA approach

3.1.1. Relevance of the three production indicators

A significant correlation was found between the FTSW1 values simulated over the 3-year experiment and the pruned wood weights ($R^2 = 0.58^*$), and between the simulated FTSW2 values and the obtained yields ($R^2 = 0.59^*$). No significant relationship was noted between FTSW3 and the sugar content, the sugar content/total acidity ratio, or the N content in must.

3.1.2. Analysis of the sensitivity of MCDA outputs to the agreement and discordance functions

The success of the different intercrop management plans was not much affected by variations in the different threshold values used in the agreement and discordance functions. The same trend was noted for the three main threshold values limiting the agreement area (0.6, 0.3 and 0.1). Increasing the threshold values resulted in a slight decrease in success for all IMPs. The frequency of assignment was reduced by 1–3 years out of 30, especially when there was an intercrop sown on a large surface area and/or permanent or present until grapevine flowering. Decreasing the threshold values affected most IMPs on deep soils. The frequency of assignment increased slightly, i.e., 1 or 2 years more out of 30 years. Moreover, this variation often occurred with a 5% or 15% increase or decrease in the threshold values, and did not change with higher modifications (initial threshold value more or less 20%).

The same trend was noted when variations in the veto values were considered. In this case, the results of simulations carried out for IMPs on shallow soils were more sensitive than those carried out for IMPs on deeper soils. The IMPs were more successful when the veto value was reduced by 5% or 10% (i.e., equal to 0.0475 or 0.045). The frequency of assignment increased by 1–3 years out of 30, but the results did not change for greater decreases in veto values (15% or 20%). IMPs were slightly less successful when the veto value was increased. They were rejected 1 or 2 years more out of 30 than with the initial threshold.

3.1.3. Expert evaluation of MCDA outputs

In 2004, the classification of IMPs obtained independently with the MCDA and by the winegrower led to the same conclusion. The cropping system with a temporary intercrop was considered as the most effective (Table 1). The values of criteria related to yield (FTSW2) and quality (FTSW3) were too high for the bare soil treatment to make it satisfactory, whereas the quality criterion was too

Table 1
Classification of the three treatments from the multiple criteria assessment and from the winegrower over the 3 years of experiment (2004–2006).

<table>
<thead>
<tr>
<th></th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Multiple criteria results</strong></td>
<td>Tlc &gt; Ptc &gt; BS</td>
<td>Tlc &gt; Ptc &gt; BS</td>
<td>Ptc &gt; Tlc &gt; BS</td>
</tr>
<tr>
<td><strong>Winegrower’s decision</strong></td>
<td>Tlc &gt; Ptc &gt; BS</td>
<td>Tlc &gt; BS &gt; Ptc</td>
<td>BS &gt; Tlc &gt; Ptc</td>
</tr>
</tbody>
</table>

Ptc, permanent intercrop; Tlc, temporary intercrop; BS, bare soil.
high for permanent intercropping. In 2005, the MCDA did not differentiate the three cropping systems, which all fulfilled the three production objectives. The same year, the winegrower decided to select grapes from the temporary intercrop and bare soil systems, since grapes harvested from the permanent intercropping system had a too high sugar content, and exhibited premature defoliation at harvest time. In 2006, the MCDA indicated that the temporary intercrop was the most effective system, i.e., better than the permanent intercrop and bare soil systems. The winemaker selected grapes from the permanent intercropping system grapes to the permanent intercropping system had a too high sugar content and a lack of acidity.

3.2. Assessing the robustness of intercrop management plans fulfilling only production criteria

IMP with an intercrop until budbreak obtained the best frequency of assignment for any type of soil and grass type. For most of the IMPs, the main reasons for rejection were low FTSW2 and/or FTSW3 values, close to their veto value or lower (i.e., excessive water stress conditions). Nevertheless, the frequency of assignment increased for all IMPs with soil depth: it was on average 17, 22 and 24 years out of 30 for soils with a TTSW of 100, 170 and 250 mm, respectively.

In the first step, management plans were evaluated with respect to production criteria for vineyards planted on shallow soil (TTSW = 100 mm) and where deep-rooted intercrops (VC type) were sown on over 70% of the soil surface area (i.e., in all interrows). Situations with various intercrop durations were compared (Fig. 2a). The success of the management plans decreased with the length of intercropping period. When intercropping was limited to winter time (i.e., intercrop destroyed at grapevine budbreak, CB treatment), the IMPs fulfilled the production criteria in 25 years out of 30. When it lasted until grapevine flowering (CF) or was permanent (PC), the frequency of assignment increased to 18 and 11 years out of 30, respectively. The bare soil treatment (BS) presented the same trend as the CF treatment.

These results could be related to the mean annual soil water inflow (infiltration) and outflows (soil evaporation, intercrop evapotranspiration, grapevine transpiration, and drainage; Fig. 3a). Over 30 years, there were no significant differences between the BS, CB and CF treatments with respect to the mean annual water balance (ASW) calculated during the grapevine growing season. Nevertheless, the outflow distribution changed with the duration of the

**Fig. 2.** Frequency of assignment to the “good” class of BS, CB, CF and PC treatments for (a) a shallow soil, sown with a VC intercrop on over 70% of the soil surface area, (b) a shallow soil, sown with a LC intercrop on over 70% of the soil surface area, (c) a shallow soil, sown with a VC intercrop on over 30% of the soil surface area and (d) a deep soil, sown with a VC intercrop on over 70% of the soil surface area.

**Fig. 3.** Mean annual water inflow and outflows (mm) over 30 years simulated for a shallow soil, with a VC intercrop sown on over 70% of the inter-row surface (a) during the grapevine production cycle, and (b) during winter. Infiltration (□), soil evaporation (dotted lines), grapevine transpiration (horizontal lines), intercrop evapotranspiration (■) and drainage (■). Significant differences between treatments (p < 0.01) are indicated on the right side by different letters, nd, not determined. From top to bottom, letters refer to infiltration, soil evaporation, grapevine transpiration, intercrop evapotranspiration and drainage. There was no grapevine transpiration during winter.
intercropping period. When the intercropping period increased, the decrease in soil evaporation and grapevine transpiration were compensated for and overtaken by the intercrop evapotranspiration in the CF and PC treatments, and infiltration increased during rainy years. Mean annual infiltration was indeed significantly higher for the PC than for the CB treatment during the grapevine growing season.

In winter, this infiltration increase was accentuated in the PC treatment, as the growth of the intercrop resumed as soon as the climatic conditions were favourable (Fig. 3b). During this period, the mean ASW was significantly lower for the BS treatment than for the intercropped treatments \( p < 0.01 \), whereas those of the CB and CF treatments were similar. These contrasted flow distributions had impacts on the soil water dynamics over the years. For example, in 1994 and 1995 (Fig. 4), the soil water reserve was not replenished at the end of winter and the FTSW values at budbreak were similar among intercropping periods (around 0.8 for the BS treatment and 0.6 for the CB, CF and PC treatments). In 1994, rainfall was infrequent but regular enough (193 mm) to maintain an acceptable FTSW value for the BS and CB treatments during the production cycle. This was not the case for the CF and PC treatments for which rainfall was not sufficient to meet the water uptakes of both the grapevine and the intercrop. In 1995, rainfall was rare and low (117 mm) and did not provide a good FTSW level for any treatment.

When an LC grass type intercrop was grown (shallow-rooted, lower covering rate), the same trends were noted despite a slight decrease in the frequency of assignment for the CB and CF treatments, i.e., down to 23 and 16 years out of 30, respectively (Fig. 2b). With an LC intercrop, there was less infiltration but also more grapevine transpiration due to the lower water stress than with the VC intercrop. Nevertheless, over the 30-year simulation, the mean annual ASW did not differ significantly between the LC and VC intercrops. Some years, the mean annual ASW was lower for the LC than for the VC intercrop. This could lead to a greater FTSW decrease during the growing season. Thus, although an IMP with a VC intercrop could be accepted during these years, the same combination with an LC intercrop was rejected because the veto value was reached for FTSW\(_2\) and/or FTSW\(_3\).

When the sown area was reduced from 70% to 30% with the VC intercrop, there was even less of a difference between treatments, with winter intercropping being successful 20 years out of 30 and bare soil and permanent intercropping being successful 18 years out of 30 (Fig. 2c). There were few significant differences in inflow or outflows between the four treatments (Fig. 5a and b).

The initial intercrop management plans were all more successful when carried out on a deep (TTSW = 250 mm) rather than on a shallow soil. The CB treatment always fulfilled the production criteria, whereas longer intercropping periods (CF and PC treatments) were successful for 22 and 25 years out of 30, respectively, and intermediate results were obtained with bare soil (Fig. 2d). On deep soil, IMPs were more successful during dry years. As the potential soil water reserve (FTSW) was higher, the rainy periods were sufficient enough to replenish the soil reserve and the two crops thus had a ready supply of water throughout their growth cycle. In 1994, as there was high winter infiltration, in the four treatments, the grapevine growing season began with a high FTSW level of around 0.7 and 0.8 (Fig. 6). Due to lower outflows, a better FTSW level was reached for winter intercropping, but acceptable FTSW values were obtained in all treatments throughout the grapevine cycle. In 1995, the CF treatment had the lowest FTSW level during the growing season. In contrast to the PC treatment, the CF treatment had not benefited from the rainfall which occurred in September 1994 and FTSW therefore remained stable during the next winter. FTSW decreased markedly due to grapevine and intercrop transpiration and reached low values before and after flowering (FTSW\(_1\) = 0.49, FTSW\(_2\) = 0.20).

### 3.3. Effect of introducing environmental criteria on the assessment of intercrop management plans

Differences between candidate IPMs were lower when priority was given to the reduction of environmental impacts. The results
obtained in the previously studied situations with a low level of required performances ($s = 0.4$) are represented in Table 2. Regardless of the soil depth, with an intercrop sown on over 70% of the soil surface area with VC or LC intercrops, the frequencies of success for cropping systems with bare soil and winter intercropping remained relatively stable. With priority given to production criteria, the final scores of these IMPs, i.e., their degree of overall compatibility, were around 0.7 on average. Introducing an environmental criterion resulted in a decrease in the final score, but the good production outcomes kept the degree of overall compatibility above the “$s$” threshold. In contrast, the positive effect on runoff due to the longer intercropping period (until grapevine flowering, or permanent) led to good results for the environmental criterion. When the CF and PC treatments obtained a low frequency of success when priority was given to production criteria ($R(a)$ close to 0.4), the good environmental performance could partly compensate for this in the final score, particularly during rainy years. Unsuccessful years were rejected because of the low production performances or because the veto value had been reached by a production criterion.

With a reduced sown surface area on shallow soils, the results remained stable for all treatments. The frequency of assignment increased by only 1-year for the three intercropping systems. The reduction in the sown surface area decreased the positive impact of the intercropping systems (CB, CF and PC) on the environmental criterion.

If high performances were required ($s = 0.7$), a marked decrease in the frequency of success was obtained for any soil type and intercrop management plan (Table 2). The decrease was less for longer intercrop durations. All treatments were seldom successful on shallow soils, i.e., from 2 to 6 years out of 30 for the bare soil and PC treatments, respectively. On deep soils, the difference between the PC treatment and the three others was greater. In fact, the IMP production performances were higher on deep soils (see above). Moreover, the final score obtained for the PC treatment remained above the threshold because its environmental performances were also better than in the other treatments.

4. Discussion

4.1. Limitations of the biophysical model

The biophysical model was implemented on the basis of some assumptions that had an impact on the multiple criteria analysis results. Water was the only soil resource represented by the model. Other soil resources like nitrogen were not considered, yet they could also affect the interaction between grapevines and intercrops and their resulting growth and yield. Nevertheless, the soil water dynamics partly govern the nitrogen supply and, by representing the soil water content, nitrogen stress is indirectly considered (Celette et al., 2009).

Moreover, one of the main characteristics of the cropping system studied here is that grapevines are perennial. Multi-year simulations were carried out because the initial soil water content values for 1-year depends on the water balance of the previous year. However, the winter carbon and nitrogen reserves in perennial species, which also determine interactions between successive crop cycles, were not taken into account.

<table>
<thead>
<tr>
<th>0.4</th>
<th>nb of years where IMP was accepted</th>
<th>Difference with the productive strategy (years)</th>
<th>0.7</th>
<th>nb of years where IMP was accepted</th>
<th>Difference with the productive strategy (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 mm BS</td>
<td>18</td>
<td>0</td>
<td>2</td>
<td>-12</td>
<td></td>
</tr>
<tr>
<td>Sown CB</td>
<td>25</td>
<td>+1</td>
<td>5</td>
<td>-18</td>
<td></td>
</tr>
<tr>
<td>Surface = 70% CF</td>
<td>21</td>
<td>+3</td>
<td>4</td>
<td>-4</td>
<td></td>
</tr>
<tr>
<td>VC PC</td>
<td>19</td>
<td>+8</td>
<td>6</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>250 mm BS</td>
<td>25</td>
<td>-3</td>
<td>3</td>
<td>-17</td>
<td></td>
</tr>
<tr>
<td>Sown CB</td>
<td>28</td>
<td>-2</td>
<td>4</td>
<td>-18</td>
<td></td>
</tr>
<tr>
<td>Surface = 70% CF</td>
<td>26</td>
<td>+4</td>
<td>8</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>VC PC</td>
<td>27</td>
<td>+2</td>
<td>19</td>
<td>-2</td>
<td></td>
</tr>
<tr>
<td>100 mm BS</td>
<td>18</td>
<td>0</td>
<td>2</td>
<td>-12</td>
<td></td>
</tr>
<tr>
<td>Sown CB</td>
<td>21</td>
<td>+1</td>
<td>3</td>
<td>-16</td>
<td></td>
</tr>
<tr>
<td>Surface = 30% CF</td>
<td>20</td>
<td>+1</td>
<td>3</td>
<td>-11</td>
<td></td>
</tr>
<tr>
<td>VC PC</td>
<td>19</td>
<td>+1</td>
<td>6</td>
<td>-8</td>
<td></td>
</tr>
<tr>
<td>100 mm BS</td>
<td>18</td>
<td>0</td>
<td>2</td>
<td>-12</td>
<td></td>
</tr>
<tr>
<td>Sown CB</td>
<td>23</td>
<td>0</td>
<td>4</td>
<td>-14</td>
<td></td>
</tr>
<tr>
<td>Surface = 70% CF</td>
<td>20</td>
<td>+5</td>
<td>2</td>
<td>-4</td>
<td></td>
</tr>
<tr>
<td>LC PC</td>
<td>18</td>
<td>+7</td>
<td>5</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Another assumption concerned variations in the soil surface characteristics throughout the year. When an intercrop was destroyed, the soil surface was either tilled or covered with mulch after chemical treatment. In fact, the model did not represent this pattern and considered the soil as a compacted bare soil as soon as the intercrop had been destroyed. Consequently, the positive effect of tillage or mulching on water infiltration was underestimated for cropping systems with intercrops (Léonard and Andrieux, 1998). The differences between cropping systems with intercrop management plans and bare soil would actually be higher.

4.2. Irregular quality of crop performance indicators

In the present study, the vegetative development and yield indicators were based on average FTSW values during the vegetative period and during the flowering to veraison period, respectively. They were correlated with measured pruned wood and yield values, respectively. These results are in agreement with the findings of various studies which highlighted the sensitivity of crop growth processes to water stress (Wery, 2005; Pellegrino et al., 2005; Celette, 2007). In contrast, the average FTSW value during the veraison to maturity period was not correlated as expected with any measured quality variable. This could have been due to the complexity of the relationships between water stress and the fruit quality development or to the choice of FTSW as a water stress indicator. In contrast with biomass production, which is mainly regulated by one major variable, i.e., stomatal conductance, fruit quality is actually a set of properties that depend on water stress through different types of regulation activated at different fruit development times (Guichard et al., 2001). Moderate water stress during the veraison to maturity period can result in higher concentrations of sugars, anthocyanins and aroma in grapes (Coomb and Iland, 2005). Earlier water stress, i.e., during the flowering to veraison period, results in a small berry size that is correlated with high concentrations of phenolics and aroma (Ojeda et al., 2002). However, excessive water stress during grape veraison and maturity has negative effects on berry quality due to problems during berry ripening (Morlat et al., 1992; Pellegrino et al., 2005; Peyrot des Gachons et al., 2005). FTSW$_3$ thus might not have been averaged over the right period of the crop cycle. Furthermore, FTSW is correlated with the predawn leaf water potential with an exponential relation (Lebon et al., 2003; Pellegrino et al., 2004; Celette, 2007). Consequently, in a range of low predawn leaf water potential values (e.g., between −0.6 and −1.0 MPa), which is common during the veraison to maturity period and corresponds to high to severe water stress (Carbonneau, 1998), FTSW was not very sensitive (between 0.09 and 0.02) to water stress. A FTSW value averaged over a period of several weeks could hardly enable differentiation of optimal and suboptimal (too high or too low) water stress values. On the basis of previous results (Gary et al., 2005), FTSW$_3$ was kept as an indicator of harvest quality in the MCDA, but this indicator would deserve further analysis.

4.3. An effective multiple criteria decision analysis method

The performances of the different IMPs were not very sensitive to threshold variations in the agreement and discordance functions. The use of fuzzy logic in these functions avoided abrupt changes of category (acceptable vs. not acceptable) and therefore limited the sensitivity of the MCDA outputs to variations in criteria thresholds (Loyce et al., 2002a). Furthermore, as a number of criteria were combined, any uncertainty in the agreement and discordance functions of one criterion was offset when all criteria were weighted and aggregated. Yet a result close to the veto value for one criterion still had a negative impact on the final score, which was confirmed by the results obtained after introducing the environmental criterion (runoff). This method was therefore effective for eliminating IMPs which did not fulfill the production and/or environmental criteria with regard to the performance demand expressed by the user with the “$+$” threshold.

4.4. Climate variability and robustness of IMPs

This exploratory study allowed us to analyse the dynamics of the grapevine soil water status for several climatic years, soil depths and IMPs. The most tailored management plans differed depending on the soil and climate context and on the objectives to meet, which confirms and extends previous experimental results. For example, Chantelot et al. (2004) observed a higher frequency of low grapevine growth in shallow soils than in deep ones (decrease in leaf area, up to a 40% decrease in pruned wood weights). Similarly, in the present analysis, the production and environmental objectives were highly fulfilled for all treatments on deep soils, whereas they were more frequently not fulfilled on shallow or intermediate soils. Indeed, in the latter types of soil, although winter intercropping was effective in meeting the production criteria, its overall efficiency decreased when the environmental concerns were considered, in contrast with cropping systems with a longer intercropping period. In the same way, although decreasing the sown soil surface in vineyards intercropped until grape flowering or permanently better fulfilled the production criteria, there was less of a positive impact on the environment. Consequently, the frequency of success of most candidate IMPs was too low to satisfy any farmers, who could certainly not economically tolerate 8 or 10 unsuccessful years out of 30.

This study highlights the difficulty of designing an intercrop management plan that would be able to cope with inter- and intra-annual climatic variability and still meet the performance demand for the same set of objectives. In this respect, deep soils offset rainfall variations with respect to water availability. Nonetheless, it was not possible to draw conclusions about the effectiveness of an IMP when considering only seasonal averages in various water flows. The rainfall distribution during the crop cycle had more impact on the dynamics of the soil water status than its quantity, particularly after a dry winter during which soil water reserves were not replenished. This suggests that it would be beneficial to introduce changes in the intercrop management plan in time to maintain the grapevine activity within the trial corresponding to the farmers’ objectives. The discrepancy between a changing environment and fixed intercrop management plans certainly explains the low frequency of success of many IMPs.

The cropping system modelling could be improved in two ways. First, all intercrop management plans explored in the present study were characterized by three variables only. This substantially limited the combination of possible technical options. Second, farmers actually tailor their technical operations to circumstances (e.g., climatic, technical or economical events) in order to maintain their cropping system in the range of expected performances (Cros et al., 2004). The cropping system is therefore constantly subject to modifications. This strategy has been formalised and used for different management problems including tomato production in greenhouses (Rellier et al., 1998) or rotational grazing (Cros et al., 2003). Introducing the management strategy in the model, i.e., linking a decision model to the existing biophysical model, could introduce flexibility and adaptation to intra- and inter-annual climatic variability.

In the case of intercropped vineyards, winegrowers can modify the timing of some operations over the year, such as the frequency of mowing or time of destruction of the intercrop in relation to current climatic conditions or the state of the crop–soil system. On a yearly scale, if some of the grower’s objectives have not been
satisfied, he may decide to change the intercrop characteristics (percentage of covered area, period of activity, etc.) or use alternative cultivation techniques such as water or nitrogen management, in relation to the past performances of the cropping system (Hofmann, 2006).

5. Conclusion

Modelling and evaluation of IMPs under different soil conditions over a range of climatic years generated elements for designing new cropping systems. The frequency of success of the IMPs increased with the soil depth, and a long intercropping period could be recommended in this case. On the contrary, the frequency decreased on shallow soils for IMPs permanently intercropped or until grapevine flowering. As expected, introducing an environmental criterion limited the success of the cropping systems with a short intercropping period or without intercropping. However, to achieve a high level of required performances, some improvements would have to be made to increase the effectiveness of all IMPs. Coordinated management of intercrops and grapevines is essential to fulfill the objectives (production and/or environmental services) required for both crops. However, this management has to be dynamic and adapted to changing climatic conditions, and within the farmers’ leeway limits. Other indicators of sustainability (environmental, social, economical) could be included in the multiple criteria assessment. Combinning a decision model with a biophysical model and evaluating the cropping systems thus defined should help more realistically identify cropping systems tailored to both farmers’ and society’s demands.

Acknowledgements

This work was carried out with the financial support of the Agence Nationale de la Recherche – (ANR; French national research agency) under the Programme Agriculture et Développement Durable, ANR-05-PADD-010, GeDuQuE project. The first author received a fellowship from INRA and Languedoc-Roussillon region (France). We thank C. Clipet who contributed to the expert evaluation of the MCDA approach, Y. Bouisson who managed the experimental setup, and D. Manley for his linguistic support.

References


