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A simulation framework for the design of grassland-based beef-cattle farms

G. Martin [a,b,*], R. Martin-Clouaire [b], J.-P. Rellier [b], M. Duru [a]

[a] INRA, UMR 1248 AGIR, F-31326 Castanet Tolosan, France
[b] INRA, UR 875 UBIA, F-31326 Castanet Tolosan, France

A R T I C L E I N F O

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A B S T R A C T

Grassland-based beef-cattle farms are dynamic systems that are difficult to manage, particularly because of their sensitivity to uncontrollable environmental factors such as weather. The design of farms and management strategies capable of coping with a wide range of conditions is thus a challenging issue. The SEDIVER discrete-event simulation framework presented in this article has been developed to support the construction of dynamic simulation models of grassland-based beef-cattle farms for evaluation and empirical design purposes. The originality of the models built with SEDIVER lies in the explicit representation of: (i) management strategies as the planning and coordination of activities in time and space through which the farmer controls the biophysical processes occurring within the system and (ii) the diversity in plant, animals, grassland and farmland, and the management opportunities and difficulties that this might induce. An application example illustrates the kind of simulation-based investigations enabled by SEDIVER. A grassland-based beef-cattle farm in France is examined for two contrasted management strategies: the first one corresponding to the actual practice and the second one paying increased attention to and exploiting plant and grassland diversity. The simulation results showed that the second one could roughly double fodder yields and thus ensure farm self-sufficiency for fodder. Thanks to the capacity of a SEDIVER-based model to take practical production considerations into account, it is possible to increase the realism of farm simulations and the credibility and relevance of the farming systems which can thus be designed.

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Software availability

Software name: SEDIVER (version 3.6)
Contact address: Jean-Pierre Rellier, rellier@toulouse.inra.fr
Year first available: 2009
Hardware and Operating System: SEDIVER runs on Linux and Microsoft Windows platforms. The DIESE library precompiled for Linux or for Windows respectively must be installed on the selected platform. On Microsoft Windows platforms, the distribution free Linux-like environment Cygwin must first be installed (see http://www.cygwin.com for current availability).
Software required: A Java runtime environment to inspect/develop the SEDIVER framework 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: The functional parts of the SEDIVER framework are written in C++. The input files contain specifications written in a specific language documented in the DIESE package. Interpreters for this language are included in the DIESE library.
Availability: The material can be downloaded from http://carlit.toulouse.inra.fr/diese/. It comprises the DIESE package (libraries and documentation) which can be downloaded from the 'Télécharger' page, and the SEDIVER framework and a set of input/output files which can be downloaded from the 'Applications' page.

1. Introduction

In less-favourable areas, beef-cattle production involves the management of a wide diversity of semi-natural grasslands. Herbage production is highly variable in space and time (Pleasants et al., 1995) due to between-field differences in vegetation types, soil conditions and topography and also to weather variability within and between years. Similarly, beef-cattle feeding requirements change over time and between beef-cattle classes (INRA, 2007). Farmers need to be able to take decisions for planned

* Corresponding author at: INRA, UMR 1248 AGIR, F-31326 Castanet Tolosan, France. Tel.: +33 5 61 28 54 75; fax: +33 5 61 73 55 37.
E-mail address: guillaume.martin@toulouse.inra.fr (G. Martin).

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management that in turn is able to take situation-dependent factors into account in order to achieve the most efficient use of production resources (grasslands, labour, etc.) over space and time to meet their objectives through a sustainable production system. The design of grassland-based beef-cattle farms capable of coping efficiently with a wide range of conditions (including climate variability and climate change and changing socio-economic conditions, etc.) is thus a challenging issue. This includes changes in the production resources of farms or in farmers' management.

In such systems, we believe that there is great potential for farmers to improve their efficiency through better use of plant (within-field), grassland (between-field), animal and farmland diversity. Diversity adds potential flexibility that can be used in organizational and operational decision-making to cope with variations in uncontrollable factors, such as climate (e.g. White et al., 2004; Andrieu et al., 2007; Martin et al., 2009). For instance, grassland diversity means that particular fields may be suitable for various forms of use, matching the feeding requirements of different beef-cattle classes (e.g. cows vs. heifers) characterized by specific and fluctuating animal intake rates (White et al., 2004). In addition to this organizational flexibility, within-field plant diversity makes it possible to take advantage of operational flexibility in grassland management (Martin et al., 2009), i.e. the extent to which the use of a given grassland may be brought forward or held in reserve at various times of the year.

Simulation (McCown, 2002) is an obvious tool for the study of grassland-based production systems as their complexity makes analytical evaluation or optimization more difficult. However, its potential usefulness as a tool for the empirical design of agricultural systems with extension services and farmers depends on the conceptual richness of its modelling functions. To ensure that the systems designed and evaluated by simulation are credible and relevant to stakeholders' needs, day-to-day farm operations need to be integrated in the model (Keating and McCown, 2001) in order to deal with the practical questions farmers have to answer such as "what should I do, where, when and how?" The model might then focus on the variability of biophysical processes over time and in space, the generated opportunities and constraints on grassland use and the way the farmer copes with them when planning and coordinating farming activities. Besides, developing credible farm-scale simulation models is a costly task that requires considerable agronomic knowledge and modelling skills. To make the simulation approach more accessible and to increase the reusability of previous modelling efforts, the simulation methodology needs to support the modelling process by providing generic knowledge patterns and functions which are suitable for dynamic simulation.

These considerations prompted the development of SEDIVER (Simulation-based Experimentation on livestock systems with plant, grassland, animal and farmland DIVERsity), a discrete-event simulation framework for supporting the construction of farm-scale dynamic models capable of reproducing the interactions on grassland-based beef-cattle farms between the biophysical and management processes in response to external factors such as weather. The purpose of this article is to present both this framework and an example of its application that illustrates the kinds of investigation enabled. In Section 2, the modelling approach and the ontology of agricultural production systems on which it relies are briefly described. Section 3 describes the domain-specific concepts underlying SEDIVER. An example is provided in Section 4 to illustrate how the modelling capabilities of SEDIVER are applied in a case study to compare the performance of a novel management strategy with the one already being used. Section 5 discusses the results obtained and situates SEDIVER with respect to related simulation models. Section 6 summarizes the main points and suggests possible future developments.

2. Ontology-based modelling

In Section 2.1 we outline our approach to the study of grassland-based beef-cattle production systems. The backbone of the approach is a production system ontology introduced in Section 2.2.

2.1. Approach overview

SEDIVER is a dynamic farm-scale simulation framework for supporting the design and evaluation of grassland-based beef-cattle production systems, which pays special attention to the management strategies used in these systems. It is intended for use by researchers, occasionally working with farm advisors and/or farmers, to investigate the relevance and performances of a given management strategy regarding the system settings and objectives under various climatic conditions. SEDIVER was actually built as a more specialised tool based on DIESE. DIESE, which offers a more abstract framework (Fig. 1), provides an ontology of single-manager production systems and an execution environment implementing a discrete-event simulation engine (Martin-Clouaire and Rellier, 2006, 2009). Basically, this ontology, which is described in Section 2.2, provides schemata for defining useful concepts for the domain of interest such as the entities composing it, their properties and the causal relationships that drive the change of state of these entities. The ontology is based on concepts that are relevant to all production systems such as, for instance, the manager and the operating and biophysical systems of which a production system consists (Figs. 2 and 3a), or the concept of activity controlled by the manager. Formally, in DIESE, the concepts are expressed in a frame-like representation implemented in C++. The simulation machinery and services (e.g. the interface and functions) provided by DIESE directly process the models declared with this language.

In SEDIVER, described in Section 3, a set of concepts specific to grassland-based beef-cattle production systems (see Fig. 2) have been introduced such as the entities, fields or herds, and processes such as herbage growth or animal intake. In other words, the development of SEDIVER has involved declaring the domain classes, their relations and attributes, data structures and system parameters by using the classes and services of the DIESE modelling framework. The classes created inherit from DIESE classes that carry the ontological background. The SEDIVER classes are generic to the domain in the sense that they provide the description primitives applicable to any production system in that domain. The genericity is of course bounded by the scope of the intended studies to be carried out with these systems. With SEDIVER, the focus is on the study of management strategies for efficient exploitation of plant, animal, grassland, and farmland diversity in grassland-based beef-cattle production systems. This explains the emphasis put on modelling (i) the heterogeneous nature of the biophysical processes occurring in the system and the subsequent constraints on herbage use, and ii) the farmer's management behaviour on a daily scale to coordinate the production activities (Fig. 4) that are constrained by this diversity over time and space.

Given the DIESE framework, specialised through the addition of the SEDIVER body of knowledge, a model of a given farm is made by specializing the domain classes provided by the framework (Fig. 2). Fig. 5 shows the declaration of part of the management strategy to be simulated. To run a simulation, the DIESE user needs to specify the size of the smallest possible increment of time (i.e. clock unit) − valued as the smallest step of the processes involved − and the duration of the simulated period. Some data files corresponding to the external factors influencing the system of interest have to be

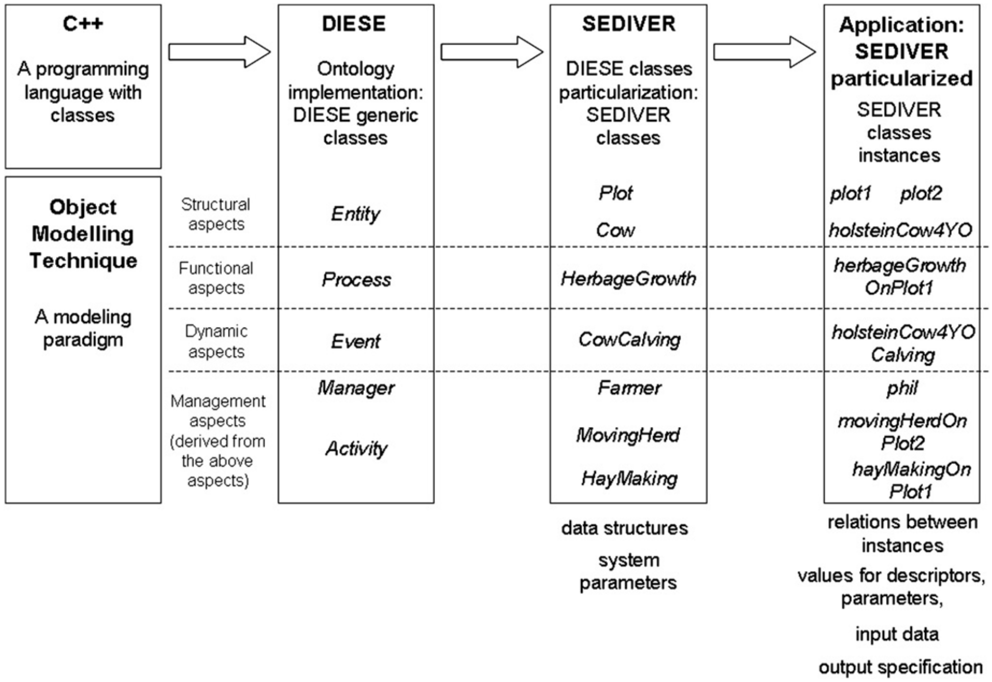

Fig. 1. Different software layers involved in ontology-based modelling.

provided, the most important of which concerns weather time series. Running a simulation with this model and these data means firing on them with the discrete-event simulation engine provided by DIESE.

Fig. 1 summarizes the modelling philosophy followed in the project. First (the first two columns) the production system ontology was designed by computer scientists and then implemented as C++ simulation software manipulating the ontology concepts outlined in Section 2.2. The domain knowledge in SEDIVER, presented in Section 3, was then developed by farming system researchers. Finally, particular cases of grassland-based beef-cattle production systems were coded and simulated by these researchers as discussed in Section 4.

2.2. Ontology and modelling framework

Object-modelling technology for model analysis and design is especially suitable for the declarative modelling of complex systems with numerous interacting components. This is why it is the most commonly used approach for the modelling and simulation of livestock systems (e.g. Romera et al., 2004). Using the DIESE modelling framework based on object-modelling, we then developed an ontology of agricultural production systems (Martin-Clouaire and Rellier, 2006, 2009). Basically, an ontology (Chandrasekaran et al., 1999) is an explicit and declarative description of a given domain, i.e., the concepts in the domain, the properties of these concepts and the constraints on these

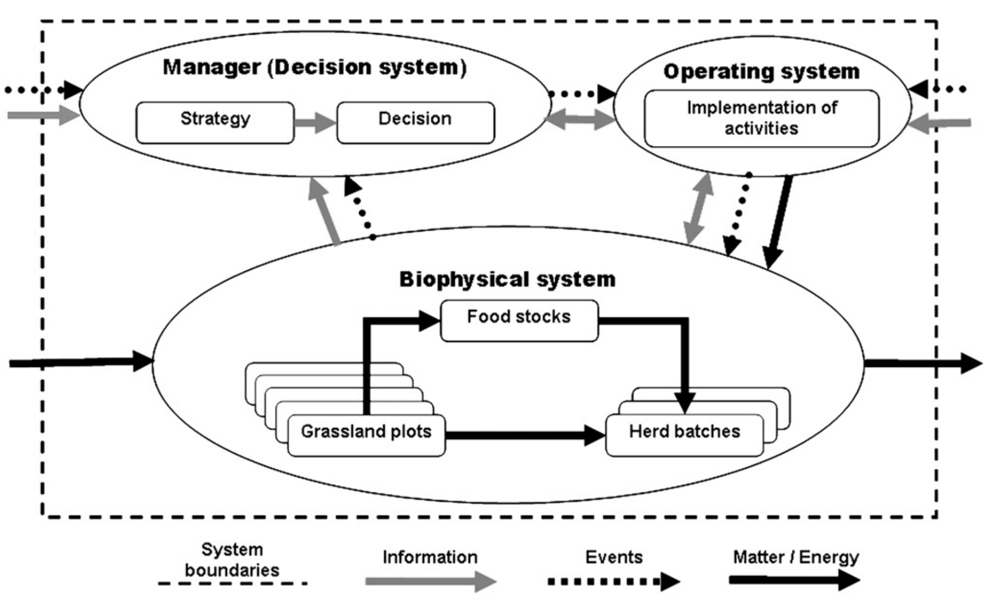

Fig. 2. Production system view in the SEDIVER model (Martin et al., in press).

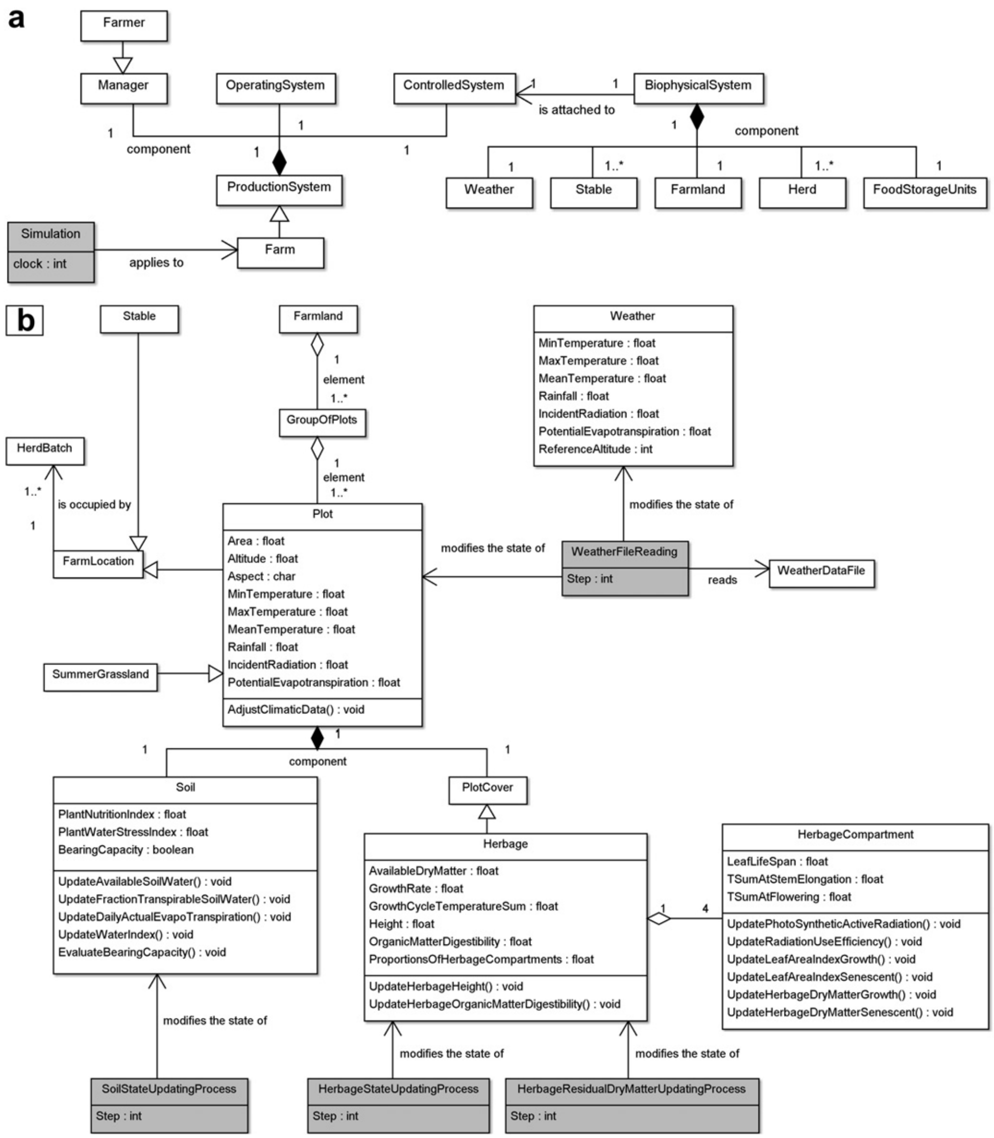

Fig. 3. Class diagrams of the biophysical model (a) and the Farmland module displaying the SEDIVER classes derived from the DIESE *Entity* (white frames) and *Process* (grey frames) classes and the relations between them, in Unified Modelling Language. Each frame represents a SEDIVER class, with its name in the upper part of the frame. Lines beginning with a full diamond refer to composition relationship, i.e. objects of higher level having a "has an" owner relationship with objects of lower level. Lines beginning with an empty diamond refer to sets of lower level element objects. Arrows with an empty triangle refer to a specialisation relationship, the lower level object being a particular type of the higher level object. Standard arrows refer to association between two classes implemented through the attribute of one class that refers to another class.

properties. In addition to providing a shared vocabulary and disambiguation of meaning, an ontology enables the reuse of pre-formalized concepts and templates and thus serves as a conceptual meta-model for the modelling framework. Such concepts and templates can then be specialised (through the creation of subclasses) and mapped into an executable model interpreted with a discrete-event simulation engine. Our ontology is also a task ontology in the sense that it incorporates the necessary conceptualization for dynamic simulation. The three fundamental concepts of the ontology are entity, process and event (Fig. 1). These represent the structural, functional and dynamic aspects of a system respectively. An entity describes a kind of material or abstract item in the area of interest. The state of a system at a given moment in time is the value of the properties (attributes, containment, inheritance, associations) of the entities it comprises. A process is a specification of part of the behaviour of a system, i.e. of the entities it comprises. Typically, the process code specifying this behaviour includes the use of methods attached to entities affected by the process. A process causes a change in state when a particular event occurs. Thus, events convey the temporality of process triggers.

For managerial aspects, the ontological basic unit of analysis is activity (work). In its simplest form, an activity, hereafter called a primitive activity, is a specialisation of an entity (Fig. 1). It denotes something to be done to a particular biophysical object or location, e.g. a plot, by an executor, e.g. a worker. A primitive activity is characterized by local opening and closing conditions, defined by time windows and/or predicates (Boolean functions) referring to the biophysical states or indicators. The "something-to-be-done" component of a primitive activity is an intentional transformation called an operation, e.g. the harvest operation. The step-by-step changes to the biophysical system as the operation is carried out constitute a functional attribute of the operation. Operations can be instantaneous or durative. In the latter case, their execution might be interrupted and the duration of the operation would be determined by the product of a quantity (e.g. number of items) or area, and the speed of execution of the operation (e.g. number of items or

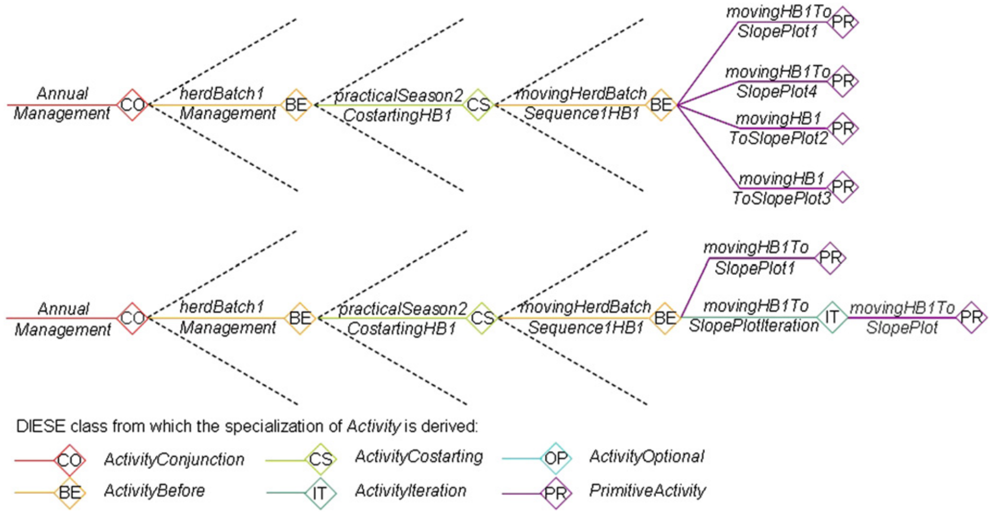

Fig. 4. Schematic example of two specialisations of a SEDIVER non-primitive activity class *AnnualManagement* with possible components referring to the actual (upper scheme) and novel (lower scheme) management strategies in the application example. Names of specialisations are similar to the class names mentioned in the text. Dashed lines refer to unrepresented components of the plan.

area which can be processed in a unit of time). The execution of an operation is constrained by feasibility conditions that relate to the biophysical system state.

Activities can be further constrained by using programming constructs enabling specification of temporal ordering, iteration, aggregation and optional execution. To this end, the ontology includes a set of programming constructs with evocative names such as *before*, *iterate*, and *optional*, which enable specification of temporal ordering, iteration, aggregation and optional execution of primitive activities by creating non-primitive activities. All the activities are connected through these constructs; the only one that does not have a higher level activity is the plan. A plan may encounter situations where the initial intention goes beyond its bounds as particular events occur, e.g. a lasting drought event. The specification of what changes should be made to a nominal plan and when is called a conditional adjustment. The triggering element of conditional adjustment is either a calendar condition that becomes true when a specific date is reached, or a state-related condition that becomes true when the current circumstances match this condition. The adjustment can be any change to the nominal plan such as the removal or insertion of activities. It can also affect the resources used in some activities. In this way, management can respond rapidly to cope with unexpected (though still possible) fluctuations of the external environment and various other contingencies.

3. Domain knowledge and dynamic functioning

A synthetic description of the conceptualization (Martin et al., in press) developed for the SEDIVER simulation framework is given in the next two sections that deal with the biophysical and management aspects respectively. In the sequel, class names start with a capital letter (e.g. *GroupOfPlots*), whereas names of class specialisations start with a lower case letter (e.g. *groupOfPlots1*). Section 3.3 outlines the dynamic functioning of the system through the processing of the event agenda.

3.1. Biophysical system modelling

The *BiophysicalSystem* class of a grassland-based beef-cattle production system consists of five entities, i.e. a farmland, one or more herds, food storage units, one or more stables and weather (Fig. 3a). The example of the farmland is further developed to display how domain knowledge has been mobilised and organised to represent the structure, functioning and dynamics of the biophysical system, i.e. the entities, processes and events created in SEDIVER, and to account for plant, grassland and farmland diversity and its consequences on the dynamic heterogeneous nature of related biophysical processes. Table 1 summarizes the result of this reasoning for herds, food storage units, stables and weather.

The entity *Farmland* (Fig. 3b) represents a set of land islets named “group of plots”. *GroupOfPlots* represents a set of *Plot*. Area, altitude and aspect (i.e. flat, south- or north-oriented) are descriptors of *Plot* and determinants of farmland diversity. The continuous process *WeatherFileReading* (Table 1) updates the state of *Weather* (Table 1) daily and, according to farmland diversity, i.e. altitude and aspect, adjusts incoming temperature and incident radiation read in the weather file on the plot scale. Based on this temperature update, it also calculates ‘thermal time’ or degree-day sums at the plot scale according to Ansquer et al. (2009). A plot is made up of two interacting components (Fig. 3b), represented by entity classes *Soil* and *PlotCover* – in this case, *Herbage*.

Soil is described by three main attributes (Fig. 3b) considered to be determinants of farmland diversity as well: a plant nutrition index (Lemaire and Gastal, 1997), a plant water stress index (Merot et al., 2008) and soil bearing capacity (Andrieu et al., 2007). These attributes are updated daily through the continuous process entitled *SoilStateUpdatingProcess*, according to the plot-scale weather conditions as well as the season for the first index.

Herbage represents grassland vegetation. Its state mainly changes through daily updated descriptors (Fig. 3b): mainly available dry matter, growth rate, growth cycle age in degree-days, height, and organic matter digestibility according to physiological and phenological attributes (i.e. leaf life span, temperature sum at stem elongation and flowering) that depend on the composition of the plant species of the herbage and govern the dynamics of herbage growth and digestibility. To account for plant species diversity, the concept of functional composition defined in plant ecology is quite helpful (Diaz and Cabido, 2001). In this approach, species are classified into groups that relate directly to function (primary production role) based on shared biological characteristics (plant traits). The leaf dry matter content weighted at plant community level is strongly associated with agronomic characteristics such as herbage digestibility (Al Haj Khaled et al., 2006) and

```
+I movingHerdBatchSequence movingSequence_HB1SlopeSpring
   +E movingHerdBatchFieldToField movingHB1ToSlopePlot1_1stRound;
       operatedObjectAttribute = <I><, HB1>;
       // herd batch operated by the moving activity
       destinationCandidatesSpec = <I><, slopePlot1Spec>;
       // destination of the herd batch through this activity
       criteria = 2;
       // specifies that the activity depends on a maximum beginning date
       // and beforehand on the impossibility to last one more day at
       // grazing on the current plot
       maxBegDay = 10;  maxBegMonth = 5;;
   +E movingHerdBatchFieldToField movingHB1ToSlopePlot4_1stRound;
       operatedObjectAttribute = <I><, HB1>;
       destinationCandidatesSpec = <I><, slopePlot4Spec>;
       criteria = 4;
       // specifies that the activity depends on herbage height (in cm) at the
       // entrance of the destination plot, minimum and maximum duration
       // stay on the current plot and on the impossibility to last one
       // more day at grazing on the current plot
       comingHerbageEntranceHeightThreshold = 18.;;
   +E movingHerdBatchFieldToField movingHB1ToSlopePlot2_1stRound;
       operatedObjectAttribute = <I><, HB1>;
       destinationCandidatesSpec = <I><, slopePlot2Spec>;
       criteria = 4;
       comingHerbageEntranceHeightThreshold = 18.;;
   +E movingHerdBatchFieldToField movingHB1ToSlopePlot3_1stRound;
       operatedObjectAttribute = <I><, HB1>;
       destinationCandidatesSpec = <I><, slopePlot3Spec>;
       criteria = 4;
       comingHerbageEntranceHeightThreshold = 18.;;
…
```

```
+I movingHerdBatchSequence movingSequence_HB1SlopeSpring
     +E movingHerdBatchFieldToField movingHB1ToSlopePlot1_1stRound;
         operatedObjectAttribute = <I><, HB1>;
         destinationCandidatesSpec = <I><, slopePlot1Spec>;
         criteria = 7;
         // specifies that the activity depends on a phenological threshold
         // on the current plot and beforehand on the impossibility to last
         // one more day at grazing on the current plot
         herbagePhenologicalStageThreshold = 600.;;
     +E movingHerdBatchFieldToFieldIteration movingHB1ToSlopePlotIteration
         maxEndDay = 10;  maxEndMonth = 9;
         closeToOpenDelays << (96 MAX); // 96 hours -> 4 days
         // specifies that at least a 4 days delay might occur before iterating
         // again
         +E movingHerdBatchFieldToField movingHB1ToSlopePlot;;
         // primitive activity iterated by movingHB1ToSlopePlotIteration
+ I operatedObjectSpecification multipleDestSpec
     preExpandedList << <I><, slopePlot3>;
     preExpandedList << <I><, slopePlot4>;
     preExpandedList << <I><, slopePlot5>;
     preExpandedList << <I><, slopePlot6>;;
// list of plots among which the destination plot of the iterated activity
// movingHB1ToSlopePlot is selected
<I><movingHerdBatchFieldToField movingHB1ToSlopePlot>
     operatedObjectAttribute = <I><, HB1>;
     destinationCandidatesSpec = <I><, multipleDestSpec>;
     destinationCriteria = 3;
     // specifies that the destination plot is the one on which the age of
     // herbage growth cycle expressed in degree days is the oldest
     criteria = 6;
         // specifies that the activity depends on a threshold of age of growth
         // cycle (expressed in degree days) of the destination plot and
         // beforehand on the impossibility to last one more day at grazing on
         // the current plot
     comingHerbageRegrowthDurationThreshold = 700.;;
…
```

Fig. 5. Declaration of two specialisations of the SEDIVER class *movingHerdBatchSequence* for the actual (upper frame) and novel (lower frame) management strategies schematized in Fig. 4. The declaration is commented on in the text in the lines preceded by "//". "+I movingHerdBatchSequence movingSequence_HB1SlopeSpring" means add to the activity plan a specialisation of class *MovingHerdBatchSequence* named *movingSequence_HB1SlopeSpring*. "+E" means add an element to the upper level activity just declared.

plant phenology (Ansquer et al., 2008). Based on this approach, *Herbage* is treated as a set of four compartments (Fig. 3b) or grass functional groups (entity *HerbageCompartment*) based on Ansquer et al. (2004), with the relative abundance of each compartment as a descriptor of *Herbage* characterizing plant and grassland diversity. The continuous process *HerbageStateUpdatingProcess* operates the *Herbage* at a daily time step (Fig. 3b). Given the state of *Soil*, plot-scale weather conditions and possible herbage harvests

Table 1
Classes created in the SEDIVER model to represent the structural, functional and dynamic aspects of the biophysical system. For each class, the corresponding DIESE class is provided as well as the relations with other classes and a brief description of the class meaning.

SEDIVER Class	DIESE Class	Relations with other SEDIVER classes	Brief description
Weather	Entity	Component of BiophysicalSystem	Weather component of the biophysical system.
WeatherFileReading	Continuous Process	Functional link with Weather Functional link with Plot	It updates the state of Weather daily and, according to altitude and aspect, adjusts incoming weather data on the plot scale based on Andrieu et al. (2007).
FarmLocation	Entity	Functional link with HerdBatch	Refers to any physical location of the biophysical system.
Stable	Entity	Component of BiophysicalSystem Specialisation of FarmLocation	Stable component of the biophysical system.
Herd	Entity	Component of BiophysicalSystem	Livestock component of the biophysical system.
HerdBatch	Entity	Element of Herd Functional link with Diet	Multiple population made of simple homogeneous populations and functional entity managed by the farmer. At this level, it is possible to represent within-herd animal diversity as egards morphological, feeding and physiological characteristics and management.
AnimalGroup	Entity	Element of HerdBatch Functional link with Animal	Simple homogeneous population, i.e. a number of animals sharing. Allows representing within-herd batch animal diversity.
Animal	Entity	–	Animal representative of its AnimalGroup characterized by morphological, feeding and physiological descriptors and when relevant a reproductive status. Specialisations of this class are Calf, Heifer, YoungCow and Cow for beef calves, beef heifers, primiparous beef cows and multiparous beef cows respectively.
BeefBovine FeedingProcess	Continuous Process	Functional link with Animal	Based on the INRA fill unit system (INRA, 2007), it updates animal feed intake according to animal type, at a daily time step.
BeefBovineState UpdatingProcess	Continuous Process	Functional link with Animal	Based on Jouven et al. (2008), it converts animal feed intake into animal products (weight, milk) at a daily time step.
CowCalvingProcess	Discrete Process	Functional link with Cow and YoungCow	It leads to the creation of a new group of calves added to the herd batch of the mother cows, and updates the reproductive status of the representative cow of the mother cow group.
CowCalvingEvent	Event	Functional link with CowCalvingProcess	Initializes CowCalvingProcess.
Diet	Entity	–	Refers to the diet assigned to a herd batch.
DietElement	Entity	Element of Diet Functional link with Food	Refers to any element of the diet assigned to a herd batch.
FoodStorageUnitSet	Entity	Component of BiophysicalSystem	Set of food storage units of the biophysical system.
FoodStorageUnit	Entity	Element of FoodStorageUnitSet	Refers to any food storage unit containing a particular food type. Specialisations of this class are SilageSilo, BaleSilageStock and Barn for silage silo, bale silage silo and barn respectively.
Food	Entity	Functional link with Herbage or with the corresponding FoodStorageUnit	Refers to any type of animal food. Specialisations of this class are GrazedHerbage, Silage, BaleSilage and Hay for herbage grazed and distributed silage, bale silage and hay respectively.

through animal grazing (as calculated by the process *BeefBovineFeedingProcess*, Table 1) or mechanized harvest, it updates available herbage dry matter based on a modified version of the model developed by Duru et al. (2009) accounting for the relative abundance of each compartment. The density of herbage stratum is also modified according to the season and to the distribution of herbage compartments. Herbage height is updated according to the difference between available herbage dry matter and herbage dry matter in the ungrazable stratum, the calculation being based on published data (Duru and Ducrocq, 1998). Herbage organic matter digestibility is then updated as specified by Duru et al. (2008).

3.2. Decision and operating systems modelling

At the production year scale, the manager's activities involve either producing fodder stocks or taking care of herd batches through animal feeding, reproduction, etc. These can be grouped into two non-primitive activity classes: *YearlyHarvestingSequence* and *HerdBatchManagement*. Specialisations of these non-primitive activities are conducted in parallel without constraints between them. Each has a dedicated and independent activity plan, although the execution of one plan can affect the execution of the others, e.g. because of concurrent use of a certain plot. Thus, the non-primitive activity *AnnualManagement* is derived from the DIESE class *ActivityConjunction* that groups together activities without further constraints between them. Examples of specialisations of *AnnualManagement* are given in Fig. 4. To display how domain knowledge has been mobilised and organised to represent the structure, functioning and dynamics of decision and operating systems, the way activities can be included and coordinated in the non-primitive activity class *YearlyHarvestingSequence* is provided as an example in the text. The same reasoning is summarised in Table 2 for *HerdBatchManagement* and for conditional adjustments.

Over a year, fodder production can be regarded as a sequence of harvests and is represented by the non-primitive activity *YearlyHarvestingSequence* derived from the DIESE class *ActivityBefore*. This sequence is itself a set of sequences (*HarvestingHerbageSequence*), e.g. a first harvest on a set of plots followed by a second harvest on the same plots, constrained by earliest and latest starting dates. From experience, farmers plan their harvesting activities so that they occur at a time that is compatible with the timing of other tasks and do not jeopardize subsequent harvesting activities. Farmers generally harvest a set of plots constituted according to their proximity, here named *HarvestingHerbageConjunction* (derived from the DIESE class *ActivityConjunction*). A conjunction can be opened only if the last harvesting activity executed in the previous conjunction has been fully completed. The grouping of activities with a *HarvestingHerbageConjunction* provides flexibility in the order of execution of these activities and enables management constraints to be attached to this set, such as a delay between the two sets of plots.

A *HarvestingHerbage* activity is a sequence derived from the DIESE class *ActivityBefore*. It consists of two primitive activities, first cutting the herbage (*CuttingHerbage*) of a grassland plot and then storing this new-mown herbage (*StoringHarvestedHerbage*). *HarvestingHerbage* has three specialisations according to the type of food made from the harvest, i.e. hay, bale silage or silage. *HarvestingHerbage* can be declared as optional (non-primitive activity *HarvestingHerbageOptional*). This means that if the *HarvestingHerbage* activity cannot be executed, e.g. if the harvest yield is expected to be too low, it is cancelled in the activity plan.

Table 2
Classes created in the SEDIVER model to represent the structural, functional and dynamic aspects of the decision and operating systems. For each class, the corresponding DIESE class is provided as well as the relations with other classes and a brief description of the class meaning.

SEDIVER Class	DIESE Class	Relations with other SEDIVER classes	Brief description
HerdBatch Management	Activity Before	Element of AnnualManagement	Sequence of periods particular to a given herd batch during which the farmer makes use of a similar type of food to feed the herd batch according to a given objective for the period.
PracticalSeason Costarting	Activity Costarting	Element of HerdBatchManagement	Simultaneous changes occurring at the beginning of each period concerning e.g. the diet assigned to the herd batch or its location and movements.
DietChanges Sequence	Activity Before	Element of PracticalSeasonCostarting	Sequence specifying the order in which diets might be assigned to a herd batch within a period.
ChangingDiet	Primitive Activity	Element of PracticalSeasonCostarting or DietChangesSequence	Activity updating the diet assigned to a herd batch.
MovingHerdBatch Sequence	Activity Before	Element of PracticalSeasonCostarting	Sequence of primitive or non-primitive activities involving movements of a herd batch.
MovingHerdBatch FieldToFieldIteration	Activity Iteration	Element of PracticalSeasonCostarting or Element of MovingHerdBatchSequence	Repetition of a herd batch movement until a latest end date or a maximum number of iterations are met.
MovingHerdBatch FieldToFieldOptional	Activity Optional	Element of PracticalSeasonCostarting or Element of MovingHerdBatchSequence	Optional activity carried out only if the opening predicate of the herd batch movement is satisfied.
MovingHerdBatch	Primitive Activity	Element of PracticalSeasonCostarting or MovingHerdBatchSequence or MovingHerdBatchFieldToFieldIteration or MovingHerdBatchFieldToFieldOptional	Activity resulting in the removal and addition of the herd batch on the list of occupiers attached to the source and destination locations respectively. The destination location can be fully determined in the plan. It can also be selected from a list of plots.
DistributingStored FoodWinterIteration	Activity Iteration	Element of PracticalSeasonCostarting	Repetition of a food stock distribution until a latest end date or a maximum number of iterations are met.
DistributingStored FoodTransitionIteration	Activity Iteration	Element of PracticalSeasonCostarting	Repetition of a food stock distribution until a closing predicate, a latest end date or a maximum number of iterations are met.
DistributingStored Food	Primitive Activity	Element of PracticalSeasonCostarting or DistributingStoredFoodWinterIteration or DistributingStoredFoodTransitionIteration	Activity resulting in the quantity stored in the food storage unit being withdrawn and the quantity distributed to the herd batch being credited.
Mating	Primitive Activity	Element of HerdBatchManagement	Activity updating the reproductive status of a cow and programming a CowCalvingEvent.
WeaningCalves	Primitive Activity	Element of HerdBatchManagement	Activity breaking down the relation established between Cow and Calf at calving and switching the diet of calves.
SellingAnimals	Primitive Activity	Element of HerdBatchManagement	Activity deleting the operated animal from the system, as well as the corresponding group and herd batch if the latter becomes nil.
AdjustmentActivities	Activity Conjunction	Element of HerdBatchManagement	Conditional adjustments that substitute a part of the nominal plan when this plan encounters situations beyond its executability domain.
BuyingStoredFood	Primitive Activity	Element of AnnualManagement	When the available quantity in FoodStorageUnit drops below a critical availability threshold, it credits the food storage unit concerned with the quantity of food bought.

For the *CuttingHerbage* activity, the object targeted by the operation *CutHerbage* is the herbage component of a plot, and the executor is the farmer equipped with a tractor and mower. The *CutHerbage* operation speed is a harvestable area per time unit. The operation creates a specialisation of the entity *HarvestedHerbage* that inherits descriptors from *Herbage* before the cut, the updating of *Herbage* descriptors on the harvested plot and, in the case of hay-making, the initialization of a continuous process *HarvestedHerbageDryingProcess* (based on Duru and Colombani, 1992) on the new harvested herbage. The opening predicate of any *CuttingHerbage* activity and consequently of the encompassing *HarvestingHerbage* activity refers, in addition to the conditions imposed by higher level activities, to biophysical states, e.g. a minimum harvestable yield, a phenological stage or a combination of these. The feasibility conditions attached to the *CutHerbage* operation concern the availability of sufficient free space in the barn to store additional material and, in the case of hay-making, proper drying conditions for the harvested herbage expected in the following days.

For the *StoringHarvestedHerbage* activity, the object targeted by the operation *StoreHarvestedHerbage* is the harvested herbage, and the executor is the farmer equipped with tractor, round-baler and trailer. The storage speed is a storable quantity of harvested herbage per time unit. This operation results in the harvested quantity being credited to the amount of food stored in the *foodStorageUnit*, minus some losses associated with harvesting. In the case of hay-making, the opening predicate of any *StoringHarvestedHerbage* activity relies on the dry matter content of the harvested herbage.

3.3. Dynamic functioning of the model: the event flow

SEDIVER is a specialised development of DIESE that implements the discrete-event simulation paradigm in which significant changes are caused by events occurring at discrete time points separated by varying intervals. Basically the simulation engine of DIESE maintains a queue of events sorted by the simulated time they should occur and by priority degrees in case of co-occurrences. The engine iteratively reads the queue, set the simulated time to the next event time, triggers the top ranked event and removes it from the queue. This loop continues until the queue is empty or until the prescribed date of simulated time is reached. Some events are introduced in the queue before the simulation starts; others are scheduled dynamically as the simulation proceeds.

The sequence diagram shown in Fig. 6 illustrates theses principles with the scenario of events triggered at the very beginning of a particular simulation. The entry point is the C++ '*main*' function of SEDIVER which first sets the desired initial state of the system through the execution of specific parsers on external files describing the structure (including the plan as shown in Fig. 5), static properties and initial values of state variables of the entire production system. This also includes filling the event agenda with all the events that are actually expected to occur in the future. Some of them are self-generated (i.e. their first occurrence is sufficient to generate successively the entire series over the simulation period).

Once the initialization phase is complete the 'Run' message is sent to the simulation engine. In our scenario example, this triggers the top event that is scheduled at time $t = 0$ with priority $p = 0$

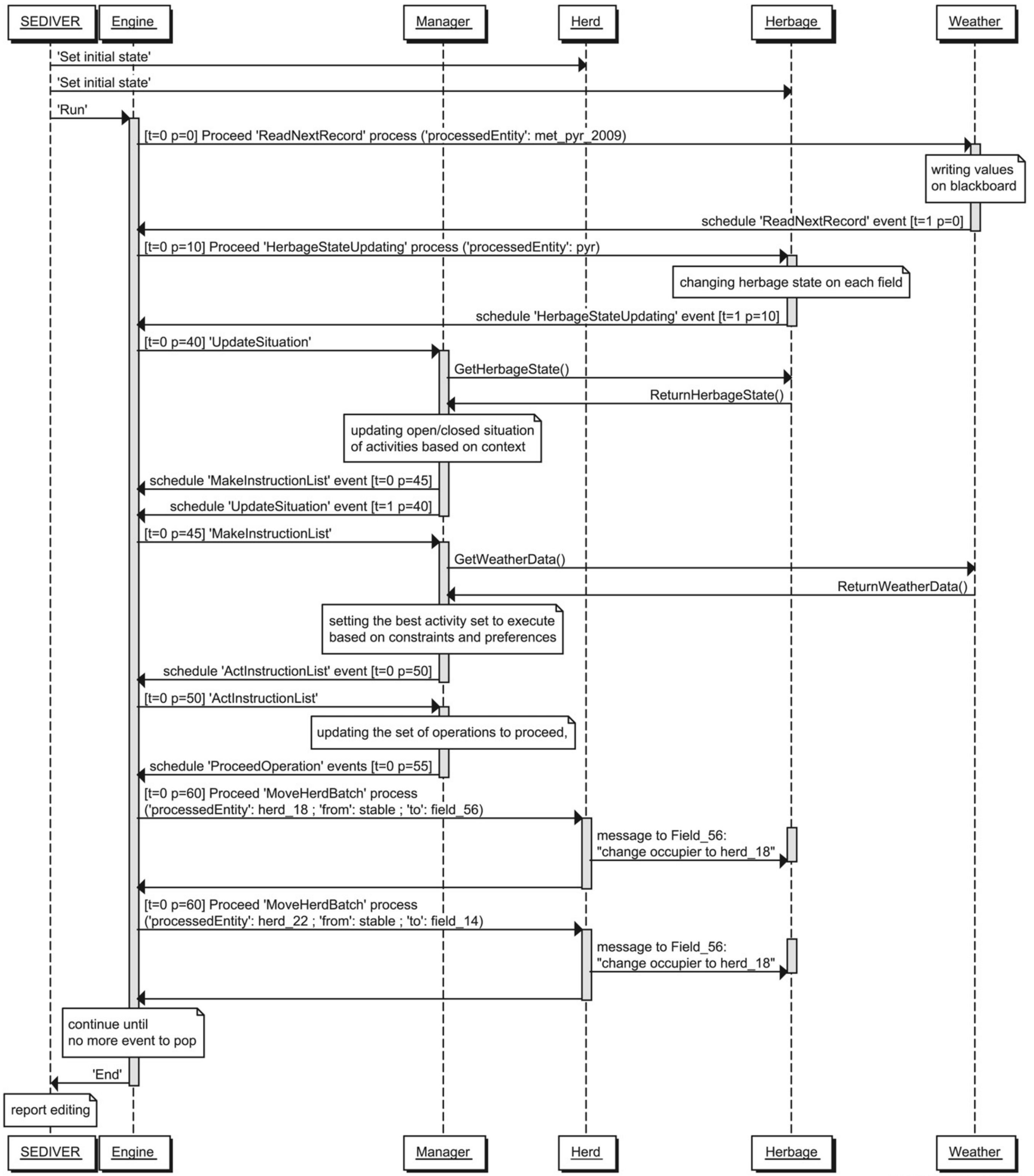

Fig. 6. Sequence diagram of a SEDIVER simulation.

which is the highest priority. This event causes the execution of a so-called 'continuous' process that reads a weather file in a step-by-step mode. At each step (actually 1 clock unit), the process moves the cursor to the next record of the designated weather file before reading it. The values read are written on a blackboard-like structure accessible in a read-only mode from anywhere in the software. Just before the engine executes a second step of the 'ReadNextRecord' process (which would happen at $t = 1$), it takes into account other events that may have precedence. As a consequence, the engine creates a new instance of the class of events that manages the 'ReadNextRecord' process and inserts it in the agenda at the right place according to its occurrence date ($t = 1$) and priority ($p = 0$).

The next event to pop up occurs at $t = 0$ and has priority $p = 10$. It initiates and maintains the process in charge of the dynamic updating of the farmland sub-system state. Here again, the engine creates a new instance of this event (at $t = 1$, with $p = 10$) and inserts it in the agenda respecting the precedence of the Update-Situation event. The latter updates the status of each activity in the plan, shifting from 'waiting' to 'open', then 'underway' and finally 'closed' by taking into consideration the opening/closing specifications of activities and the current state of the system and its environment. As an example, the 'UpdateSituation' process takes information on the Herbage component by sending it some appropriate access-oriented messages. Execution of this process terminates in scheduling two other events: one of the same class, dated at the next time step ($t = 1$), one of the class 'Make-InstructionList' at $t = 0$ (i.e. immediate occurrence) with priority $p = 45$.

The 'MakeInstructionList' event acts similarly. Besides its own effect (selecting the best set of activities to execute), it schedules the event that will take care of the operational part of the plan. The latter, an instance of the 'ActInstructionList' class, updates the list of operations to be implemented, taking into account currently running operations that might be interrupted due to lack of resources (although none is considered in SEDIVER currently). Then the 'ActInstructionList' process inserts in the agenda as many 'ProceedOperation' events as there are activities selected for concurrent execution. In our example, two herds are displaced from the stable to different relevant fields, changing the value of the 'Occupier' attribute of the fields from 'null' to a pointer to each of the two herds, respectively.

The simulation engine carries on in this way until the end date of the simulation period is reached or the agenda is empty. The latter case occurs typically when the plan has been fully executed and all processes underlying the system dynamics have been stopped intentionally. The control is then handed back to the '*main*' function of SEDIVER, which typically edits a report on the dynamics of the system in the simulation period, or some statistics summarizing it.

4. Application example

4.1. Description of the experiment

On the French side of the Pyrenees, the climate is montane. Long, cold winters prevent animals from grazing for several months. During that period, about half of the grassland-based beef-cattle farms rely on roughly 20% of external hay supply to cover the fodder needs of their herd. Amazingly, on these farms, the herbage utilization rate, i.e. the ratio of herbage grazed and harvested to the herbage grown over the year, remains low at around 50%. The SEDIVER simulation framework was therefore used to compare the behaviour of the currently used management strategy with a novel management strategy, i.e. one which is more flexible and aimed at improving fodder self-sufficiency by increasing the herbage utilization rate.

Available data about the simulated system is derived from technical literature (Institut de l'Elevage, 2006), a four-year farm survey already reported on by Coleno et al. (2005) and expert opinion. The simulated systems for model validation are presented in Martin et al. (2010) and in the supplementary material listed below. Actually, the simulated system considered in the experiment is typical of the area. It has grassland-based production of 6- to 8-month-old recently weaned beef calves (Gasconne breed). It covers an area of 30 ha with semi-natural grasslands only and rents mountain summer pastures. It has 12 ha in the valley bottom at an altitude of 650 m a.s.l., with fairly uniform, early and productive grasslands and high plant nutrition indices. On the sloping sides of the valley, plots vary from 750 m a.s.l. to 1000 m a.s.l. Grassland production lags behind the valley bottom plots, and this trend increases with altitude. Plant mineral nutrition indices also exhibit a gradient, with the lowest values for the high altitude plots. It has 25 Gasconne beef cows and 10 heifers. Each year, sales are 23 calves under 8 months in September, and 5 suckling cows for replacement in spring.

In systems like this, the actual management strategy relies on significant calendar events and herbage availability expressed in herbage height at the entrance of a plot to be grazed or in residual herbage height after grazing of a plot (Fig. 5). This strategy is based on the farmer's experience and results in quite a stable system configuration and management patterns despite variations in year-to-year weather variation. We hypothesized that to improve the herbage utilization rate, close attention should be paid to the herbage dynamics of each field in order to exploit the within-farm diversity of grassland production patterns through their timing, productivity and nutritive value. The trade-off between herbage growth and senescence, which depends on leaf life span and phenological stages of grassland plant species (Duru et al., 2009), certainly has major consequences for herbage availability and nutritive value. For example, Coleno et al. (2005) have pointed out that both the first and second harvests occur too late in the season in these systems. In both cases, at the time of harvest, herbage senescence has already overtaken growth for several days, which results in less harvested herbage and lower nutritive value. In addition, the first harvest is preceded by spring grazing, which generally occurs during the reproductive phase of the grassland. During this phase, daily growth is about twice as fast as in the non-reproductive phase (Duru et al., 2009). Thus, by removing the apex of the grass and therefore preventing the reproductive phase, spring grazing reduces the herbage yield at the subsequent harvest.

Relying on plant and grassland diversity – and their consequences for herbage dynamics – to increase the herbage utilization rate, implies a flexible configuration and management dictated by weather conditions and the ongoing system state. Consequently, herd destinations for grazing are not normally determined in advance but are chosen from a list according to the herbage dynamics on each plot (Fig. 5). Herd movements are not determined according to dates and herbage heights but according to leaf life spans and phenological stages. The first harvests are guided by phenological stages whereas the next are determined according to leaf life spans. Leaf life spans are useful insofar as they can indicate whether senescence might overtake growth or whether the growth rate might fall below a certain threshold. Phenological stages are characteristic of the herbage's transition into the reproductive phase and are an indication of when to stop grazing so as not to interfere with this reproductive phase.

The model was run for each management strategy, i.e. current and novel, for 7 real-life year-long weather series (1998–2004) taken individually from the weather station located at Ercé (altitude 670 m a.s.l.; latitude: 42°50 N; longitude: 1°17 E). Simulations started when the cattle entered the stable here on the 28th of November, continued while they were moved outside from spring, and ended when they returned to the stable about one year later. The structure of the simulated system was kept constant between simulations, as was the initial system state.

4.2. Calibration and validation of the SEDIVER-based model

Biophysical submodels can only be calibrated and validated if sufficient data is available and the process inevitably involves a statistical approach. In order to model isolated biophysical components (e.g. Duru et al., 2009) they must have gone through such statistical processing. The situation is much less favourable with dynamic farm-scale simulation models. In fact, at the farm scale, the data available on real cases are scarcer or are incomplete with respect to the set of aspects considered and given the time frame and spatial scales of interest. In addition, as the simulation results depend on interactions between models of the biophysical, decision and operating systems, identifying the respective sources of error among these is an unresolved problem.

Dynamic farm-scale simulation models are expected to display behavioural or representational accuracy of the simulated system (Küppers and Lenhard, 2005), i.e. to provide realistic chronologies and estimates of system state descriptors over several years. The variability of uncontrollable factors (such as weather) and the farmer's management behaviour is considerable and precludes any systematic exploration or sensitivity analysis. Calibration therefore mostly relies on common sense knowledge of experts or farmers in checking that the outputs are consistent considering a range of simulation inputs (Cros et al., 2004). If the outputs are considered to be inconsistent, the model of the farming system used for simulation inputs and in particular the model of the farmer's management strategy are again checked against available data. When a discrepancy is found, the model is modified (actually re-designed) until satisfying outputs are obtained. Validation consists in adopting a similar approach by comparing the available observed data and simulated data. The agreement of experts and farmers with the model behaviour, in particular on simulated decisions and actions, is then the key indicator of the validity of the model (Küppers and Lenhard, 2005), which has to be assessed in relation to its purpose.

To build trust in the research approach and in the scientists' understanding of the simulated system, the expert coordinating the survey and the two farmers involved were invited to discuss a functional analysis of their farming systems. The simulation results were subsequently presented to the expert and once to the farmers involved. It consisted of a range of aggregate indicators (e.g. the quantity of food stocks harvested, the proportion of grazing in the animals' diet), production results (e.g. harvest yields) and a calendar of key events and farming activities (e.g. beginning of grazing, departure to summer grasslands, harvests). The farmers and the expert found all three types of simulated results consistent and realistic given the weather time series considered and the purpose at issue. Consequently no extra calibration effort was required. For two real farm cases (see Martin et al., 2010), the simulation outputs were also compared (Table 3) with observed data which were available for years 1998, 1999 and 2000.

Fodder harvested annually was on average overestimated by 5% (i.e. RMSE = 277 kg, Table 3) for farm 1 and underestimated by 13% (i.e. RMSE = 158 kg, Table 3) for farm 2 but statistical tests showed that the average values of observed and simulated data were not statistically different ($P = 0.771$ and 0.184 in Student tests of Table 3). Simulations reproduced consistently the extent and the direction (increase or decrease) of between-year variations of harvested fodder as observed and simulated data displayed the same distributions ($P = 0.532$ and 0.532 in Kolmogorov–Smirnov tests of Table 3). When looking at harvests in detail, simulated harvested quantities on each field were close to those observed for first harvests (e.g. for farm 2, Fig. 7a, $n = 46$, $R^2 = 0.76$, $P < 0.001$) and a little lower for second harvests (e.g. for farm 2, $n = 31$, $R^2 = 0.65$, $P < 0.001$). Yearly fodder consumption was also well simulated as the average values and the distribution of simulated data were not statistically different to that observed (Table 3). Simulated duration of stay of animals at grazing was very close to that observed (Fig. 7c, e.g. for farm 2, $n = 61$, $R^2 = 0.67$, $P < 0.001$), with a one day difference on average between simulations and observations. This resulted in fairly well simulated percentage of grazing in animal feeding displaying RMSE of 1% in each farm (Table 3). Simulated live weight production was underestimated by 10 and 4 kg on average (Table 3) but average simulated values and distributions were not statistically different from observations. At the age of 120 days, simulated calf live weight was on average 159 kg, close to the 155 kg for the standards of the Gasconne breed. However, later in the season, daily live weight gain progressively decreased to a greater extent in the simulations as compared to the breed standards. Indeed, at the age of 210 days, if calves had not been sold, their simulated weight was around 205 kg against 245 kg for the breed standards. Simulations of current management behaviour of farmers also fitted with observations. For instance, simulated dates of displacements of animals during grazing differed from observations by three days (Fig. 7d, e.g. for farm 2, $n = 61$, $R^2 = 0.87$, $P < 0.001$). Dates of harvests were simulated with a five-day difference (Fig. 7b, e.g. for farm 2, $n = 46$, $R^2 = 0.89$, $P < 0.001$). This confirmed that simulations consistently reproduced the biophysical processes, the farmers' decision processes as well as the relations between system state, decision-making and execution of actions.

4.3. Comparison of management strategies

Harvested quantities using the novel strategy were significantly higher than with the actual strategy in years with moderate plant water stress ($P = 0.000$ in Student test of Table 4). The amount harvested increased twofold and this difference was reproduced consistently between years ($P = 0.037$ in Kolmogorov–Smirnov tests of Table 4). In years with a long stress period, the difference

Table 3
Comparison between four observed and simulated aggregate performance indicators of two farms from Martin et al. (2010). AVG is average over the data set; SD, standard deviation; RMSE, root mean square error; *t*, the *t*-value of a Student test; *D*, the *D*-value of a Kolmogorov–Smirnov test, AU means Animal Units.

	Harvested quantity (tons/AU)		Stock consumption (tons/AU)		Grazing in feeding (%)		Live weight production (kg/Cow)	
	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
Farm 1								
AVG	2316	2443	2443	2026	59	59	252	240
SD	590	389	389	384	2	1	37	21
RMSE	277		320		1		10	
t	$t = -0.311$; $P = 0.771$		$t = 1.323$; $P = 0.256$		$t = -0.802$; $P = 0.468$		$t = 0.490$; $P = 0.649$	
D	$D = 0.333$; $P = 0.996$		$D = 0.667$; $P = 0.532$		$D = 0.667$; $P = 0.532$		$D = 0.333$; $P = 0.996$	
Farm 2								
AVG	1739	1539	1863	1866	59	59	227	226
SD	200	82	102	57	3	2	13	4
RMSE	158		73		1		4	
t	$t = 1.606$; $P = 0.184$		$t = -0.044$; $P = 0.967$		$t = 0.686$; $P = 0.530$		$t = 0.131$; $P = 0.902$	
D	$D = 0.667$; $P = 0.532$		$D = 0.333$; $P = 0.996$		$D = 0.667$; $P = 0.532$		$D = 0.667$; $P = 0.532$	

Table 4
Comparison for aggregate performance indicators between two management strategies simulated, i.e. actual and novel, for years with moderate plant water stress (1998, 1999, 2000, 2002) and with lasting plant water stress (2001, 2003, 2004). AVG is average over the data set; SD, standard deviation; *t*, the *t*-value of a Student test; *D*, the *D*-value of a Kolmogorov–Smirnov test.

Strategy	Harvested quantity (tons/AU)		Digestibility of harvest (kg/kg)		Stock consumption (tons/AU)		Grazing in feeding (%)		Digestibility of grazing (kg/kg)		Herbage utilization rate (%)		Live weight production (kg/Cow)	
	Actual	Novel	Actual	Novel	Actual	Novel	Actual	Novel	Actual	Novel	Actual	Novel	Actual	Novel
Years with moderate plant water stress														
AVG	1560	3191	0,61	0,68	1810	1689	0,59	0,61	0,71	0,75	0,55	0,70	232	235
SD	107	418	0,03	0,01	107	39	0,02	0,01	0,03	0,01	0,02	0,03	7	4
t	$t = -7.560$; $P = 0.000$		$t = -4.159$; $P = 0.006$		$t = 2.137$; $P = 0.076$		$t = -2.043$; $P = 0.087$		$t = -2.449$; $P = 0.050$		$t = -8.216$; $P = 0.000$		$t = -0.919$; $P = 0.393$	
D	$D = 1.0$; $P = 0.037$		$D = 1.0$; $P = 0.037$		$D = 0.75$; $P = 0.211$		$D = 0.75$; $P = 0.212$		$D = 1.0$; $P = 0.037$		$D = 1.0$; $P = 0.037$		$D = 0.25$; $P = 0.999$	
Years with lasting plant water stress														
AVG	903	1369	0,61	0,65	1825	1804	0,57	0,57	0,74	0,76	0,51	0,61	213	205
SD	491	419	0,06	0,01	40	58	0,01	0,01	0,01	0,01	0,13	0,10	12	9
t	$t = -1.249$; $P = 0.280$		$t = -1.135$; $P = 0.320$		$t = 0.523$; $P = 0.629$		$t = -0.378$; $P = 0.725$		$t = -2.683$; $P = 0.055$		$t = -0.986$; $P = 0.380$		$t = 0.859$; $P = 0.439$	
D	$D = 0.667$; $P = 0.532$		$D = 0.667$; $P = 0.532$		$D = 0.667$; $P = 0.532$		$D = 0.667$; $P = 0.532$		$D = 1.0$; $P = 0.100$		$D = 0.667$; $P = 0.532$		$D = 0.667$; $P = 0.532$	

was not statistically significant, despite the higher average of harvested quantities using the novel strategy. This is because the harvests occurred before yield depletion caused by the increase in herbage senescence. As a consequence, in years with moderate plant water stress, three harvests were taken on all the valley bottom plots, one between stem elongation and flowering of herbage plants, and one just after a leaf life span for the two subsequent cuts. This more frequent grassland use resulted in greener standing herbage, so that digestibility of the harvest was also significantly enhanced (*P* = *0.006*, Table 4) by 0.07 kg kg^{-1}, consistently between years (*P* = *0.037*, Table 4). Since the initial system state was kept constant between simulations, including

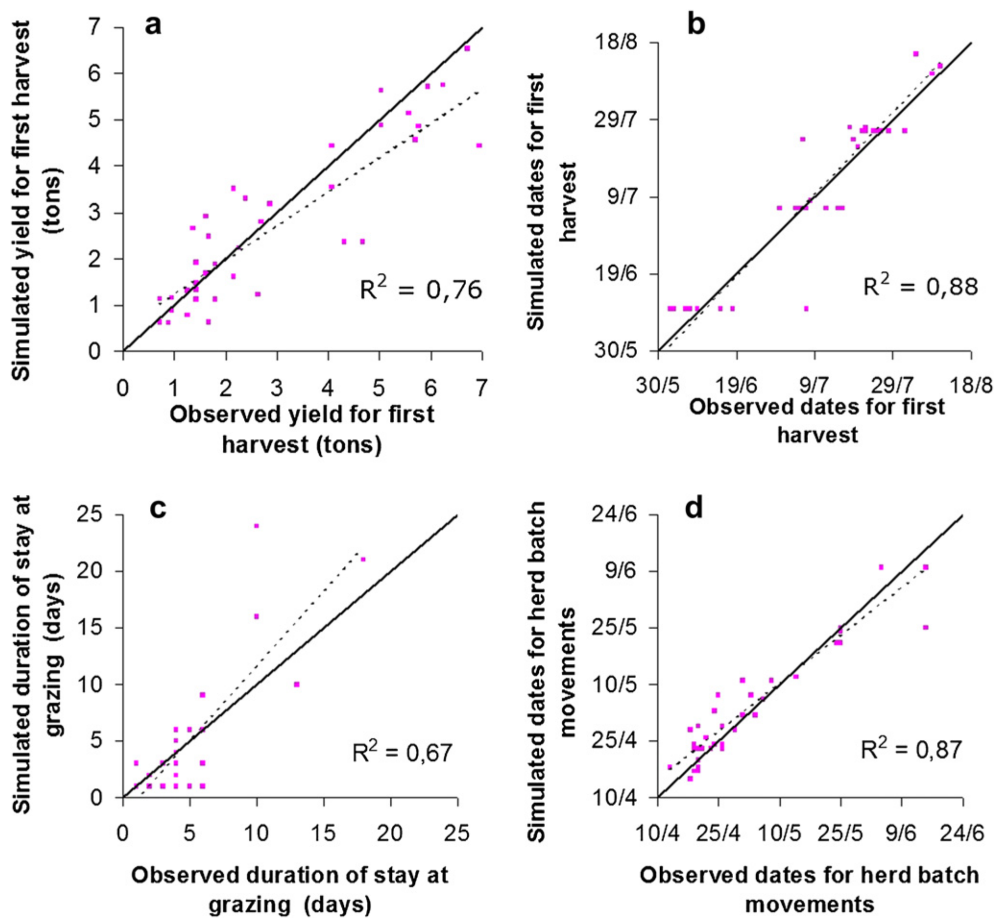

Fig. 7. Correspondence between observations and simulations for harvested quantities (a), dates of first harvest (b), duration of herd batch stay at grazing (c), and dates of herd batch movements (d) for farm 2 for years 1998–2000.

digestibility of the food stocks, the benefits of this improvement to animal feeding and production for the subsequent winter were not evaluated. Stock consumption remained in a similar range with insignificant differences between management modes whatever the type of annual weather pattern ($P = 0.076$ and $P = 0.629$ for years with moderate and lasting plant water stress respectively, Table 4). Consequently the proportion of grazed herbage in the diet of the animals was not statistically different between management modes ($P = 0.087$ and $P = 0.725$, Table 4), despite the 2% increase in average in the years with moderate plant water stress. Due to the increased frequency of grassland use with the novel strategy, digestibility of grazed herbage was significantly enhanced in favourable years ($P = 0.050$, Table 4), particularly during autumn grazing. In fact, the third harvest at the end of summer in the valley bottom ensured available herbage for grazing in autumn at about the age of one leaf life span. Given that the novel strategy followed along with herbage production, the herbage utilization rate significantly improved ($P = 0.000$, Table 4) by 15% in favourable years. The average difference (10%) observed in years with long plant water stress was not statistically significant ($P = 0.380$, Table 4). Animal production performance was maintained with the novel strategy in both favourable and unfavourable seasons ($P = 0.393$ and $P = 0.439$, Table 4).

Although the benefits of the novel strategy were more pronounced and statistically significant in favourable years, it also outperformed the actual strategy in years with prolonged plant water stress. Simulations revealed that each time a double harvest was possible (i.e. with high enough harvestable yield) on the valley-bottom plots using the actual strategy, a triple harvest was possible using the novel strategy. In unfavourable years, because the harvest occurred before senescence-related losses in yield and digestibility, harvested quantity and digestibility remained higher with the novel strategy. Providing food supplements during drought to substitute for grazing lasted as long with the actual strategy as with the novel strategy. These observations suggest that the novel strategy coped better with unfavourable years. It also performed so much better in favourable years that it would compensate for food stock shortages in an unfavourable year and thus help ensure fodder self-sufficiency. These results suggest that encouraging farmers to pay increased attention in their management to plant and grassland diversity and its consequences for herbage dynamics would be advantageous for them.

5. Discussion and related works

Effectiveness of the simulation approaches in supporting the design of farm systems, might be assessed according to three criteria (Cash et al., 2003): saliency (relevance to decision makers), credibility (scientific adequacy) and legitimacy (fair and unbiased production of information which respects stakeholders' values and beliefs).

Farms, especially in less-favoured areas, are characterized by strongly heterogeneous resource use, resulting in considerable variability of production in time and space (van Keulen, 2006). Common farm-scale modelling approaches which are typically based on linear programming models (e.g. ten Berge et al., 2000) rely on farm-averaged indicators, such as the stocking rate, and ignore this variability. Previously published simulation-oriented farm models for designing dairy- and beef-cattle production systems in temperate areas (e.g. Romera et al., 2004; Matthews et al., 2006; Jouven and Baumont, 2008; Rotz et al., 2009) did not provide a sufficiently detailed or explicit representation of plant, animal, grassland and farmland diversity. In addition, none included all four types of diversity, i.e. plant, animal, grassland, and farmland, in a single versatile model. For instance, the model from Romera et al. (2004) integrates animal diversity but does not consider plant, grassland and farmland diversity. Even though it accommodates crop diversity, the model from Matthews et al. (2006) has the same limits. While accounting for plant, grassland and animal diversity, the models of Jouven and Baumont (2008) and Rotz et al. (2009) ignore farmland diversity. This has far-reaching consequences for the realism and credibility of the simulations and also for the practical benefit – indirectly the saliency and legitimacy – that the model displays for the design of grassland-based beef-cattle production systems. The induced, dynamic heterogeneous nature of biophysical processes within a farm, and herbage dynamics in particular, has strong practical implications for the planning and coordination of activities by the farmer. Ignoring one type of diversity compromises the practical contribution a model can make to the design of farming systems. Modelling this makes it possible to deal with threats and opportunities on herbage use and animal feeding, and their consequences on system performance.

In the current version of SEDIVER, saliency, credibility and legitimacy are, however, slightly bounded by the lack of accuracy of some parts of the biophysical models. For instance, the simulations tended to underestimate harvested quantity and live weight production. The biophysical model used to simulate available herbage dry matter is very sensitive to plant mineral and water nutrition indices (Duru et al., 2009). A small error in the data, i.e. in the measurements of values used as inputs, might have led to these underestimations. Similarly, the live weight of calves was simulated fairly well at the age of 120 days but was underestimated in the last month before sale, as has been pointed out by Jouven et al. (2008) who developed this part of the model. Still, the simulation results remained consistent with respect to the extent and trend (increase or decrease) of between-year performance variations of the simulated systems. In spite of this, in the application example, the lack of accuracy of some parts of the biophysical models did not affect significantly the capacity of SEDIVER in assisting the design and evaluation of grassland-based beef-cattle production systems with farmers.

Simulation models had traditionally focused on the agronomic and technological aspects of production processes, e.g. crop responses to farming operations (e.g. Stöckle et al., 2003). When farmer's decisions were to be simulated, this was usually done by implementing a sequence of technical actions on fixed dates as simulation inputs or according to weather conditions. Many more elaborate representations of farm management have been developed as rule-based decision models (e.g. Shaffer and Brodahl, 1998; Donatelli et al., 2007) that relate the decision made to dynamic conditions. Such formalism has features that proved to be useful in simple management problems such as irrigation. The knowledge is represented in a simple, intuitive and homogeneous format which makes it easier to understand, and since the rules are modular the knowledge base can easily be extended or modified. There are some drawbacks however. With large rule-based systems it may be hard to control the order in which the rules are used, so they may actually be difficult to design and difficult to debug. Moreover there is no powerful means to create links between them so as to build management strategies that enforce a non-trivial temporal structure for the decisions and actions. Production management at farm scale raises the problem of coordinating activities because these require resources which are either limited or constrained by temporal availability and also because future activities need to be anticipated in relation to present ones. Coordination problems call for a more sophisticated structuring construct than rules can offer. An obvious approach is to organise activities in plans that are flexible and adaptable to changing conditions so that premature commitment can be avoided. This is precisely the intention of the work presented here, which aims to support the study of plan-based decision-making in production management. Other applications dealing with grassland-based systems have been reported by Cros et al. (2004), in an earlier work of some of the authors of this paper, and by Snow and Lovatt (2008) who proposed a planning model in which anticipated futures are explored by simulation to find out optimal sequences of decision.

When the conceptualization of the farm management decision process is oversimplified this seriously affects the saliency, credibility and legitimacy of farm-scale simulation models. The system simulated is then seen as a set of biophysical processes that can be controlled independently of one another, with limitless resources (labour, machinery) and instantaneous operations. As a consequence, most models suffer from unrealistic assumptions about the importance of spatial, temporal and resource restrictions in agricultural production management. Through flexible activity plans and conditional adjustments, SEDIVER integrates the way in which the farmer copes with unpredictable and uncontrollable factors, and yields different sequences of actions depending on the conditions encountered. It explicitly considers the management constraints faced by a farmer, those inherent to the farm structure (e.g. whether plots are suitable for mechanization) and those encountered in an actual dynamic process (e.g. time dependencies between activities). In this sense, SEDIVER-based models fulfill the wish of Keating and McCown (2001) to achieve “relevance to real world decision making and management practice” in farming system models.

The approach used to develop SEDIVER is known as knowledge-driven or ontology-based modelling (Villa et al., 2009). The rigorous common structure provided by the ontology used for the DIESE framework enforced model design principles. It greatly facilitated the design and implementation of novel and complex activity plans including conditional adjustments. The discrete-event paradigm used in the DIESE framework enabled a modular model construction and above all was extremely valuable for accommodating the asynchronous, concurrent and non-linear nature of the processes.

SEDIVER also proved very useful in the interactions with farmers to ensure the saliency and legitimacy of the management strategies designed. Despite the abstract nature of the representation, it provided an easily understandable basis for discussing the activity plans designed using schemes such as a more simplified version of Fig. 4. The two farmers involved in the survey and the expert conducting it confirmed the saliency and legitimacy of the simulation model as well as the relevance and practical feasibility of the novel management strategy designed and evaluated in Section 4. In addition, the results of the simulations inspired constructive discussions on the design of novel strategies.

6. Conclusion

To sum up the models of grassland-based beef-cattle production systems built with the SEDIVER simulation framework incorporate an explicit representation of management strategies and decision processes, and exploit ready-to-use biophysical models while taking into account the diversity in plant, grassland, animal, and farmland. The models constructed with SEDIVER are definitely more representative of farmer management due to explicit representation of the organisation, coordination and adaptation of management activities in a range of varying uncontrollable conditions. In order to identify the inefficiencies and vulnerability of a system it is essential to understand how the system behaves in relation to external factors and the logic and timing of the decisions made. The diversity in plant, grassland, animal and farmland is both a burden and a source of opportunities that result in a difficult coordination problem requiring context-responsive and adaptable management behaviour. The application example has shown that large gains are possible if the coordination problem is addressed properly. This application and others not reported in this paper have proved that SEDIVER provides a thought-provoking and constructive environment for researchers, experts and farmers to engage in collaborative projects for the design of farming systems. The level of detail in the representation of the decision process and the realism of the simulated behaviour of the system definitely helped establish the saliency, credibility and legitimacy of the model and the feasibility and soundness of the alternative management strategy proposed.

Future works on SEDIVER will address management issues in a wider range of livestock production systems, i.e. systems including sown grasslands, crops and dairy cattle. We anticipate that significant improvement and extension will be needed for the biophysical part. As far as management is concerned, the most important needs seem to be to incorporate the limitations of working resource requirements (e.g. labour, machinery, water) in the management and decision making processes.

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Appendix. Supplementary information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsoft.2010.10.002.

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