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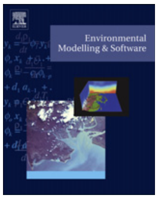

Modelling adaptive management of intercropping in vineyards to satisfy agronomic and environmental performances under Mediterranean climate

Aude Ripoche[a,e,*], Jean-Pierre Rellier[b], Roger Martin-Clouaire[b], Nakié Paré[c], Anne Biarnès[d], Christian Gary[a]

[a] *INRA, UMR System, 2 place Pierre Viala, F-34060 Montpellier Cedex 2, France*
[b] *INRA, UR 875 Biométrie et Intelligence Artificielle, F-31326 Castanet Tolosan, France*
[c] *INRA, UMR LISAH, 2 place Pierre Viala, F-34060 Montpellier Cedex 2, France*
[d] *IRD, UMR LISAH, 2 place Pierre Viala, F-34060 Montpellier Cedex 2, France*
[e] *CIRAD, UPR 26, Quartier Petit Morne, BP 214, 97285 Le Lamentin Cedex 2, Martinique, French West Indies, France*

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ABSTRACT

In the Mediterranean area, rainfed viticulture is exposed to irregular rainfall distribution. The impacts on production and environment can be mitigated by appropriate management practices like, for instance, the introduction of cover crop in the inter-rows in vineyards. This paper presents the VERDI simulation model created to study various adaptive intercrop management strategies at field scale. The purpose is to design management strategies that are responsive to the water status of the biophysical system (soil – grapevine – intercrop) and the past and current climatic conditions. VERDI realistically reproduces the dynamic interactions between the biophysical system and the decision system in varying Mediterranean rain regime. The decision system works as an interpreter of a management strategy, defined as a set of soil surface management activities (e.g. mechanical weeding of the intercrop) that are linked by temporal constraints (e.g. sequencing, synchronisation) and organisational or programmatic specifications (e.g. iteration). The adaptive capabilities of the strategies are distinguished according to the different sources of flexibility to be exploited at operational, tactical, and strategic levels. A simulation study is reported that involves more or less flexible strategies under different climate scenarios. The simulation results proved that, in case of severe drought, the most flexible strategy yields the best trade-off between agricultural production and environmental services over the years.

Software availability

Name of software: VERDI (version 4.3)
Contact address: Jean-Pierre.Rellier@toulouse.inra.fr, INRA, UR 875 Biométrie et Intelligence Artificielle, F-31326 Castanet Tolosan, Francechristian.gary@supagro.inra.fr, INRA UMR System, 2 place Pierre Viala, F-34060 Montpellier Cedex 2, France
Availability and Online Documentation: Free download of the DIESE package (libraries and documentation) at http://carlit.toulouse.inra.fr/diese/ ('Télécharger' page). The VERDI material can be downloaded from the 'Projets applicatifs' page.
Year first available: 2011
Hardware required: VERDI runs on Linux or MS Windows (tested on Windows 2000 and XP). The DIESE library precompiled for Linux or Windows respectively must be installed on the selected platform. On Microsoft Windows platforms, the distribution free Linux-like environment Cygwin must first be installed (http://www.cygwin.com for current availability).
Software required: A Java-runtime environment to inspect/develop the VERDI model and generate the corresponding C++ source code, a standard C++ compiler to generate the executable simulator from the source code and the DIESE library.
Programming language: C-C++

1. Introduction

Adaptation to climate fluctuations is a recurrent management problem in agricultural production. For perennial crops like vineyards, crop rotation is not an option but adaptation is possible

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[*] Corresponding author. Present address: CIRAD, UPR 26, Quartier Petit Morne, BP 214, 97285 Le Lamentin Cedex 2, Martinique, French West Indies, France. Tel.: +33 596 5 96 42 30 82; fax: +33 596 5 96 42 30 01.
E-mail address: aude.ripoche@cirad.fr (A. Ripoche).

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through canopy management (Lin, 2007; Smart et al., 1991), fertilization, irrigation, or soil surface and intercropping management (Celette and Gary, 2006; Chifflot et al., 2006). Because perennial crops can remain several decades in the same field, farmers have to be attentive and responsive during each production cycle to avoid endangering the productivity of their cropping systems for the following years.

The practice of cover cropping is currently increasing in vineyards as it provides various ecosystem services in relation to the soil (mitigation of runoff and erosion, Battany and Grismer, 2000), the crop (control of vegetative development, and the resulting conditions of yield formation and disease development, Valdes-Gomez et al., 2008), and the environment (limited use of pesticides as herbicides, or fungicides). But introducing a second crop can lead to undesirable competition for soil resources such as water and nitrogen (Celette et al., 2009; Chantelot et al., 2004) and result in a problem of trade-off between provisioning and regulating ecosystem services (Power, 2010). From 60% to 80% of vineyards in French continental regions like Alsace and Burgundy are intercropped, but only 14% in the Mediterranean regions (Mezière et al., 2009). This low percentage can be explained by wine growers' concerns about drought in summer and by the high inter and intra-annual climate variability (Ramos, 2001). For instance, annual rainfall in Montpellier (south of France) varied from 350 to 1200 mm between 1973 and 2003. Consequently, wine growers in those regions fear occasional episodes of strong competition for water between the two crops and are reluctant to introduce cover crops despite the regulating services they would provide.

Extension services tend to suggest standardized management plans adapted to average climate conditions and repeated every year. The limits of this approach were evaluated in a recent simulation-based study (Ripoche et al., 2010). Various intercrop management plans combining various types of options (species, covered surface area, period of intercropping) were evaluated with respect to production and environmental criteria over 30 years. Finally, none of these management plans were successful over all the years and most of them exhibited low frequencies of success. These results could be explained by the normative assumptions underlying the management plans, with little consideration for the climate variability and the resulting changes in the biophysical state of the system. However, the inter-annual variability of climate generates fluctuations in grapevine production and environmental externalities (Ramos and Martinez-Casasnovas, 2010). Therefore, more elaborate vineyard management policies should be designed to buffer the effects of climatic variations on the biophysical system. Cropping systems should be dynamic and adaptive to changes in order to meet farmers' objectives year after year (Sadras et al., 2003). A model of vineyard cropping systems should simulate the interactions between biophysical and decision processes, i.e., how biophysical processes affect farmers' activities and reciprocally.

Several studies have highlighted the relevance of considering not only the properties of the crop and material resources but also the management of activities to propose more suited cropping systems to farmers (Aubry et al., 1998; Bergez et al., 2010; Cros et al., 2003; Nesme et al., 2006; Papy, 1998; Thornton and Herrero, 2001). Yet, modelling of the management of activities remains poorly explored and the notion of activity as a work item is rarely explicitly represented in models (Woodward et al., 2008). As explained by Bergez et al. (2010), crop management is often implemented as simple options represented by fixed parameters, defined at the initialization of the simulations and independent from both the state of the biophysical system and the other activities that can occur. There are, however, some examples of simulation-based studies of production management in cropping systems (Keating et al., 2003; Stockle et al., 2003). In DeciBle, Chatelin et al. (2005) studied the impacts of several management plans on the wheat production performance considering various kinds of context-dependent tillage, sowing, and nitrogen supply. A rule-impact approach has also been developed (Donatelli et al., 2006) and integrated into the APES platform (Donatelli et al., 2009) but with no possibility of modifying the strategies from one year to another during the simulation.

To our knowledge, there are few models adapted to vineyards (Celette et al., 2010; Lakso and Poni, 2005; Nendel and Kersebaum, 2004; Valdes-Gomez et al., 2009) and currently no model explicitly represents (adaptive) vineyard management plans. We hypothesised that including the relationships between the agricultural activities, the weather (past and present), and the state of the biophysical system in the modelling of vineyard cropping systems would help in the design of efficient, robust, and innovative management plans. As our main objective was to study the agronomic and environmental relevance of introducing flexibility in management strategies of intercropped vineyards systems, we adopted the DIESE platform (DIscrete Event Simulation Environment, Martin-Clouaire and Rellier, 2009), which facilitates the modular construction of the biophysical model and the specification of the decision model in charge of monitoring and purposefully influencing behaviour that monitors and operates on the biophysical processes of the production system.

In this paper, we present the VERDI model (simulation of Vineyard intERcropped with DIese) designed to realistically reproduce the dynamic interactions between biophysical and decision processes in cover cropped vineyards. The structure of the model including its biophysical and management components is described. The relevance of this modelling approach for designing more robust cropping systems is analysed through a simulation study in which various adaptive management plans are evaluated under different climatic scenarios in terms of grape production and mitigation of runoff.

2. Description of the VERDI model

The aim of the VERDI model is to simulate flexible inter-row management plans in vineyards. To this end, the model represents the relationships between the agricultural activities carried out in the field and the biophysical system under the influence of weather. Management plans are called flexible because they generate management behaviours that are responsive to weather and condition of the biophysical system. In this section, the different types of flexibility implemented in the model are described, as well as the main principles of the DIESE platform and the functioning of the biophysical and decisional model in VERDI.

2.1. Types of flexibility in management plans

Considering agricultural production system, flexibility can be defined as the capacity of the farmer to change the structure, properties or behaviour of the system in order to adapt it to external changes (Cohendet and Llerena, 1999; Tarondeau, 1999) without changing the overall objective of the management efforts. As reported by several authors (Dedieu and Ingrand, 2010; Fountas et al., 2006), the sources of flexibility in an agricultural system can be found at different levels: strategic, tactical, and operational. These different levels are considered in the present work.

Strategic flexibility is the ability to modify the plan of actions because of changing circumstances, e.g. modifications of biophysical system dynamics or climatic evolution. The modifications induced by bringing strategic flexibility into use commit the manager for the mid- to long-term future. These modifications often lead to long-term impacts on the biophysical system. For example, sowing an intercrop strongly affects vineyard performance and the impact is irreversible until the next year. As the objective was to design more robust systems in terms of grapevine performance, the strategic adjustments were mainly made contingent to the soil water status.

Tactical flexibility is the capacity of the manager to adapt the implementation of activities by changing some of their properties or the time of their execution. This flexibility enables one to determine the optimal time to start each activity related to the current conditions of the biophysical system and external environment. Tactical flexibility influences the dynamics of the system without changing the objectives underlying the manager's strategy.

Operational flexibility concerns decisions regarding the execution of activities. It relates to the state-dependent conditions of feasibility of the underlying operation, the availability of resources, and other activities considered for concurrent execution. The actual execution date of an operation can be adjusted to meet more favourable climatic conditions (e.g., delay of the sowing date because of rain). If two operations cannot take place concurrently on a field, flexibility allows one to delay any of them and execute the one of greater priority. Operational flexibility neither alters the system dynamics nor the appropriateness of the current tactical decision process.

To summarize, the strategic, tactical, and operational levels of flexibility are complementary and enable management to be adapted to what is believed or perceived about the current, past, and future state of the production system and its environment. They can lead to different schedules of activities (operational and tactical levels) or different annual plans of activities (strategic level).

2.2. *Overview of the DIESE modelling framework*

DIESE is a modelling/simulation object-oriented framework implemented as a C++ package whose rationale, design, and functioning are fully described in Martin-Clouaire and Rellier (2009). Entity, process, and event are the three fundamental concepts used at this level to represent the structural, functional, and dynamic aspects of a system.

The ontology underlying this approach consists of the various concepts and properties that can be used to describe and represent the domain of knowledge. This enables reusing pre-formalized templates to match meaningfully the reality of the domain of concern thanks to well-defined, intuitive, and ready-to-use constructs. In this simulation framework, three interactive subsystems compose an agricultural production system: the manager, the operating system, and the biophysical system (Fig. 1). The manager acts in compliance with a strategy that, briefly expressed, is a purposive collection of interrelated activities.

A primitive activity denotes something to be done to a particular object (e.g., intercrop mowing) and has opening/closing conditions. Activities can be further constrained by operators enabling specification of temporal ordering, iteration, aggregation, and optional execution. Primitive activities constrained through such operators form non primitive or aggregated activities that can themselves be further constrained in the same way. DIESE provides a set of non primitive activities with evocative names such as *Before*, *Iterate*, and *Optional*. Others specify choice of one activity among several (*Or*), and grouping of activities in an unordered collection (*And*). Finally, all the activities are connected to form a plan, which constitutes the so-called strategy from which the manager derives the day-to-day agricultural decisions and actions. An operation represents the 'something to be done' component of a primitive activity (e.g. mowing operation). The change that the operation induces on the considered object is encoded in a functional attribute called 'state transition procedure'. Another important functional attribute specifies the feasibility conditions that preclude the execution of the operation if they are not satisfied at the intended execution time. The resources required (labour, equipment described in the operating system) are specified for each operation and, consequently, an operation can be delayed in case of competition for the same resources with another one.

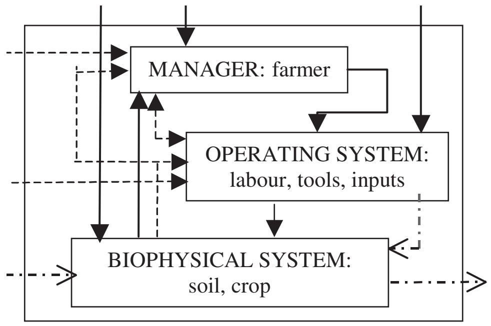

Fig. 1. Conceptual representation of an agricultural production system (from Martin-Clouaire and Rellier, 2009). - - - - ▶ Information. ——▶ Events. – · – · – > Matter or energy.

The DIESE simulation engine iteratively (every day typically) extracts from the plan the primitive activities whose opening conditions are satisfied and whose operations have satisfied feasibility conditions. The execution of these activities is then run until the next examination of the plan. The biophysical state changes under the influence of the biophysical processes that run concurrently and under the influence of the executed activities.

2.3. *Modelling of the biophysical system*

The VERDI model was conceived to be as generic as possible for a vineyard, either intercropped or not, and its management at field scale. The architecture of the biophysical system model was therefore built to take into account the diversity of layout encountered in vineyards.

The biophysical system model is made of a set of entities linked by different types of relationships and a set of biophysical processes coming from WaLIS, a water balance model designed for intercropped vineyards (Celette et al., 2010). The WaLIS model was parameterised in Mediterranean conditions (south of France) and evaluated on independent data sets from experiments carried out in Mediterranean and Atlantic regions (Delpuech et al., 2009). This model simulates the daily change in soil water availability expressed by the fraction of transpirable soil water (FTSW). This indicator was chosen in relation to its correlation with the grapevine water status and the grapevine performances, as shown by several authors (Baeza et al., 2007; Lebon et al., 2003; Pellegrino et al., 2005).

2.3.1. *Architecture of the biophysical system model*

In this study, we considered that a vineyard is a cropping system where two sub-cropping systems co-exist. The grapevine row and the inter-row were distinguished as they are associated with different management plans and differ in biophysical behaviours, in particular with respect to their water balance (Celette et al., 2008). The inter-row may also hold a crop (e.g., intercrop). The architecture of the biophysical system proposed takes into account this distinction (Fig. 2).

A *Vineyard Cropping System* is an entity composed of a *Field* and a *Weather* entity. The *Weather* entity conveys the current climatic conditions (temperature, rainfall, potential evapotranspiration) of the field of interest. A *Field* is composed of a *Vegetal Compartment* and a *Soil Reservoir*. The *Vegetal Compartment* describes the structure of the field through four elements of type *Row*. The first one is a *Grapevine row*, the second one is an *Inter-row next to the previous*

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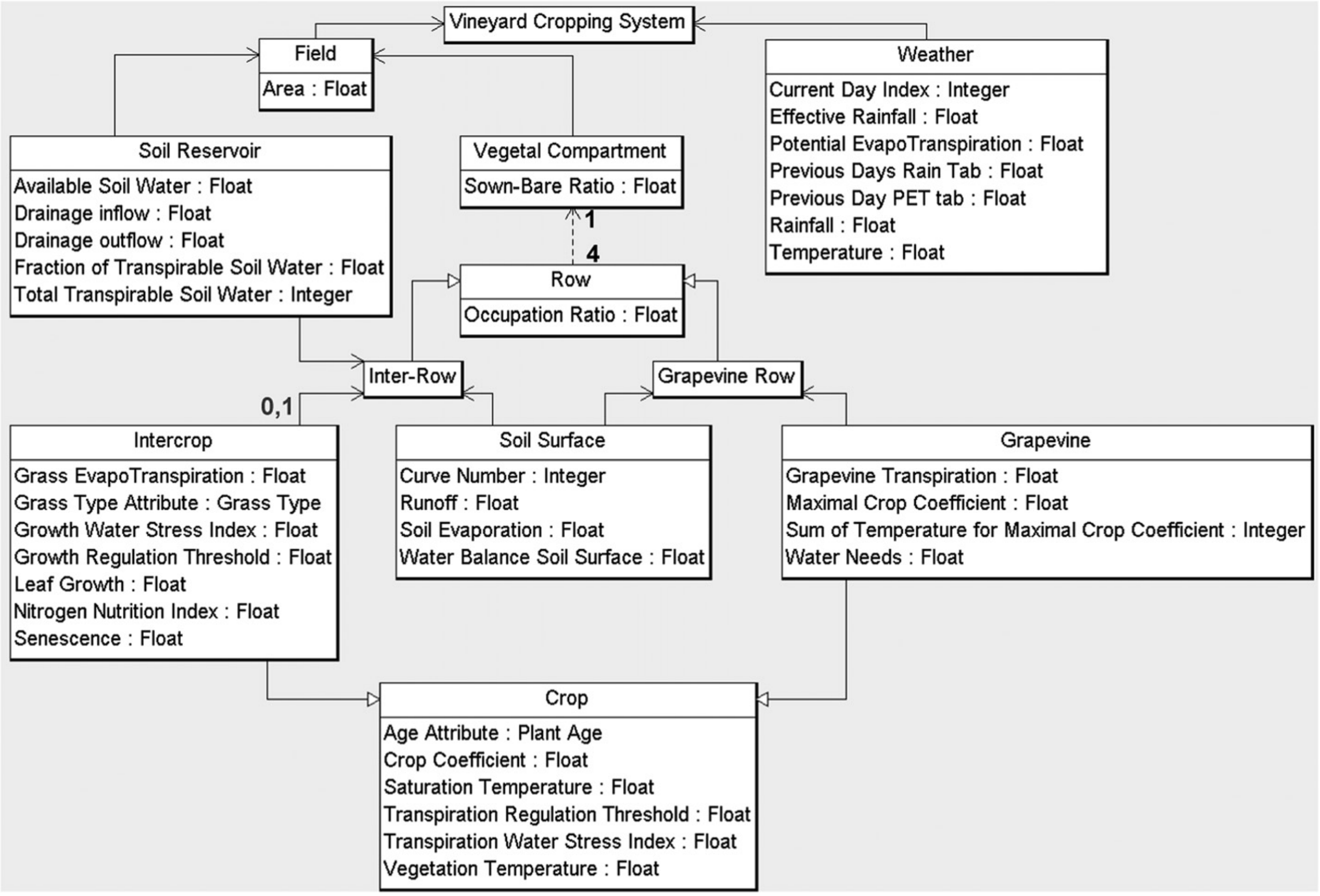

Fig. 2. Architecture of the biophysical system in VERDI (entities and associated descriptors). ——> Is a component of. ——▷ Is a particularization of. - - - - - -> Is an element of. The number above the *Row* entity means the *Vegetal Compartment* entity can have 4 elements of type *Row*. The numbers above the *Intercrop* entity means this entity can be a component of the *Inter-row* entity or not (e.g., in the case of a bare inter-row).

Grapevine row, the third is another *Grapevine row*, and the fourth is an *Inter-row next to the latter Grapevine row*. Typically in the first pair [*Grapevine row*; *Inter-row*], the *Inter-row* has an *Intercrop* component, whereas in the second pair it does not. The notion of next row is defined with respect to a side chosen arbitrarily for the two cases.

Each row has a descriptor ‘Occupation ratio’ that has the value p, $1 - p$, p', or $1 - p'$ where p is the proportion of the width of the grass strip with respect to the cumulated width of the inter-row and the *Grapevine row*, and p' is the proportion of the width of the bare inter-row with respect to the same cumulated width, which is assumed constant over the field (see Fig. 3). The ratio of the sown inter-rows (i.e. inter-rows holding an intercrop element) to the total number of inter-rows is captured in the ‘Sown-bare ratio’ descriptor of the *Vegetal Compartment* entity that has the value q.

Each row is linked to a particular *Soil Surface* entity. A *Soil Reservoir* component is also attributed to the *Inter-row* to

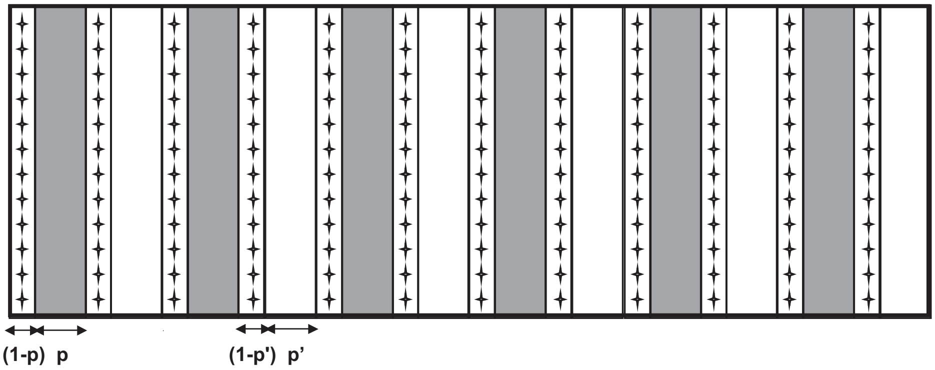

Fig. 3. Schematic representation of a vineyard cropping system in VERDI, example where the ‘Sown-bare ratio’ $q = 0.5$. The grey strips represent the sown inter-rows and the white strips represent the bare inter-rows. The parameters p and $(1 - p)$ represent the soil proportion dedicated to the inter-row and grapevine row, respectively, in a couple [sown inter-row; grapevine row]. The parameters p' and $(1 - p')$ represent the soil proportion dedicated to the inter-row and grapevine row, respectively, in a couple [bare inter-row; grapevine row] $(0 \leq (p \text{ and } p') \leq 1)$.

calculate the soil water balance in the compartment explored by the intercrop root system whereas the grapevine root system can explore both the *Soil Reservoir* of the inter-row next to it and the *Soil Reservoir* of the field. As explained by Celette et al. (2010), the two soil reservoir components communicate. When the soil reservoir of the inter-row is replenished, the water is drained from this component to the soil reservoir of the field. Finally, an entity *Crop*, having *Grapevine* and *Intercrop* as specializations, was created to gather the attributes shared by these two crops.

2.3.2. Biophysical processes

The main processes are runoff, drainage, and soil evaporation (in relation to a *Soil Surface* entity), plant growth and phenological development (in relation to *Intercrop* and *Grapevine*), and water balance (in relation to the *Soil Reservoir* of the *Field* or of the *Inter-row*).

The dynamics of the soil water reserves is assimilated to the dynamics of the available soil water (ASW). The daily changes in ASW in the *Soil Reservoir* of the *Inter-row* and of the *Field* are calculated as follows:

- in an *Inter-row* (if the *Inter-row* is bare, p should be replaced by p')

$$\Delta \mathrm{ASW}_{\mathrm{ir}}(j) = (P_{\mathrm{ir}} - R_{\mathrm{ir}}) \times p - \mathrm{ETR}_{\mathrm{ir}} - T_{\mathrm{g}} \times \mathrm{ASW}_{\mathrm{ir}}(j-1)/\mathrm{ASW}_{\mathrm{f}}(j-1) \tag{1}$$

- in the *Field*, if all inter-rows are sown, i.e., $q = 1$ (if all inter-rows are bare, $(1 - p)$ should be replaced by $(1 - p')$),

$$\Delta \mathrm{ASW}_{\mathrm{f}} = (P_{\mathrm{r}} - R_{\mathrm{r}}) \times (1 - p) + D_{\mathrm{ir}} - \mathrm{Es}_{\mathrm{r}} - T_{\mathrm{g}} \times \left(1 - \mathrm{ASW}_{\mathrm{ir}}(j-1)/\mathrm{ASW}_{\mathrm{f}}(j-1)\right) + \Delta \mathrm{ASW}_{\mathrm{ir}} \tag{2}$$

where ‘ir’ refers to the inter-row, ‘r’ to the row, and ‘g’ to the grapevine; P is rainfall, R the runoff, ETR the evapotranspiration of the intercrop, D the drainage, T the transpiration of the grapevine, and Es the evaporation of the bare soil.

The daily soil water status is calculated at field level ($\mathrm{FTSW}_{\mathrm{f}}$); it corresponds to the ratio of the $\mathrm{ASW}_{\mathrm{f}}$ over the total transpirable soil water of the *Field Soil Reservoir* ($\mathrm{TTSW}_{\mathrm{f}}$). On day j, the total ASW available to the grapevine is:

$$\mathrm{ASW}_{\mathrm{f}}(j) = \mathrm{ASW}_{\mathrm{f}}(j-1) + \Delta \mathrm{ASW}_{\mathrm{f}}(j) \tag{3}$$

$$\mathrm{FTSW}_{\mathrm{f}}(j) = \mathrm{ASW}_{\mathrm{f}}(j)/\mathrm{TTSW}_{\mathrm{f}} \tag{4}$$

The other formalisms used in the WaLIS model were described by Celette et al. (2010) and Lebon et al. (2003). To take into account the parameters and variables used for the processes related to intercrop growth, an entity *Intercrop Type* was created, linked to the *Intercrop* entity through the descriptor ‘Grass Type Attribute’.

Some adaptations were made to deal with the phenology of both the grapevine and the intercrop. In the original model, the main grapevine phenological stages are not all represented and, when they are, they occur at fixed dates; the emergence is the only stage of the intercrop that is represented. Because some activities or processes used in the present work depend on these stages, we had to represent them explicitly and dynamically. For instance, processes related to intercrop growth are activated at the ‘emergence’ stage of the intercrop whereas those related to grapevine growth begin at budbreak. Considering these points, *Plant Age* and *Phenology* entities were added in relation to the *Crop* entity (Fig. 4), equipped with general services that check whether a shift to the next stage is required, operate the change, and trigger possible casual consequences.

Six stages were defined for the grapevine: budbreak, flowering, veraison, maturity, harvest, and dormancy. Only three stages were defined for the intercrop: germination, emergence, and death. Indeed, the objective of the intercrop in the vineyards we considered here is not the production of grass but of ecological services. Consequently, the intercrop flowering and harvest stages are never reached. Budbreak and dormancy are defined by a fixed date whereas the other grapevine phenological stages are defined by a sum of growing degree-days calculated from budbreak. These parameters were based on previous experiments (unpublished data). For both grapevine and intercrop, the changes of the phenological stages, which consist in modifying the value of the descriptor ‘Current Stage Index’, occur when the corresponding date or the threshold of cumulated growing degree-days is reached. In the case of the intercrop, ‘germination’ or ‘death’ is reached when sowing or intercrop destruction is carried out, respectively.

2.4. Modelling of the management system

In this work, we studied the behaviour of intercropped vineyards in response to different types of soil surface management. The activities related to the management of bare and intercropped soils at the field scale are central in this investigation, but no

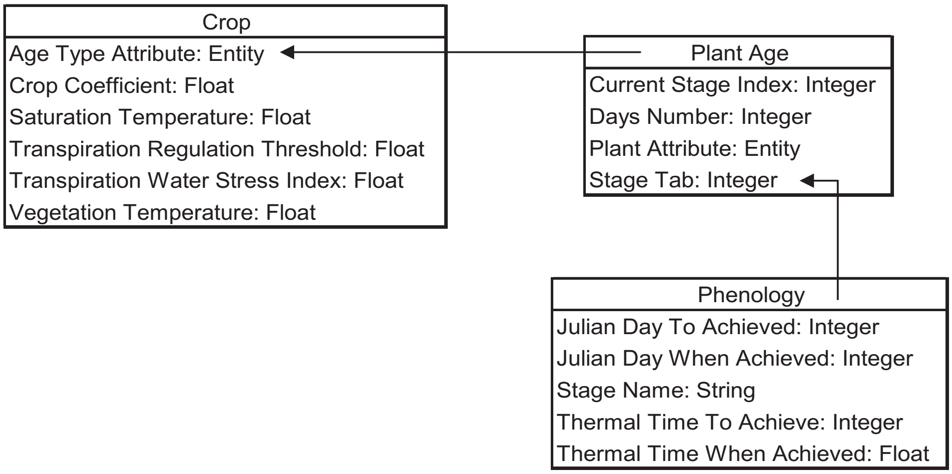

Fig. 4. Relationships between the *Crop*, *Plant Age* and *Phenology* entities and description of their associated descriptors.

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consideration was given to possible competition with activities occurring on other fields, i.e., it was assumed that there is no shortage of resources such as labour or machinery at the farm scale. As the management of the inter-row included some activities occurring during the grapevine production cycle, this could induce in-field competition between the activities to carry out on the grapevine row and on the inter-row. We considered the most important activities on the grapevine, i.e. those related to the grapevine protection, and gave them priority over any activity related to inter-row. We established the characteristics of each activity and operation on the basis of surveys carried out in the Mediterranean region (Barbier et al., 2009), relevant literature (Roby and Van Leeuwen, 2000), and interviews of experts. Like the biophysical system, the management system was simulated with a one-day time step.

2.4.1. Primitive activities and their associated operations

Five types of activities were defined: chemical pest control, chemical weeding, tillage, sowing, and mowing. Different specializations of chemical weeding and tillage have been developed by exploiting the inheritance facility provided by DIESE. The different activities are detailed in Table 1 and the example of tillage is detailed below. The tillage activities were separated into two categories depending on their period of execution: autumn or spring. This distinction corresponds to a difference of objective: on the one hand, to decompact the soil or prepare the seedbed in autumn, on the other hand, to destroy the intercrop or maintain the soil bare during the grapevine growth cycle. A further differentiation in the case of autumn tillage can be made by choosing an operation that either decompacts the soil or prepares the seedbed in an intercropping strategy.

In the case of the spring tillage, we differentiated a spring tillage aimed at destroying the intercrop ("*ST for destruction*") from tillage aimed at maintaining the soil bare ("*Spring Tillage*"). The latest date for executing these activities was at mid or end of July. These two activities differ with respect to the operations they use (either "*Mechanical intercrop destruction*" or "*Mechanical weeding*") and with respect to their opening conditions, which add up to those applicable to any spring tillage activity, i.e. elapsed time constraint since last spring tillage and rainfall related constraint. The "*ST for destruction*" activity is an intercrop destruction that depends on the soil water status ('reference' $\mathrm{ASW_f}$, see Table 1). To define this reference value, we estimated the grapevine water needs for 15 days from budbreak to July (potential time of intercrop destruction). This two-week interval was chosen to enable accurate assessment of the dynamics of the soil water status. According to the optimal trail of water stress established by Pellegrino et al. (2006), which allows the FTSW dynamics to be related to the grapevine agronomic performances, we defined an 'optimal' soil water reserves value for every 15 days too. Then, we calculated the 'reference' $\mathrm{ASW_f}$ every two weeks from budbreak to July as the sum of the optimal $\mathrm{ASW_f}$ value and the grapevine water needs.

Spring tillage is done in relation to either grapevine protection ("*ST before chemical treatment*") or weather conditions and the time lag since the previous tillage. The different consequences induced on the biophysical system are expressed via their corresponding operations, i.e., the "*Mechanical intercrop destruction*" and the "*Mechanical weeding*" operations, detailed in Table 2.

The effect of the tilling operations was a modification of the curve number (CN) value in relation to the change in the characteristics of the soil surface they induced. When the soil is tilled, the ratio runoff/infiltration is modified (Leonard and Andrieux, 1998).

Table 1
Description of the activities represented in the VERDI model. The activities in bold print are the five main types of primitive activities. Earliest and latest dates refer to the dates within which the activity can be opened. ST = Spring Tillage, $Z = X = 21$; $Y = 30$ mm. The 'reference' $\mathrm{ASW_f}$ is the value below which the water stress is not acceptable for grapevine. LAI for mowing is the LAI value above which the cover crop has to be mowed, here LAI for mowing = 3.

Activity	Opening conditions	Closing conditions	Earliest date	Latest date	Operation(s) associated
Chemical pest control	–	–	–	–	*Chemical pest operation*
Chemical weeding	–	–	15th January	15th July	*Chemical weeding operation*
Chemical weeding before budbreak	–	–	15th January	15th July	*Chemical weeding operation for bare soil*
Chemical weeding for destruction	$\mathrm{ASW_f} <$ 'reference' $\mathrm{ASW_f}$		Grapevine stage = budbreak	15th July	*Chemical intercrop destruction*
Last chance for chemical weeding before summer	Intercrop stage ≠ DEATH		16th July	21st July	*Chemical weeding operation for bare soil*
Mowing	LAI > LAI for mowing	–	1st February	15th July	*Mowing operation*
Sowing	–	–	15th October	Beginning of pruning (November)	*Sowing operation*
Tillage activity	–	–	–	–	*Tilling operation*
Autumn Tillage	–	–	***Z*** days after harvest	Beginning of pruning (November)	*Soil decompaction* **or** *seedbed preparation*
		–	–	–	
Spring Tillage	No ST already occurred **or** (ST already occurred, **and *x*** days between the STs **and *Y*** mm of rainfall during this ***X*** days period)	– –	15th January –	15th July –	*Spring tilling operation*
ST before chemical treatment	–	–	15th January	First chemical treatment for grapevine protection	*Mechanical weeding*
ST for destruction	$\mathrm{ASW_f} <$ 'reference' $\mathrm{ASW_f}$	–	Grapevine stage = budbreak	15th July	*Mechanical intercrop destruction*
Last chance for ST for destruction before summer	Intercrop stage ≠ 'DEATH'	–	16th July	21st July	*Mechanical intercrop destruction*
Last chance for ST for weeding before summer	No ST occurred from budbreak	–	16th July	21st July	*Mechanical weeding*

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Table 2
Conditions characterizing the operations represented in VERDI. The operations in bold correspond to the five main types of primitive activities. P = rainfall; CN = curve number; j = current day. $X_1 < Y_1$ and $X_2 < Y_2$, where $X_1 = 40$ mm; $Y_1 = 60$ mm; $X_2 = 2$ mm; $Y_2 = 10$ mm.

Operation	State transition procedure	Feasibility conditions
Chemical pest operation	–	$(P[j-7;\, j] < \mathbf{X}_1$ and $P(j) < \mathbf{X}_2$ **or** $P[j-7;\, j] < \mathbf{Y}_1$ and $P(j) < \mathbf{Y}_2)$ **and** $P(j+1) = 0$
Chemical weeding operation	–	
Chemical weeding operation for bare soil	–	$P[j-7;\, j] < \mathbf{X}_1$ and $P(j) < \mathbf{X}_2$
Chemical intercrop destruction	Intercrop stage modification to ‘Death’	$P(j-1) < \mathbf{X}_1$ and $P(j) < \mathbf{Y}_2$
Mowing operation	LAI = LAI after mowing	$P(j-1) < \mathbf{Y}_2$ and $P(j) < \mathbf{Y}_2$
Sowing operation	Activation of the process of the intercrop phenology evolution Modification of the intercrop stage to ‘Germination’	$P[j-10;\, j] < \mathbf{X}_1$ and $P(j-1) < \mathbf{X}_2$
Tilling operation	CN modification	
Autumn tilling operation	CN modification	$P[j-10;\, j] < \mathbf{X}_1$ and $P(j-1) < \mathbf{X}_2$
Seedbed preparation	CN modification Soil prepared for sowing	$P[j-10;\, j] < \mathbf{X}_1$ and $P(j-1) < \mathbf{X}_2$
Soil decompaction	CN modification Soil not prepared for sowing	$P[j-10;\, j] < \mathbf{X}_1$ and $P(j-1) < \mathbf{X}_2$
Spring tilling operation	CN modification	
Mechanical intercrop destruction	CN modification Intercrop stage modification to ‘Death’	If $P[j-7;\, j] < \mathbf{X}_1$ and $P(j) < \mathbf{X}_2$
Mechanical weeding	CN modification	If $P[j-7;\, j] < \mathbf{Y}_1$ and $P(j) < \mathbf{Y}_2$

This causality is taken into account through the change of the CN value used in the runoff process. Activating the operation of intercrop destruction involves a move to the ‘death’ stage for the intercrop, which indirectly deactivates the processes related to the intercrop growth and activates the process of soil evaporation. The conditions of feasibility also differ according to the considered operations. In the case of intercrop destruction, the thresholds of rainfall cumulated over a week were higher because the presence of an intercrop in the inter-row improves field trafficability. These few examples show how the tactical and operational flexibility were represented in the model. The management system monitors the biophysical system through different types of indicators used in the opening–closing conditions of the activities and the feasibility conditions of the operations. The indicators refer to the past and present weather (e.g., feasibility conditions based on rainfall), the phenological stages reached by the grapevine (e.g., opening conditions of autumn tillage), the soil water status, or the state of intercrop growth (e.g., opening conditions of intercrop destruction or mowing).

2.4.2. Building of the strategies

As explained above, we considered a strategy as the association of the plans established for the two sub-cropping systems (row and inter-row). The strategies were built at the grapevine production cycle scale (it starts just after the harvest of a year n and stops at the harvest of year $n+1$) but plans were established to be run repeatedly over several years.

The annual management plan defined for the *Grapevine row* is limited to crop protection, which consisted of an iteration of pesticide application (Fig. 5a). A pesticide application is always given higher priority than any other activity. This plan is the same for all strategies and is considered because of possible in-field competition with the activities in a plan for the *Inter-row*. A pesticide application activity is opened every 15 days (‘Iterate’ activity). The earliest date for executing this activity is three weeks after budbreak and its latest date corresponds to the achievement of the phenological grapevine stage ‘veraison’.

Three annual management plans (Fig. 5b, c, d), including flexibility at tactical and operational levels, were defined for the *Inter-row*:

a) Grapevine pest control

```
Iterate (Chemical Pest Control)
```

b) Permanent intercropping

```
Before (
        Autumn Tillage,
        Sowing,
        Iterate (Mowing)
       )
```

c) Permanent bare soil

```
Before (
        Optional (Autumn Tillage),
        ST before chemical treatment,
        Iterate (Spring Tillage),
        Optional (Last chance for ST for weeding before summer)
       )
```

d) Temporary intercropping

```
Before (
        Autumn Tillage,
        Sowing,
        Before (And (Iterate (Mowing)),
                     Iterate (Optional (ST for destruction))),
             Optional (Iterate (Spring Tillage)),
             Optional (Last chance for ST for destruction before summer),
       )
```

e) Mixed plan

```
Before (
        Optional (Autumn Tillage),
        Optional (Sowing),
        Or (Before (And (Iterate (Mowing)
                          Iterate (Optional (ST for destruction))),
                  Optional (Iterate (Spring Tillage))),
            Before (ST before chemical treatment,
                     Iterate (Spring Tillage),
                     Optional (Last chance for ST for weeding before summer)))
       )
```

Fig. 5. Description of the annual management plans for grapevine protection (a), permanent intercropping (b), permanent bare soil (c), temporary intercropping (d), and the mixed plan (e). ST = Spring tillage. Primitive activities are in italics. The non primitive activity defined by the operator ‘Before’ allows sequencing the different primitive or non primitive activities. The non primitive activity defined by the operator ‘Optional’ means the activity may never be open, it not compromises the plan. The non primitive activity defined by the operator ‘Or’ specifies an exclusive choice among different activities whereas the non primitive activity ‘And’ allows the occurrence of different activities without ordering. Finally, the non primitive activity defined by the operator ‘Iterate’ allows repeating an activity.

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- **permanent intercropping**: the intercrop is sown after an autumn tillage and maintained throughout the year whatever the soil water status. Then, some mowing activities are repeated in relation to the value of the leaf area index of the intercrop (Fig. 5b);
- **permanent bare soil**: the soil is kept bare throughout the year by chemical or mechanical weeding (Fig. 5c);
- **temporary intercropping**: the intercrop is sown, maintained with mowing, and possibly destroyed depending on the soil water status (Fig. 5d).

Fig. 5c presents the mechanical option of the annual management plan for permanent bare soil. In this plan, the "*Autumn Tillage*" activity can be cancelled ('Optional' activity, line 2) in relation to unfavourable climatic conditions to execute soil decompaction. The "*Last chance for ST for weeding before summer*" activity is also declared as optional (line 5). It is opened if no "*Spring Tillage*" is executed during the grapevine growth cycle to maintain the soil bare during summer and thus to avoid any competition between weeds and grapevine.

For temporary intercropping (Fig. 5d), after sowing, mowing is iterated until circumstances might require to turn to destruction of the intercrop. This possibility is given by the use of the 'And' activity (line 4) associating an iteration of mowing with an optional iteration of destruction. In this plan, the destruction of the intercrop is decided with respect to the soil water status, i.e., if ASW_f is lower than the 'reference' ASW_f (opening conditions of the "*ST for destruction*"), checked every 15 days ('Iterate' activity, line 5) from budbreak to mid July. Ultimately, if not already achieved, the destruction is forced in mid July with the opening of the activity "*Last chance ST for destruction before summer*".

To build a strategy including flexibility at strategic, tactical, and operational levels, we defined the plan called 'mixed plan' by combining the three plans above (Fig. 5e). This 'mixed plan' implements the idea that the intercrop may be introduced temporarily or permanently according to the soil water status. The sowing activity may be cancelled in case of unfavourable climatic conditions or late grape harvest and was therefore declared optional in the plan (line 3). When no sowing is done, plan e becomes similar to the annual bare soil strategy (line 7–9), through its second alternative of disjunction ('Or' activity, line 4). Conversely, if sowing is done, mowing is iterated until circumstances require destroying the intercrop as in the temporary intercropping plan. Nevertheless, in this 'mixed' plan, if no destruction is done, the intercrop is maintained throughout the year as in a permanent intercropping plan.

Finally, a plan like the 'mixed' one can lead to three possibilities according to the state of the biophysical system and of the weather conditions. Other plans were created based on this example in which the destruction of the intercrop was associated to a change in the field configuration or a modification of the intercrop sown the next year. In the first case, parameter q was modified from 1 to 0.5 in case of intercrop destruction whereas in the second case, an intercrop less demanding in water was sown the next year.

As explained above, a strategy is the combination (through an 'And' activity) of an annual plan defined for the *Grapevine row* and another one for the *Inter-row*. For more readability, an annual strategy can therefore be described as the following, based on the different plans presented in Fig. 5 (referenced as a, b, c, d, and e):

And (a,b) And (a, c) And (a, d) And (a, e)

As pluriannual simulations had to be done, the annual strategies that we created are iterated over several grapevine growth cycles. Thus, the pluriannual strategies are described as follows:

Iterate (And (a, b)) Iterate (And (a, c)) Iterate (And (a, d)) Iterate (And (a, e))

3. Comparison of three strategies

3.1. Material and methods

3.1.1. The climatic scenarios and the strategies simulated

A simulation study was carried out (i) to evaluate the ability of the model to correctly represent the adaptive management of intercropping and (ii) to test the relevance of the flexibility to maintain agronomic and environmental performances despite climate variability. Three strategies were studied in this example: a bare soil strategy in which the soil was maintained bare with mechanical weeding, a permanent intercropping strategy, and a strategy based on the 'mixed' plan described above (Section 2.4.2.).

Three climatic scenarios over four-year-long periods were used. The scenarios consisted in 1) alternating a rainy year with a dry one, 2) alternating two dry years with two rainy ones, 3) using the climatic record in the Mediterranean region (Villeneuve-lès-Maguelone, 43°31 N, 3°51 E) over the years 2005–2008. In the first two options, the temperature and potential evapotranspiration were the same over all the years. The rainy year was defined to be at the limit of the fifth quintile in the distribution of yearly rain in the region (950 mm, 2004), whereas the dry year was defined to be at the limit of the first quintile (475 mm). In both cases, the rainfall partitioning was the one observed in 2004. The initial input values and parameters used for the simulation study and presented in Table 3 were taken from the literature (Celette et al., 2010; Duru et al., 2009; McMaster et al., 2005) or based on experiments.

3.1.2. Model validation and evaluation of the performances of the strategies

The three strategies were simulated over the three climatic scenarios. In relation with our interest in modelling adaptive management plans, the ordering and timing of the activities executed for these strategies were compared. To analyse the consistency of the model, the grapevine phenological stages simulated over the real climatic scenario (2005–2008) were compared to data observed in the field, as well as the mowing schedules in the permanent cover cropping strategy (Celette, 2007; Ripoche et al., 2011). Experts evaluated the schedules of activities for the bare soil strategy.

Table 3
Inputs and parameters used for the three strategies of soil surface management. GDD = growing degree-days, LAI = leaf area index.

Biophysical parameters	Bare soil strategy	Permanent intercropping/ mixed strategy
Soil parameters		
CN bare soil	91	91
CN tilled soil	80	80
CN sown soil	–	84
Grapevine parameters		
Budbreak	31/3	31/3
Flowering	350 GDD	350 GDD
Veraison	1170 GDD	1170 GDD
Maturity-harvest	1540 GDD	1540 GDD
Vegetation temperature	10	10
Sum of GDD for maximal cultural coefficient	600	600
Transpiration regulation threshold	0.4	0.4
Intercrop parameters		
Vegetation temperature	–	0
Saturation temperature	–	18
Growth regulation threshold	–	0.9
Transpiration regulation threshold	–	0.6
Emergence	–	150 GDD
LAI for mowing	–	3
LAI residual after mowing	–	0.3
LAI rate	–	0.9
Leaf life span	–	700 GDD
Input variables		
Occupation ratio (p or p')	0.7	0.7
Sown-bare ratio (q)	0	1
$TTSW_f$	250	250
ASW_f (0)	250	250
$TTSW_{ir}$	–	95
ASW_{ir} (0)	–	95

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The consequences of flexibility with respect to the agronomic and environmental performances of the strategies were assessed using the methodology presented by Ripoche et al. (2010) and based on a multiple criteria analysis (Loyce et al., 2002). Four criteria were defined: vegetative development, yield, product quality, and environmental impact. The three indicators related to the agronomic criteria (vegetative development, yield, product quality) were based on the average values of FTSW calculated over three periods: from grapevine budbreak to flowering, from flowering to veraison, and from veraison to harvest, respectively. The ratio annual runoff/annual rainfall was used as the indicator of environmental impact.

The agreement and discordance degrees ($C(a)$ and $D(a)$, respectively) were calculated for the four criteria. They represent the degree of satisfaction or dissatisfaction relative to the objectives of agronomic and environmental performance expected from the cropping systems. Considering the agronomic criteria, $C(a)$ and $D(a)$ were calculated on the basis of the optimal trajectory of FTSW established by Pellegrino et al. (2006). They were aggregated considering the same weight (w_j) for each criterion to obtain a final score, the degree of overall agreement called $R(a)$ (for more details, see Ripoche et al., 2010):

$$C(a) = \sum_{j=1}^{4} w_j * C_j(a) \tag{5}$$

$$D(a) = 1 - \prod_{j=1}^{4} \left(1 - D_j(a)^{w_j}\right) \tag{6}$$

where j represent the criteria, $\sum_{j=1}^{4} w_j = 1$ and $w_j = 0.25$.

$$R(a) = C(a) * (1 - D(a)) \tag{7}$$

The closer to 1 the final score $R(a)$, the better the performance of the cropping system.

3.2. Results

The comparison between observed and simulated dates of the grapevine phenological stages and schedule of mowings over the real weather scenario (2005–2008) in the permanent intercropping strategy showed that the VERDI model simulated faithfully the grapevine development and cover crop growth (Fig. 6, Table 4).

In spite of the fact that budbreak was fixed at the same date over the years, the simulation of the phenological stages was satisfactory (Fig. 6). The RMSE calculated for each stage were relatively low (from 1.3 to 3.1 days for flowering and harvest respectively). The higher difference between observed and simulated dates was observed in 2008 at harvest. The timing of the simulated sequence of mowings was consistent with the one observed in the field for the permanent intercropping strategy (Table 4). The number of mowings, simulated or observed, evolved over the 2005–2008 years in relation to weather and to the resulting cover crop growth. The same order of magnitude was observed between the two sets of data (simulated and observed). The difference between observed and simulated occurrences of mowings in the permanent intercropping strategy could be related to an overestimation of the cover crop growth during the winter with a LAI that rose above the threshold and thus activated mowing, or a competition with other activities (carried out on other fields of the farm or on other components of the field, e.g. grapevine row management) and not taken into account here. For the bare soil strategy, the number of mechanical weedings occurring during the grapevine production cycle varied from 2 to 5 per year in relation to the quantity of rainfall during this period that seemed consistent with the experts' judgement.

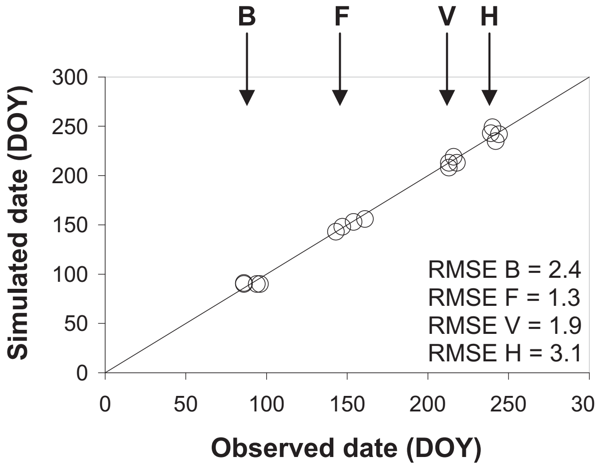

Fig. 6. Observed and simulated date of budbreak (B), flowering (F), veraison (V) and harvest (H) under the 2005–2008 climate scenario. DOY = day of year, RMSE = root mean square error (in days).

Table 4
Observed and simulated dates of mowings for the permanent intercropping strategy over the third climatic scenario (2005–2008).

	Date observed	Date simulated
2005	09/05	05/05
2006	–	01/02
	11/05	16/04
2007	–	01/02
	27/03	01/04
	23/04	30/04
	11/05	24/05
	25/06	22/06
2008	–	02/03
	02/04	24/04
	13/05	22/05
	05/06	14/06

Considering the 'mixed' strategy, an evolution of the management plan and therefore of the annual schedule of activities was observed for example over climatic scenario 2 (alternation of two dry years with two rainy ones). The LAI dynamics of the cover crop and the operations executed on it are presented in Fig. 7.

The dates of sowing varied between 14 October and 24 October. The inter-row cover crop growth was particularly low during the first two dry years (one or no mowing) whereas during the rainy years, 3–4 mowings were executed; the activity was opened when the cover crop LAI had exceeded 3 (see Table 3). Table 5 presents the dates of the cover crop destruction observed in the 'mixed' strategy under the three climatic scenarios.

In the first climate scenario (one rainy year alternating with a dry one), the cover crop was destroyed only once the second year, when the climate was dry. In the second scenario, destruction occurred twice, during the two dry years at two different periods, the first year close to grapevine flowering (03/06), the second year at budbreak (02/04) because the drought was already severe due to the cumulated effect of the two dry years. Under the real weather (scenario 3), the intercrop was destroyed in 2006, 2007, and 2008. In 2006, this can be explained by the severe drought during the production cycle (65 mm from March to August) whereas in 2007 and 2008, it was mainly due to a dry winter (328 mm from September to March in 2007–2008) or heavy rains that generated a high runoff (Gaudin et al., 2010) and did not allow good water infiltration as in September 2006 (e.g., 100 mm in one day, over 480 mm during the winter 2006–2007).

The impacts of the different strategies were assessed in terms of production and environmental performances for each climatic scenario (Fig. 8).

In the case of the first scenario, i.e. one rainy year alternating with a dry one (Fig. 8a, d and g), the agronomic performances of the three strategies were high over the four years. The score obtained with the three strategies was maximal or close to it. Considering the environmental performance, the score was higher during the dry years whatever the strategy in relation to the lower rainfall

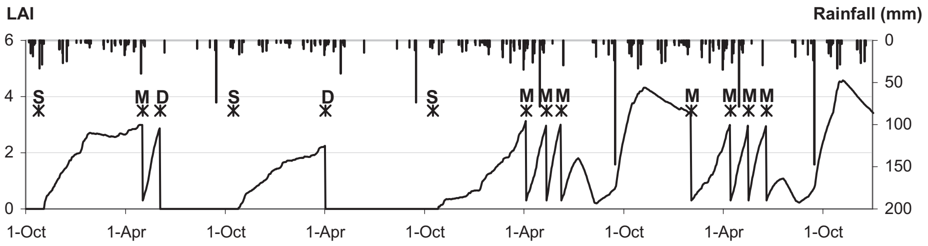

Fig. 7. LAI dynamics and occurrence of the different operations of the intercrop over scenario 2, i.e., alternation of two dry years and two rainy years. The occurrences of the different operations are indicated by an asterisk: S = sowing, M = mowing, D = destruction.

and consequently lower runoff than during the rainy years. Nevertheless, the scores remained satisfying (above 0.17 corresponding to a ratio runoff/rainfall lower than 0.3). The alternation of dry and rainy years reduced the risk of a severe drought. During the humid year, the winter rainfalls replenished the soil reserves, which met the demand during the subsequent dry year (FTSW = 0.9 or 0.7 at budbreak during the dry years for the permanent intercropping and 'mixed' strategies, and the bare soil strategy, respectively). In contrast, a sequence of two dry years decreased the agronomic performances sharply the second dry year (Fig. 8b, e, h) especially for the bare soil and permanent inter-row cover cropping strategies whereas the score obtained in the 'mixed' strategy remained high (around 0.36 and 0.23 *vs.* 0.66 respectively). As for the first climatic scenario, the environmental performance was lower during the rainy years. Noticeably, the 'mixed' strategy resulted in high performance for both the agronomic and environmental criteria all along the four years of scenario 2.

The same trend was observed under the real weather in 2008 (scenario 3; Fig. 8c, f and i); the bare soil and permanent inter-row cover cropping strategies showed lower agronomic performances than the 'mixed' strategy (around 0.64, 0.5, and 0.75 respectively). This resulted from the dry winter and the little rainfall during the grapevine cycle (190 mm from March to August 2008). In this scenario, environmental performances were more contrasted than for the two other climatic scenarios (from 0.16 to 0.22). It could be explained by intensive rainfall in short period inducing higher runoff whatever the strategy considered.

In spite of similar agronomic performances in 2007, the FTSW of the 'mixed' strategy was higher than the FTSW simulated for the permanent intercropping and for the bare soil strategies during all the grapevine cycle (Fig. 9).

As the level of FTSW remained satisfactory for the three strategies, the difference was slight in terms of agronomic performances. Nevertheless, the drought observed the following year (2008) accentuated the contrast between the 'mixed' strategy and the two others. As the soil water reserve was not replenished during the 2007–2008 winter, the FTSW values were lower than in 2007 whatever the strategy. Consequently, the average FTSW values over the three different periods of interest for the bare soil and the permanent intercropping strategies were less satisfactory than those of the 'mixed' one. The agronomic performances were higher in bare soil strategy than in the permanent cover cropping one (Fig. 8c, f). These results were validated by field observations (Ripoche et al., 2011), in which yield decreased sharply between 2007 and 2008 and the average yield observed on bare soil was higher than the one observed in permanent intercropping treatment (4.8–3.2 kg plant^{-1} for bare soil and 3.3–1.6 kg plant^{-1} for permanent intercropping strategy).

Table 5
Annual rainfall (mm) and occurrences of intercrop destruction for the 'mixed' strategy simulated over the three climatic scenarios. Scenario 1 = rainy and dry year alternately; scenario 2 = two dry years followed by two rainy ones; scenario 3 = climatic record in a Mediterranean region over the years 2005–2008.

	Scenario 1		Scenario 2		Scenario 3	
	Annual rainfall	Date of destruction	Annual rainfall	Date of destruction	Annual rainfall	Date of destruction
Year 1	950	No destruction	475	03-Jun	690	No destruction
Year 2	475	06-Jul	475	02-Apr	650	19-may
Year 3	950	No destruction	950	No destruction	550	01-Apr
Year 4	475	No destruction	950	No destruction	660	31-Mar

4. Discussion and conclusion

4.1. Interest of the modelling approach

As a knowledge-based computing environment supporting the modelling and simulation of production system, DIESE has certainly fastened the modelling process by bringing ready-to-use structures and principles. The gain was in the guidance and rigour provided by the framework and in the reduction of the programming effort. We did not encounter any major difficulty in designing the VERDI model and organizing our knowledge on the vineyard cropping systems and their biophysical and management components. The activity-based modelling of management ensured by DIESE allowed for a more natural representation of management behaviour and the various interactions either within the decision system (e.g., the use of non primitive activities like '*Before*', '*Optional*'… to express the relationships between primitive activities) or within the biophysical system and the external environment. It captures a level of detail about information flow that is very useful in explaining the timing and relevance of the management process. The distinction between activity and operation enabled us to structure the different types of conditions that these notions imply: e.g., opening or closing conditions for activities, state transition procedure or feasibility conditions for operations. These capabilities were essential to design new management plans for inter-rows in which flexibility could be integrated at different levels (operational, tactical and strategic). Several studies on crop-livestock farming systems also emphasized the importance of management flexibility towards more sustainable farming systems (Darnhofer et al., 2010; Dedieu and Ingrand, 2010). For example, Coléno and Duru (1999) and Martin et al. (2011) highlighted the relevance of flexible grazing strategies to satisfy farm performances (herbage production and quality, farm organization). Almost all other modelling frameworks dealing with cropping systems management rely on a rule-based representation that can become cumbersome when the number of rules is high, making

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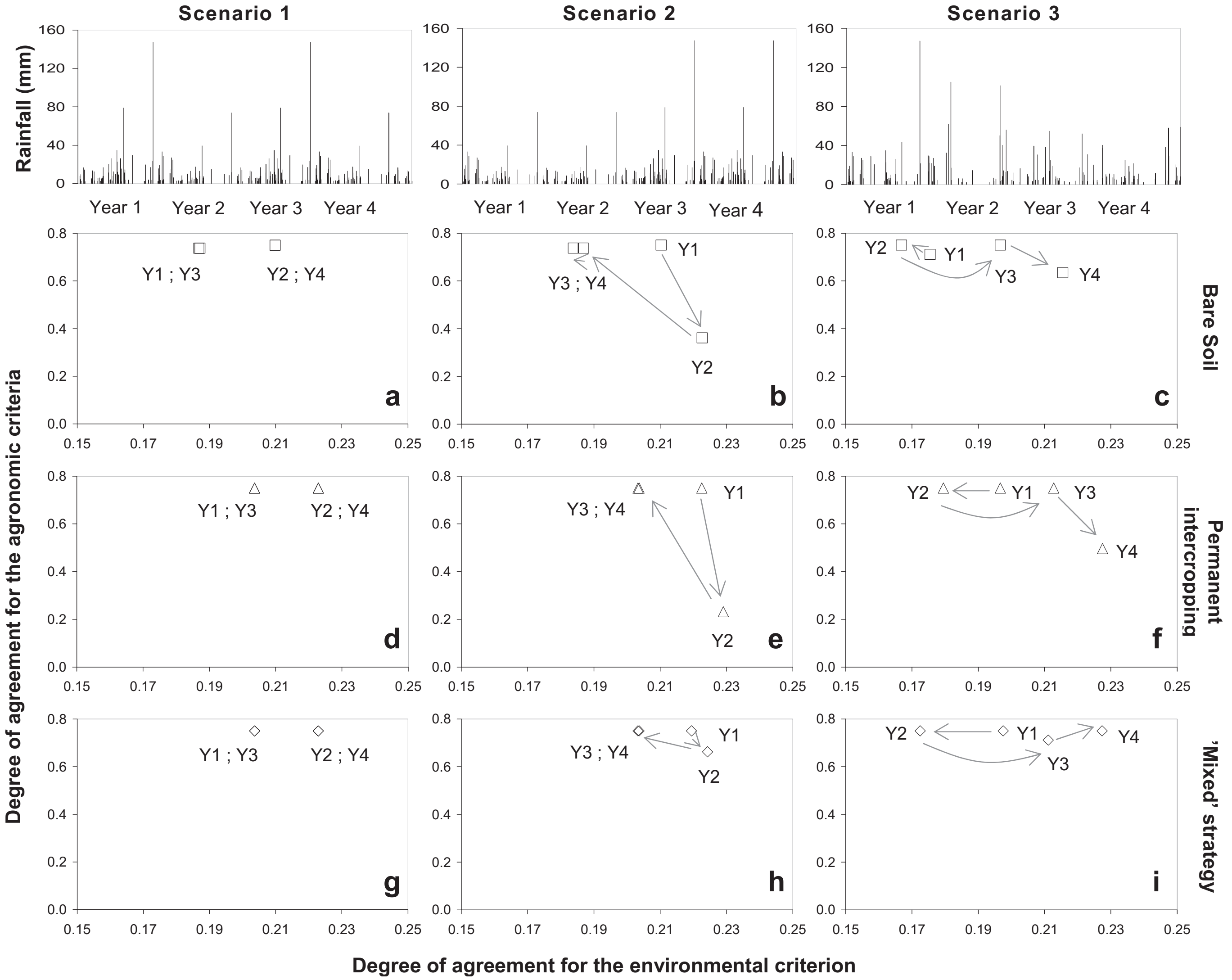

Fig. 8. Degree of agreement for agronomic and environmental criteria obtained over the three climate scenario for bare soil (a, b and c; □), permanent intercropping (d, e and f; △) and 'mixed' strategy (g, h and i; ◇). The maximal degree of agreement was 0.75 and 0.25 for productive and environmental criteria respectively. Y = Year. Fort the scenario 3, Y1, Y2 Y3 and Y4 correspond to 2005, 2006, 2007 and 2008 respectively.

their control problematic (Chatelin et al., 2005; Le Gal et al., 2010; Navarrete and Le Bail, 2007). They might also have difficulties in dealing with the priorities between activities (e.g. fertilization *vs.* crop protection) and their dynamic (context-dependent) processing (Donatelli et al., 2009; Nesme et al., 2006).

4.2. Contribution of the VERDI model

In the present study, the VERDI model aimed at supporting the design of new inter-row management plans in vineyards featuring higher robustness to climate variation regarding the trade-off

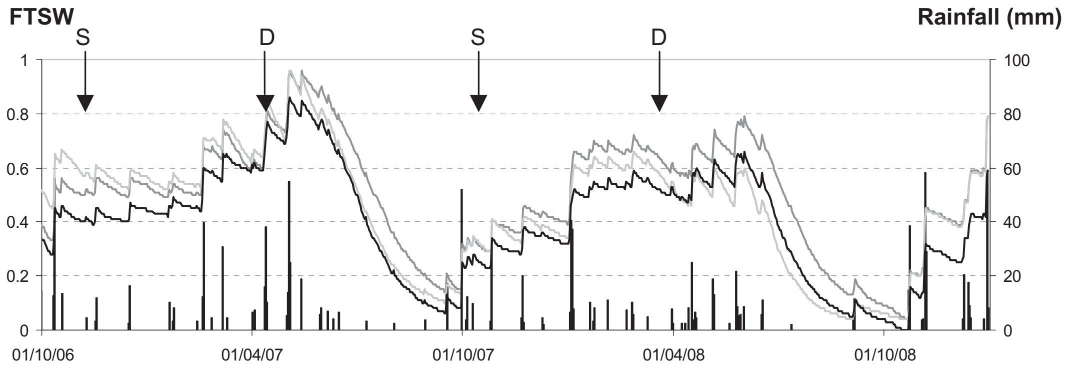

Fig. 9. Daily rainfall and dynamics of FTSW simulated for the three strategies (bare soil: ▬; permanent intercropping: ▬ and 'mixed' strategy: ▬) over the years 2007–2008 in the third climatic scenario. The arrows indicate the dates of the sowing of the intercrop (S) and of its destruction (D) observed in the 'mixed' strategy.

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between agronomic and environmental performances. The results of our short simulation study showed that VERDI was able to represent realistically the relationships between the weather, the biophysical system, and the management systems. In this study, field data were not available for some management and biophysical variables especially for the 'mixed' strategy never applied in the field. The overall consistency of the model was therefore tested according to field data and experts' judgement as proposed by other authors who had to validate decision models or indicators (Bockstaller and Girardin, 2003; Martin et al., 2011; Mérot and Bergez, 2010). According to field observations and previous works (Celette et al., 2010; Ripoche et al., 2011), the model simulated correctly both the grapevine and cover crop development in spite of the simplicity of the representation of these processes. Considering the grapevine phenological stages, the results were close to those observed by Parker et al. (2011) for several grapevine varieties using a simple model to simulate flowering and veraison based on growing degree-days but with a base temperature fixed at 0 °C. The simulated dynamics of FTSW under the real weather conditions for the bare soil and permanent intercropping strategy were consistent with the field observations as better agronomic performances were observed in both cases (simulated and observed results) for bare soil strategy (Ripoche et al., 2011). In the case of the cover crop, the additional mowing and the delay between field observations and simulation results with VERDI for the permanent intercropping strategy could be related to a model overestimation of the cover crop growth or a lack of consideration of the competition for labour resource at field or farm scale in the model. Nevertheless, the subsequent mowings carried out occurred consistently with expectation.

The 'mixed' strategy, which was the most flexible in the simulation study, allowed buffering the effect of climatic variations on the agronomic performances evaluated in relation to the FTSW. This effect was not so noticeable in the case of a succession of dry and rainy years (scenario 1) during which all strategies were judged satisfactory over the years. In contrast, the positive impact of the flexible strategy was obvious when the drought was severe and extended over two years. The same trend was observed for the environmental performance but the results were very similar whatever the climate scenario tested. Although performances of the bare soil strategy remained generally lower than those of the two other strategies, they differed only slightly. The intercrop destruction did not stimulate the runoff because it occurred during dry seasons, and consequently, did not decrease the environmental score. Considering the bare soil strategy, the positive impact of tillage on the soil surface properties was too short in time to positively affect the annual performance. Although the model gave consistent results with those observed in the field in terms of agronomic performances (bare soil strategy with higher performances than those of the permanent intercropping strategy over the real scenario), the introduction of a more detailed approach to simulate the evolution of the soil surface characteristics affected by soil activities as the one recently proposed by Paré et al. (2011) seems necessary to better discriminate the different strategies.

Given the strong constraints of the vineyard cropping systems, the results obtained in this study corroborate the idea that the adaptiveness of a cropping system enhances its chance to reach a trade-off between agronomic and environmental services over the years. Some experiments done on rainfed cropping systems showed that adopting adaptive management could help producers to better manage risks (Felter et al., 2006; Merrill et al., 2007; Tanaka et al., 2002). In these examples, the flexibility came from the choice of the crop to sow before wheat in relation to the soil water availability in spring in order to avoid compromising the production cycle of the wheat crop. In the climate change context where extreme events could be accentuated (Salinger, 2005), the design of flexible strategies constitutes a real challenge for research (Clingeleffer, 2009; Hanson et al., 2007; Sadras et al., 2003).

4.3. Limitations and future works

The production system model could be improved on several aspects. At the biophysical level, the representation we used was based on the WaLIS model (Celette et al., 2010), which makes pluriannual simulations as the dynamics of the soil water reserve observed one year relates to the water balance of the previous year. Nevertheless, we did not take into account that the changes in soil surface management could affect the grapevine itself. They could strongly affect not only the water but also the nitrogen dynamics in the soil and grapevine, and consequently, the grapevine vegetative and reproductive development (Ripoche et al., 2011). As a perennial crop, the conditions experienced by the grapevine during a season may have an impact on the grapevine performance of the following year. Yet, integrating these effects requires the explicit modelling of the nitrogen balance (Nendel and Kersebaum, 2004) and of the vegetative and reproductive development of grapevine, which is currently in progress (Metay et al., 2010). Moreover, simulations over a larger range of strategies and climatic scenarios and over a longer period are necessary to extend the scope of our study. Adding other adjustments like fertilization or irrigation could offer a larger leeway for designing flexible cropping systems.

In the decision model, we considered only the soil surface management of the inter-row in order to focus on the design of robust vineyard cropping systems with flexible management of the intercrop. Currently, only schedules and trends between bare soil and permanent strategy have been validated with experts or in field. A valuable and instructive experiment would consist in enlarging the panel of evaluators (Ferraro, 2009) to farmers and extension services as done by Nesme et al. (2006) to assess irrigation and fertilisation strategies simulated with the Epistics model designed for apple-orchards. The intercrop LAI was used as an indicator for activating mowing yet it was not commonly used by farmers. Another indicator more familiar to farmers (e.g., cover crop height) would be necessary for future discussions with them.

Finally, the study would definitely be more profitable if carried out at farm scale because any activity to perform on a field would depend on the whole biophysical system as well as on the other activities intended anywhere on the farm, and consequently, on the availability of resources (labour, equipment). The competition for these resources could impede the exploitation of management flexibility and affect the cropping systems' performance. New indicators could be formed to extend performance evaluation to economic and social aspects by considering labour and resources, as for banana farming systems (Blazy et al., 2009). This aspect is currently the subject of specific research to represent activities and their organization at farm level (Mérot et al., 2009).

Dealing with flexibility induces some costs, for farmers and also for research in terms of modelling. For farmers, flexibility implies the ability to react rapidly to the modifications of the biophysical system or to climatic events, and this is conditioned by accessibility to relevant data. For instance, one must have enough time to observe indicators of the behaviour of the system regularly as proposed in the 'mixed' strategy, have the capacity of operating in a highly reactive way, and have enough funding to make repeated sowings every year if needed. Therefore a learning process seems necessary to apprehend the transition from current to adaptive management (Darnhofer et al., 2010; Pahl-Wostl, 2007). Modellers must have comprehensive knowledge of the functioning of the

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cropping system, considering both the biophysical and management sub-systems and their interactions. The detailed modelling we used to represent the management system of the inter-rows was necessary to take into account the complexity of the system, which increases with the number of activities and elements considered (Guerrin, 2009; Mérot and Bergez, 2010). Our results confirmed that this approach may be useful to design innovative and more sustainable cropping systems, the adaptive strategy achieving better performances than those observed in a previous study with fixed management options (Ripoche et al., 2010).

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