Farmer Integrated Decision Model: integration between beef cattle and rice production in Rio Grande do Sul, Brazil.

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To

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Declaration

I hereby declare that this thesis has been composed by myself, and is the product of my own work.

Signed: Date: 5/11/99

Abstract

Rio Grande do Sul is the southern state of Brazil. The Southern part of the Rio Grande do Sul state, an area of approximately the size of England, is part of the Campos sub-region of the Rio de La Plata temperate sub-humid grasslands ecosystem. Beef cattle and the rice crop are the main economic activities in this region.

The main goal of this thesis was to simulate the dynamic nature of the farm with the partnership between finishing beef cattle and the rice crop that can be carried out in Rio Grande do Sul, Brazil. To achieve this goal, crop, livestock and economic models were developed and integrated to simulate farm conditions in the South of the Rio Grande do Sul state.

Models as tools for decision support need to be dynamic in concept to simulate the real farm environment. The information base is classified as "natural" and "simulated". The "natural" results from past experience. The "simulated" is based on quantitative formal scientific information. This work presents a framework that deals with adaptive behaviour as a response to natural and simulated information. Decisions about animals, pasture, soil, land use and economics are incorporated. These decisions impact on the biological and economic models and generate scenarios resulting from these decisions. As the farmer's decisions are sequential and dynamic, the model simulates the bio-socio-economic environment in which farm decisions occur at established time-steps. The Farm Integrated Decision Model (FIDM) supplies the farmer with information about economic and biological aspects of the farm and asks the farmer about each decision. Therefore, when a farmer takes a decision the "natural" state is a pre-condition of the simulation.

Case study simulations were made, and the results of the proposed methodology are presented to demonstrate the potential use of this approach, generating different scenarios for the farmer. Dialogue between extension worker and farmer permits the interactive evaluation of existing technologies. Flexibility in model construction will allow incorporation of new technologies as and when information becomes available.

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CHAPTER 1

INTRODUCTION

Rio Grande do Sul is the southern state of Brazil between latitude 49.9°W and 57.3°W and longitude 27.0°S and 33.3°S. It has an area of 282.184 km^2 and a population of 9.7 million inhabitants, respectively 3.3% of the area and 6.2% of the population of Brazil. The state's gross domestic product in 1997 was US$ 56.7 thousand million, which represents 8.3% of the Brazilian gross domestic product (GNP) (FEE, 1998).

The southern part of the Rio Grande do Sul state, with an area of approximately 140.000 km^2, is part of the Campos sub-region of the Rio de La Plata temperate sub-humid grasslands ecosystem (Figure 1.1). Several authors have discussed the absence of trees in this region. The situation of a negative water balance during part of the year and soil with fine texture and poor aeration are conditions which benefit grasses more than trees. (Soriano, 1992).

The climate is mesoderm and subtropical with rainfall distributed throughout the year. The annual average rainfall is 1350 mm, of which 34% occurs in winter, 25% in spring, 25% in autumn and 16% in summer. January, with a mean daily average of 24°C, is the hottest month and June, with a mean daily average of 12.5°C is the coldest. Extreme temperatures are – 4°C and 41°C and the relative humidity ranges from 75 to 85%. Frosts occur occasionally between May and September. (Macedo, 1987).

Beef cattle and rice production are the main economic activities in the southern part of the Rio Grande do Sul. Before the arrival of Europeans in this region, the whole grassland region was only used by a small number of herbivore species. Cattle were introduced around 1607 from the Pampa sub-region in Argentina (Soriano, 1992).

Figure 1.1. North Campos in the Rio de La Plata grassland.

Rio Grande do Sul had 13.4 million beef cattle in 1997. The British breeds (Hereford, Aberdeen Angus and Devon) and Charolais are the main breeds. These have been crossbred with *Bos indicus* over the last years.

German immigrants introduced rice production in the northern part of Rio Grande do Sul in the late 19th century. They initially grew the rice for their own consumption. In the early 20th century the Brazilian government took action to maintain the balance of international trade and to protect the coffee crop, which depended on external borrowing. Rice importation was therefore reduced which indirectly resulted in the development of internal rice production. In 1916 more than 100 thousand tons of rice were produced in Rio Grande do Sul (Massera, 1983). In 1994/95, the area occupied by the rice crop was 962 thousand hectares with a production of 4.5 million tons. (IRGA, 1995).

The main goal of this thesis was to simulate the dynamic nature of the farm with a combination of partnership between finishing beef cattle and rice production that can be carried out in Rio Grande do Sul, Brazil. To achieve this goal, crop, livestock and economic models were developed or modified and integrated to simulate farm conditions in the south of the Rio Grande do Sul state.

Chapter 2 presents a description of farm systems utilised in the region and the potential use of models to help farmers in their decisions. The way in which integration occurs between the rice crop and beef cattle is described. There is a general review of models available in the literature and their potential for use in this study is also cited.

The methodology used in the construction of the farm integrated decision model (FIDM) is part of Chapter 3. The FIDM simulates the farm environment and the responses to farmer decisions in this environment. The decisions of the farmer (behaviour) are treated inside the model with direct impact on the biological and economic components.

To simulate the biological components of the system, models that simulate the soil, plant and animal were constructed. The overview of the grassland model, which integrates soil-plant-animal and the pasture sub-models, is described in Chapter 4. The soil sub-model and the animal sub-model are described in Chapters 5 and 6 respectively. The structure of these chapters is the same; first the description of the model is made and then results of simulations are presented.

The rice crop and economic factors are the two other components in the FIDM and these are presented in Chapter 7. An economic model developed in Brazil was used to simulate beef meat prices and for rice prices a historical series was used.

The flow of information in the farmer decision model is presented in Chapter 8. The FIDM simulations and the scenarios generated by FIDM are shown in Chapter 9. The conclusion and future work to be developed with the model in Rio Grande do Sul are addressed in Chapter 10.

CHAPTER 2

SYSTEM PRODUCTION AND MODEL APPLICATION

Until the 1950's the south western part of Rio Grande do Sul was characterised by natural grassland, grazed by both beef cattle and sheep. Crops were produced to meet the requirements of farm household consumption. Gaúchos, who are a product of the clash between the Spanish and the Portuguese empires and cultures in Rio de La Plata, tended the animals. Their language is a blend of Spanish and Portuguese, and various Indian tongues (Popino, 1973). Management of stock by gauchos, however, did not involve intervention with processes like reproduction, selection, health or food supply, so natural pasture was the main agent in the system. At that time, the beef cattle production system could truly be described as a **natural system.** The bulls spent all year with the cows and steers were slaughtered at five or more years old. The physical structure of the farm was characterised by a small number of paddocks, or sometimes the farmer just fenced the perimeter to delineate the farm (FAO, 1964).

This scenario began to change with the introduction of improved pasture species. The first experiments with Italian ryegrass (*Lolium multiflorum Lam.*) were made in 1949 (Gonçalves, 1979) while white clover (*Trifolium repens* cv. Lousiana S1) was cultivated in paddocks for the first time in 1959 (Reis, 1987). Initially, the land was cultivated by horse-drawn equipment, so it was possible only to till a limited area. At the same time, the first drugs were used to control animal diseases.

With the advent of " the green revolution" the landscape in this region was further modified with the introduction of soyabean, maize, sorghum and most importantly rice, which were grown for commercial purposes and therefore mechanised farming methods were introduced. Sons or grandsons of immigrants from central Europe, mainly Germans and Italians, who lived in the centre and northern part of Rio Grande do Sul had the resources and expertise to cultivate the land. Initially, they rented land from beef cattle farmers (Gaúcho), but later most of them bought their own land. This socio-economic mixture brought changes to production systems, to the landscape and the culture of the region. The interaction between the Gaúchos and the immigrants proved to be effective in land utilisation.

Today, many farmers are contemplating the introduction of crop production. Careful planning is needed because animals and crops compete for resources (e.g. land, money, labour) and respond differently to environmental changes. This chapter first examines the viable systems, which have been practised by farmers in Southwest Rio Grande do Sul, with special attention to the systems, which involve both beef cattle fattening and the rice enterprise. The potential use of the model in explaining the complex interacting socio-biological system is described.

2.1. Description of systems

The systems described result from the interaction of four main factors: man, animals, pasture and crops: beef cattle and sheep in the case of animals; natural and improved pasture, crops cultivated in dry or irrigated conditions and finally man. Figure 2.1 shows a further division into breeding, growing or fattening for the animal enterprises, annual or perennial pastures and crop production according to season.

The **traditional system** is when all types of livestock production (breeding, growing and fattening), and natural pasture are involved. This system can be considered the basic farming system for the region. Systems including natural and improved pasture, animals and irrigated crops (rice) will be described separately, because the objective is to fully understand the components and how they interact.

2.1.1. Pasture

Natural pasture is still the main source of food supply for ruminants in south west Rio Grande do Sul (Silva & Jacques, 1993). Grass species are the main components of natural pasture. There can be a range of up to 400 species of C_3 and C_4 grass types and in addition a small number of legumes and weeds. These are found in variable proportions according to soil type and paddock management. These facts underline the complex nature of the natural pastures of the area and point to difficulties in management (Girardi-Deiro & Gonçalves, 1987; Carambula, 1991).

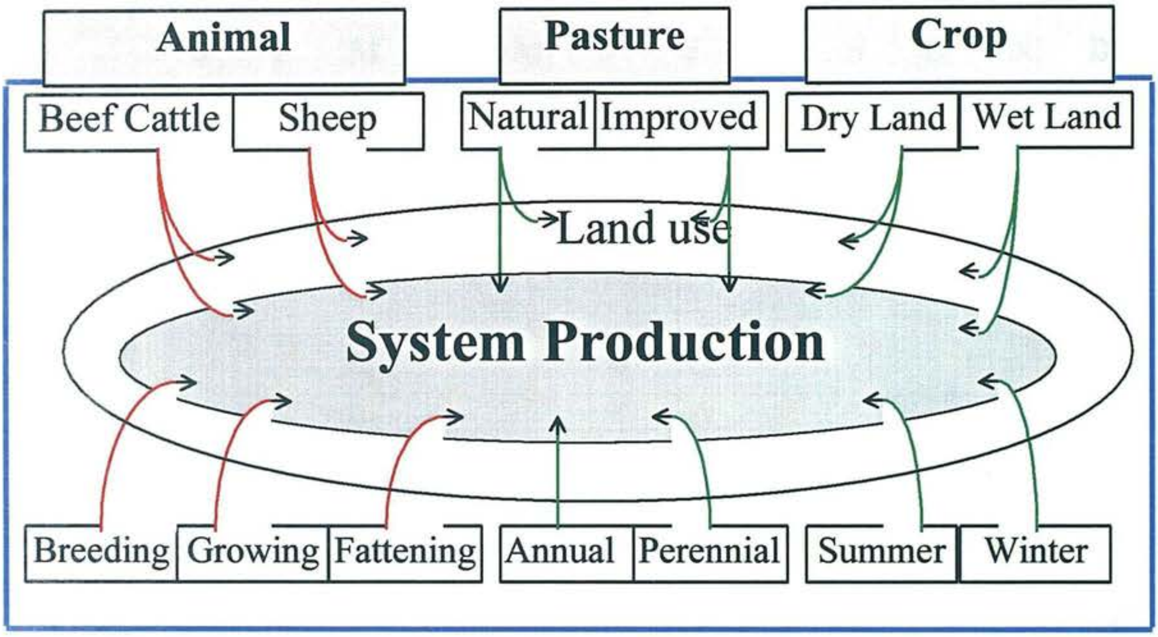
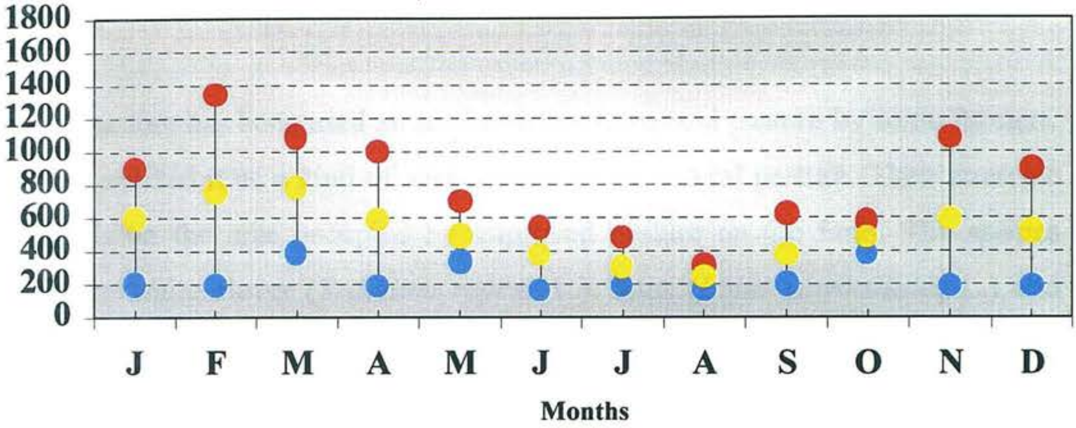


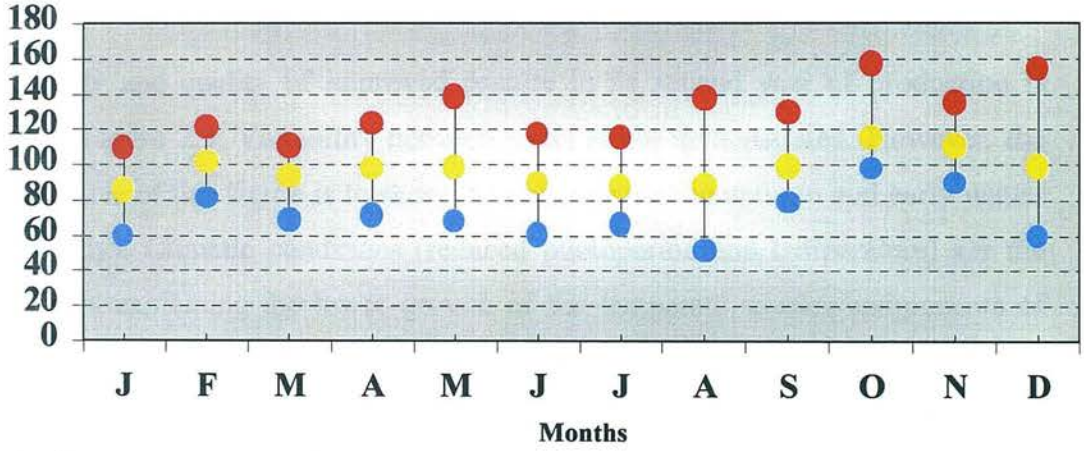
Figure 2.1. Feasible land use production systems in South Rio Grande do Sul.

Figure 2.2 shows a five-year average of monthly growth and crude protein content, and digestibility of organic matter for natural pasture at one location. The maximum quantity and quality of production occurs between September and March while the minimum is between April and August. Substantial variation within months is shown by these average figures (Salomoni, 1996) and the seasonal variation is obvious. Therefore, growth of natural pasture is dependent on climatic conditions and these have a great influence, particularly, the amount and timing of summer rains and winter frosts. Production in the same place varies widely between years. For example, 22.7 kg/DM/ha per day was produced in February in years with abundant

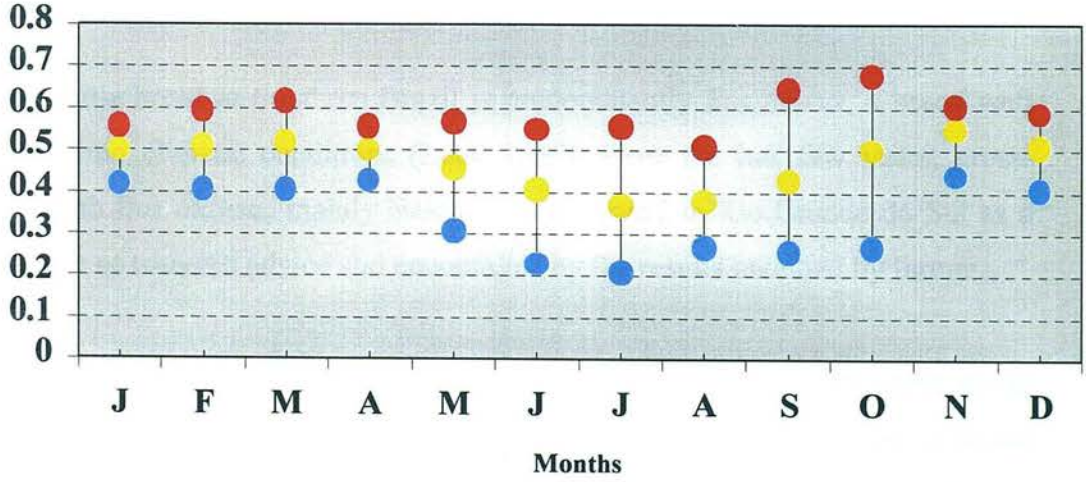
(a) Dry matter production (kg/ha)



(b) Crude protein (g/kg DM)



(c) In vitro digestibility of organic matter



Source: Salomoni (1996)

Figure 2.2. Monthly growth and quality of natural pasture in Bagé, average five years (● Minimum, ● Maximum, ● Mean).

rain, but only 3.6 kg/DM/ha per day was produced in years with restricted rains, at the same place (Berretta, 1991).

Improved pasture has been used as an alternative to natural pasture by some farmers. They have utilized it as a kind of supplement to the natural pasture. Their strategic use depends on the area occupied by improved pasture on the farm. The species involved are white clover (*Trifolium repens* L.), lotus (*Lotus corniculatus* L.) and Italian ryegrass (*Lolium multiflorum* L.) (Macedo & Reis, 1987). However, some farmers experience problems with the initial costs of establishment, slow growth in winter and reinfestion by natural pasture. These are some of the reasons why only 8.5% of the pasture area is in an improved state (IBGE, 1990).

The quantity and quality of improved pasture in its second year of production is showed in Figure 2.3. Variability between years is not demonstrated. However, the main objective of this figure is to show the lower growth in autumn and early winter (May to July). Climatic conditions (reduced photoperiod and temperature) are the main factors explaining the lower growth of the temperate species components of improved pasture. In addition, the lower quality of pasture in summer is a result of the reproductive stage of species components at this time (Gonçalves, 1987).

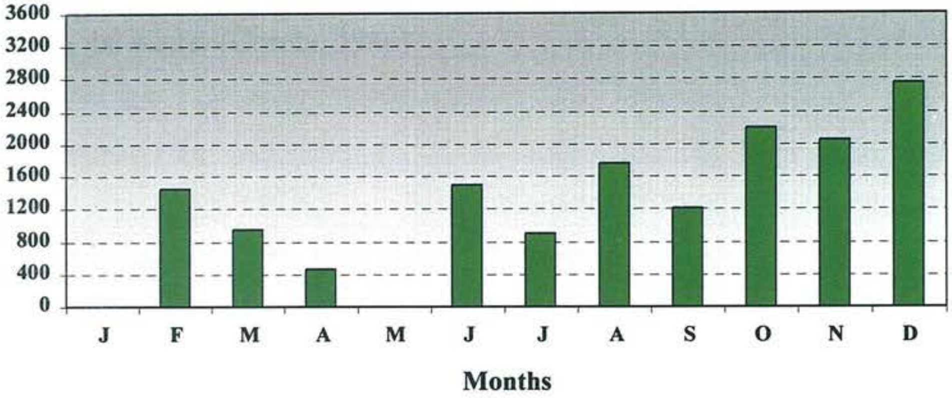
2.1.2. Beef Cattle

The beef cattle breed in Southern Brazil is predominantly *Bos taurus*, a breed well adjusted to the climatic conditions (Leal, 1987). Over the last few years, cross-breeding with *Bos indicus*, mainly Nelore, has increased in Rio Grande do Sul as a consequence of research advice and encouraged by the results obtained by farmers.

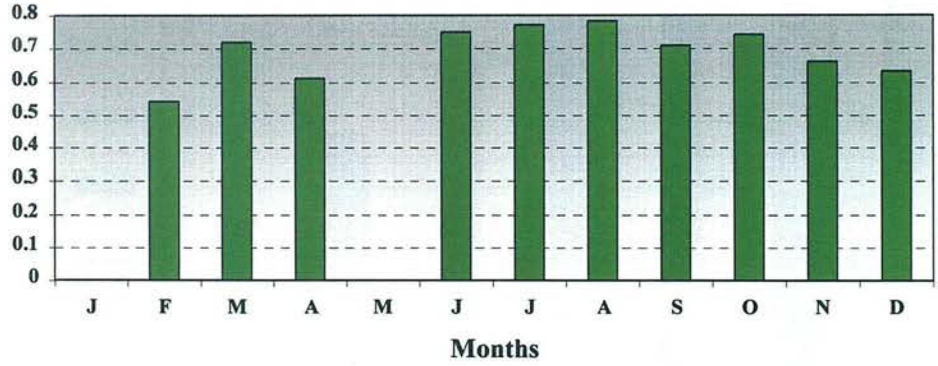
All sectors of cattle production (breeding, raising and fattening) can be found in the region and Figure 2.4 provides information about total numbers of animals in Brazil and Rio Grande do Sul. The percentage of the Brazilian herd represented by cattle in Rio Grande do Sul has declined from 16% in 1950 to 9% in 1995. At the same time the herd of Rio Grande do Sul has increased from 8,421 to 13,935 thousand head.

The Brazilian herd has been increased by the occupation of new areas, mainly in the central area of Brazil. In Rio Grande do Sul, new areas created the opportunity for more cattle until 1970 but after that the herd has been increased by the use of more intense management practises.

(a) Dry matter production (kg/ha)



(b) In vitro digestibility of organic matter

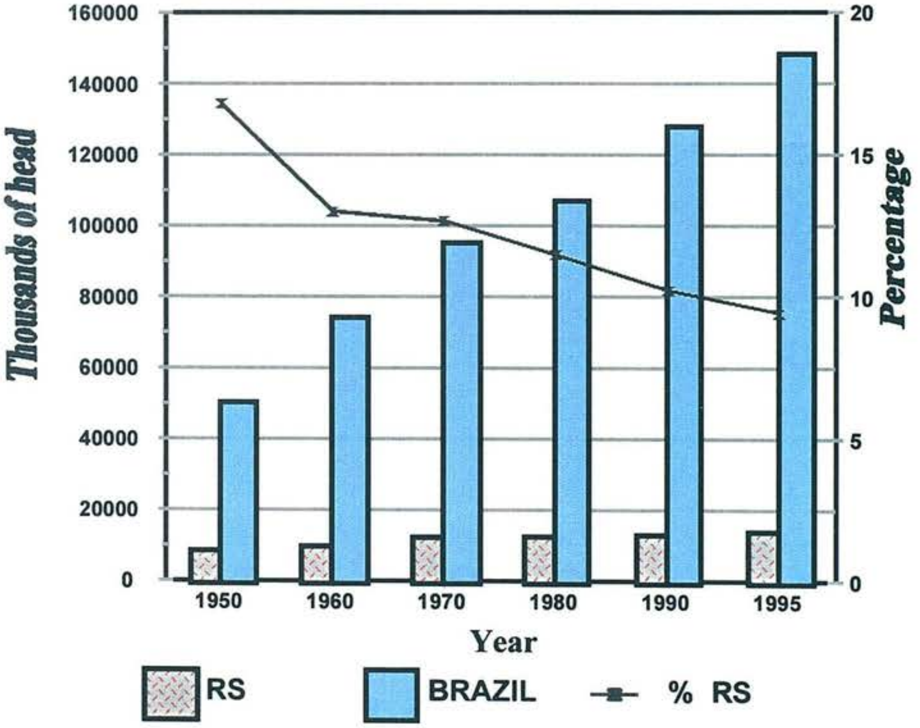


Source: EMBRAPA/CPPSUL (not published)

Figure 2.3. Dry matter production and in vitro digestibility (IVD) of improved pasture in Southern Rio Grande do Sul (1993-1994).

Farmers normally keep cows together with bulls for 60-160 days mainly between October and March. The time that cows and bulls stay together varies according to the knowledge and management objectives of the farmer. As a result, calves are born between July and January and weaning occurs between March and June.

Farmers maintain all paddocks with animals by continuous grazing throughout the year. Because of the seasonal growth pattern of natural pastures, farmers adopt strategies to effectively utilise the dry matter produced. Two basic actions are: (i) reduction of the number of animals on the farm during the winter by selling animals in the autumn and; (ii) some paddocks are not grazed in autumn to provide a feed supply in the winter (standing hay). However, these strategies are not applied at an intensity sufficient to avoid loss of live weight and sometimes death of animals by starvation in the winter (Corrêa, 1986).



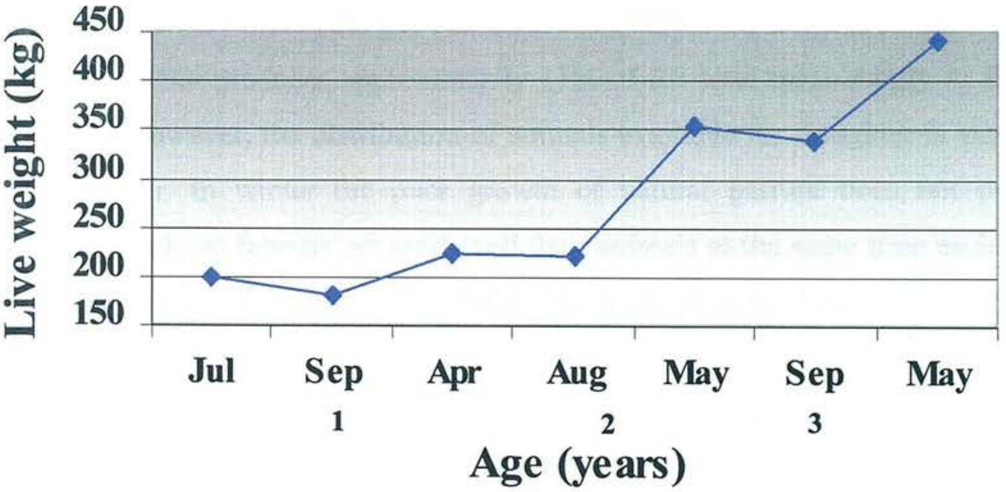
Source:IBGE 1950;1960;1970;1980;1990;1995

Figure 2.4. Number of cattle in Brazil and Rio Grande do Sul (RS).

Normally, cows are maintained on natural pasture, such that the latter part of gestation occurs during the period of minimum production of natural pasture. Consequently, at calving, cows are weak and generally are not in good enough condition to conceive during the next breeding season (Corrêa, 1986; Leal, 1987).

Hence, the regional calving rate (calves per cow per year) in Rio Grande do Sul is very low.

After weaning, the growth rate of calves has two marked periods. In the first period, normally from September to May, animals gain live weight as a consequence of the good condition of natural pasture, while in the other they lose live weight due to poor food supply and weather conditions. Other factors that have a negative effect on the potential live weight of the animal are the presence of ticks (*Boophilus sp.*) and endoparasites of genera *Haemonchus sp.*, *Trychostrongylus sp.* and *Oesophagostomum sp.* An example of the patterns of live weight achieved is illustrated in Figure 2.5 for calves which were born in September, but broadly the same pattern occurs with all calves born in the spring-summer season.



Source: Adapted from Del Duca & Salomoni, 1987

Figure 2.5. Live weight of beef cattle after weaning on natural pasture.

As can be seen in Figure 2.5 when animals graze on natural pasture, they are 3.5 years of age before they have a sufficient live weight to begin the fattening process.

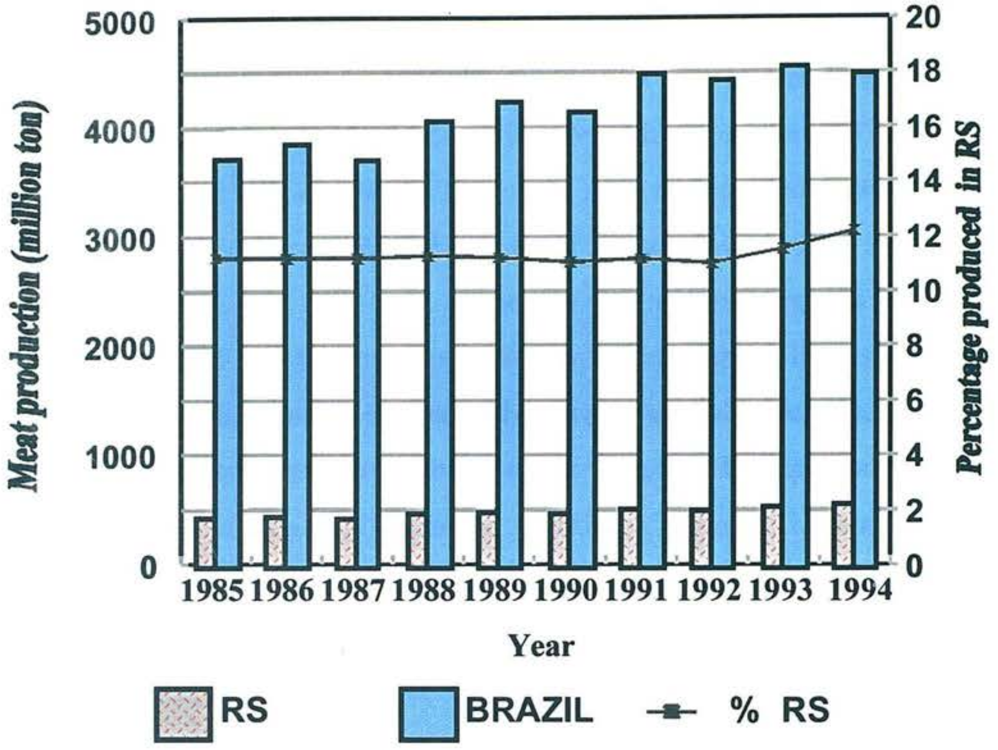
Farmers who grow improved pasture use them mainly for fattening animals. Nevertheless, farmers have experienced some problems with improved pasture as explained before. Consequently, over the last few years, cereal silage (maize and sorghum) and silage from improved pasture has been adopted as an alternative food supply in winter. However, forage conservation, including hay from improved pasture, is still a minor element in the feed supply for fattening cattle. Lack of access to appropriate machinery and a traditional approach to farm management are two key elements that have limited the introduction of improved pasture management systems.

Residues and by-products from the cereal industry (mainly rice) have been used as feed supplements for beef cattle. These have been utilised by animals grazing both natural and improved pasture as a means of improving diet quality (Silveira et al., 1992; Silveira et al., 1993; CAAL, 1993; Silveira, et al., 1994).

Rio Grande do Sul produces approximately 11% of the total meat supply in Brazil (Figure 2.6). However, the distribution of animals available for slaughter is variable during the year. In winter the poor growth of natural pasture does not permit finishing of stock, so farmers generally sell their animals at the same time each year (December to June), which results in depressed prices (Figure 2.7). Consequently, farmers do not have sufficient income to invest in future production which leads to a vicious cycle of low economic output and subsequent low input.

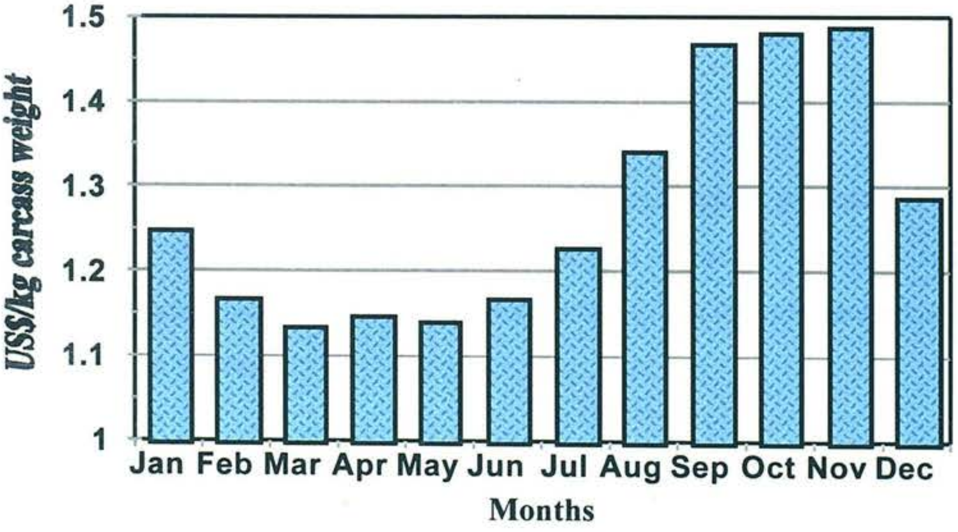
2.1.3. Irrigated rice production

In the south west Rio Grande do Sul drought is common as a result of irregular and variable precipitation (called **contingent drought**). The occurrence during the year is unpredictable, but is usually between December and February (Mota et al., 1970). This limits the capacity for rain-fed crop production in the region, so that yield per hectare of soybean, sorghum and maize is lower than in other regions of Rio Grande do Sul (Table 2.1).



Source: ANUALPEC, 1995

Figure 2.6. Meat production in Brazil.



Source:ANUALPEC, 1995

Figure 2.7. Meat price in Brazil monthly average 1975-1994.

Rice is produced in the region by flood irrigation using water from a river or a specially constructed dam. In 1994/95, the area of rice in Rio Grande do Sul was 976,540 hectares with a yield of 4.5 million tons which represents 43.0% of the total harvested in Brazil (IBGE, 1997). The south west region produced 41.0 % of total rice produced in Rio Grande do Sul in spite of slightly lower yields than for the state as a whole (Table 2.1). The area of rice in the region increased by 73 per cent between 1990 and 1994. However, this rate of expansion has not continued, as suitable land for the crop is limited. Also, water available for rice irrigation from rivers is limited and new areas have to be irrigated through water from dams. Opportunity for building new dams has also become limited because areas meeting the necessary requirements at low cost have already been utilised. Consequently, additional irrigated areas have to be carefully evaluated by the expected cost/benefit ratio and environmental impact.

The main weed that competes for nutrients with rice is *Echinochloa sp*. In extreme situations of infestation rice production can be reduced by 80 % (Andrade, 1982). Between 3% and 5% of harvested yield is a residue composed of weed seeds (mainly *Echinochloa sp)*, broken rice grain, rice grain with or without a husk, green rough rice, etc. These residues are available for use with ruminants directly as supplement or indirectly as an ingredient of a supplement (Silveira, et al., 1992; Silveira et al. 1993; CAAL, 1993; Gonçalves & Saccol, 1995).

New varieties of rice, which have been used in the region, produce less straw than old varieties. This combined with soil conditions at harvest (flooded soil) and the lower nutritional quality of straw, are reasons to explain the minimum use of straw as animal feed in winter.

Table 2.1. Number of hectares cultivated and average yield per hectare in Rio Grande do Sul and Southwest of Rio Grande do Sul from 1990 to 1994.

	Rio Grande do Sul							Southwest Rio Grande do Sul						
	Area (Ha)					Yield (Kg/Ha)		Area (Ha)					Yield (Kg/Ha)	
	1990	**1991**	**1992**	**1993**	**1994**	**Mean**	**Variance**	**1990**	**1991**	**1992**	**1993**	**1994**	**Mean**	**Variance**
Barley	63,728	66,524	41,531	35,468	33,960	1,419	0,065	2,510	2,690	2,695	3,400	3,113	1,239	0,101
Maize	1645,951	1795,379	2007,320	1741,492	1721,487	2,341	0,472	53,850	61,552	65,350	61,870	59,240	1,720	0,113
Oat	147,788	179,313	206,885	202,628	208,143	904	0,014	4,500	3,750	3,750	6,750	6,250	1,036	0,002
Rice	**698,099**	**804,085**	**897,585**	**981,526**	**976,540**	**4,759**	**0,104**	**217,090**	**301,410**	**342,870**	**301,410**	**375,900**	**4,970**	**0,280**
Sorghum	49,800	42,866	50,490	43,319	31,241	1,952	0,083	28,200	20,700	23,150	22,400	14,420	1,763	0,089
Soybean	3516,048	3166,577	2876,568	3078,313	3185,058	1,830	0,017	128,80	91,500	81,670	102,950	129,690	1,294	0,105
Wheat	988,158	617,413	486,614	598,312	554,129	1,426	0,090	49,840	29,830	20,235	24,960	25.700	1,444	0,032

Source : IBGE 1997.

2.1.4. Integration of crop and beef cattle

Beef cattle and crop production are managed by farmers from two different cultures. Therefore, the integration of two farming systems has been considered as an important goal. Land is used for rice production by the Immigrant farmers for 7 months between September/October and April/May, and the Gaúchos graze their beef cattle on the stubble until September when the process is repeated. The payment for the land is made by the rice farmer in rice. Normally this process is repeated for 2 or 3 years. After that, improved pasture is grown for 3 or 4 years without irrigation before it returns to rice production again. This rotation has been recommended to improve the physical and chemical conditions of the soil and to increase the stock carrying capacity (Dreyer, 1980; Acevedo, 1987). Nevertheless, large areas still exist in which after the rice natural pasture is allowed to return.

Another form of integration occurs as a result of residues and by-products from the rice crop being used in supplementation of beef cattle. These residues have been used either in a natural state or preserved by chemical treatment (ammonia), or by dry processing in bags or silos as a supplement for raising and fattening cattle.

Irrigation of improved pasture is an alternative that could be explored in the region: advantages could occur to both systems. For livestock systems, increased stocking rates following greater forage availability could be possible while in the rice crop the number of weed seeds (specially *Echinochloa sp*) could be greatly reduced also reducing the need for chemical treatment. Another way to improve crop production is by strategic irrigation of otherwise rain-fed crops as a means of counteracting the effects of drought. This alternative needs to be considered for the region and it can form an important way to integrate crop and beef cattle production in a sustainable framework.

2.2. Models to study complex agricultural socio-bio-economic systems.

To bring about improvement in the complex agricultural systems found in the region, technological advice is necessary. However, the traditional physical research approach, conducted by field experimentation, has been questioned particularly in locations characterized by climatic variability. Differences between treatments may be relevant only for the year and the specific conditions of the trial. Other circumstances may negate or reverse treatments priorities. Repetition over years only expands the cost without necessarily improving the information provided and results in unacceptable delays (Dent, 1996).

Computer modelling is a tool that can be used to reduce the time and cost of field experimentation. The models have been classified as either empirical or mechanistic. Mechanistic models require that all quantified processes have a sound physical or physiological basis, whist, empirical models consist of functions that are chosen (often arbitrarily) to fit measurements from field or laboratory (Monteith, 1996). Empirical models are therefore site Specific and not transferable across agro-ecological zones (Dent et al., 1994). Mechanistic models, due to their framework, can be made transferable and can be used to explore a wide range of treatments in different locations which would be impossible with field experimentation due to the cost and time required.

Mechanistic modelling is a tool that permits the collation of relevant data of a system obtained in trials and in laboratory studies. This is an important way to help in understanding outputs obtained in real systems where a holistic approach is required. Moreover, such models make evident specific gaps in knowledge: consequently, models become an important tool to indicate the priorities for research. Mechanistic models are tools that facilitate the analysis of complex biological systems (Beck & Dent, 1987; Dent & Thornton, 1988) found in the region and can generate alternatives to improve the design of farming systems in respect to physiological and economic sustainability.

Biologists have made substantial progress in modelling individual elements of livestock, pastoral and arable systems to the extent that acceptable models now exist for the major production systems occurring in each of these sectors. Models have been constructed to simulate soil processes resulting in nutrients (basically nitrogen) and water available to the plant (Yin & Huang, 1996; Parton et al, 1994; Verberne, 1992; Fernandez & McCree, 1991; Scholefield et al., 1991; Thornley & Verberne, 1989; Parton et al, 1988; Gregson et al., 1987; van Keulen & Wolf, 1986; Williams et al., 1985; Jones et al., 1984; Reuss & Innis, 1977; Cameron & Kowalenko, 1976; Burns, 1974; Stanford & Smith, 1972). These together with environmental and management variables, are the main inputs to plant growth models (Herrero, 1995; Thornley et al., 1995; Thornley & Johnson, 1990; Bachelet et al., 1989; Blackburn & Kothmann, 1989; Thornley & Verberne, 1989; Hanson et al., 1988; Laurenroth et al., 1986; Johnson & Thornley , 1985; Coughemour et al., 1984; White, 1984; Detling et al., 1979; Parton & Singh, 1976; Gilbert, 1975) which simulate mainly dry matter production and dead material that are inputs to animal and soil models respectively.

Modelling the interface between plants and animals has been recently reviewed by Herrero et al. (1998). However, models of pastoral farms are rarely seen in the literature. Simulation of Production and Utilisation of Rangelands (SPUR) is a whole farm model which was released in 1987 and was a culmination of an extensive long-term effort by a team of scientists with the necessary range of diverse skills to address the five basic components identified as necessary for comprehensive rangeland simulation (i.e. climate, hydrology, plant, animal and economics) (Carlson and Thurow, 1996; Hanson & Baker, 1994; Wight and Skiles, 1987). Recently, another whole model GRAZPLAN by Donnelly et al. (1997) was developed in Australia to improve the effectiveness of the transfer of new information and technology to farming practise.

Reviews of the strengths and weaknesses of livestock and pastoral models are found widely in literature (see for example Herrero et al., 1998; Carlson and Thurow, 1996; Bernues et. al., 1995; Edwards-Jones & McGregor, 1994; Dent et al. 1994; Tsuji at al., 1994; MacNeil et al., 1985; Hanson et al., 1985; Chudleigh & Cezar, 1982).

These models and sub-models have been helpful in the construction of a grassland model relevant to the Southwest of Rio Grande do Sul.

Models developed for specific crops are widespread and 35 separate crop-simulation models were found available by Ritchie (1995). However, two groups of modelers have been prominent in constructing crop models. One group, largely based in the USA, the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT), incorporated the shell of crop models into a system called Decision Support System for Agrotechology Transfer (DSSAT) (Tsuji at al., 1994) which included 6 cereals (barley, maize, millet, rice, sorghum and wheat), 3 legumes (dry bean, soybean and peanut) and 3 rootcrops (aroids, cassava and potato). The other group from the Netherlands has been working on a system called Crop Growth Monitoring System (CGMS) and has developed models to simulate the growth of barley, maize, rice, wheat, sugar beet, potatoes, field beans, soybeans, winter oilseed rape, and sunflower (Supit et al., 1994). Rice models have been developed thorough Simulation and Systems Analysis for Rice Production (SARP) in an international rice research network involving the International Rice Research Institute in The Philippines, DLO Research Institute for Agrobiology and Soil Fertility, and the Department of Theoretical Production Ecology of the Wageningen Agricultural University, The Netherlands. Rice models from DSSAT and from SARP need to be calibrated for cultivar type and validated before being used for simulating conditions in Rio Grande do Sul.

Finally, in the developed and developing world, *ex ante* assessment would seem to be an essential step in developing good and effective agricultural policy. Such assessments may relate to the exact nature of uptake, including spatial and temporal considerations, and should consider the exact response of the farm to the policy (Dent et al., 1995).

2.3. Concluding Remarks.

Beef cattle and rice production have a substantial economic and social importance in the Southwest of Rio Grande do Sul. In this chapter, a brief description of production systems has been undertaken, so that the complexity could be perceived. Technological advice has been given to farmers throughout the last decades to try to increase productivity and to help with their decisions on the farm. However, traditional research and extension methods have been questioned mainly due to the cost and time of providing solutions for problems experienced by farmers. Considering their characteristics, computer models are an important tool in supporting technological advice and in improving agricultural system performance in the Southwest of Rio Grande do Sul.

CHAPTER 3

METHODOLOGY OF INTEGRATED SOCIO-BIO-ECONOMIC MODEL

This chapter discusses the concept of whole system models followed by the methodology used in this work.

3.1. Concepts of integrated socio-bio-economic model

The farm is a complex organisation involving biological as well as physical, sociological and economic factors (Dent & Pearse, 1973). Farming systems are characterised by the fact that man is attempting to control biological systems in an uncertain environment to achieve some goal, which is predominantly economic in nature.

Different approaches were proposed by Hardaker et al. (1997) to deal with risk in agriculture. However, this work was largely influenced by Makeham et al. (1968):

> *"Our approach to risky choice is subjective. For this no apology is made. It is the only correct approach because, after all, decisions makers are individuals. The best choice for one may not be the best for another since they will differ in their attitude to risk, in their desire for money, and in their strengths of conviction about the occurrence of uncertain events."*

Recently, Jones et al. (1997) discussed previous research dealing with modelling farming systems. They cited early research before the 1950s, which emphasised farm budget analysis. The emphasis shifted in later 1950s and 1960s to the use of linear programming (LP). With this tool, economists analysed farm growth, response to policies, cost minimisation and minimum resource requirements for specific farm income, assuming profit maximisation behaviour by the farmer.

This approach was criticised by Dent et al. (1995):

> *"When modelling the dynamics of agriculture systems, economists recognised that farms vary and that this variation is important, but rather than attribute this variation to social factors, they concentrated on defining farm types by structural variables such as farm size and enterprise mix. The socio-economic element of these farms has been assumed to act as rational financial maximiser. An alternative to this economist' approach is to consider every farm as a unique unit, and to hypothesise that the relationship between its specific environmental, structural and social variables will determine its response to policy and legislative frameworks."*

In early 1980s, hybrid LP-simulation models were introduced and allowed more comprehensive interactions among farm components, and sequential decisions to mimic farm progress over multiple time-periods more realistically. One type of hybrid farm model involves using biophysical simulation models to derive input-output coefficients that are then used in a mathematical programming model. As example for uses of this approach cited by Jones et al. (1997) are the works of Veloso et al. (1994) in Brazil and Herrero et al. (1996) in Costa Rica. Also, Alocilja et al. (1997) used a multi-criteria approach to deal with minimising excess manure phosphorus, feed cost and cropland requirement for dairy-crop production systems in Michigan, USA. However, whole-farm models generally consider crop farms and the diversity and complexity of animal-crop production systems are rarely addressed (Dent & Thornton, 1988, Jones et al., 1997).

Jones et al. (1997) suggested a three-level classification to the farm-scale models (Table 3.1). The unconstrained production level describes the biophysical potential of a prescribed set of management practices without any consideration of farm constraints other than land. The resource-constrained production level identifies the economically optimal production for a set of management options, given the internal farm resource constraints and biophysical conditions. The adaptive production level adds social considerations: farm goals (which may be far more complicated than

Table 3.1. Suggested levels of farm-scale models with associated inputs, model components and outputs.

Farm production level	Inputs	Model components	Outputs
1.Unconstrained	Endogenous: fields, enterprises Exogenous: technology packages, weather, prices Initial conditions: physical characteristics	Soil, crop, livestock, ecological, budgeting, resource accounting Decisions: none	Production, costs, profits, resources needed, non-market outputs, risk
2. Resource-constrained	Endogenous: fields, enterprises options, technology options, labour, capital, equipment Exogenous: weather, prices Initial conditions: physical characteristics, resources (labour, capital, etc.)	Soil, crop, livestock, ecological, budgeting, resource accounting Decisions: enterprise mix, resource use conflicts, household consumption	Production, costs, profits, resources needed, non-market outputs, risk, enterprise mix, technology, constraints
3.Adaptive	Endogenous: fields, enterprises options, technology options, labour, capital, equipment, farmer characteristics Exogenous: weather, prices, social factors Initial conditions: physical characteristics, resources	Soil, crop, livestock, ecological, budgeting, resource accounting Decisions: enterprise mix, resource use conflicts, household consumption, technology adoption, farm expansion/contraction	Production, costs, profits, resources needed, non-market outputs, risk, enterprise mix, technology, constraints

Source:Jones et al. (1997)

external constraints and biophysical conditions of the farm. In theory, the analyst could progress from unconstrained to resource-constrained to adaptive levels in a building-block approach, similar to that used by many crop-modelling efforts.

3.2. Framework for integrated socio-bio-economic model

The information used by farmers can be classified as "natural" or "simulated". "Natural" arising from past experience, information and knowledge that are adapted according to new circumstances in order to solve problems, set objectives and monitor the production system. The "simulated" is based on quantitative formal scientific information. This work presents a framework that deals with adaptation linking of both "natural" and "simulated" information. Decisions about animals, pasture, soil, land use and economic aspects are treated. These decisions impact on the biological and economic models and generate scenarios. The farmer's decision is dynamic occurring at established time-steps (Figure 3.1). If the aspirations or subjective views of decisions makers are different, the decision they will choose to make can be different. There is no universally optimal set of decisions for any farming system, which is independent of these goals, values, aspirations and perceptions about future changes in the external environment. Even when confronted with exactly the same set of information and advice, individual choice can be different (Fawcett, 1996). The FIDM supplies information about economic and biological aspects of the farm and prompts the farmer for the decision to be made. Therefore, when farmer takes the decision, the "natural" information is considered simultaneously with "simulated" information.

The sequence of the FIDM construction was:

1. Knowledge of systems used in the region.
2. Theoretical concepts of systems advantages and disadvantages
3. Developing, adaptation and validation of biological and economic models.
4. Development of farm decision model.

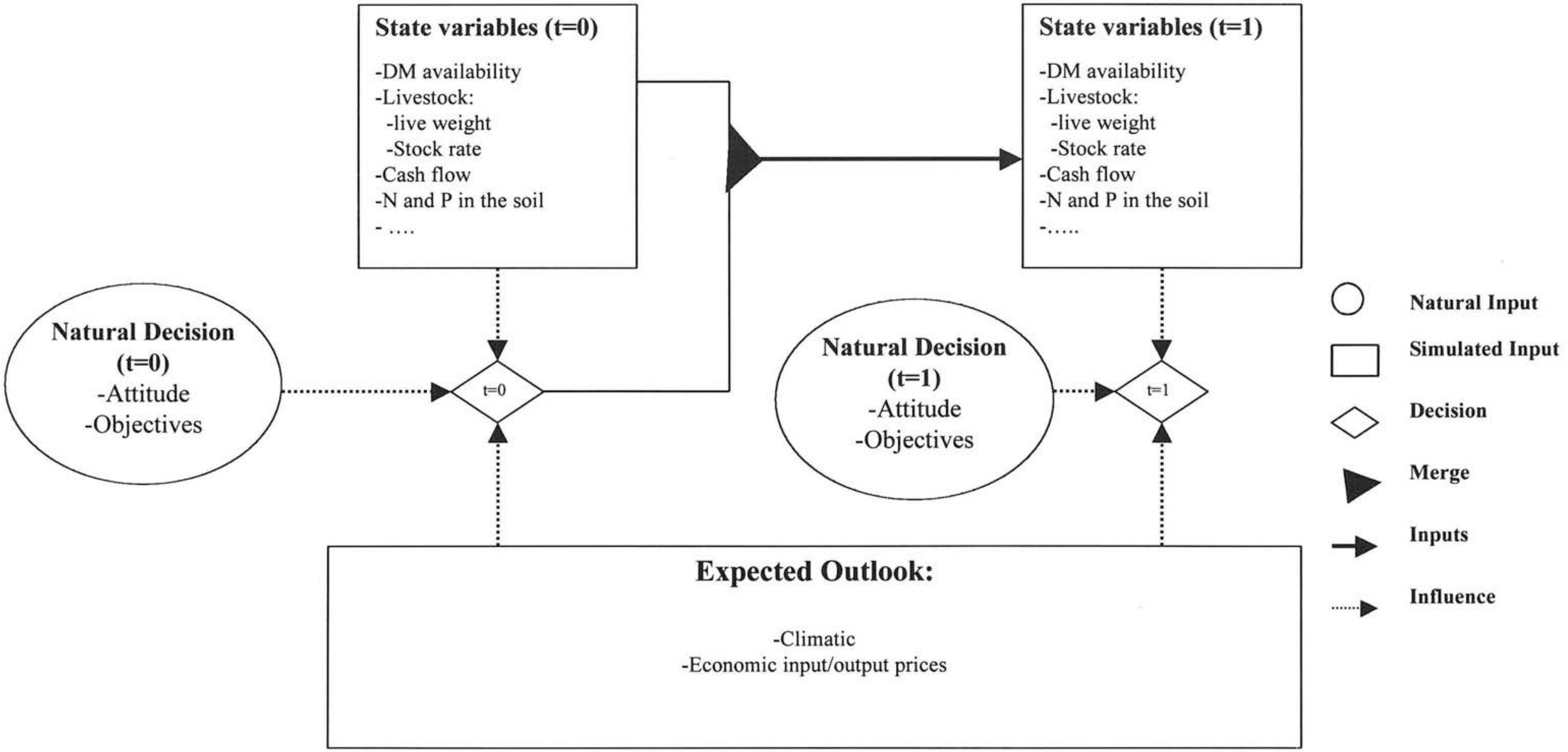


Figure 3.1. The dynamic decision approach at farm level.

The points 1 and 2 were described in Chapter 2. The third point is crucial and the subject of the next four chapters. The last point was the development of a farm decision model which is described in Chapter 8.

Figure 3.2 shows the sub-models involved to produce the "simulated" information of the farm. The internal links among the biological sub-models are indicated and will be described in the next chapters. As the "simulated" information is a result of outputs generated by the sub-models, the amount of information available to the decision-maker is directly linked with the capacity of the sub-models to generate these outputs.

The SB-ModelMaker software, version 3.0.3 (Zeton Tech, Nottingham, UK) was used to build the prototype model described in this thesis.

3.3. Concluding remarks

This chapter introduced the approach adopted in the thesis. The main goal is to provide a model to help farmers in their decision making. The framework adopted allowed for farmer behaviour as a sub-model block inside the whole model. This sub-model is flexible to capture the individual reactions of the farmer to the socio-bio-economic environment in which he exists.

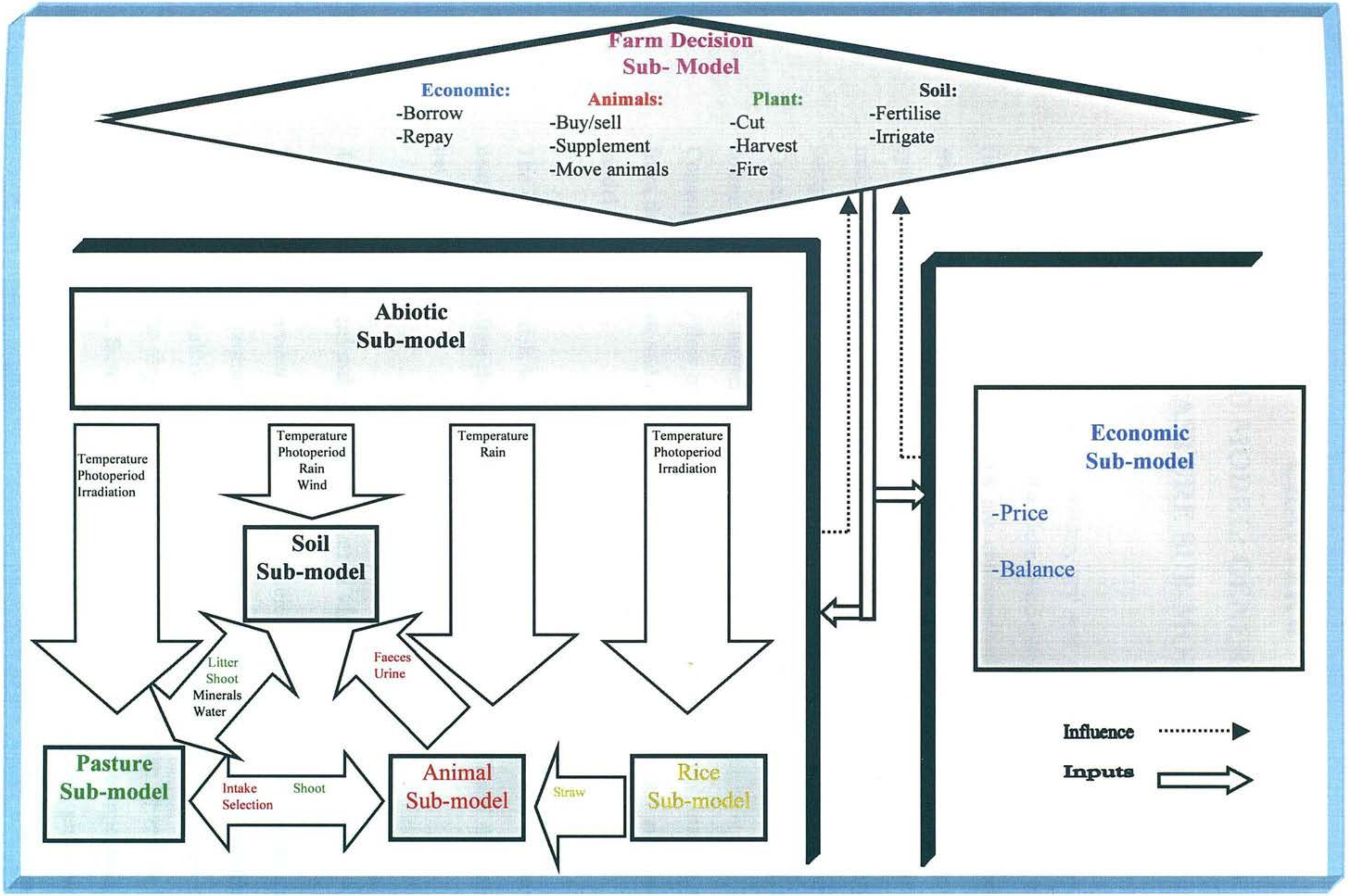


Figure 3.2. Diagram of models involved producing "simulated" information.

CHAPTER 4

GRASSLAND MODEL: GENERAL VIEW AND PASTURE SUB-MODEL

To develop the grassland model, pasture, soil and animal sub-models should be considered simultaneously due to the close relationship between inputs and outputs (interfaces). Grassland ecosystems are characterised by a complex relationship, where abiotic factors have a crucial influence on the biotic components of the system. Thus, grassland models need to consider temperature, light and water as the main driving forces of biotic sub-systems. However, the physiognomy and composition of most grasslands are strongly determined by wild or domestic grazing. Concurrently, various ecosystem processes are affected by high rates of forage consumption and nutrient recycling by large grazers (Chaneton et al., 1996). Consequently, the flow of nutrients, mainly nitrogen (N) and phosphorus (P), to and from the soil, plant and animal are important factors to be included in a grassland model.

The individual models will be described in the following sections and chapters. The next section describes the general view of biological sub-models and the interfaces between them.

4.1. Biological sub-models: general view

In Chapter 2, a review was made of available soil and pasture models and the interface between pasture and animal models. These models and sub-models have been helpful in establishing a grassland model relevant to the south west of Rio Grande do Sul. The diagram of the proposed grassland model can be seen in Figure 4.1. All the abiotic factors have a crucial influence on the biotic components. Plant biochemical reactions are temperature-dependent, consequently net photosynthesis and growth rates are reduced at lower and higher than optimum temperatures

(Crawley, 1997). Lower rates of soil mineralization are observed at extreme temperatures as result of reduced soil fauna activity (Floate, 1970c; Stanford et al. 1973). Herbivores are also affected, mainly through reduction in food intake; at extreme temperatures. This reduction is accelerated at lower temperature and wet conditions (NRC, 1987). Therefore, temperature is an important input from an abiotic sub-model that affects directly all components of biotic grassland systems.

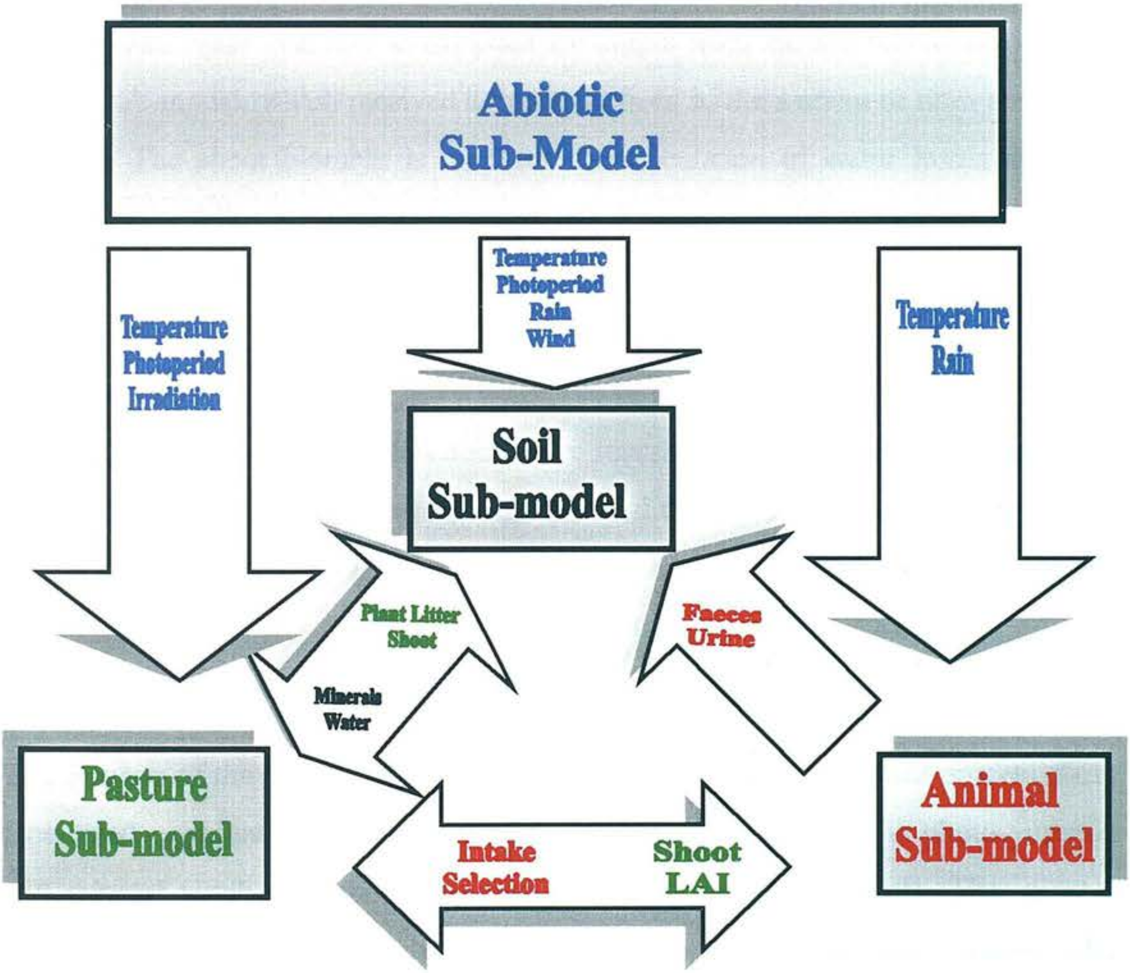


Figure 4.1. Diagram of the grassland biological system model.

Rain is another input from an abiotic sub-model that determines the water available to the soil fauna and plants. However, rain has an indirect input from the abiotic sub-model to the pasture sub-model through the soil sub-model. The soil sub-model controls the effective amount of minerals and water available to the plant.

The other inputs from abiotic to pasture sub-models are photoperiod and irradiation which have an action mainly on photosynthesis and plant phenology. The wind and photoperiod inputs to the soil sub-model are necessary to calculate the water losses due to evaporation and transpiration following the classical approach of Penman (1956).

Minerals and water available to the plant are output from the soil sub-model into the pasture sub-model, which received as an input from it, the amount of litter and shoot biomass. The shoot biomass is used for the calculation of water losses and soil temperature, following the approaches of Penman (1956) and Parton (1984) respectively. The others input to the soil sub-model come from the animal sub-model through faeces and urine.

The interface between plant and animal are represented in the model by shoot and leaf area index (LAI) from the pasture model and the amount of intake of shoots and plant selection from the animal sub-model.

4.2. Plant multi-species sub-model

The diagram of the pasture model can be seen in Figure 4.2. The plant process starts from seed germination or re-growth. To simulate plant growth, the photosynthesis and mineral uptake sub-models supply carbon, water and minerals. The mineral uptake sub-model represents the interface between the soil and plant model. The plant growth sub-model simulates the partition of these nutrients to shoot and root growth. These processes are affected by the disturbance and ontogenic sub-models. The dead material attached to the plant is simulated in the plant litter sub-model and is another interface between the plant and soil models.

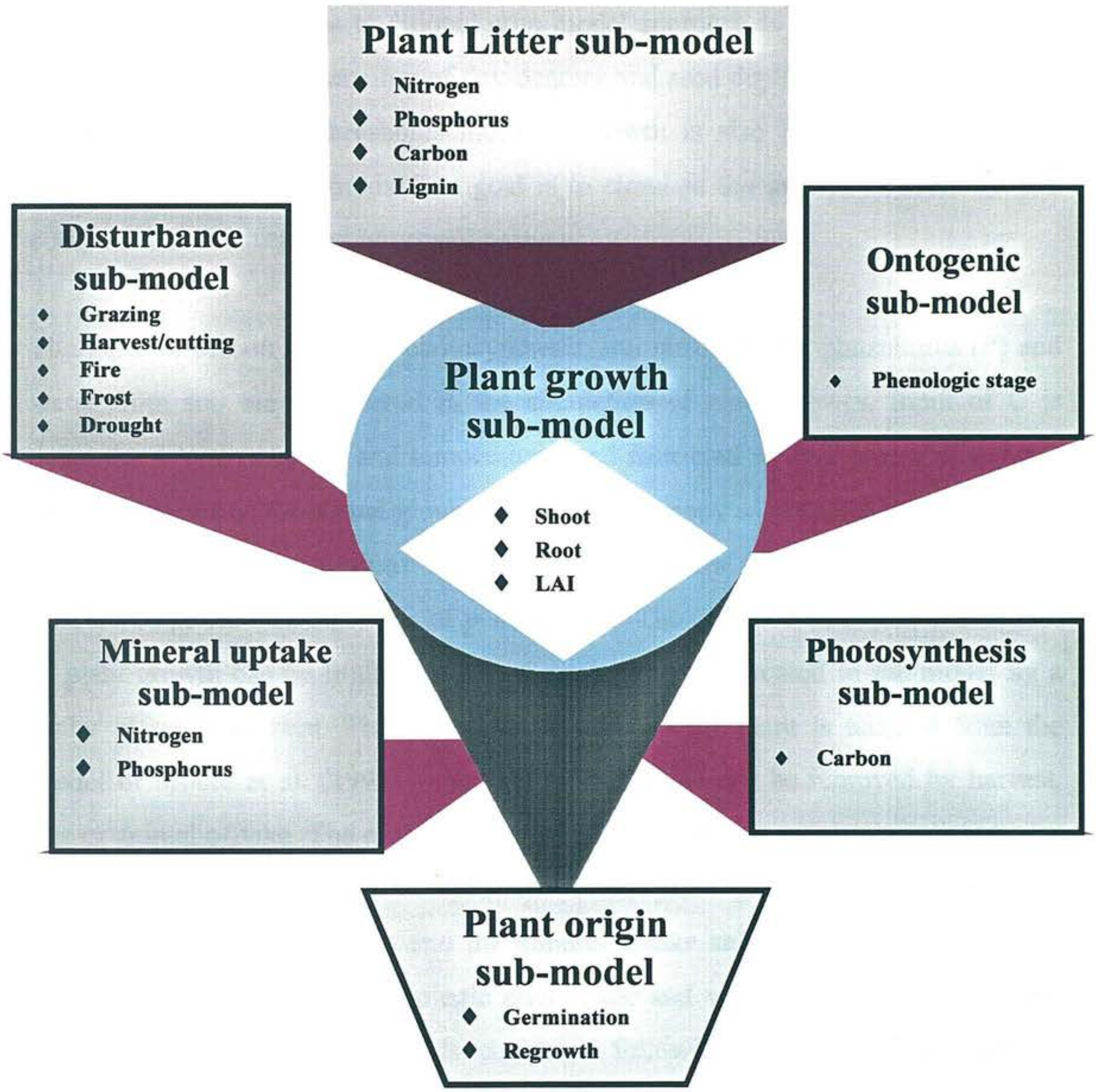


Figure 4.2. Diagram of the Plant Multi-species Model

4.2.1. Description of the model

As described in Chapter 2, natural pasture in the Southwest of Rio Grande do Sul is characterised by a large number of C_3 and C_4 plants with annual or perennial growth (Girardi-Deiro & Gonçalves, 1987). In addition, Italian ryegrass (*Lolium multiflorum*

Lam.), which generally is the main species component of improved pasture, is an annual species. Consequently, the model has to describe both the germination and regrowth processes. Germination starts after temperature, moisture and light conditions are fitted. The traditional crop model approach is adopted of simulating emergence as related to number of day-degrees and seed depth. In addition, the LAI is considered as light thresholds index. Regrowth is also linked to temperature, moisture and light thresholds. The goal is to simulate the growth of multi-species components of natural and improved pasture.

The input of carbon (C) from photosynthesis, and nitrogen (N), phosphorus (P) and water from soil are considered in the simulation of plant growth. Input of C is determined by irradiation and temperature, and restricted by leaf area index (LAI) for each species or functional group present in the canopy as described by Johnson & Thornley (1984). Restrictions of and competition for N and P from soil are considered in the whole process of plant growth. The effective C, N and P available to plant growth can be limited by water availability represented in the model by a scalar effect from zero. The phenological stage of the plant is adapted from the model of Moore et al. (1997). Above-ground biomass can be removed by harvest, fire or animal offtake. The preference of animals for specific species is a disturbance factor, which affects plant competition. Thus, plant growth is determined by nutrients from photosynthesis and the mineral uptake sub-model together with the influence of animals, the phenologic plant stage and water availability. The plant growth and allocation process is simulated following the general approach of Johnson & Thornley (1985). This approach has been expanded to adapt other phenological stages of the plant than just the vegetative ones.

Most of the equations, used in the model, have their origin in papers available in the literature: Johnson & Thornley (1984), Johnson & Thornley (1985), Johnson & Thornley, (1987), Alocilja & Ritchie (1988), Hanson et al. (1988), Thornley & Verberne (1989), Moore et al. (1997). In the thesis, only the new or modified equations are described.

The subscript $_s$ relates to species or functional group (e.g. C_3 annual, C_3 perennial, C_4 annual, C_4 perennial). In the formulas, parameters are shown in bold to make them easy to identify. The state variables and other variables are presented in the Appendix 4.1, the parameters are presented in the Appendix 4.2. The model is set to a one-day time-step.

4.2.2. Germination and Regrowth sub-model

Germination is an important process, but, the mechanism of seed germination is complex and depends on intrinsic and external factors (Kigel & Galili, 1995). These factors and their interactions are particularly difficult to simulate in natural pasture where the seed bank is uncertain particularly under grazing (Fenner, 1992). Hanson et al. (1988) describes one simple approach that has been adapted for use here.

Following Hanson et al. (1988) to initiate germination soil temperature and moisture are considered. Thus, the median temperature over last ten days (T10) has to be smaller than the parameter maximum threshold temperature ($TMaxTGerm_s$) and higher than the minimum threshold temperature ($TMinTGerm_s$). The superficial soil moisture (MSoilsup), obtained from the soil sub-model (Chapter 5), has to be greater than the parameter drought tolerance coefficient (DTC_s). However, the light reaching the bottom of the canopy is another important effect to be considered. A low level of light prevents germination under conditions in which the young seedling would be exposed to severe competition (Deregibus et al., 1994). This effect is simulated in the model, based on the canopy leaf area index (CLAI) that can not exceed the parameter of light for seed germination ($LSeedGerm_s$).

After germination has begun, the thermal time is adopted to simulate the period from germination to emergence ($DDTG_s$) of the seedling from the soil surface. The time needed for the shoot to appear at the surface of the soil ($TEmerg_s$) depends on amount of degree-day per cm depth of seed ($DDpcm_s$) and the sowing depth ($Sowdepth_s$).

$$TEmerg_S = \boldsymbol{DDpcm_S}\ \boldsymbol{Sowdepth_S} \qquad \textbf{4.1}$$

Emergence is completed when $DDTG_s$ is equal or higher than $TEmerg_s$, at this moment the counter $Emergcont_s$ is equal to 1. The model assumes that during the process between germination and emergence, the partition of nutrients between root and shoot is 50:50 (Alocilja & Ritchie, 1988). Therefore, nutrients are so allocated, after emergence, in this proportion into the pools of first root and first shoot.

$$AlloSeedPhy_S = \boldsymbol{Gprop_S}\ SeedAvGerm_S \qquad \textbf{4.2}$$

$AlloSeedPhy_s$ is the allocation from seed to phytomass. The amount of phytomass depend on the amount of seed available to germinate ($SeedAvGerm_s$) that effectively became seedling ($GProp_s$).

The amount of $SeedAvGerm_s$ has its origin in sowing or from the seed bank in the soil ($SeedBank_s$). If germination occurs from the $SeedBank_s$ it is assumed that the seeds are at the same depth as sown seeds. The $SeedBank_s$ is simulated in the model and will be described in the seed production (section 4.2.8). However, changes in the $SeedBank_s$ in the soil are not simulated and is assumed that seed availability is not limited in natural pasture. This assumption is made, because the number of factors and their interactions which affects seed in the soil are particularly difficult to simulate, mainly under grazing conditions (Fenner, 1995). Therefore, the amount of $SeedAvGerm_s$ from bank of seed in the soil ($SeedBank_s$) is assumed to be the same as that from sowing. In improved pasture, the same assumption is made, but the plant during the previous year has to produce some seeds.

For perennial plants, regrowth starts after plant dormancy finishes and temperature and moisture thresholds are met. The time during which the plant stays in the dormancy stage, is simulated in the ontogenic sub-model (section 4.2.5).

The main adaptations made in the Hanson et al. (1988) germination model was the inclusion of the effect of light and the depth of seed at sowing. The inclusion of light effect simulates the consequences of pasture cover in the seed germination from the seed bank. The depth of seed was included to simulate the time of emergence of new plants after germination, following the approach used by the crop models.

4.2.3. Pasture growth sub-model

The growth sub-model is simulated following the approach by Johnson & Thornley (1985) and Thornley & Verbene (1989). The above authors established only those elements required to simulate vegetative growth. In this study, an expansion has been formulated to encompass all phenological stages. Models by Detling et al. (1979), Coughenour et al. (1984), Alocilja & Ritchie (1988), Hanson et al. (1988), Thornley (1996) and Moore et al. (1997) were all considered while formulating this expansion.

The model assumes that above-ground dry matter may occupy nine compartments. The eight compartments described by Thornley & Verberne (1989); growing sheath-stem and leaves, first fully expanded sheath-stem and leaves, second fully expanded sheath-stem and leaves and senescing sheath-stem and leaves, plus the new stand dead compartment. Roots are considered in the same general way representing the transition from growing to dead roots according to Thornley & Verberne (1989). However, here roots are also split into two types: structural and active roots and the reason for this will be discussed later. Every live leaf compartment has one corresponding leaf area index compartment. Each nutrient simulated in the model has a soluble pool, C from photosynthesis and N and P from soil uptake flow into the model through respective soluble compartments.

The main objectives of the pasture growth sub-model were to simulate: (a) germination (regrowth) and emergence of the plant; (b) allocation of nutrients according to the different phenological stages; (c) harvest of phytomass and/or seeds; (d) plant responses to grazing by large mammals.

4.2.3.1. General structure of sub-model

Plant growth processes are simulated according to Thornley & Verbene (1989) and Johnson & Thornley (1985), but with adaptation due to ontogenic effects on plant processes and the inclusion of phosphorus.

The live structural shoot (Sh_s) and root (R_s) comprise four age categories (subscript $_a$). The shoot dry matter components are subdivided into lamina and sheath-stem, following Thornley & Verbene (1989). However, the root dry matter components are subdivided into active and structural roots.

$$R_{as} = Rac_{as} + Rst_{as} \qquad \textbf{4.3}$$

The response to deficiency of soil-based resource is a change in the pattern of growth, favouring root growth over shoot growth. However, increased root growth will not necessarily result in increased nutrient uptake, and hence alleviation of the deficiency. Since nutrient uptake depends on a greater extent on the geometry of the root system, the greatest return on this investment will be achieved ifs root length is maximised. This implies that the production of fine roots will be favoured, since they achieve the greatest root length for a given weight (Fitter, 1997). Therefore, in the model the active roots represent the thinner roots while structural roots represents the thicker roots. These types of roots influence the rates of mineral uptake (section 4.2.5.).

In addition to these live compartments, the stand dead compartment ($ShDead_s$) and roots dead compartment ($RDead_s$) were created. These make the link between the plant and the soil model and they will be described latter in the senescence and recycling of nutrients section (section 4.2.7).

There are three plant substrates: substrate C (SC_s), substrate N (SN_s) as Thornley & Verbene (1989), and substrate P (SP_s). The SC_s is represented in the model by:

$$\frac{SC_S}{dt} = Cinput_S + SCS_S - Rg_S - Rm_S - Rmu_S - CAlloSeed_S \tag{4.4}$$

Where $Cinput_s$ is the daily carbon input from photosynthesis and SCS_s is the rate of supply of C from recycling. The terms Rg_s, Rm_s and Rmu_s represents the C loss by substrate pool to growth, maintenance and respiration respectively associated with mineral uptake. C loss also occurs during the reproductive stage due to allocation to seed ($CAlloSeed_s$).

After emergence of the new plant, the model assumes that during the first days before Shs_s appears, the maintenance of the plant is obtained from the seed. Therefore, during this time, the SC_s is represented by:

$$\frac{SC_S}{dt} = Cinput_S + \left(AlloSeedPhy_S\ CGMax_S\right) \tag{4.5}$$

$CGMax_s$ is the C to maximum growth obtained by:

$$CGMax_S = 0.2\ \ \boldsymbol{FC_S} \tag{4.6}$$

FC_s is the parameter fraction of C in the plant structure. The value 0.2 is the numerical assumption obtained from Johnson (1985). In optimum conditions, 16 per cent of C in the plant could be assumed as soluble.

In perennials, when re-growth begins, the same assumption is made, but AlloSeedPhy$_s$ is changed by roots content of plant (R$_s$) as source of soluble C.

The substrates N (SN$_s$) is calculated by:

$$\frac{SN_S}{dt} = NP_S + SNS_S - (\boldsymbol{FN_S} \times (GSh_S + GR_S)) - NAlloSeeds \qquad \textbf{4.7}$$

The daily amount of nitrogen uptake (NP$_s$) and the rate of supply N from senescence (SNS$_s$) are the inputs to the substrate pool. The fraction of N in the live plant structure (FN$_s$), utilised in the synthesis of new shoot (GSh$_s$) and root (GR$_s$), represent the N loss from the pool. The NAlloSeed$_s$ represents the allocation of N to seed.

The same assumption as for C is made for N after emergence of the new plant or re-growth. Consequently, the SN$_s$ during this time is represented by:

$$\frac{SN_S}{dt} = NP_S + (AlloPhy_S \; NGMax_S) \qquad \textbf{4.8}$$

Johnson (1985) suggested 33 per cent as an optimum value for soluble N in the total plant N. The soluble N can be calculated as 50% of plant structural N that corresponds to 33 per cent of N in the plant.

$$NGMax_S = 0.5 \, \boldsymbol{FN_S} \qquad \textbf{4.9}$$

The P substrate has similar inputs and outputs to N, only with a change of symbol (N for P) in the name of variables (e.g. FN$_s$ by FP$_s$).

4.2.3.2. Growth and partition of nutrients

The rates of synthesis of new structural dry matter in shoot (GSh_s) and root (GR_s) are given by

$$GSh_S = Gc_S . C_S . N_S . P_S \ .\gamma Sh_S .Sh_S$$

and **4.10**

$$GR_S = Gc_S . C_S .N_S .P_S \ .\gamma R_S .R_S$$

The growth coefficient (Gc_s) is obtained, following Johnson (1985), by

$$Gc_s = \frac{\mathrm{PGR}_s}{0.5\,\mathrm{CGMax}_{s.}\ \mathrm{NGMax}_{s.}\ \mathrm{PGMax}_s} \qquad \textbf{4.11}$$

PGR_s is the potential growth rate and $CGMax_s$, $NGMax_s$ and $PGMax_s$ are the optimum substrate concentrations at the potential growth rate (equations 4.6 and 4.8). The potential growth rate for seedling plants can be considered as twice that of adult plants (Hunt et al., 1993), so in the model this fact is simulated by

$$\begin{array}{lcl} PGR_S = 2\,\boldsymbol{SGR_S} & \multirow{2}{*}{\textit{if}} & Emergcont_S \le TEFoL_S \\ PGR_S = \boldsymbol{SGR_S} & & Emergcont_S > TEFoL_S \end{array} \qquad \textbf{4.12}$$

$Emergcont_s$ is the counter that starts when emergence is completed (section 4.2.2). $TEFoL_s$ is the time between emergence and the first dead leaf of a new plant (flow out of fourth compartment, section 4.2.3.5). Therefore, until the first leaf dies, the model considers the plant has a two-fold SGR_s.

γSh_s and γR_s, in the equation 4.10, are dimensionless functions that determine the relative partitioning between shoot and root. It is assumed that $\gamma Sh_s + \gamma R_s=1$. The model uses a teleonomically determined partitioning function that leads to maximum growth rate, considering two root functions (N and P), following Johnson & Thornley (1987).

$$PT_S = \frac{FR_S}{FSh_S} \times \frac{\left[(N_S + \boldsymbol{FN_S})/N_S + (P_S + \boldsymbol{FP_S})/P_S\right]^{-1}}{C_S/(C_S + \boldsymbol{FC_S})} \qquad \textbf{4.13}$$

The main addition to the general structure, the growth and partition of plant sub-models described by Thornley & Verbene (1989), was made in the root structure. The partition of roots between structural and activity play an important part to simulate plant adaptation to the soil environment. The adoption of the same teleonomic approach, which simulate allocation of nutrients to shoots and roots used by Thornley & Verbene (1989), capture the soil environment deficiency. The partition between structural and active roots is directly linked to γR_s. When there is a mineral deficiency in the soil, greater will be γR_s and more active roots will grow. In contrast, in a soil with a richer mineral environment, γR_s will be small and more structural roots will grow.

The parameter growth coefficient becomes a variable, which is calculated from the potential growth rate. This modification was needed because the model considers the germination and seedling plants when the maximum growth rate is modified in the plant (Hunt et al, 1993).

4.2.3.3. Leaf area index

The new structural shoot growth (GSh_s) produces new lamina, or new sheath plus stem. $Flam_s$ is a fraction of new shoot growth partitioned to lamina. This partition is affected by the phenological stage of the plant that is added to the Thornley & Verbene (1989) model.

$$\begin{aligned} Flam_S &= \boldsymbol{flamVeg_S} & & PhStage_S < 2 \\ & & \text{if} & & \\ Flam_S &= \boldsymbol{flamRep_S} & & PhStage_S \geq 3 \end{aligned} \qquad \mathbf{4.14}$$

The parameters $flamVeg_s$ and $flamRep_s$ are the fraction of nutrient partition to leaf during vegetative and reproductive stage (section 4.2.6.).

4.2.3.4. Substrate utilisation and respiration

The growth rate of new structure is $GSh_s + GR_s$, which requires fluxes of C_s, N_s and P_s from the respective substrate pools. C can be lost by respiration associated with growth, maintenance and mineral uptake. C loss associated with respiration costs of mineral uptake (RMu_s) is represented by

$$RMu_S = \ \alpha \boldsymbol{M_S} \,(NP_S + PP_S) \qquad \mathbf{4.15}$$

The parameter αM_s represents the respiratory costs of mineral uptake. The NP_s and PP_s are the amount of N and P uptake daily (section 4.2.5).

The other loss from the C substrate pool is linked to the ontogenic stage of plant growth. When the reproductive stage initiates, C is allocated to the propagule ($AlloCProp_s$) which is considered as a sink pool in the model. The full description of this process will be described latter in the seed production sub-model (section 4.2.8).

4.2.3.5. Fluxes between age categories

The fluxes of plant structure between compartments are associated with temperature-dependent rate parameters, γSh_s in shoots and γR_s in roots. Therefore,

$$\begin{aligned} &Shf_S \rightarrow SHs_S : 2\gamma\mathbf{Sh_s}\ Leaff_S\ ,\ 2\gamma\mathbf{Sh_s}\ Stemf_S \\ &Shs_S \rightarrow SHt_S : \gamma\mathbf{Sh_s}\ Leafs_S\ ,\ \gamma\mathbf{Sh_s}\ Stems_S \\ &Sht_S \rightarrow SHfo_S : \gamma\mathbf{Sh_s}\ Leafs_S\ ,\ \gamma\mathbf{Sh_s}\ Stemt_S \end{aligned} \tag{4.16}$$

$$\begin{aligned} &Rf_S \rightarrow Rs_S : 2\gamma\mathbf{R_s}\ RAcf_S\ ,\ 2\gamma\mathbf{R_s}\ RStf_S \\ &Rs_S \rightarrow Rt_S : \gamma\mathbf{R_s}\ RAcs_S\ ,\ \gamma\mathbf{R_s}\ RSts_S \\ &Rt_S \rightarrow Rfo_S : \gamma\mathbf{R_s}\ RAct_S\ ,\ \gamma\mathbf{R_s}\ RStt_S \end{aligned} \tag{4.17}$$

The model assumes that compartment Shs_s and Rs_s are approximately twice the weight of the average for Shf_s and Rf_s, so the flows between them are duplicated.

After the emergence of the plant, when the seed phytomass is allocated in the first shoot and root compartment, the fluxes between compartments are altered. This happens because the new plant has only growing leaves (first compartment), so the second, third and four compartments are empty. The flow between the first and second compartment initiates when the number of days after emergence meets the variable times to end leaf as growing leaf ($TEFL_s$). The same procedure is adopted to start the flux between the second and third compartment, when number the days meet the variable time to end leaf as first fully expanded leaf ($TESL_s$). The same procedure is followed to the flows between the third and fourth compartments and to the flow out of the fourth compartment. Therefore,

$$\begin{aligned} &TEFL_S = \frac{1}{\gamma\mathbf{Sh_s}} \\ &TESL_S = 2\ \frac{1}{\gamma\mathbf{Sh_s}} \\ &TETL_S = 3\ \frac{1}{\gamma\mathbf{Sh_s}} \\ &TEFoL_S = 4\ \frac{1}{\gamma\mathbf{Sh_s}} \end{aligned} \tag{4.18}$$

The same procedure is followed for the below-ground compartments,

$$TEFR_S = \frac{1}{\gamma \boldsymbol{R}_s}$$

$$TESR_S = 2\,\frac{1}{\gamma \boldsymbol{R}_s}$$

$$TETR_S = 3\,\frac{1}{\gamma \boldsymbol{R}_s} \qquad \mathbf{4.19}$$

$$TEFoR_S = 4\,\frac{1}{\gamma \boldsymbol{R}_s}$$

The fluxes between aerial compartments may be modified also due to frost stress, harvest or animal breakdown. The full description of these effects will be described latter in the disturbance sub-model (section 4.2.9.).

These modifications in the fluxes between compartments were aggregated to the Thornley & Verbene (1989) model because of the inclusion of the phenologic and disturbance sub-models. Consequently, the structural modifications of the plant as a result of internal and external factors, can be simulated.

4.2.4. Photosynthesis sub-model

Models of photosynthesis are available in the literature, separately or as part of plant models with higher or lower degrees of complexity (Detling, 1979; Monteith, 1981; Johnson & Thornley, 1983; Johnson & Thornley, 1984; Rimmington, 1984; Hanson et al., 1988; Johnson et al., 1989; Hanson, 1991; Johnson et al., 1995). They generally consist of two sub-models. The first is concerned with light interception and canopy architecture, and calculates the irradiance reaching a leaf within the canopy. The second sub-model describes the photosynthetic rate of a leaf as a function of its irradiance; the canopy photosynthetic rate is then obtained by integrating for the leaf-area index of the canopy (Johnson et al., 1989). Temperature, water and nutrients, mainly nitrogen, are also considered as variables reducing maximum photosynthesis rate.

Most of these models use a rectangular hyperbola to describe single leaf photosynthesis. However, Johnson & Thornley (1984) justified the advantages of using non-rectangular hyperbola. The model devised for this study basically follows the photosynthesis model used by Johnson & Thornley (1984), that considers only irradiance and temperature effects on leaf photosynthesis. Modifications, however, in weight units from kilogram to gram and inclusion of a different approach to the effects of temperature were made. The approach used to simulate the effect of temperature was modified from the linear effect adopted by Johnson & Thornley (1984) to a Bell function following Hanson et al. (1988). Water stress is also included as a factor to reduce photosynthesis rate. Competition for light is not considered in the model, because of the relative homogeneous leaf distribution in the pasture canopy that is managed by grazing or frequent cutting (Hanson et al. 1988; Thornley & Johnson, 1990).

Recently, Johnson et al. (1995) included direct solar and diffuse-sky radiation components that are estimated from total daily solar radiation. This modification in irradiance input is correlated with LAI, hence, it becomes important with increases in LAI. However, in natural pasture in Southwest of Rio Grande do Sul, LAI does not normally exceed 1 with grazing or 1.5 without grazing (Sala et al. 1986). Therefore, this modification was not employed, but, if necessary, the modular approach adopted permits an easy replacement of the adopted photosynthesis sub-model. More information can be found in Johnson & Thornley (1984, 1985) and Thornley & Johnson (1990).

The effect of temperature on plant processes ($ETPP_s$) is represented by the bell function, following Hanson et al. (1988). The bell function was chosen because normally physiological processes in plants have an optimum temperature and consequently temperatures below or above this point depress plant activity (Hanson et al. 1988; Mooney & Ehleringer, 1997). The ascending arm of the curve represents a temperature-dependent stimulation of photosynthesis up to an optimum; the descending arm is associated with deleterious effects, some of which are reversible while others are not (Taiz & Zeiger, 1991). Therefore, the bell function is considered to be better than a linear equation to represent the effect of temperature on plant behaviour. This equation is adopted in the model for all processes in the plant which are affected by temperature.

The effective C available for plant growth can be limited by water plant stress. The effect of water on the plant processes is represented in different models through a scalar effect (0-1). However, this scalar has origin in different way to related water in the soil and plant use. The relationship of the ratio of actual to potential transpiration is used by Verberne (1992) and Moore et al (1997), while Hanson et al. (1988) used the water potential to establish this relationship. The model uses the water content in the soil (MSoilTot) in relation to field capacity (Wfc) and wilting point (Wwp) from the water sub-model to establish soil moisture. This ratio is considered to simulate the effect of soil moisture on plant processes ($ESMPP_s$). However, during the seedling phase of the plant the superficial water content in the soil (MSoilsup) is considered.

$$\begin{array}{llll} ESMPP_S = \dfrac{\dfrac{MSoilSup - \mathbf{Wwp}}{\mathbf{Wfc\text{-}Wwp}}}{\mathbf{DTc_S}} & & Emergcont_S \leq TEFoR_S & \\ & if & & \mathbf{4.20} \\ ESMPP_S = \dfrac{\dfrac{MSoilTot - \mathbf{Wwp}}{\mathbf{Wfc\text{-}Wwp}}}{\mathbf{DTc_S}} & & Emergcont_S > TEFoR_S & \end{array}$$

The parameter for the drought tolerance coefficient (DTC_s) determines the minimum level of soil moisture that plant processes are not affected. After that, the model assumes the reduction of soil moisture as a linear scalar effect until wilting point.

4.2.5. Mineral uptake sub-model

The rate of mineral uptake by the plant depends on the soil and plant conditions. In the mineral uptake sub-model, soil conditions follow the approach of the root activity in the nutrient depletion zone. This zone defines the limits of the soil from which the root is able to readily extract nutrient elements. However, it varies from one element to another, depending on the solubility and mobility of the element in the soil. Nitrate is readily soluble and highly mobile in the soil while phosphorus is less soluble and relatively immobile (Hopkins, 1995). Therefore, plants that have higher level of mineral uptake generate root depletion zones more quickly than plants with lower rates of uptake. This fact is considered in the model through the parameter minimum N soil ($MNSoil_s$) and minimum P soil ($MPSoil_s$). In addition, the mineral level in the soil has a directly influence on the root type (structural and active roots). The influence of plant condition is simulated by the effect of the soluble substrate level on the plant uptake.

Johnson (1985) suggested 33 per cent as an optimum value for soluble N. $NGMax_s$ (equation 4.8) plus the amount of structural N needed for maximum daily growth are assumed to be the potential N uptake per gram of roots ($PNUGR_s$) in an optimum environment. PGR_s is the potential daily growth rate (equation 4.12).

$$PNUGR_S = NGMax_S + (PGR_S \; \boldsymbol{FN_S}) \qquad \textbf{4.21}$$

In order to become quantitative, the theoretical approach, proposed by Tilman (1997), is used to express the effect of N in the soil ($ENSoil_s$).

$$ENSoil_S = \frac{NAPL_S}{\boldsymbol{MNSoil_s}} \qquad 4.22$$

$NAPL_s$ is the amount of N in the soil that is obtained from the soil sub-model (Chapter 5). The $MNSoil_s$ is a parameter that represents the minimum amount of N in the soil where the flow of mineral to the nutrient depletion zone is not affected. Note that the uptake by roots is raised according to increasing level of N in the soil until the optimum environmental conditions are achieved. Consequently, plants that have a higher threshold are less competitive at a lower level of N in the soil. The other result obtained is the simulation of strategies used by plants that have similar FN_s and $MNSoil_s$ but different PGR_s. In this case, plants with higher PGR_s have an advantage in a competitive environment.

The maximum daily nitrogen uptake is affected by the soluble substrate level in the plant. The model assumes a scalar effect of plant nitrogen ($ENplant_s$) that is represented in the model by:

$$ENplant_S = \frac{NGMax_S + \boldsymbol{FN_S} - NPlant_S}{\frac{NGMax_S}{2}} \qquad 4.23$$

$NGMax_s$ is the maximum soluble N in the plant (equation 4.8) and $NPlant_s$ is the total N concentration in the live plant (Thornley & Verbene, 1989). The parameter FN_s is the fraction of N in the structural plant. Therefore, the model assumes that there is a maximum soluble nitrogen in the plant (Johnson 1985; Murtagh et al., 1990) above which nitrogen uptake ceases. In addition, it is assumed a linear depressive effect in the nitrogen uptake from this limit to 50% of it (Figure 4.3).

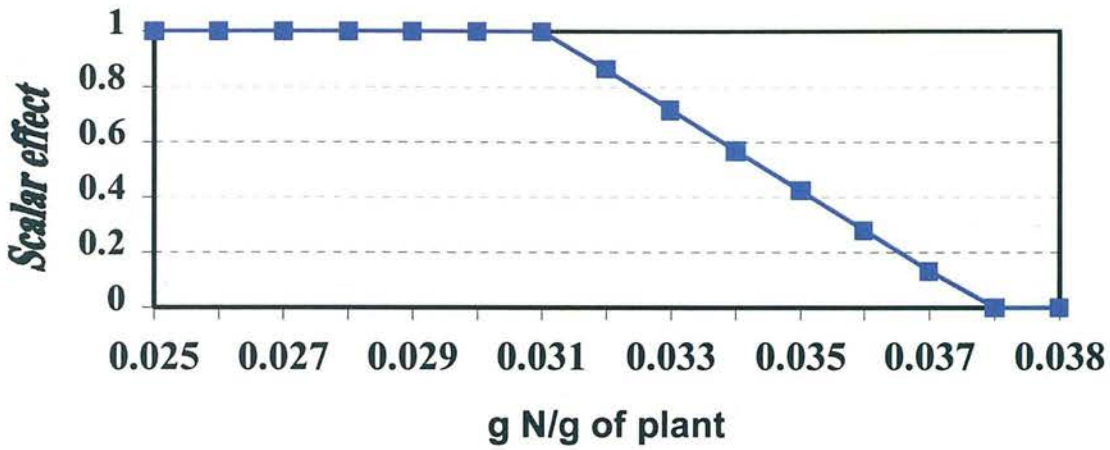


Figure 4.3. Effect of increase nitrogen content in the plant on the nitrogen uptake.

In the model two type of roots are considered (section 4.2.3.1), structural and active, with different uptake capabilities. Therefore, in the model active roots are considered as 100 per cent of capability to uptake mineral. Except the $Racfo_s$ where the uptake efficiency of the fourth compartment is assumed to be a half of the others because of the senescent stage of the roots. However, the structural roots are considered to have a half capability of active roots to uptake minerals due their thickness. Therefore, root capability (RC_s) is

$$RC_s = RAcf_s + RAcs_s + RAct_s + RAcfo_s\,0.5 + (RStf_s + RSts_s + RStt_s)\,0.5 + RStfo_s\,0.25 \quad \textbf{4.24}$$

Therefore, the potential N uptake (PNU_s) by roots is

$$PNUs = RCs\ PNUGRs\ ENSoils\ ENPlants \quad \textbf{4.25}$$

Finally, the abiotic factors have to be considered, so the effective amount of nitrogen uptake by the plant (NP_s) is calculated after being adjusted for temperature and moisture effects.

$$NP_S = PNu_S \; ETPP_S \; ESMPP_S \tag{4.26}$$

Phosphorus uptake by the plant is simulated in the same way as nitrogen, but the symbiotic association between fungus (mycorrhizae) and roots must be considered. The extent of the primary cause of mycorrhizal-enhanced growth appears to be enhanced uptake of nutrients, especially phosphorus in impoverished soil (White, 1987;Hopkins, 1995). Mycorrhizal association increases the area of contact of the roots with the soil and infected roots can transport phosphate at a rate more than four times higher than that of an uninfected root (Taiz & Zeiger, 1991). In the model, the mycorrhizal effect (Meff) is simulated as a linear effect according to the amount of phosphorus available to the plant in the soil (PApl).

$$\begin{array}{lcl} Meff = 4-(1.5\;PApl) & \multirow{2}{*}{if} & PApl <= 2 \\ Meff = 1 & & PApl > 2 \end{array} \tag{4.27}$$

In this way, the model accords with that proposed by Rowel (1994). In soil with large concentrations of available phosphorus, mycorrhizae do not increase uptake, because the root demand is easily satisfied by diffusion. The other equations to simulate phosphorus uptake follow the same nitrogen approach, only with a change of symbol (N for P) in the name of variables or parameters (e.g. NP_s by PP_s).

The mineral uptake sub-model simulates the uptake of minerals by the plant with internal and external restrictions. The internal restriction is represented by the level of soluble nitrogen in the plant, and the external restrictions are represented by the amount of available nutrients (N and P) in the soil, and the effects of soil moisture and temperature. The efficiency of plant uptake will depend on the amount of grams of each type of roots. Plants growing in a rich environment contain high proportion of structural roots, which are less efficient than active roots (section 4.2.3.2). The model adopted a relative efficiency of 50% between structural and active roots. The surface to volume contact area of thinner roots is two times greater than that for thicker roots. Consequently, when the soil becomes deficient in a determined element, it increases the proportion of active roots and the efficiency of plant uptake increases by each new gram of root generated.

4.2.6. Ontogenetic sub-model

The phenological stage of the plant must be considered in the pasture model because allocation of nutrient patterns among root, shoot and seed are also altered by the phenological stage. Recently, Moore et al. (1997) described a sub-model that contemplates the environmental variables (day length, temperature and soil moisture) as the driving variables that operate at different stages in a plant's life cycle. The simplified model of Moore et al. (1997) was used as the basis to simulate the phenological stages of the plant. The ontogeny of plant growth is represented here by numbers (thus, the stage from germination to emergence = 1, vegetative = 2, reproductive before flowering = 3, reproductive from flowering to seed maturity = 4 and senescence or dormancy = 5) as a way to simplify the formulation of the ontogenetic sub-model.

After emergence, when the phytomass is allocated to root and shoot, the vegetative stage ($Veget_s$) starts. The end of the vegetative stage occurs due to daylength or degree-day control. Therefore, C_3 species with daylength control, $Veget_s$ finishes when the daylength is greater than the parameter value for daylength for the start of the reproductive phenostage ($DLsrep_s$). In C_4 species, $Veget_s$ finishes when the daylength is less than $DLsrep_s$.

For plants with degree-day control, $Veget_s$ finishes when the degree-day control is more than the parameter value for degree-day sum for the start of reproductive phenostage ($DDsrep_s$). However, plants begin reproductive phenostage only if there is sufficient reserves, which is represented in the model by parameter (MTl_s) that considers leaf area index as an index of plant reserves.

The reproductive stage is split into two phases: preflowering and flowering to seed maturity. Therefore, when the reproductive stage starts, two degree-day counts are initialised - the degree-day count for the reproductive stage ($DDrep_s$) and for flowering ($DDflow_s$). Flowering begins when $DDflow_s$ meets the parameter value for degree-day to start flowering ($DDsflow_s$). Flowering is considered to occur when 50% of ramets have at least one flower (Moore et al. 1997). The reproductive stage finishes by degree-day or due to a moisture effect. In annuals, the senescence stage begins while in perennials the new vegetative cycle starts or the plant begins the dormancy stage. This starts when $DDrep_s$ is greater than, or equal to, the parameter value for degree-days to start of senescence ($DDssen_s$) or $ESMPP_s$ falls below the parameter value for available soil water threshold below which the reproductive phenostage can end ($Aswfrep_s$).

If the plant is harvested during the reproductive stage, the degree-day count for flowering is set to zero, so the plants revert to the vegetative stage. However, after the plant recovers its reserve, and the condition $SLAI_s > MTl_s$ the reproductive stage starts again. In this case, when the reproductive stage is finished, DDflows has to be at least half of $DDrep_s$ for the seed to be considered mature. Therefore, if the harvest occurs later, the seed maturity does not finish and then the propagule pool is transferred to the dead shoot pool ($ShDead_s$, section 4.2.7.) together shoot phytomass.

The model considers the plant reserve as a limiting factor to begin the reproductive stage. This was the main inclusion in the phenologic model described by Moore et al. (1997). This factor is important in plants that prioritise the vegetative stage as perennial. The reproductive stage begins only when an advantageous situation is presented.

4.2.7. Senescence and recycling sub-model.

The fluxes out of the fourth leaf and stem compartments (FOLeaffo$_s$; FOStemfo$_s$) and the flux out of the fourth root active and structural compartments (FORAcfo$_s$; FORStfo$_s$) are simulated by

$$\begin{aligned} FOLeafo_S &= \gamma \boldsymbol{Sh_S}\ Leaffo_S \\ FOStemfo_S &= \gamma \boldsymbol{Sh_S}\ Stemfo_S \\ FORAcfo_S &= \gamma \boldsymbol{R}_S\ RAcfo_S \\ FORStfo_S &= \gamma \boldsymbol{R}_S\ RStfo_S \end{aligned} \qquad \textbf{4.28}$$

Therefore, the total flux out of the shoot (FOShfo$_s$) and root (FORfo$_s$) live compartments are:

$$\begin{aligned} &FOShfo_S = FOLeafo_S + FOStemfo_S \\ &and \\ &FORfo_S = FOAcfo_S + FOStfo_S \end{aligned} \qquad \textbf{4.29}$$

It is assumed that there is no loss of substrate of C, N and P with these fluxes, but some structural C, N and P could be returned to the respective substrate pool, simulating recycling of nutrients in the plant. The amount of N and P recycling depends on the substrate concentration and C is assumed to be associated with N recycling. The parameter value for structural degradation for N and P (SdN$_s$; SdP$_s$) and the substrate concentration determine the recyclable fraction of N (ϕN$_s$) and P (ϕP$_s$), so

$$\phi N_s = \frac{\boldsymbol{SdN_s}}{N_s + \boldsymbol{SdN_s}}$$

and

4.30

$$\phi P_s = \frac{\boldsymbol{SdP_s}}{P_s + \boldsymbol{SdP_s}}$$

Thus, the amount of N supplied from recycled shoots (SNSSh$_s$) and roots (SNSR$_s$) are:

$$SNSSh_s = N_s FNR_s \frac{FN_s}{FNR_s} FOShfo_s$$

and 4.31

$$SNSR_s = N_s FNR_s \frac{FN_s}{FNR_s} FORfo_s$$

FNR$_s$ is the parameter fraction nitrogen in degradable structure. As with N, the amounts of P supplied from recycled shoots (SPSSh$_s$) and roots (SPSR$_s$) are:

$$SPSSh_s = \phi P_s \boldsymbol{FPR_s} \frac{\boldsymbol{FP_s}}{\boldsymbol{FPR_s}} FOShfo_s$$

4.32

and

$$SPSR_s = \phi P_s \boldsymbol{FPR_s} \frac{\boldsymbol{FP_s}}{\boldsymbol{FPR_s}} FORfo_s$$

The amounts of C recycled from shoot (SCSSh$_s$) and root (SCSR$_s$) are:

$$SCSShs = \phi N_s \ \boldsymbol{FCR_s} \frac{\boldsymbol{FN_s}}{\boldsymbol{FNR_s}} FOShfo_s$$

and 4.33

$$SCSR_s = \phi N_s \ \boldsymbol{FCR_s} \frac{\boldsymbol{FN_s}}{\boldsymbol{FNR_s}} FORfo_s$$

The rates of supply of C, N and P from senescence (SCS_s ;SNS_s and SPS_s) are simulated by

$$\begin{aligned} SCS_S &= SCSh_S + SCSR_S \\ SNS_S &= SNSh_S + SNSR_S \\ SPS_S &= SPSh_S + SPSR_S \end{aligned} \qquad \textbf{4.34}$$

To make the link between the plant and the soil model the attached shoot and root compartment was divided by each element of the model. Therefore, C, N and P have a shoot and dead root compartment. The individual dead shoot compartments for each element ($ShDC_s$; $ShDN_s$ and $ShDP_s$) are respectively,

$$\begin{aligned} ShDC_S &= FCDSh_S - \left(ShDC_S\ \boldsymbol{DecaySh_S}\right) \\ ShDN_S &= FNDSh_S - \left(ShDN_S\ \boldsymbol{DecaySh_S}\right) \\ ShDP_S &= FPDSh_S - \left(ShDP_S\ \boldsymbol{DecaySh_S}\right) \end{aligned} \qquad \textbf{4.35}$$

And the dead root compartments (RDC_s; RDN_s and RDP_s) are,

$$\begin{aligned} RDC_S &= FCDR_S - \left(RDC_S\ \boldsymbol{DecayR_S}\right) \\ RDN_S &= FNDR_S - \left(RDN_S\ \boldsymbol{DecayR_S}\right) \\ RDP_S &= FPDR_S - \left(RDP_S\ \boldsymbol{DecayR_S}\right) \end{aligned} \qquad \textbf{4.36}$$

$DecaySh_s$ and $DecayR_s$ are the parameters that represent the fall of dead shoot and root material to the soil. $FCDSH_s$, $FNDSH_s$ and $FPDSH_s$ are the flows of C, N and P respectively from live shoot to dead shoot pools.

$$\begin{aligned} FCDSh_S &= (\boldsymbol{FC_S}\ FOShfo_S) - SCSSh_S \\ FNDSh_S &= (\boldsymbol{FN_S}\ FOShfo_S) - SNSSh_S \\ FPDSh_S &= (\boldsymbol{FP_S}\ FOShfo_S) - SPSSh_S \end{aligned} \qquad \textbf{4.37}$$

The flows to dead roots (FCDRs; FNDRs; FPDRs) are represent by

$$FCDR_s = (\boldsymbol{FC_s}\ FORfo_s) - SCSR_s$$
$$FNDR_s = (\boldsymbol{FN_s}\ FORfo_s) - SNSR_s \qquad \textbf{4.38}$$
$$FPDR_s = (\boldsymbol{FP_s}\ FORfo_s) - SPSR_s$$

The dead shoot pool (ShDead$_s$) is calculated by

$$ShDead_s = FOShfo_s - \left(ShDead_s\ \boldsymbol{DecaySh_s}\right) \qquad \textbf{4.39}$$

To link the plant and animal models, the model simulates the fractions of C, N and P in dead shoot material.

$$FCShD_s = \frac{ShDC_s}{ShDead_s}$$
$$FNShD_s = \frac{ShDN_s}{ShDead_s} \qquad \textbf{4.40}$$
$$FPShD_s = \frac{ShDP_s}{ShDead_s}$$

The ground fluxes also could be modified by disturbances like the other above-ground fluxes. The full description of these effects will be described later in the disturbance sub-model (section 4.2.9.).

The amount of N in the surface and root litter (Nsl;Nrl) is represented by

$$Nsl = \sum_{i=1}^{s}\left(ShDN_s\,\boldsymbol{DecaySh_s}\right)_i$$

and $\qquad \textbf{4.41}$

$$Nrl = \sum_{i=1}^{s}\left(RDN_s\,\boldsymbol{DecayR_s}\right)_i$$

and P (Psl;Prl) is represented by

$$Psl = \sum_{i=1}^{s} \left(ShDP_s \, \boldsymbol{DecaySh_s} \right)_i$$

$$and \qquad \textbf{4.42}$$

$$Prl = \sum_{i=1}^{s} \left(RDP_s \, \boldsymbol{DecayR_s} \right)_i$$

C is split into a lignin and C fraction. The lignin fraction (Lsl;Lrl) is represented by

$$Csl = \sum_{i=1}^{s} \left(\left(1 - Plig_s \right) ShDC_s \; \boldsymbol{DecaySh_s} \right)_i$$

$$and \qquad \textbf{4.43}$$

$$Crl = \sum_{i=1}^{s} \left(\left(1 - Plig_s \right) RDC_s \; \boldsymbol{DecayR_s} \right)_i$$

The lignin fraction (Lsl;Lrl) is represented by

$$Lsl = \sum_{i=1}^{s} \left(Plig_s \; ShDC_s \; \boldsymbol{DecaySh_s} \right)_i$$

$$and \qquad \textbf{4.44}$$

$$Lrl = \sum_{i=1}^{s} \left(Plig_s \; RDC_s \; \boldsymbol{DecayR_s} \right)_i$$

Finally, the percentage of lignin ($Plig_s$) is obtained by

$$Plig_s = \frac{\boldsymbol{FLplant_s}}{\boldsymbol{FC_s}} \qquad \textbf{4.45}$$

where the parameter value for the fraction of lignin in the plant ($Flplant_s$) is ontogenic-dependent.

The senescence and recycling sub-model was developed to make the link between plant and soil models. It considers the recycling simulation processes described by Thornley & Verbene (1989) and the individual mineral inputs needed by the Century model (Parton et al. 1987), to simulate plant litter degradation. Consequently, the amount of each individual nutrient present in the plant litter, after the recycling process by the plant following Thornley & Verbene (1989), is considered.

4.2.8. Seed production sub-model

To simulate seed production the reproductive stage is split into two stages in the ontogenic sub-model: before flowering (stage 3) and after flowering to seed maturity (stage 4). When the vegetative stage finishes, two new compartments are created: the propagule_s and seedpro_s compartments. The propagule_s is represented by:

$$\frac{Propagule_S}{dt} = PSAPropagule_S - MProp_S - FPropseed_S \qquad \textbf{4.46}$$

MProp_s is the propagule_s maintenance respiration rate and FPropSeed_s is the fraction of propagule_s allocated to seed.

PSAPropagule_s is the rate of synthesis of new structural dry matter in shoot (GSh_s) allocated to propagule_s. The parameter value for the percentage of synthesis allocated to propagule_s (PAlProp_s) determines the amount of this allocation. However, evidences show that the plant begins this allocation during pre-flowering but the full allocation happens later. Therefore, in the model it is assumed that allocation during the pre-flowering stage has a linear increment to a maximum according to the number of pre-flowering degree-days. This situation is represented in the model by:

$$\begin{array}{lcr} PSAPropagule_S = Gsh_S \dfrac{\boldsymbol{PAlProp}_S\ DDflow_S}{\boldsymbol{DDcflow_s}} & & PhStage = 3 \\ & if & \\ PSAPropagule_S = Gsh_S\ \boldsymbol{PAlProp_s} & & PhStage\ \ 4 \end{array} \qquad \textbf{4.47}$$

The plant in the reproductive stage ceases growth. This is simulated in the model by the allocation of rest of the GSh_s in the second shoot compartment ($Leafs_s$ and $Stems_s$). The same assumption is made to the roots ($RAcs_s$ and $RSts_s$).

The flow from $propagule_s$ to $seedpro_s$ occurs only during the phenological stage 4. The fraction of $propagule_s$ allocated to $seed_s$ ($FPropSeed_s$) is

$$FProSeed_S = \boldsymbol{PAlProSeed_s}\ Propagule_S \qquad \textbf{4.48}$$

The parameter $PAlPropSeed_s$ determines the amount of propagule that is allocated to the $seedpro_s$ compartment. However, the nutrients present in the seed are different from those present in the propagule, so an adjustment in the nutrient composition is necessary. This adjustment is simulated by:

$$\begin{aligned} CAlloSeed_S &= (\ \boldsymbol{FCS_s}\ FProseed_S\ ) - (\ \boldsymbol{FC_s}\ FProSeed_S\ ) \\ NAlloSeed_S &= (\ \boldsymbol{FNS_s}\ FProseed_S\ ) - (\ \boldsymbol{FN_s}\ FProSeed_S\ ) \\ PAlloSeed_S &= (\ \boldsymbol{FPS_s}\ FProseed_S\ ) - (\ \boldsymbol{FP_s}\ FProSeed_S\ ) \end{aligned} \qquad \textbf{4.49}$$

FCS_s, FN_s and FPS_s are the parameter values for the C, N and P in the seed. Therefore, the soluble pools of nutrients give or receive nutrients during the flow from $propagule_s$ to $seedpro_s$.

When the reproductive stage is finished and the plant begins the senescence, DDflows has to be at least half of $DDrep_s$ for the seed to be considered mature. After that, the seed could be harvested or it is transferred to the seed bank in the soil. Therefore, when the plant dies, the $propagule_s$ is transferred to the dead shoot pool

($ShDead_s$) together with shoot phytomass. However, if seed maturity does not finish the $seedpro_s$ is also transferred to the ($ShDead_s$).

The Thornley & Verbene (1989) model contemplated only the vegetative stage of the plant. During the reproductive stage, modifications in the allocation of nutrients were simulated. The seed production sub-model considers the structural difference existent between the plant and seed in C, N and P content.

4.2.9. Disturbances sub-model

Two types of disturbance are contemplated in the model: natural disturbance and human disturbance. Frost and drought are considered as natural disturbances while harvesting or cutting, fire and grazing by large mammals are considered as human influence that can modify plant processes.

4.2.9.1. Drought and Frost

The effect of drought is simulated through the effect of soil moisture on plant processes ($ESMPP_s$) that were described earlier in the photosynthesis section. This effect has an impact on different processes in the plant. However, the frost effect is delineated through modifications in the flow between shoot compartments. Therefore, when the minimum temperature falls below the parameter value for plant frost resistance ($Frostresist_s$) the flow between compartments is accelerated. The increase in the speed of flow is determined by the parameter value for the percentage of mortality by frost ($PMFrost_s$). Thus, the flow between live compartments described before is modified by multiplying with the parameter $PMFrost_s$. In this way, the impact of successive frosts can cause the plant to die.

4.2.9.2. Fire

The plant is considered dead when fire occurs. Therefore, all live and dead compartments above-ground of plants are considered empty and the minerals (N and P) go directly into the available plant mineral pool (NApl and PApl) in the soil sub-model. The C, N and P present in the live compartments below ground are allocated to the corespondent dead root compartments, RDC_s, RDN_s and RDP_s respectively.

4.2.9.3. Harvest or cutting

To calculate the dry matter yield from cutting, the increases in shoot structural dry matter are first calculated and the harvestable dry weight ($HarvSh_{si}$) obtained by

$$\begin{aligned} HarvSh_{si} &= Sh_{si} - Sh_{si}(t-1) & \quad \text{if} \quad & Sh_{si} - Sh_{si}(t-1) > 0 \\ HarvSh_{si} &= 0 & & Sh_{si} - Sh_{si}(t-1) \leq 0 \end{aligned} \qquad \mathbf{4.50}$$

The total harvestable dry weight per species is then taken to be

$$ShHarv_s = \frac{ShTot_s \times \sum_{i=1}^{s} Hsh_i}{Sh_s} \qquad \mathbf{4.51}$$

The effective shoot harvest ($EShHarv_s$) at the moment of cutting must be related to the amount of forage that remains on the field. This is simulated as the proportion of material in the third and fourth leaf compartments that remain on the field ($LeafReT_s$; $LeafReFo_s$).

Therefore,

$$\begin{aligned} LeafReT_s &= 1 - 0.017\ ShHarv_s & \quad \text{if} \quad & ShHarv_s \leq 50 \\ LeafReT_s &= 0.15 & & ShHarv_s > 50 \end{aligned} \qquad \mathbf{4.52}$$

and

$$
\begin{array}{lll}
LeafReFo_s = 1 & & ShHarv_s < 50 \\
LeafReFo_s = 1.2 - .004\ ShHarv_s & if & ShHarv_s \geq 50\ and \leq 200 \\
LeafReFo_s = 0.4 & & ShHarv_s > 200
\end{array}
\qquad \mathbf{4.53}
$$

The same assumption was made for the third and fourth stem compartments that remain on the field ($StemReT_s$; $StemReFo_s$).

The percentage of harvestable forage that remains on the field will be higher when less forage is available to be harvested. Therefore, the model assumes that the effective harvest by plant or functional group ($EShHarv_s$) is simulated by:

$$EShHarv_s = ShHarv_s - \left(LeafReT_s + StemReT_s + LeafReFo_s + StemReFo_s\right)ShT_s \qquad \mathbf{4.54}$$

and the total harvestable dry weight is

$$ShHarvTot = \sum_{i=1}^{s} EShHarv_i \qquad \mathbf{4.55}$$

After harvest or cutting, the model assumes that the first and the second above-ground compartments are empty, so the flux between them and the flux between the second and third compartments of model are altered. The same assumptions for flux after germination is applied (section 4.2.3.5.). Consequently, the flows between compartments start again when the numbers of days after harvest meeting the variables $TEFL_s$ and $TESL_s$ (equation 4.18) respectively.

When the whole-plant photosynthetic capacity is reduced by substantial defoliation the effects of reduced carbon supply rapidly propagate through a growing plant, affecting shoot growth, root respiration, nutrient uptake and root growth (Richards, 1993). These effects are simulated in the model:

- Mineral uptake ceases for 2 days (NP_s and PP_s equal zero, equation 4.26).
- Flows in below ground compartments are duplicated simulating roots dying.
- Flows between the third and fourth compartments and flow out of the fourth compartment are double delayed simulating the recovery of leaf photosynthesis activity.

These two last effects cease when the C balance becomes positive. The C balance ($Cbalance_s$) is simulated by

$$CBalance_S = Cinput_S + SCS_S - Rg_S - Rm_S - Rmu_S - CAlloSeed_S \quad \textbf{4.56}$$

4.2.9.4. Grazing

Grazing by large ruminants is simulated by a direct impact on the above-ground compartments. Each above-ground compartment (live and dead) could give some contribution to the total daily animal intake. The amount of biomass that each species and consequently each compartment of species gives to the total is defined in the animal sub-model. Therefore, the amount of biomass from each species compartment consumed by the animal (e.g. intake of shoot from first compartment ($Leaff_s$ plus $Stemf_s$) is subtracted from the species compartment (e.g $Leaff_s$ and $Stemf_s$).

This is the main disturbance of animal on the pasture, but another effect is caused by trampling. The biomass trampled by livestock (BTL_s) is represented in the model following Hanson et al. (1988).

The effect on each species compartment is proportional to the compartment contribution to total species plant biomass. Therefore, the effect on the leaf first compartment ($BTLeaff_s$) is simulated by

$$BTLeaff_s = \frac{Leaffl}{Sh_s} BTL_s \qquad 4.57$$

The same method is used to simulate the impact of trampling on the other above ground compartments.

The amount of N, P and C present in the biomass trampled by livestock (BTL_s) is directly added to N, P and C in the surface litter (NSl_s; PSl_s ; CSl_s and LSl_s, equations 4.41, 4.42, 4.43 and 4.44).

The disturbance sub-model includes the main external factors that modify plant growth. The impact of these factors are simulated in a simple way and adaptations from the Hanson et al. (1988) and Thornley & Verbene (1989) models were used.

4.3. Simulations

To compare outputs produced by the grassland model with data available in the literature from the studied region, climatic data from the region was necessary. These data were obtained from a database available at the Centre for Cattle Research in Southern Brazil Grasslands region (CPPSUL), a unit of the Brazilian Agricultural Research Corporation (EMBRAPA). The driving variables used by the abiotic sub-model can be seen in table 4.2.

The pasture sub-model was run to constrain its results with data available from the literature for monospecies (Italian Ryegrass) and multispecies (natural graminae C_3 and C_4) in the studied region.

Table 4.1. Driving variables used in the grassland model.

Name	Description	Unit
Rain	precipitation	mm day^{-1}
RH	relative humidity	%
Sun	bright sunshine hours per day	h
TMean	mean daily temperature	°C
TMax	maximum daily temperature	°C
TMin	minimum daily temperature	°C
T10	Ten-day average air temperature	°C
Wind	mean wind speed at 2 m height	Km h^{-1}

4.3.1. Italian Ryegrass

The Italian Ryegrass cultivated in the Rio Grande do Sul was introduced by Italian immigrants. The original plants, after years of natural selection, form today a population adapted to the ecological conditions of Rio Grande do Sul. Therefore, the Italian Ryegrass used by the farmers was not selected for response to nitrogen and the production is low when compared with production obtained in Europe, (Gonçalves, 1979; Piana & Zanini Neto, 1986).

The outputs produced by the plant sub-model were compared with experimental data obtained by Gonçalves (1979). Five levels of nitrogen was studied, 0; 50; 100; 150 and 200 kilograms of N per hectare. Sowing was at the end of May and three harvests were made in August, September and November. Fertiliser was divided into three equal applications. The first application was after plant emergence, the second after the first harvest and the last one after the second harvest.

Appendix 4.2 contains the parameters linked with the plant sub-model used in the simulation and the soil parameters are presented in Appendix 5.2. The parameters used in the pasture sub-model that were obtained from the literature are indicated in Appendix 4.2. Parameters in the Appendix without origin were obtained through a combination of: firstly, from a blending of literature data, the papers where the data come from are cited in the text,; secondly, by direct consultation with specialists in the area (colleagues from CPPSUL/EMBRAPA).

The outputs produced by the model have the same tendency as the experimental production data (Figure 4.4). The main difference occurs at the level of 50 Kg of N per hectare, where the model does not capture the rapid increase in the dry matter production compared to the zero level of N fertiliser. However, at the fertiliser levels of 100, 150 and 200 kg of N the model results in a good fit, particularly at the 200 kg of N level.

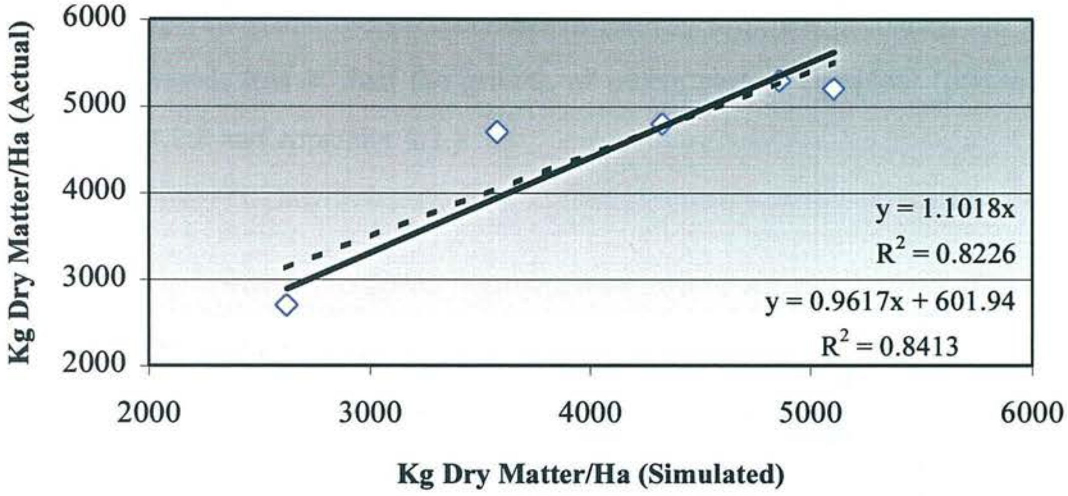


Figure 4.4. Differences between the predict by the simulation model and the observed responses in dry matter production (kg/ha) to the application of 0; 50; 100; 150 and 200 kg of nitrogen fertiliser per hectare.

Two of the more important advances in the monospecies model compared to the model described by Thornley & Verberne (1989) were the introduction of phenology and the partition of the root compartments (structural and active). To demonstrate these effects on the performance of model, the same parameters were used to compare the model performance with experimental data. The sub-model simulates the pasture growth without cuting at two levels of N fertilisation, zero and 200 kilograms per hectare. Figure 4.5 shows the evolution of the above-ground dry matter throughout the year.

Simulation of growth without application of fertiliser shows the maximum production at the end of August. This is a result of a high availability of N in the soil in the early stages of the vegetative stage. After that, growth is reduced by the availability of N in the soil (section 5.3, Chapter 5). During the rest of the vegetative period, plant production tends to be similar. However, during the reproductive stage a small increment in dry matter production is observed. This happens probably due to two factors. Firstly, the increment in the rate of soil mineralization due to favourable temperature and moisture conditions (late spring), and secondly, the seed production demands less N than the growth of others part of the plant (parameter FNS_s, section 4.2.8 and appendix 4.2.).

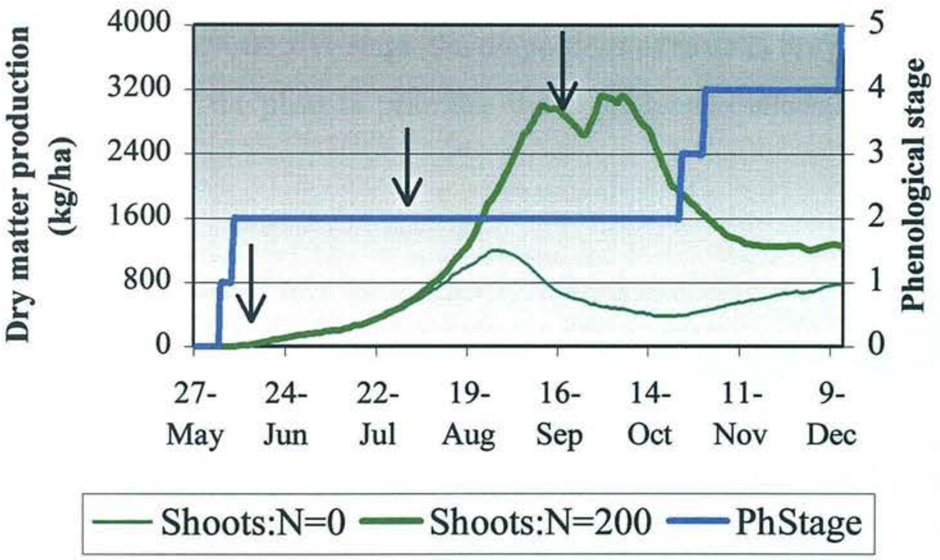


Figure 4.5. Above dry matter production per hectare for two levels of N fertilisation, simulated for different phenologic stages. (→ date of fertiliser application).

In the early stage of growth, a high level of N fertilisation produced a similar level of dry matter production as soil without fertilisation. After August, the level of availability of N in the soil permitted the production of nearly four times more dry matter than that obtained in soil without fertilisation. When production starts to decrease because of nitrogen stress, a third application of N (September as described before) increases production again. However, after that due to the high demands for N and the absence of new fertilisation, the production decreases quickly. This happens until seed production starts (PhStage 4) and the plant reduces structural growth and prioritises seed production.

The proportion of roots in the whole plant (Figure 4.6.) during the first ten days is nearly 50 %. This simulates the establishment of a new plant with partition of new growth to shoot and root to obtain N and P from the soil and C from photosynthesis. After the establishment of a new plant, the proportion of roots in the plant is nearly 35%, this agrees with data from the literature for plants growing at optimum soil conditions (Johnson & Thornley, 1987). This proportion increases quickly in plants growing in soil without fertilisation as a direct response to soil N deficiency. However, in the reproductive stage, the proportions of roots in the plant dropped as a direct response of the plant to prioritise the C production allocating energy to the seed.

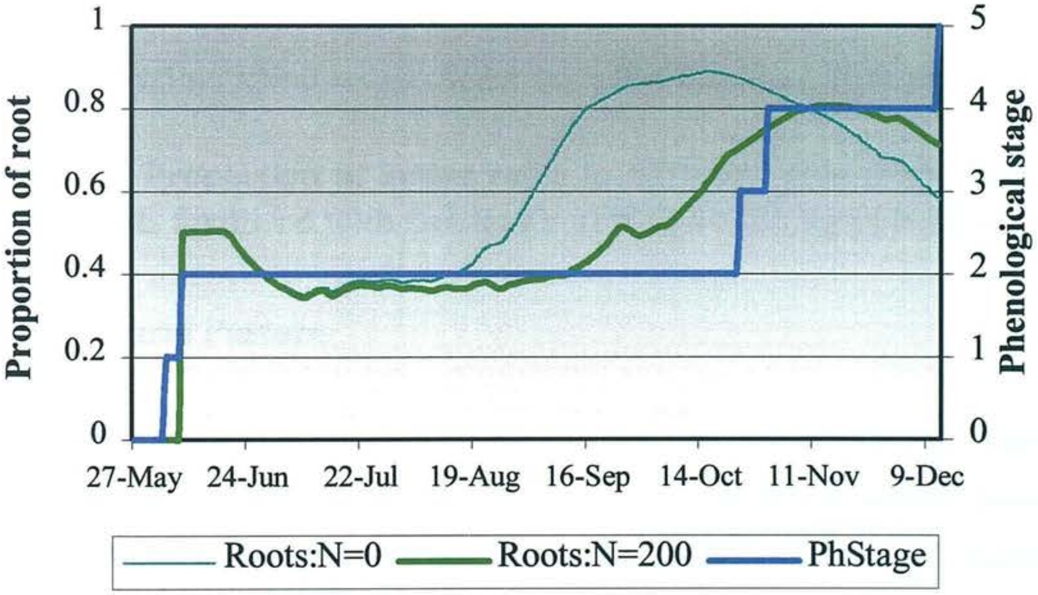


Figure 4.6. Proportion of total roots in relation to the whole plant in the different phenologic stages.

The proportion of active roots (Figure 4.7) follows the pattern showed by the proportion of roots in the whole plant. Plants without fertilisation present around 55% of total roots as active roots. This simulates the efficiency of plants in attempting to maximise the use of scarce resources available and agrees with the fact that the structure of roots change according to the soil environment. Large amounts of thinner roots are normally found in plants growing in poor soil conditions, but in plants of the same species growing in soils rich in nutrients the amount of thinner roots is reduced (Fitter, 1997).

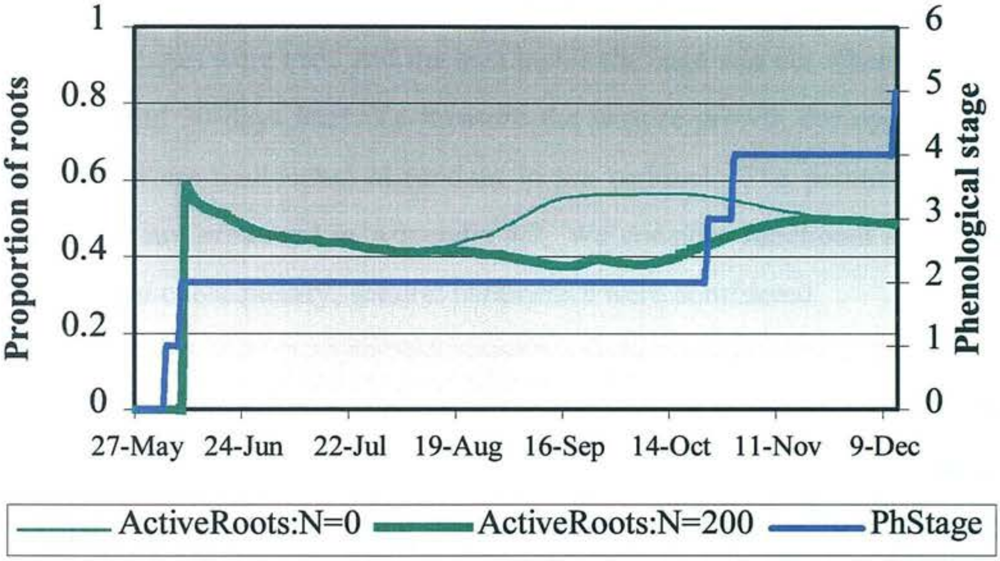


Figure 4.7. Proportion of active roots in different phenologic stages for plants fertilised with two levels of N (0 or 200 kg of N/ha).

4.3.2. Natural Pasture

The complex nature of natural pasture in the studied region was described in Chapter 2. Grass species, mainly C3 species, are the main components of natural pasture (Freitas et al., 1976). Based on this fact, the climate index developed by Fitzpatrick & Nix (1970) was tested and applied with good results by Mota et al. (1981). This index uses average air temperature, rainfall and sunshine to predict dry matter production. The climate effect is one of the main factors influencing natural grassland production. However, the impact of farm management through the variation in stocking rate, paddock-resting, cutting and burning are factors that determine modifications in plant growth. These factors are included in the model as components that are considered by the farmer as a normal procedure in farm management.

Simulations were made to evaluate the model performance in predicting the monthly growth of natural pasture during four years (1985-1988). The results of the last three years were contrasted with original data (field data) used by Salomoni in his publications (Salomoni , 1987; Salomoni & Silveira 1996). The monthly growth of natural pasture was measured in a paddock with grazing beef cattle. Twelve exclusion cages were used and the area inside the cage was cut when the cages where installed and 30 days later. To measure the pasture growth during the next months the cages were reallocated at random in the paddock. The parameters used in the simulation are presented in Appendix 4.2. We consider functional group (annual C_3 and C_4) and consequently, general parameters were considered.

Figure 4.8 shows the maximum and minimum monthly growth that was obtained in the cages. Large variation in growth can be observed in the same paddock. Spatial distribution of soil fertility and species can be considered as factors to explain this variation. In general, the model simulated results inside the intervals and followed the tendency curve of production among years. The main model bias occurs in June and July with low simulated pasture production. This fact is clearly observed in figure 4.9 that represents the seasonal pasture growth.

For the three years simulated, the winter production was close to or below the minimum actual production observed. Consequently, spring growth was close to or above actual spring production. This fast simulated growth in spring was a result of nutrient accumulation in the soil. The twelve seasons simulated, in only three seasons the total growth is out of the maximum and minimum growth interval (maximum - spring/86, minimum - autumn/88 and winter/88).

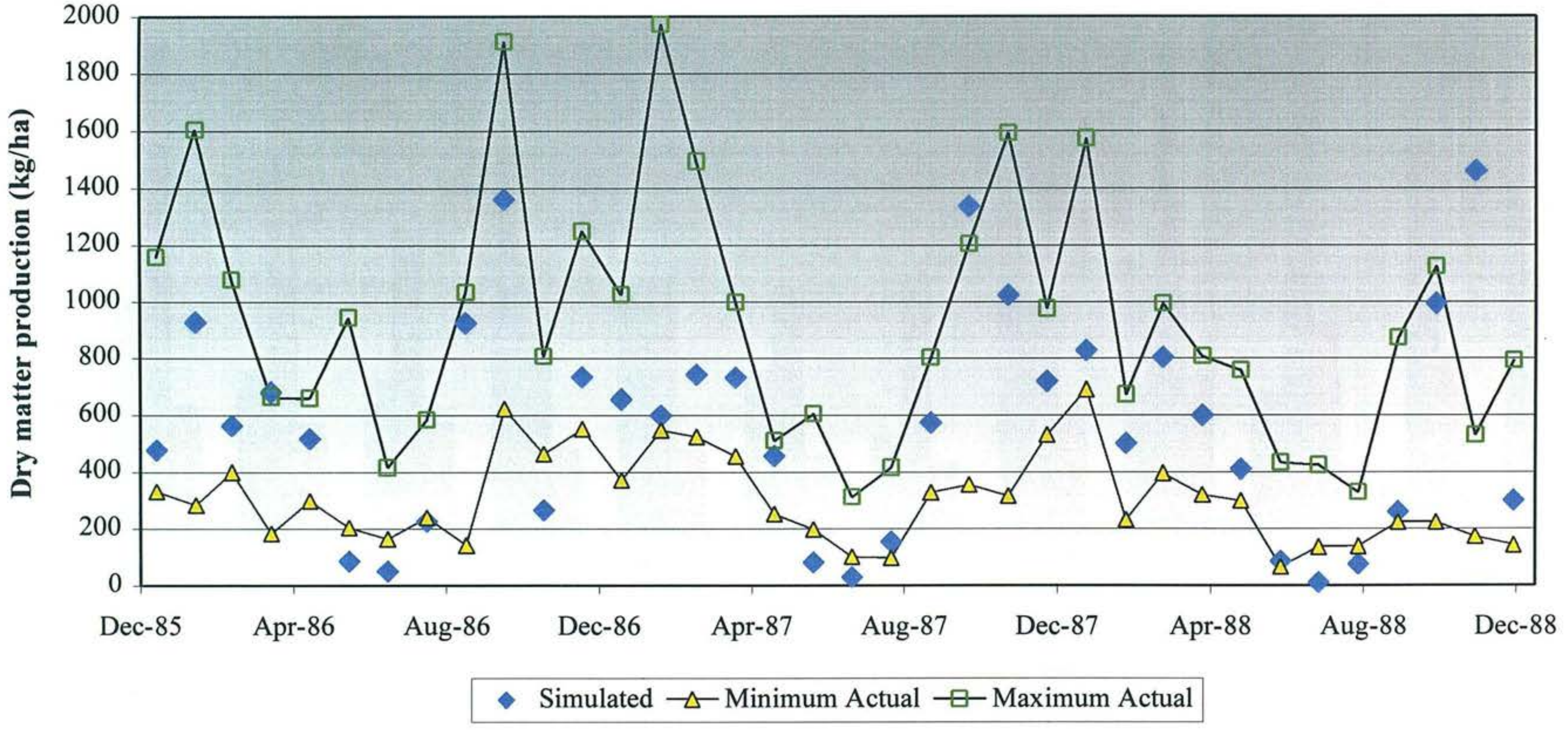


Figure 4.8. Maximum and minimum monthly measured growth of natural pasture compared to simulated monthly growth of natural pasture for three years.

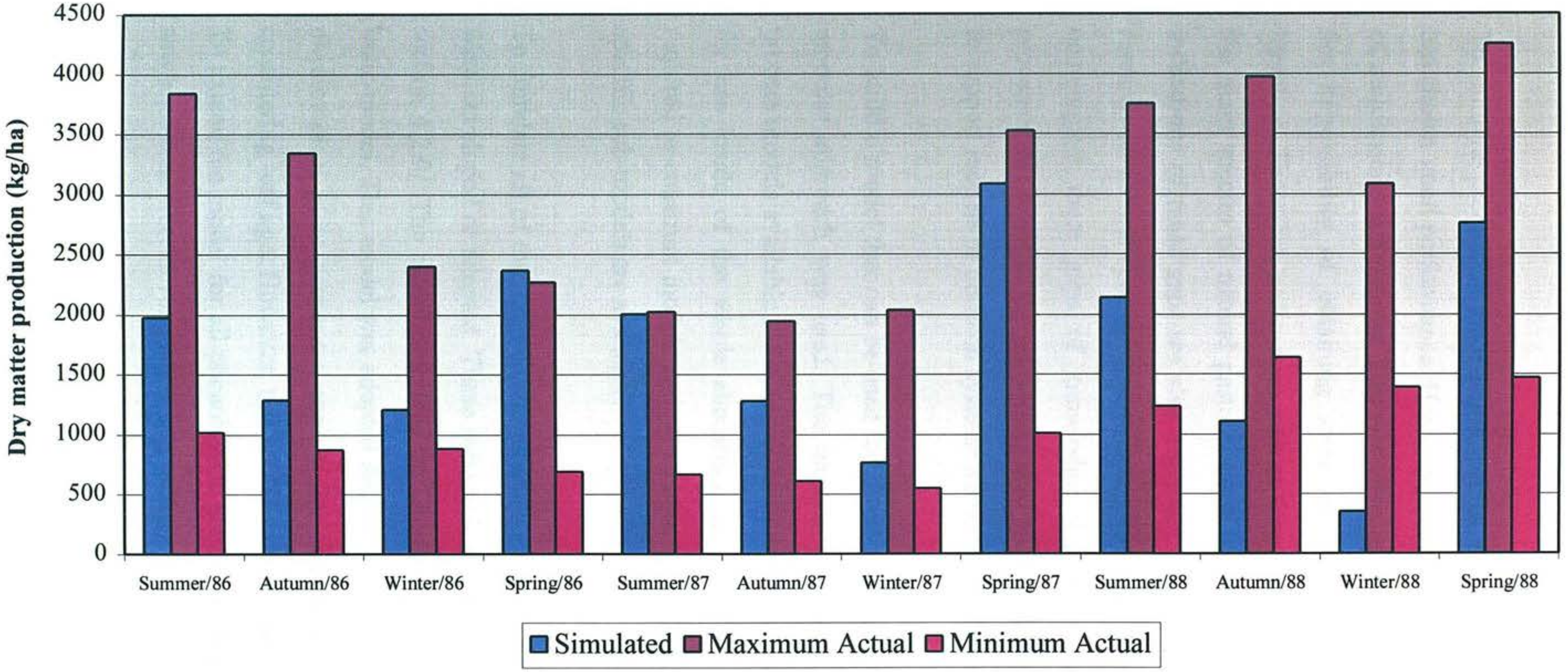


Figure 4.9. Maximum and minimum seasonal growth of natural pasture compared to simulate seasonal growth of natural pasture.

4.4. Concluding remarks

To simulate production from single species, the sub-model described in this chapter has shown good performance. However, substantial work is still needed, in the case of multispecies simulations. This was expected due to the complex relationships and the impossibility of obtaining some parameters for natural species from the literature. Therefore, parameters such as those needed to simulate photosynthesis for the main species of natural pasture, must be obtained in future experiments. The indications of these gaps are also important results supplied by the model. Future research on natural species present in the Rio de la Plata grassland ecosystem must contemplate these gaps of knowledge. The knowledge of these physiological processes can increase the performance of the models and consequently the outputs, to support models of decision systems for use by farmers and policy makers.

To build a model that can be used for simulating mono and multi species swards, a modular approach was used. The modular approach allows the use of specific process models available in literature. Little modifications are needed to adapt them for use inside of the whole simulation model. This approach reduces the time required to construct models and permits an update on the whole model when new specific sub-models are available.

To simulate all of the main physiological plant processes, eight specific sub-models were developed or adapted. These sub-models were described from section 4.2.2 to section 4.2.9. The model described by Thornley & Verberne (1989) was used as a basic model. This model was adopted due to its mechanistic approach for simulating physiological plant processes, mainly the simulation of shoots in compartments considering leaf age. However, this model contemplates plants in a vegetative stage. To extend the model for all phenological stages, some processes were incorporated, new equations were developed or adapted based on information in the literature.

To simulate mineral uptake a sub-model was developed. The division of roots into structural and active, simulates the adaptive behaviour of the plant to the soil environment. The soluble mineral in the plant and the availability in the soil were considered to simulate the capacity of mineral uptake by the plant. This is particularly important in simulation of improved pastures when fertiliser is used. The phenological sub-model developed by Moore et al. (1997) can be cited as an example of a sub-model incorporated in the model with small modifications.

To test the efficiency of the model, new simulations are needed. The inclusion of the perennial functional groups, mainly C_3 plants, can fill the production gap detected in autumn/88 and winter/88. Improvements needed to be made to the model will be discussed in the future when the model is transposed to a more powerful language.

CHAPTER 5

GRASSLAND MODEL: SOIL SUB-MODEL

Soil is an essential component of grassland ecosystems because their sustainability depends on the amount of nutrients that can be extracted and recycled from it. Simulation of nutrient cycles is necessary for appropriate description of the system. The flow of energy and the functioning of living species depend on the flow of nutrients, especially water (Halm et al., 1972). Minerals are transported through biological processes such as plant uptake and utilisation by water. Therefore, biogeochemical and hydrologic cycles of the pasture ecosystem are virtually inseparable (Wilkinson and Lowrey, 1973).

5.1. The soil mineral sub-model

After reviewing different soil models with varying objectives and complexity, but compatible for use in grassland ecosystem (Jones et al. 1984; Parton et al, 1987; Wight & Skiles, 1987; Parton et al, 1988; Thorley & Verberne, 1989; Verberne, 1992; Parton et al., 1994; Yin & Huang, 1996), a concise model has been developed for this study.

The framework adopted in the model reflects the consideration pointed out by Bosatta & Agren (1991):

"Pioneers in this field who used simple conceptual schemes of the interactions in the soil and analysed their data accordingly. The absence of convenient formalisation has made the field more and more crowded with details. No doubt, in the search for an "equation of state" of the soil, we must, in some way go back to the old simplicity".

Simple incubation experiments, which integrate gross mineralization and immobilisation, provide insight into mineral mechanisms, but more accurate descriptions require isotopic tracers to identify degradation pathways and specific classes of substrates. Unfortunately, the detailed biomass studies and tracer experiments required to test mineralization models are difficult to interpret and are problematic to perform (Ellert & Bettany, 1988).

The main objective of a soil model is to simulate the nutrients, nitrogen (N), phosphorus (P) and water available for plants in a simple way. Therefore, the "traditional" approach, where soil organic matter (SOM) is simulated in different pools, according to their stability and relationship to the carbon in each pool, has not been adopted.

5.1.1. Description of the model

The soil mineral model diagram is shown in Figure 5.1. The model details the availability of minerals to plants. Degradation processes are affected by soil temperature and moisture that are generated from abiotic and water sub-models.

Easily degradable plant litter (metabolic litter) and excreta are simulated as inputs to the pool of minerals available to the plant. The dynamics of structural litter are not simulated and the input of minerals is assumed through potential mineralization of soil. Rain and fertiliser are other possible inputs to the pool of minerals available to the plant.

Organic residues to the soil are usually higher in grassland than in crops. These are higher under grazing than under mowing, as a result of the return of dung, urine and plant litter (Hassink, 1994). Therefore, these inputs help to simulate changes in minerals obtainable by plants in one stable ecosystem where climatic conditions and ungulate animals are the main causes of disturbance.

The state variables and other variables are described in the Appendix 5.1. The parameters are presented in Appendix 5.2. The time-step used is one day. As in the pasture model, most of the equations used in the model were taken from papers available in the literature: Burns (1974), Parton et al. (1987), Hanson et al. (1988), Parton et al. (1988), Parton et al. (1994).

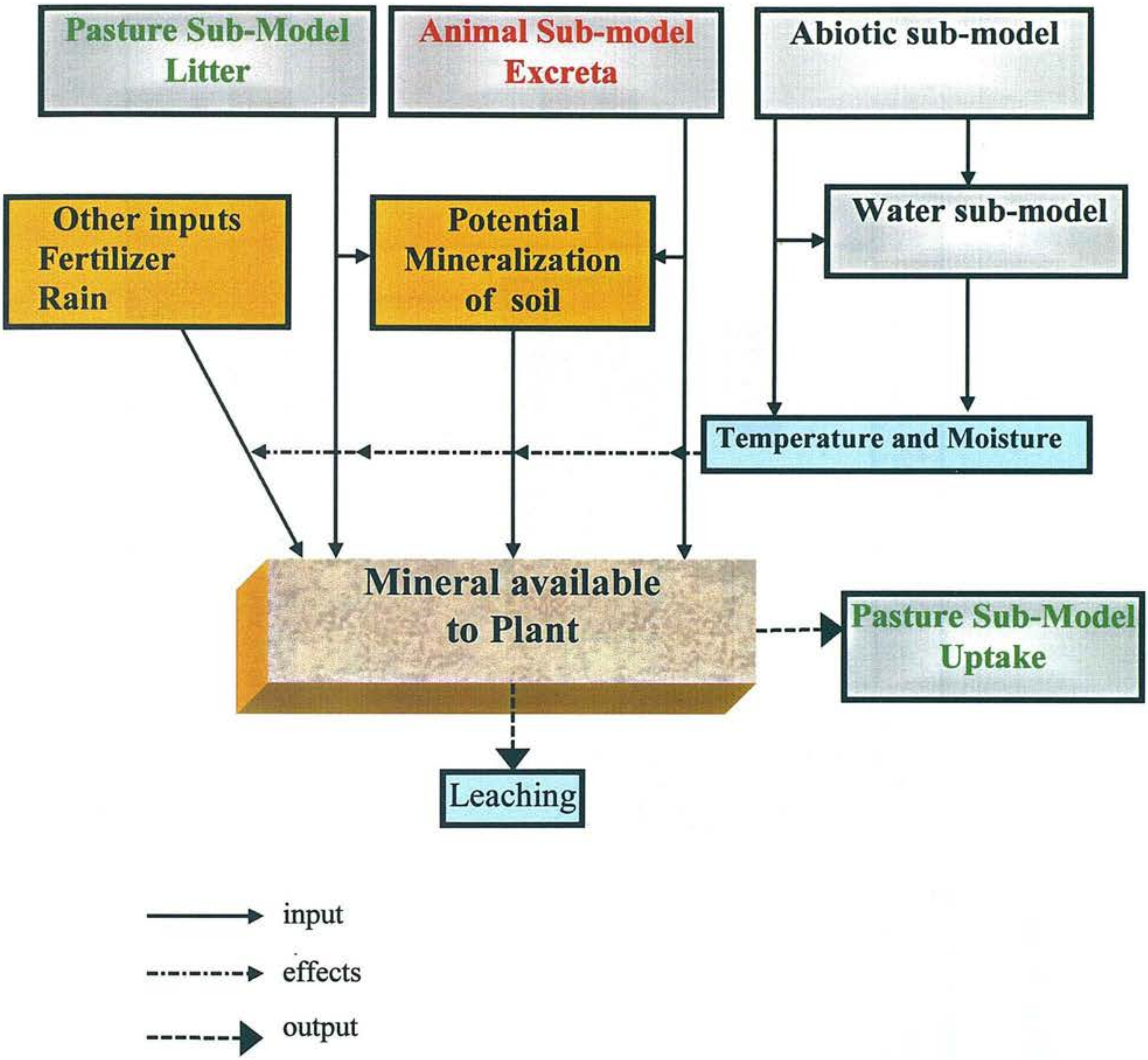


Figure 5.1. Diagram of soil sub-model

Dynamics of N and P are represented in Figure 5.2. The N available to the plant is modelled following the method of potential mineralization of soil proposed by Stanford & Smith (1972). It has been defined as that fraction of the organic nitrogen pool that is susceptible to mineralization. In this method, soil is incubated for 30 weeks in laboratory conditions to determine the potential mineralization of organic

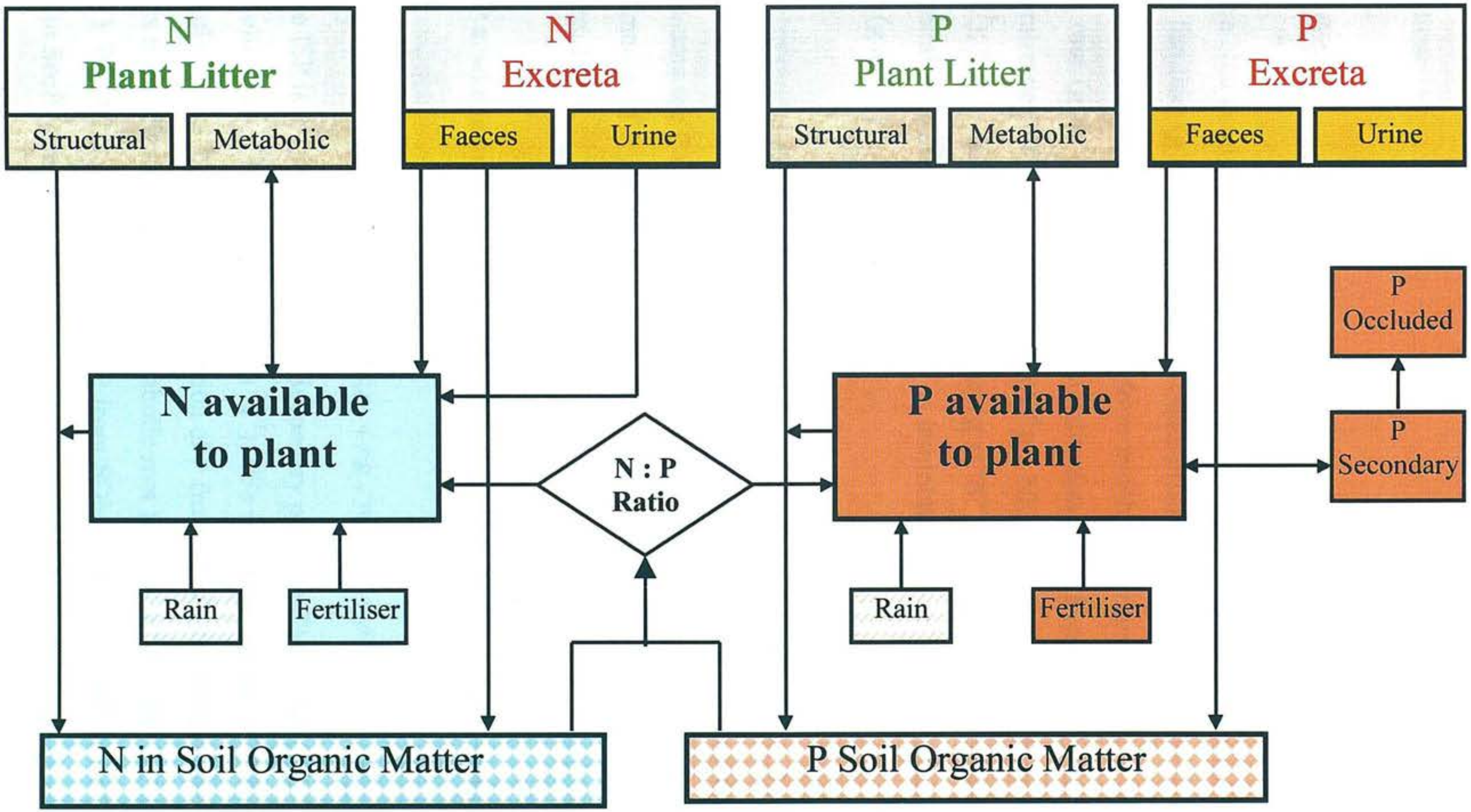


Figure 5.2. Dynamic of N and P in the model.

matter. Therefore, direct mineralization during the first stage of plant litter and animal excreta decomposition (metabolic litter) has to be simulated independently.

The N available to plant (NApl) is calculated from the following differential equation:

$$\frac{dNApl}{dt} = NFa + NFe + NM_{rl} + NM_{sl} + NR + NSOM + NU - NL - NP - NS_{rl} - NS_{sl} \qquad \textbf{5.1}$$

Where NFa is mineralization of N from faeces (g $m^{-2}d^{-1}$); NFe is mineralization of N from fertiliser (g $m^{-2}d^{-1}$); NM_{rl} is mineralization of N from metabolic root litter (g $m^{-2}d^{-1}$); NM_{sl} is mineralization of N from metabolic surface litter (g $m^{-2}d^{-1}$); NR is N from rain (g $m^{-2}d^{-1}$); NSOM is mineralization of N from SOM (g $m^{-2}d^{-1}$); NU is mineralization of N from urine (g $m^{-2}d^{-1}$); NL is the N leaching from root zone (g $m^{-2}d^{-1}$); NP is the N uptake by plant (g $m^{-2}d^{-1}$); NS_{rl} is immobilisation of N from structural root litter (g $m^{-2}d^{-1}$); NS_{sl} is immobilisation of N from structural surface litter (g $m^{-2}d^{-1}$).

P is also modelled through potential mineralization of the soil (figure 5.2). However, to estimate P potential mineralization in the laboratory is very complex. Therefore, we assume the P mineralization rate is directly linked with N mineralization rate, so the amount of P mineralised from SOM occurs according to the N:P ratio of soil (White, 1987).

The P available to plant (PApl) is calculated from the following differential equation:

$$\frac{dPApl}{dt} = ISP + PFa + PFe + PM_{sl} + PM_{rl} + PR + PSOM - OSP - PL - PP - PS_{sl} - PS_{rl} \qquad \textbf{5.2}$$

Where ISP is the flow of P from the Secondary pool (SecP) to PApl (g $m^{-2}d^{-1}$); PFa is mineralization of P from faeces (g $m^{-2}d^{-1}$); PFe is mineralization of P from fertiliser to PApl (g $m^{-2}d^{-1}$);PM_{sl} is mineralization of P from metabolic surface litter (g $m^{-2}d^{-1}$); PM_{rl} is mineralization of P from metabolic root litter (g $m^{-2}d^{-1}$); PR is P from rain (g $m^{-2}d^{-1}$); PSOM is mineralization of P from SOM (g $m^{-2}d^{-1}$); OSP is flow of P from PApl to SecP (g $m^{-2}d^{-1}$); PL is the leaching of P from the root zone (g $m^{-2}d^{-1}$); PP is the P uptake by plant (g $m^{-2}d^{-1}$); PS_{sl} is mineralization of P from structural surface litter (g $m^{-2}d^{-1}$); PS_{rl} is mineralization of P from structural root litter (g $m^{-2}d^{-1}$).

This approach, which considers potential mineralization of soil, is supported by soil conditions in natural pasture ecosystems, where the organic matter pool is relatively stable for each type of soil.

5.1.2. Plant litter decomposition sub-model

The Century model (Parton et al., 1987; Parton et al., 1994) is the basis of the plant litter decomposition sub-model. Two different types of litter are considered depending on their position: surface (subscript $_{sl}$) and root litter (subscript $_{rl}$). We describe equations for surface litter, but the same equations are used to simulate root litter with change in the subscript $_{sl}$ by $_{rl}$.

Lignin-to-nitrogen ratio ($L_{sl,}/N_{sl,}$) determines the split of plant residue into a structural (slow degradation) and metabolic material (easily decomposable in less than 1 year). The slow degradation plant residue is not simulated and consequently the mineral input from structural litter is reflected in the potential mineralization of soil (see section 5.1.3).

When organic litter is decomposed, essential elements are converted from combined forms to simple inorganic forms through microbial respiration (White 1987; Hassink, 1994). The model assumes that 60% of CF_{sl} is lost through microbial respiration. Inorganic forms are released when the assimilated material is more than the growth demand of the microorganism that decomposes the organic material. The model assumes that SOM is maintained at a fixed C: N and C: P ratio according to the kind of soil. For decomposition to occur the pools of mineral available to the plant (NApl and PApl) have to be positive.

N and P flow from metabolic litter depend on C flows. The model assumes that N and P are bonded with C, so that the proportion of N or P present in metabolic litter is liberated for direct mineralization when CO_2 is produced during decomposition. However, inorganic minerals can be immobilised from NApl or PApl. This happens when the ratio C: N or C:P in the flow from decomposition material to SOM is less than the ratio in organic matter (CN and CP). Thus, NIM_{sl} or PIM_{sl} are quantities of mineral that have to pass from metabolic litter to SOM, in a way which maintains the ratio C: N and C:P.

$$NIM_{sl} = \frac{CF_{sl}\, 0.4}{\boldsymbol{CN}} \tag{5.3}$$

$$PIM_{sl} = \frac{CF_{sl}\, 0.4}{\boldsymbol{CP}} \tag{5.4}$$

The effective amount of C that flows from metabolic surface litter to SOM is 40% of total. The rest is assumed to be lost by microbial respiration as explained before. Therefore, the quantity of mineral (NM_{sl} and PM_{sl}) which is liberated or immobilised from NApl and PApl is respectively:

$$NM_{sl} = CF_{sl} \frac{NMet_{sl}}{CMet_{sl}} - NIM_{sl} \tag{5.5}$$

$$PM_{sl} = CF_{sl} \frac{PMet_{sl}}{CMet_{sl}} - PIM_{sl} \tag{5.6}$$

Although the structural litter degradation is not simulated in the model, in order to maintain the C: N and C: P ratio in SOM, the flow of N and P into SOM must be calculated. The amount of N or P in the structural litter ($PStru_{sl}$) is obtained by:

$$NStru_{sl} = N_{sl} \left(1 - Fm_{sl}\right) \tag{5.7}$$

$$PStru_{sl} = P_{sl}\left(1 - Fm_{sl}\right) \qquad \textbf{5.8}$$

The flow of N or P from structural litter to SOM must maintain the ratios (C: N; C: P) in the SOM, according to the type of soil. Therefore, the amount of N or P from structural surface litter or root litter (CP_{sl}) is,

$$CN_{sl} = \frac{C_{sl}\left(1 - Fm_{sl}\right)}{\boldsymbol{CN}} \qquad \textbf{5.9}$$

$$CP_{sl} = \frac{C_{sl}\left(1 - Fm_{sl}\right)}{\boldsymbol{CP}} \qquad \textbf{5.10}$$

The relationship between $CNStru_{sl}$ - $NStru_{sl}$ and $CPStru_{sl}$ - $PStru_{sl}$ determines how much N and P is eventually immobilised (NS_{sl} ;PS_{sl}) from NApl or PApl.

$$NS_{sl} = CNStru_{sl} - NStru_{sl} \qquad \textbf{5.11}$$

$$PS_{sl} = CPStru_{sl} - PStru_{sl} \qquad \textbf{5.12}$$

Thus, if NS_{sl} or PS_{sl} was negative N or P is immobilised from NApl or PApl. Mineralization is assumed to be reflected by the potential mineralization of soil.

The plant litter decomposition sub-model is a simplification of the Century model. The different pools of organic matter are not considered, and the sub-model simulates the metabolic litter degradation process directly to the pool of mineral available to the plant (NApl and PApl).

5.1.3. Potential mineralization sub-model

The model is based on the potential mineralization of the organic matter pool. This approach was adopted because organic soil conditions in natural pasture ecosystems are relatively stable.

Stanford & Smith (1972) proposed a mathematical model that was based on the hypotheses that only a fraction of the total N of the soil is potentially mineralizable (Parentoni et al. 1988). Evidence has shown that this procedure may give accurate predictions of N availability under field conditions (Smith et al., 1977).

The rate of N supply by stable organic matter is obtainable under ideal laboratory conditions. However, soil water and temperature greatly influence mineralization of soil organic nitrogen. The understanding of the quantitative relationships involved is essential as a basis for predicting amounts of mineral N released to the plant under specified climatic conditions (Stanford & Epstein, 1974; Cameron & Kowalenko, 1976; Cassman & Munns, 1980).

These effects are considered in the model with the same equations that were used on degradation of metabolic litter. These equations are used because the microbial fauna, which degraded stable organic matter, is similar to that of degraded metabolic litter. Therefore, the model assumes temperature and moisture have similar effects on both kinds of fauna (Parton et al., 1988).

Therefore, the effective inorganic N from stable organic matter (NSOM) that flows into NApl is represented by:

$$NSOM = Nmin\ \ ETD\ \ EMD \qquad \textbf{5.13}$$

Nmin is the amount of N mineralized per day and it is obtained by:

$$Nmin = \frac{\boldsymbol{ESNo\ MinRate\ DBD\ ds}}{100} \qquad 5.14$$

ESNo is the estimate of soil N mineralization potential (ppm) and MinRate is mineralization rate constant at 35 °C which are obtained following the method of potential mineralization of soil proposed by Stanford & Smith (1972). DBD is dry bulk density of the soil (g cm^3) and ds is the depth of soil (cm). The value 100 present in the formula is used to convert centimetre to metre and parts per million to grams.

Phosphorus cycling is governed by its stability (low solubility), and its low mobility in soil. Immobilization of P has been thought to occur in plant materials containing less than 0.2% P or when the C:P ratio is greater than 100 to 1 (White, 1987;Wilkinson & Lowrey, 1973). In the model, the flow of P from metabolic or structural surfaces and root litter to SOM is described above in the plant litter decomposition sub-model. Orthophosphate that is released by mineralization is rapidly adsorbed by the soil particles where its availability steadily declines with time (White 1987). This factor is simulated through a secondary pool of phosphorus (SecP, section 5.1.5.1). The model assumes that P flow is bonded with N flow from organic matter. Therefore, PSOM is the effective flux of inorganic P from SOM into PApl is represented by:

$$PSOM = \frac{NSOM}{\boldsymbol{NP}} \qquad 5.15$$

In this way, the ratio N: P (NP) in stable soil organic matter is maintained.

This approach of potential soil mineralization was adopted because the goal of the model is to simulate natural and improved pasture in stable agricultural systems. To simulate crop systems, the use of the plant litter decomposition model in DSSAT models would be useful.

5.1.4. Animal excreta decomposition sub-model

When herbage is consumed by grazing animals, a very small proportion of the total mineral intake is retained in animal products. They are present in organic and/or inorganic forms in excreta, depending on the particular mineral. Thus, returned nutrients may be in readily plant-available forms or in forms that require mineralization before they are available for plant uptake. Significant mineralization of organic P in plant occurs during passage through the animal digestive tract and, in addition, much of the N is excreted as urea, which is rapidly converted to the readily plant-available NH4 and NO3 forms. Consequently, the amount of N and P returned in animal excreta is more rapidly available to plants than are N and P in decaying plant residues (Floate, 1970a; Wilkinson & Lowrey, 1973; Haynes & Williams, 1993).

The complete disappearance of cattle dung depends on water content, climatic conditions and the activity of soil fauna, so degradation time ranges between 2 weeks and 17 months (Castle & MacDaid, 1972; Barth et al., 1994; Williams & Haynes, 1995).

N is excreted in urine and faeces in different proportions that are dependent on the quality of the diet. Faecal excretion of N, in sheep and cattle, is usually about 0.8 g N 100 g^{-1} of dry matter consumed, regardless of the N content of the diet. Therefore, the different content of N in urine, which can be increased by raising the nitrogen level in feed, results in different proportions of N excreted between urine and faeces (Henzell & Ross, 1973; Haynes & Williams, 1993).

The total N excreted in the faeces (g $m^{-2}d^{-1}$), Nfaeces, per day is assumed by:

$$Nfaeces = 0.008\ ADMISM \qquad \textbf{5.16}$$

ADMISM is the animal forage and supplement intake per square metre (g $m^{-2}d^{-1}$) that is input from the animal sub-model.

The bulk of the N in faeces is in organic form, so it must first undergo microbial mineralization before it is released in mineral form. However, N mineralization from the plant material is slower after it has been digested by the animals, because faeces contain a large proportion of C in undigested fibres (Haynes & Williams, 1993).

N in metabolic faeces (g $m^{-2}d^{-1}$), NMfaeces, is represented in the following equation:

$$\frac{dNMfaeces}{dt} = Nfaeces\ 0.2 - NFa \tag{5.17}$$

The amount of N mineralization from faeces (NFa) is closely related to the total N content of faeces. However, in faeces from animals fed on Agrostis-Festuca, only 15% of N content was decomposed into nitrate and ammonium when incubated at 10°C for 12 weeks (Floate, 1970b; Floate, 1970c; Floate, 1970d). MacDonald et al. (1973) found only 22% N in the dung is mineralisable. Therefore, we assume that only 25% of N in the faeces can be mineralised. The mineralization ratio is affected by temperature (ETDf) and moisture (EMDf), represented in the model by the following equations based on the papers by Floate (1970a,b,c and d):

$$ETDf = \frac{Tsoil + 5}{15} \tag{5.18}$$

$$EMDf = 1 - exp^{(-3.25\ MsoilSup)} \tag{5.19}$$

The Tsoil is soil mean temperature, calculated following Parton (1981). MsoilSup is moisture in the top of the soil. It is a linear scalar effect that depends on the water field capacity of the soil (Wfc), value=1, and water content at air dryness (Wair), value=0, in the first 5 cm of soil.

$$MsoilSup = \frac{W - \boldsymbol{Wair}}{\boldsymbol{Wfc} - \boldsymbol{Wair}} \qquad \textbf{5.20}$$

Where W is the quantity of water in the first 5 cm of soil obtained from the water sub-model.

NFa is the flow of N mineralized from NMfaeces. It is calculated as follows:

$$NFa = NMfaeces\ \boldsymbol{Kfn}\ ETDf\ \ EMDf \qquad \textbf{5.21}$$

Kfn is a parameter which controls the maximum faeces decomposition at 10°C (Floate, 1970c).

The input of N from urine (Nurine) is expressed by:

$$Nurine = (-0.64 + 0.96\ NCintake)\,0.01\ \ ADMISM \qquad \textbf{5.22}$$

The percentage of N in the diet (NCintake) determines the quantity of N present in urine. Typically, 30-70% of nitrogen ingested by cattle is excreted in the urine (Vallis et al. 1982).

Urea is the main component of urine and its degradation to ammonia is quicker than in commercial urea (Sherlock & Goh, 1984). Loss of ammonia from urine patches depends on temperature and moisture. This loss represents from 4% to 46% of urine N and losses of 15% to 25% are common (Haynes & Williams, 1993).

The abiotic effect on ammonia loss (ETMUavol) is represented by the following equation modified from Vallis et al. (1982):

$$ETMUavol = (-0.926 + 0.533\ \ Tsoil + 16.1\ \ Msoil)\ \ Nurine \qquad \textbf{5.23}$$

Therefore, the input of N mineralization from urine (NU) to NApl is the result of differences between Nurine and ETMUavol.

$$Nminurine = Nurine\ (1 - ETMUavol) \tag{5.24}$$

Faeces represent a predominant pathway in which P returns to the soil, as opposed to N, in which urine is an important pathway of excretion (Barnett, 1994). Only traces of P are normally detected in the urine and consequently the P in urine is not considered in the model. However, like N in the urine, total P content in faeces (PFaeces) is strongly correlated with the total intake of P and therefore with P content of the diet (Pcintake) (Rowarth et al., 1988; Barnett, 1994).

$$PFaeces = (-0.09 + 3.19 \times PCintake)\ 0.01\ ADMSI \tag{5.25}$$

The proportion of inorganic P in faeces increases as total P intake increases, but the content of organic P remains relatively constant. The division between organic and inorganic P (PifFaeces) in faeces is given by (Floate, 1970b):

$$PifFaeces = \frac{0.84\ PCintake - 0.0411}{PCintake}\ Pfaeces \tag{5.26}$$

The PifFaeces was found to be as effective a P source as readily soluble fertiliser P. However, the organic P content was not available, at least in the short term (Haynes & Williams, 1993). Therefore, the model assumes its mineralization occurs through potential phosphorus mineralization (PSOM).

The amount of inorganic P is simulated in the following differential equation:

$$\frac{dPIfaeces}{dt} = PifFaeces - PFa \tag{5.27}$$

The physical breakdown of the dung is the controlling factor in the movement of inorganic P from faeces into the soil. Season is an important factor, which affects the dung breakdown. Dung patches deposited in spring and summer disappeared more slowly than those deposited in autumn and winter (Weeda, 1967; Castle & MacDaid, 1972; MacDiarmid & Watkin, 1972a; Barth et al., 1994; Williams & Haynes, 1995). In addition, the main activity of earthworms is during the autumum/winter period. They could account, at least in part, for the rapid disappearance of dung patches in autumn/winter (MacDiarmid & Watkin, 1972b).

In the model, abiotic effects in faeces breakdown are influencied by moisture (EMDf), seen above, and temperature (ETBDf), which is demonstrated by:

$$ETBDf = 1 - \left(1 - exp\left(-0.085\ Tsoil\right)\right) \quad \mathbf{5.28}$$

The action of the above equations affect the maximum rate of dung breakdown (kfbd) (Weeda, 1967). Therefore, the P mineralization from faeces, PFa, is represented in the model by:

$$PFa = PifFaeces\ \boldsymbol{Kfbd}\ ETBDf\ EMDf \quad \mathbf{5.29}$$

The inclusion of the animal excreta decomposition sub-model in the soil sub-model was necessary because the purpose of this work is the simulation of the pastoral farm system. Consequently, the impact of different stocking rates in the cycling of plant and soil nutrients can be simulated.

5.1.5. Other inputs and outputs

5.1.5.1. Phosphorus occluded and secondary pool

The inorganic P available to plant (PApl) is not stable. Therefore, P inorganic has one secondary P (SecP), which is interchangeable with PApl. More information can be obtained from Parton et al. (1988).

5.1.5.2. Rain

The quantity of nutrients in the rainfall is derived from the nutrient concentration and quantity of rainfall (Allen et al., 1968). Contribution of N from rain (NR) is assumed in the model is to the same as in the SPUR model (Hanson et al., 1988).

$$NR = 0.004\ Rain \qquad \textbf{5.30}$$

The concentrations of P in rain are often in the range 10-100 $\mu g\ l^{-1}$, although they can be lower (Newman, 1995). The model assumes 3×10^{-5} as a value to multiply the quantity of rain. This value has its origin in data by Allen et al. (1968). Therefore, the amount of P from rain (PR) is:

$$PR = 0.00003\ \ Rain \qquad \textbf{5.31}$$

5.1.5.3. Fertiliser

Urea is the primary nitrogen fertiliser used worldwide because it is relatively inexpensive to manufacture and handle. It also has a high N concentration (Burch & Fox, 1989). However, urea has great potential for ammonia losses. This process is linked to the weather conditions and soil properties. The magnitude of loss will depend on the conditions existing at the time of urea application. Therefore, the efficiency of fertiliser N can vary from one environment to another (Fenn & Hossner, 1985).

The abiotic effect on ammonia loss (ETMFavol) is represented by:

$$ETMFavol = -0.926 + 0.533\,Tsoil + 16.1\,Msoil \qquad \textbf{5.32}$$

Therefore, the input of N mineralization from fertiliser to NApl (NFe) is the result of differences between the amount of N from fertiliser (QNfe) and the loss of ammonia (ETMFavol):

$$NFe = \frac{QNfe\, 0.46\, (1 - ETMFavol)}{10} \qquad 5.33$$

The index 0.46 represent the percentage of N in the urea (White, 1987), and the factor 10 the change from kg/ha to g m^{-2}.

P fertiliser is considered in the model taking into account its relative agronomic potential, which is a comparison of rock phosphate to other P fertilisers (Sanyal & Datta, 1991). Here the triple superphosphate is adopted as a pattern following Leon et al. (1986). All P content in the triple superphosphate is incorporated in PApl. However, as with the other P fertilisers, the relative agronomic effectiveness (RAE) must be considered. Consequently, the fraction (PAfe) is incorporated in PApl and the other fraction (Psecfe) is incorporated to SecP pool. In the model this is shown by:

$$PAFe = \frac{QPFe\ 0.44\ \mathbf{RAE}}{10} \qquad 5.34$$

$$PSecFe = \frac{QPfe\ 0.44\ (1 - \mathbf{RAE})}{10} \qquad 5.35$$

QPFe is the quantity of P fertiliser, taking as base the P in P_2O_5, applied in kilograms per hectare. The index 0.44 represent the percentage of P in P_2O_5 (White, 1987), and the factor 10 the change from kg/ha to g m^{-2}.

5.1.5.4. Leaching

The model follows the approach by Burns (1974) which considers water and mineral entering into the soil as completely mixed with the water and mineral already present in the soil. The water flow out of the root zone is obtained from the water sub-model.

The main goal of the soil mineral sub-model is the simulation of mineral cycling in a pastoral farm system. The degradation process of minerals from plant litter and animal excreta is simulated in combination with the potential soil mineralization. These processes are affected by temperature and moisture, which are considered in the model. In addition, the fertiliser process is simulated considering these effects.

5.2. The water sub-model

A pasture growth model must keep track of the soil moisture to determine when and to what degree the plants are exposed to water stress. Many complex water models are currently available (Ross, 1990; Johnson et al., 1991; Thornley, 1996), but, most of the times, a lack of appropriate data to run these models is a major obstacle.

Soil water models in pasture and crop environments (Renard et al., 1987; van Keulen and Seligman, 1987; Verberne, 1992; Supit et al., 1994; Walker and Langridge, 1996) were reviewed and the approach used by Verberne (1992) was chosen. However, parts of other models have been incorporated to obtain a simple (easy parameterisation) but mechanistic enough approach capable to simulate basic water soil dynamics in the soil.

The maximum potential evaporation and maximum potential transpiration have been calculated following the classical approach of Penman (1956). The development of the Penman formula carried out by Supit et al. (1994) was used.

5.2.1. Description of the model

The model treats the soil as a multi-horizontal-layered system with a variable number of layers, each one with variable thickness. The soil moisture is calculated from the combined effect of precipitation, runoff, irrigation, soil evaporation, and transpiration by plants and downward movement (Figure 5.3).

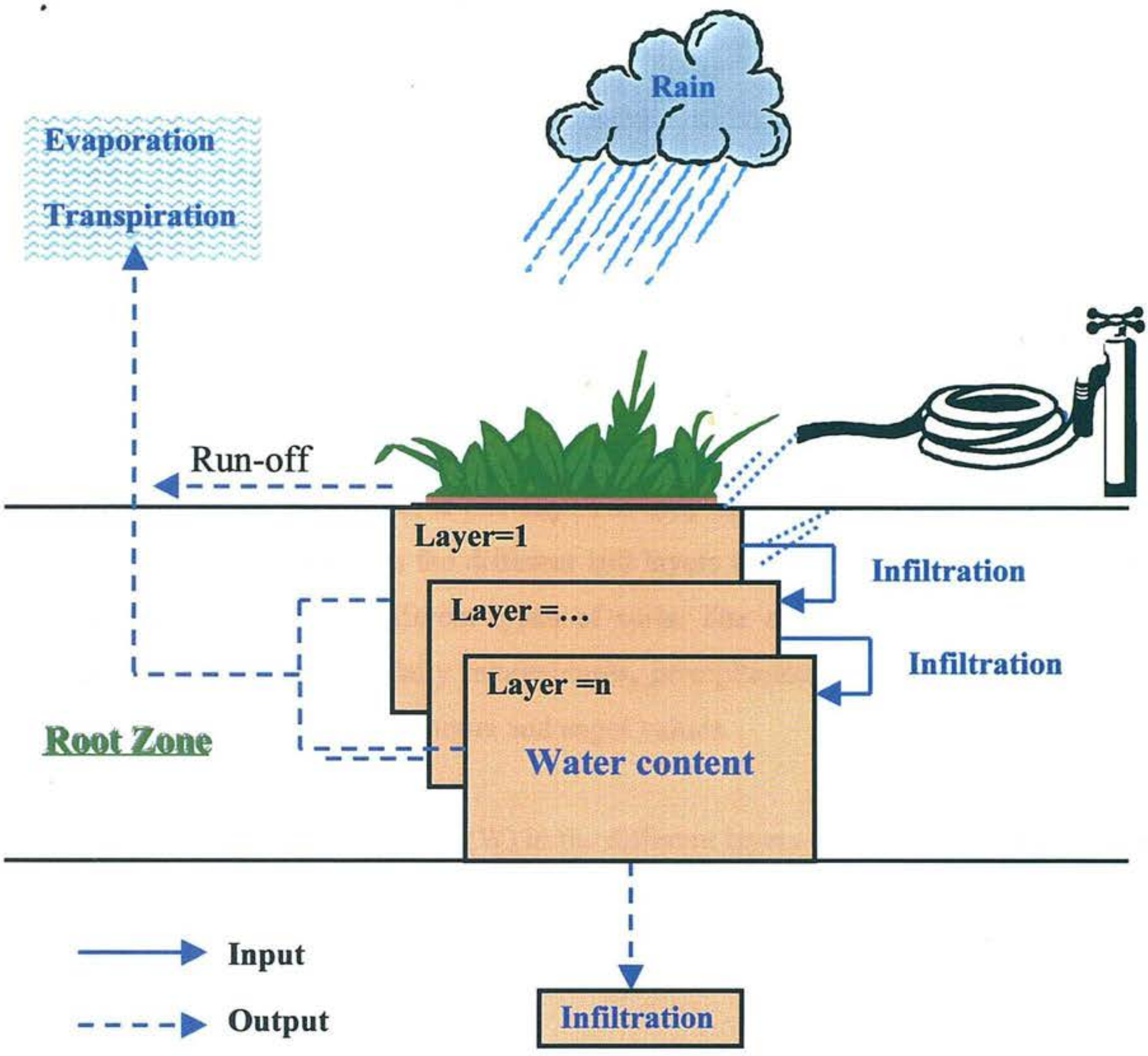


Figure 5.3. Diagram of water sub-model.

Interception of incoming rainfall by vegetation is not considered. The model assumes this effect on soil moisture is counteracted by the fact that, during rainfall, the evaporation of intercepted water from vegetation surface reduces the amount of soil water that is lost via soil evaporation and transpiration (Walker and Langridge, 1996).

Run-off depends on precipitation intensity and duration, vegetation cover, soil type and surface slope. There is not a simple way to include all these processes into the model. However, run-off is a important feature of most areas. It has been incorporated following the work of Williams et al. (1985), which considers a soil retention parameter.

Finally, the model assumes that there is no groundwater influence (water table). Consequently, capillary rise is not considered.

The origin of the equation used in the model is from the following papers: Renard et al. (1987), Supit el al. (1994), Verberne (1992) and Van Keulen & Seligman (1987).

The time-step for integration is one day. The only state variable of the model is the volumetric water content in the different soil layers considered. Water potential can be easily calculated in different types of soils. The driving variables are: mean, maximum and minimum daily temperatures, precipitation, relative humidity, wind speed, photoperiod, sunshine hours and angot values.

The actual soil moisture content (W) in the different layers considered (subscript z) is expressed by the following differential equation for layers z=2 to z=n.

$$\frac{dW_z}{dt} = Inf_{z-1} - Eva_z - Tra_z - Inf_z \qquad \textbf{5.36}$$

The actual soil moisture content in surface layer (z=1) is represented by:

$$\frac{dW_z}{dt} = Rain + Irr - Run - Eva_z - Tra_z - Inf_z \qquad \textbf{5.37}$$

Where Rain is precipitation ($cm^3H_2O\ cm^{-2}soil\ day^{-1}$); Irr is irrigation ($cm^3H_2O\ cm^{-2}soil\ day^{-1}$); Run is water runoff ($cm^3H_2O\ cm^{-2}soil\ day^{-1}$); Eva_z is actual soil evaporation in layer z ($cm^3H_2O\ cm^{-2}soil\ day^{-1}$); Tra_z is actual plant transpiration in layer z ($cm^3H_2O\ cm^{-2}soil\ day^{-1}$); Inf_z is water infiltration in layer z ($cm^3H_2O\ cm^{-2}soil\ day^{-1}$).

The actual soil moisture content can not be less than the water content at air dryness (Wair, $cm^3H_2O\ cm^{-2}soil$).

The relative water content in layer z (Wr_z) is obtained from the following equation:

$$Wr_z = \frac{W_z}{dn\ d_z} \qquad 5.38$$

Where dn is density of water ($cm^3\ H_2O\ cm^{-3}$) and d_z is thickness of layer z (cm).

5.2.2. Run-off

Run-off (Run) is computed from the U.S. Soil Conservation Service curve number (CN_I), following the approach by Renard et al. (1987). From this curve number daily surface runoff (Run) is estimated (Williams et al., 1985; Renard et al., 1987).

5.2.3. Downward movement: infiltration and percolation

Water infiltration (Inf_z), from rain and irrigation, occurs into the surface soil layer. Each soil layer is filled with water until field capacity (Wfc_z: maximum water storage capacity of a soil). Excess water drains to the next soil layer or below root zone.

$$\begin{array}{lcl} Inf_z = W_z - Wfc_z & \multirow{2}{*}{if} & W_z > Wfc_z \\ Inf_z = 0 & & W_z \le Wfc_z \end{array} \qquad 5.39$$

5.2.4. Calculation of potential evapotranspiration

The calculation of water losses due to evaporation and transpiration is based on the potential evapotranspiration. If this variable is available from climate databases, it can be incorporated directly in the model. If environmental variables as temperature, relative humidity of air and wind speed are available, potential evapotranspiration (ETO) can be calculated following the classical approach of Penman (1956). In the model, ETO has been calculated following the equations written by Supit et al. (1994).

Potential evapotranspiration ETO is the sum of maximum potential transpiration of the plant (TRAmp) and potential bare soil evaporation (EVAmp).

5.2.5. Evaporation

Potential soil evaporation (EVAp) can be calculated from the potential bare soil evaporation (EVAmp). It depends on the amount of energy that reaches soil through the canopy. Actual evaporation (Eva) is a fraction of potential soil evaporation that depends on the soil moisture.

$$EVA = Beva \quad EVAp \tag{5.40}$$

Beva is a reduction factor accounting for the influence of soil moisture content of the surface layer on evaporation. It is defined as a function of dimensionless soil moisture number (a_1) (van Keulen and Seligman, 1987; pg. 94-95):

$$\begin{array}{lcl} Beva = 0.25\,a1 & & 0 \le a1 < 0.2 \\ Beva = -1.31 + 6.8\,a1 & if & 0.2 \le a1 < 0.325 \\ Beva = 0.85 + 0.15\;a1 & & 0.85 \le a1 < 0.15 \\ Beva = 1 & & a1 \ge 1 \end{array} \tag{5.41}$$

The dimensionless soil moisture number (a_1) is represented by:

$$a_1 = \frac{W_1 - Wair}{Wfc - Wair} \tag{5.42}$$

W_1 is actual soil moisture content in surface layer ($cm^3 H_2O\ cm^{-2}$soil). The parameters Wair and Wfc are respectively the volumetric water content of the soil at air dryness and field capacity. The total actual soil evaporation is withdrawn from the different soil layers according to an exponential decay curve obtained from Verberne (1992).

5.2.6. Transpiration

Potential plant transpiration (TRAp) can be calculated from the potential transpiration for a closed canopy (TRAmp),. It depends on the amount of radiation intercepted by vegetation. The actual transpiration of vegetation in each layer (Tra_z) is obtained by the following equation:

$$TRA_z = RDef_z \ Btra_z \ TRAp \tag{5.43}$$

$Btra_z$ is a reduction factor to account for the effect of soil moisture on transpiration in layer z (van Keulen and Seligman, 1987). $RDef_z$ is a weighing factor accounting for withdrawal of moisture due to transpiration in layer z (Verberne, 1992).

5.2.7. Variables to link mineral sub-model and pasture model

To simulate the effect of water in plant processes and microorganisms of the soil the following equations are needed.

$$MsoilSup = \frac{\frac{Wr_1 + Wr_2}{2} - \boldsymbol{Wwp}}{\boldsymbol{Wfc - Wwp}} \tag{5.44}$$

$$MsoilTot = \frac{Wr - \boldsymbol{Wwp}}{\boldsymbol{Wfc - Wwp}} \tag{5.45}$$

$$RAT = \frac{Wr - \boldsymbol{Wair}}{\boldsymbol{Wfc - Wair}} \tag{5.46}$$

The water sub-model follows the model described by Verberne (1992). The main modifications made in the sub-model are the inclusion of runoff and the effect of soil moisture on soil evaporation.

5.3. Simulations

To evaluate the soil sub-model performance, soil data generated simultaneously with the simulations of the pasture sub-model (section 4.3, chapter 4) were used. Appendix 5.2 contains the parameters used in the sub-model.

In Chapter 2, it was emphasised that frost and drought are the main climatic challenges for the pastoral farm systems in the South of Rio Grande do Sul. Simulated data of the water content in the soil for five years is shown in Figure 4.4. The influence of water on plant production is well known. When observing the output from the water sub-model, it can be seen that from December to February the average amount of water in soil is less than half of the scale for some years. Therefore, the plant is subjected to water stress and consequently the production is reduced (Figures 4.8 and 4.9, Chapter 4). The results simulated by the model agree with the conclusions of Mota et al. (1970) that in this region of Rio Grande do Sul, drought usually occurs between December and February.

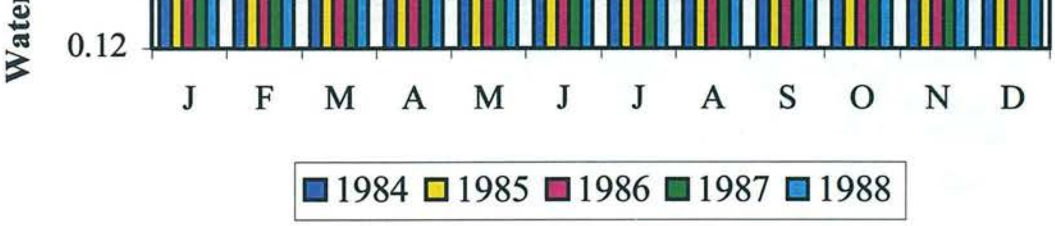
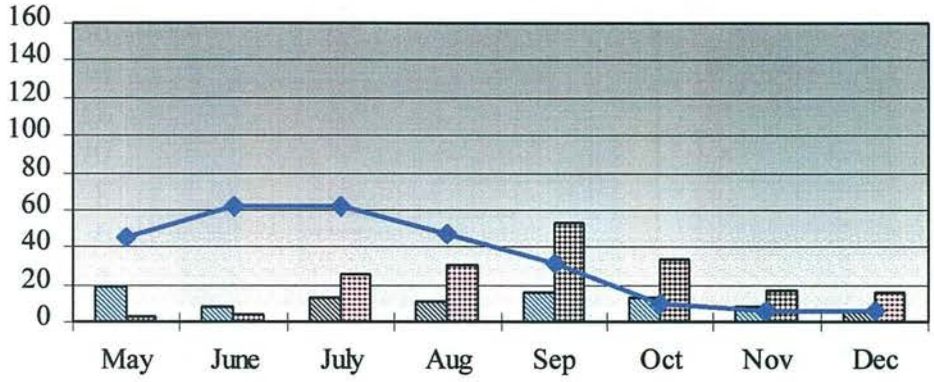


Figure 5.4. Five years simulated average water content in a soil with a wilting point of $0.12\ m^3\ m^2$ and field capacity of $0.32\ m^3\ m^2$.

The simulation of N available to the plant in the soil cultivated with Italian ryegrass for two levels of fertilisation (zero and 200 kg/ha of N) is shown in Figure 5.5. The monthly input and output of N is also demonstrated. In the soil without fertilisation, the monthly N balance was always negative after June with a maximum deficit in September. A different behaviour can be seen in Figure 5.5b as a result of the fertilisation in June, August and September. However, while the fertilisation in June and August maintains the input of N greater than the output, the fertilisation in September cannot avoid a negative balance as a result of high N demands from the Italian ryegrass pasture. The lack of fertilisation after September produced a huge deficit and consequently the amount of N available to the plant was drastically reduced.

(a) N content (kg/ha) in the soil without fertiliser.



(b) N content (kg/ha) in the soil fertilised with 200 kg N/ha.

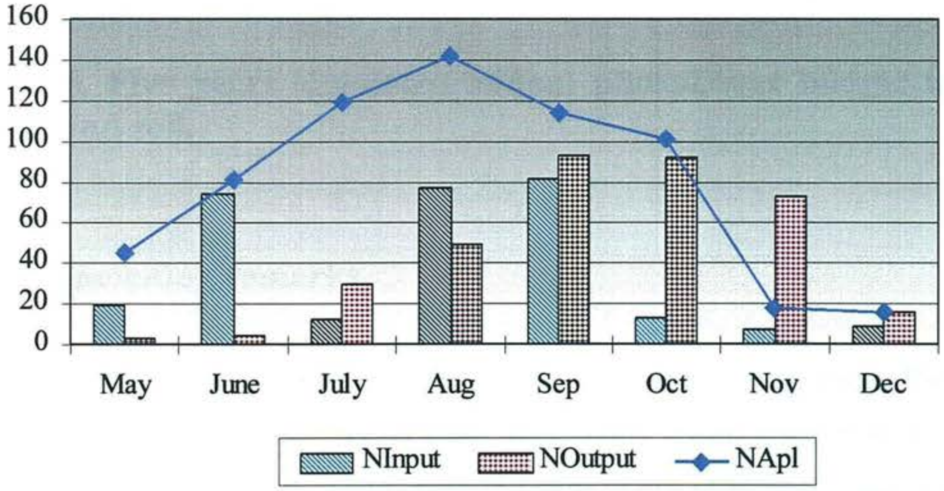


Figure 5.5. Simulated N available to plant in soil cultivated with Italian ryegrass.

Simulated annual P budgets in the grassland soil are shown in figure 5.6. The balance of P is quite stable in this system, if the whole group of years is considered.

However, large variation can be observed among years. This is a result of recycling of nutrients by the animals and the climate influence on soil and plant activity, because no fertiliser is used in this ecosystem. Chaneton et al. (1996), working in the same ecosystem, studied the N and P cycling in grazed and ungrazed situation and found that this native grassland showed a relatively stable equilibrium in N and P.

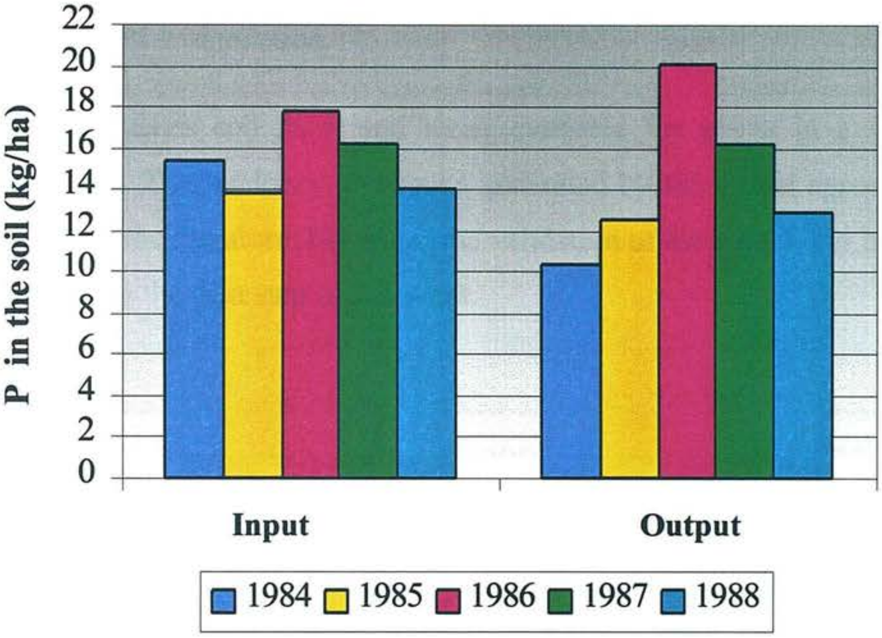


Figure 5.6. Five years simulated annual phosphorus budget in the grassland soil.

5.4. Concluding remarks

The soil sub-model like the plant sub-model follows a modular approach. The plant litter decomposition was incorporated from the Century model (Parton et al., 1987; Parton et al., 1994). This sub-model made the link as the plant decomposition sub-model to simulate the cycle of nutrients between soil and plant. The main new contribution is the animal excreta sub-model. This sub-model simulates the link among soil-plant-animal-soil in a pastoral farm system. The inclusion of this sub-model became important when animal stocking rate increases in an intensive system.

To build it, equations were derived from papers available in the literature using mainly laboratory data, which can be extrapolated to the conditions in the south west of Rio Grande do Sul.

The approach used by Verberne (1992) was chosen for development of the water sub-model. Simulations of five layers showed a satisfactory performance when compared with ten layers of soil. Verberne (1992) demonstrated that the performance dropped quickly with less than five layers and this is the minimum number of layers required for effective simulation.

This model simulates soil N, P and water available for plants in a simple but mechanistic way. The tendency of outputs generated by the model agrees with the data available in the literature. However, the validation of the model will be obtained in the field during the next step of this work.

CHAPTER 6

GRASSLAND MODEL: ANIMAL SUB-MODEL

The animal sub-model is the remaining model to be described in simulating the biological pastoral system. The animal sub-model simulates the intake and digestion of an individual animal and extrapolates the results obtained from an individual to that of a herd. Animals are the main biological output in a pastoral system and consequently represent the main link between biological and economic models in the pastoral farming system.

6.1. Description of the model

To simulate animals in the paddock, the approach demonstrated in Figure 6.1 is followed. The herd is simulated as an extrapolation of individual animals. Firstly, to simulate genetic potential, breeds are considered. Cattle breeds are classified into maturity groups following AFRC (1993) into early, medium and late maturity breeds (table 2.2, p. 28). Secondly, the model assumes that each genetic group has a normal distribution. Following the empirical rule of normal distribution 68% of animals are between the average and 1 standard deviation, 27% between 2 and 3 standard deviations and the remainder greater than 3 standard deviations (Anderson et al., 1994). Therefore, five points on the normal distribution curve were chosen as an individual simulation point (Figure 6.1). This approach is followed due to software restrictions and to reduce machine processor time. To distribute animals into three simulation points the minimum number of animals in the genetic group needed is eight. This is adopted in the model as the minimum number of animals in each genetic group possible to be simulated. However, the five simulation points are simulated when the genetic group has at least 34 animals (see equation 6.3).

Intake, digestion and production for each individual are simulated (simulation point). The herd is considered in the production and intake sub-model to determine the

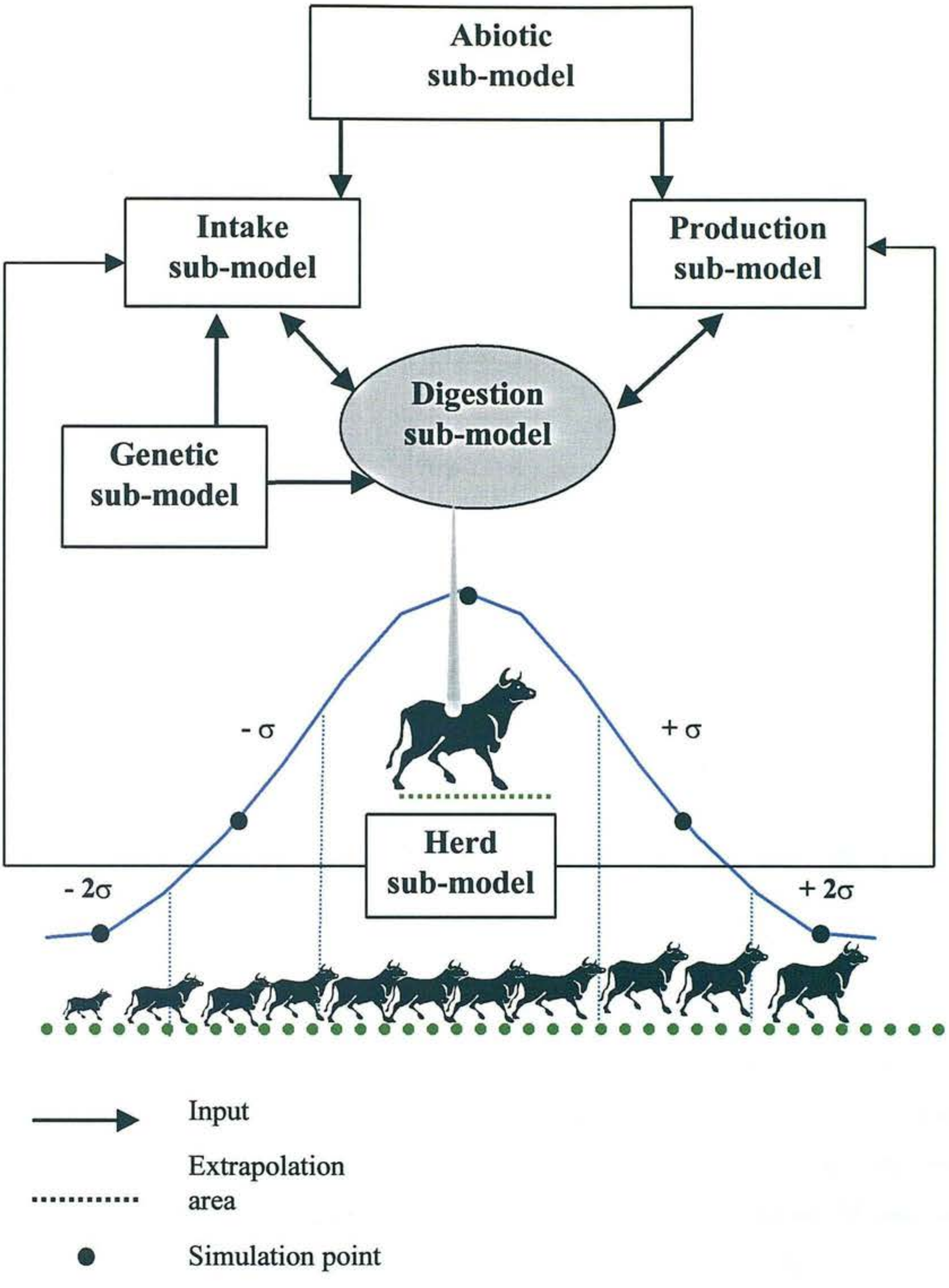


Figure 6.1. Diagram of the animal sub-model.

amount of dry matter removed from the pasture sub-model and the animal production for each paddock. In a similar manner to the pasture and soil sub-models some equations used in the model were obtained from the following publications:

ARC (1980), CSIRO (1990), Illius & Gordon (1991), AFRC (1993) and NRC (1996).

6.1.1. Herd sub-model

To simulate the herd in each paddock (subscript $_p$) the genetic composition of herd is considered. The herd could be composed by animals from early ($NAnE_p$), medium ($NAnM_p$) and late ($NAnL_p$) maturing breeds (AFRC, 1993).

$$NAn_p = NAnE_p + NAnM_p + NAnL_p \tag{6.1}$$

The average of animals in the paddock ($AvAn_p$) is obtained by

$$AvAn_p = \frac{NAnE_p}{NAn_p} AvAnE_p + \frac{NAnM_p}{NAn_p} AvAnM_p + \frac{NAnL_p}{NAn_p} AvAnL_p \tag{6.2}$$

Therefore, the average is as result of a live weight average (kg) from the different genetic groups.

The model considers five points on the normal distribution curve as points of simulation (SP) for each genetic group (Figure 6.1). To extrapolate results from this point to the part of population that it represents, the number of animals in each extrapolation area is need. We describe the simulation for animals from the early genetic group (E), but the same equations are used to simulate medium (M) and late (L) animals genetic group by changing the letter E for M or L, respectively.

The arrangement of animals in the extrapolation areas follows the empirical rule of normal distribution. Adjustment was made since the values in each extrapolation area have to be integers.

$$AESP1_p = truncate\,(NAnE_p\ 0.03)$$

$$AESP2_p = truncate\,(NAnE_p\ 0.13)$$

$$AESP3_p = truncate\,(NAnE_p\ 0.68) \qquad \textbf{6.3}$$

$$AESP4_p = truncate\,(NAnE_p\ 0.13)$$

$$AESP5_p = truncate\,(NAnE_p\ 0.03)$$

In this way, animals are distributed from the middle to both sides of a normal curve. At the end of this distribution, the difference between the number of animals in the early maturing group ($NAnE_p$) and the sum of animals in $AESP1_p$ to $AESP5_p$ is added to $AESP3_p$.

The simulation point, which represents the mean in the simulation area (Figure 6.1), is calculated for each extrapolation area by

$$ESP1_p = AvAnE_p - (2.5\ SDAnE_p)$$

$$ESP2_p = AvAnE_p - (1.5\ SDAnE_p)$$

$$ESP3_p = AvAnE_p \qquad \textbf{6.4}$$

$$ESP4_p = AvAnE_p + (1.5\ SDAnE_p)$$

$$ESP5_p = AvAnE_p + (2.5\ SDAnE_p)$$

The simulation point is only calculated when there are animals in the extrapolation area. These calculations consider the average ($AvAnE_p$) and the standard deviation ($SdAnE_p$) to set the value of the simulation point.

6.1.1.1. Animals in the paddock sub-model

When animals are put into the paddocks according to decisions taken in the farm decision-maker model (Chapter 8), a new number of animals, average and standard deviation must be calculated.

The number of animals in the early maturity groups in the paddock ($AnInE_p$), the average ($AvInE_p$) and the standard deviation ($SDInE_p$) are supplied by the decision-maker model.

$$NAnE_p = NAnE_p + AnInE_p \tag{6.5}$$

To consider the possible difference in the standard deviation between the old and new population, the same procedure followed in equations 6.3 and 6.4 is used. The difference is the addition of the letter T at the begin of the variable for the temporary new population (e.g. $AESP1_p$ = $TAESP1_p$). After that, the calculation of a new average is made.

$$AvAnE_p = \sum_1^n \frac{TAESP_{np}}{NAnE_p} TESP_{np} + \sum_1^n \frac{AESP_{np}}{NAnE_p} ESP_{np} \tag{6.6}$$

To calculate the new standard deviation of the population, the difference between the individuals in the population and the new average must be considered. First, the value of the extrapolation area has to be positive (e.g. $AESP1_p > 0$) to allow the program to continue to calculate the individual contribution in this area. In the positive case, each animal contribution (EAC1) is calculated considering the number of animals in the extrapolation area.

$$EAC1 = \frac{SDAnE_p}{AESP1_p - 1} \tag{6.7}$$

The first calculation of the difference between the lower live weight and the new average is made and stored in a counter (VE).

$$VE = \left(\left(AvAnE_p - 3\,SDAnE_p\right) - AvAnE_p\right)^2 \qquad \textbf{6.8}$$

The following live weight is calculate by

$$CEW1 = \left(AvAnE_p - 3\,SDAnE_p\right) + EAC1 \qquad \textbf{6.9}$$

And after that by

$$CEW1 = CEW1 + EAC1 \qquad \textbf{6.10}$$

These will be executed many times until the number of animals in the extrapolation area is met. At each live weight calculation, the difference with the average is also counted.

$$VE = VE + \left(CEW1 - AvAnE_p\right)^2 \qquad \textbf{6.11}$$

The same procedure is followed for the next extrapolation areas, so the equation 6.7 now is represented by

$$\begin{aligned} EAC2 &= \frac{SDAnE_p}{AESP2_p - 1} \\ EAC3 &= \frac{SDAnE_p}{AESP3_p - 1} \\ EAC4 &= \frac{SDAnE_p}{AESP4_p - 1} \\ EAC5 &= \frac{SDAnE_p}{AESP5_p - 1} \end{aligned} \qquad \textbf{6.12}$$

And the equation 6.9 by

$$
\begin{aligned}
CEW2 &= \left(AvAnE_p - 2\,SDAnE_p\right) + EAC2 \\
CEW3 &= \left(AvAnE_p - SDAnE_p\right) + EAC3 \\
CEW4 &= \left(AvAnE_p + SDAnE_p\right) + EAC4 \\
CEW5 &= \left(AvAnE_p + 2\,SDAnE_p\right) + EAC5
\end{aligned}
\tag{6.13}
$$

Also, as in equation 6.11, at each live weight calculation the difference with the average is counted.

$$
\begin{aligned}
VE &= VE + \left(CEW2 - AvAnE_p\right)^2 \\
VE &= VE + \left(CEW3 - AvAnE_p\right)^2 \\
VE &= VE + \left(CEW4 - AvAnE_p\right)^2 \\
VE &= VE + \left(CEW5 - AvAnE_p\right)^2
\end{aligned}
\tag{6.14}
$$

To consider the temporary new population, the same procedure followed in equations 6.7 to 6.13 is used with substitution of the variables $AvAnE_p$ by $AvInE_p$, $SDAnE_p$ by $SDInE_p$ and $AESP1_p$ to $AESP5_p$ by $TAESP1_p$ to $TAESP5_p$. After all extrapolation areas are calculated, the new group standard deviation is obtained by

$$
SDAnE_p = \sqrt{\frac{VE}{(NAnE_p - 1)}} \tag{6.15}
$$

6.1.1.2. Animals removed from the paddock sub-model

The way that animals are removed from a paddock depends on the decision made by the farmer (Chapter 8). Therefore, animals can be removed in relation to their live weight or in a random manner from the paddock and these options produce different simulations in the model.

6.1.1.2.1. Animals remove by live weight.

When the farmer decision is to remove animals by live weight two ways can be chosen: lowest or highest live weight. Following the lowest choice the animals are removed from the left to the right side of the normal curve and this simulation will be described below. The withdrawal by highest live weight follows the same procedure with removal from the opposite side of the normal curve, from right to left.

The removal procedure assumes that the paddock contains animals from different genetic groups. Consequently, the model assumes animals are removed from the early to the late maturity group in each simulation area. Also, the model contemplates a sub-division in the medium extrapolation area ($AESP3_p$, $AMSP3_p$ and $ALSP3_p$) as a way to reduce the effect of the amount of animals present in this area (68 percent of animals in the paddock). Animals present in the left side of the medium extrapolation area ($LeftAE_p$, $LeftAM_p$ and $LeftAL_p$) are simulated by:

$$
\begin{aligned}
&\mathit{LeftAE}_p = \mathit{truncate}(\mathit{AESP3}_p \;\; 0.5) \\
&\mathit{LeftAM}_p = \mathit{truncate}(\mathit{AMSP3}_p \;\; 0.5) \qquad \mathbf{6.16} \\
&\mathit{LeftAL}_p = \mathit{truncate}(\mathit{ALSP3}_p \;\; 0.5)
\end{aligned}
$$

These sub-divisions will be considered later when animals from a medium simulation area will be removed. The first animals to be removed are those from the left of simulation area for the early maturing genetic group ($AESP1_p$). Therefore, the number of animals to be removed from the paddock ($AnOut_p$), which is an input from the decision-maker model, is reduced by the amount of animals in the early genetic group ($AESP1_p$).

$$AnOut_p = AnOut_p - AESP1_p \tag{6.17}$$

Also, the animals out from each genetic group must be calculated. The animals out from the early genetic group ($AnOutE_p$) are simulated by

$$AnOutE_p = AnOutE_p + AESP1_p \tag{6.18}$$

To obtain the average weight of animals out of paddock in each genetic group, the amount of kilograms removed ($SAvOutE_p$) is computed through the multiplication of the number of animals ($AESP1_p$) by the average ($ESP1_p$) of the extrapolation area.

$$SAvOutE_p = AESP1_p \;\; ESP1_p \tag{6.19}$$

After that, the temporary variable $TAESP1_p$ is created and assumes the value of $AESP1_p$ and $AESP1_p$ is set to zero. The $TAESP1_p$ will be used later to calculate the new standard deviation in the paddock and also for the group of animal's discharge from the paddock.

If the amount of animals to be removed is less than the amount of animals in the simulation area ($AnOut_p < AESP1_p$), the following procedure is following. The equation 6.18 is modified to

$$AnOutE_p = AnOutE_p + AnOut_p \tag{6.20}$$

And equation 6.19 is changed to

$$SAvOutE_p = AvOutE_p + \left(\left(AvAnE_p \text{ - } SDAnE_p \right) + \left(EAC1 \frac{AnOut_p}{2} AnOut_p \right) \right) \tag{6.21}$$

Where EAC1 is calculated following equation 6.7. After that, the variable $AnOut_p$ is set to zero.

If the numbers of animals in the extrapolation area $AESP1_p$ is less than the amount of animals to be removed, the program starts the same procedure for animals in the medium genetic group (M). Therefore, the equation 6.17 becomes

$$AnOut_p = AnOut_p - AMSP1_p \tag{6.22}$$

The same procedure is carried out following equations 6.18 to 6.20 and if animals out ($AnOut_p$) are still positive, the next simulation area ($ALSP1_p$) is used. These procedures are followed in the others extrapolation areas until the $AnOut_p$ equal zero. If the medium extrapolation area ($AESP3_p$, $AMSP3_p$ and $ALSP3_p$) is considered the program follows the equation 6.15 to split the area.

To calculate the average weight of animals out of paddock for each genetic group the follow equations are calculated

$$AvOutE_p = \frac{SAvOutE_p}{AnOutE_p}$$

$$AvOutM_p = \frac{SAvOutM_p}{AnOutM_p} \tag{6.23}$$

$$AvOutL_p = \frac{SAvOutL_p}{AnOutL_p}$$

The number of animals that still remain in the paddock for each group is simulated by

$$NAnE_p = NAnE_p - AnOutE_p$$

$$NAnM_p = NAnM_p - AnOutM_p \qquad \textbf{6.24}$$

$$NAnL_p = NAnL_p - AnOutL_p$$

and the average weight of animals for each maturity group that stay in the paddock is calculated by

$$AvAnE_p = \frac{AvAnE_p - \left(\left(\frac{AnOutE_p}{NAnE_p + AnOutE_p}\right) AvOutE_p\right)}{\left(\frac{NAnE_p}{NAnE_p + AnOutE_p}\right)}$$

$$AvAnM_p = \frac{AvAnM_p - \left(\left(\frac{AnOutM_p}{NAnM_p + AnOutM_p}\right) AvOutM_p\right)}{\left(\frac{NAnM_p}{NAnM_p + AnOutM_p}\right)} \qquad \textbf{6.25}$$

$$AvAnL_p = \frac{AvAnL_p - \left(\left(\frac{AnOutL_p}{NAnL_p + AnOutL_p}\right) AvOutL_p\right)}{\left(\frac{NAnL_p}{NAnL_p + AnOutL_p}\right)}$$

Before, the calculation of the new average the old average is stored in the temporary variable TAvAnE to be used to calculate the new standard deviation below.

To calculate the standard deviation for the group of animals that stay in the paddock the individual live weight must be calculated as in equation 6.7. Also, the values of extrapolation area have to be positive (e.g. $AESP1_p > 0$) to allow the program to continue to calculate the individual contribution in this area. After that, each animal contribution (EAC1) is calculated considering the number of animals in the extrapolation area before removing the animals from the paddock.

$$EAC1 = \frac{SDAnE_p}{TAESP1_p - 1} \tag{6.26}$$

The difference between the animal with the lowest live weight that remains in the paddock and the new mean weight of the group is calculated and stored in a counter (VStay).

$$VStay = \left(\left(\left(TAvAnE_p - 2\,SDAnE_p\right) - \left(EAC1\,AESP1_p\right)\right) - AvAnE_p\right)^2 \tag{6.27}$$

The new number of animals in the extrapolation area is considered to calculate the minimum live weight of animals that stay in the paddock.

If no animals were taken out of the paddock, the minimum animal live weight will be $TAvAnE_p - 3\ SDAnE_p$. If animals were removed from the genetic group the live weight of the first animal in the new group that remain in the paddock is calculated by

$$CEW1 = \left(\left(\left(TAvAnE_p - 2\,SDAnE_p\right) - \left(EAC1\,AESP1_p\right)\right) - AvAnE_p\right) + EAC1 \tag{6.28}$$

and the weight of the rest of the animals in the extrapolation area are calculated by

$$CEW1 = CEW1 + EAC1 \tag{6.29}$$

These will be executed many times until the number of animals in the extrapolation area is met. At each live weight calculation, the difference with the average is also counted.

$$VStay = VStay + \left(CEW1 - AvAnE_p\right)^{2} \tag{6.30}$$

The same procedure is followed for the next extrapolation areas, so the equation 6.26 now is represented by

$$\begin{aligned} EAC2 &= \frac{SDAnE_p}{TAESP2_p - 1} \\ EAC3 &= \frac{SDAnE_p}{TAESP3_p - 1} \\ EAC4 &= \frac{SDAnE_p}{TAESP4_p - 1} \\ EAC5 &= \frac{SDAnE_p}{TAESP5_p - 1} \end{aligned} \tag{6.31}$$

And the equation 6.28 by

$$\begin{aligned} CEW2 &= \left(\left(\left(TAvAnE_p - SDAnE_p\right) - \left(EAC2\ AESP2_p\right)\right) - AvAnE_p\right) + EAC2 \\ CEW3 &= \left(\left(\left(TAvAnE_p + SDAnE_p\right) - \left(EAC3\ AESP3_p\right)\right) - AvAnE_p\right) + EAC3 \\ CEW4 &= \left(\left(\left(TAvAnE_p + 2\ SDAnE_p\right) - \left(EAC4\ AESP4_p\right)\right) - AvAnE_p\right) + EAC4 \\ CEW5 &= \left(\left(\left(TAvAnE_p + 3\ SDAnE_p\right) - \left(EAC5\ AESP5_p\right)\right) - AvAnE_p\right) + EAC5 \end{aligned} \tag{6.32}$$

In addition, as in equation 6.30, at each live weight calculation the difference with the average is stored.

$$\begin{aligned} VStay &= VStay + \left(CEW2 - AvAnE_p\right)^2 \\ VStay &= VStay + \left(CEW3 - AvAnE_p\right)^2 \\ VStay &= VStay + \left(CEW4 - AvAnE_p\right)^2 \\ VStay &= VStay + \left(CEW5 - AvAnE_p\right)^2 \end{aligned} \tag{6.33}$$

After all extrapolation areas are calculated, the standard deviation for animals that stay in the paddock is obtained by

$$SDAnE_p = \sqrt{\frac{VStay}{(NAnE_p - 1)}} \tag{6.34}$$

Before the calculation of the new standard deviation, the old standard deviation is stored in the temporary variable TSDAnE. This variable will be used to calculate the standard deviation of animals out of paddock that remains to be calculated. First the program considers the number of animals in the extrapolation area ($AESP1_p$) is different from the numbers of animals in the temporary extrapolation area ($TAESP1_p$). In the positive case, indicates that animals were removed from the extrapolation area, and the individual contribution is calculated by

$$EAC1 = \frac{TSDAnE_p}{TAESP1_p - 1} \tag{6.35}$$

The value for the gap from the average for the first animal is obtained by

$$VOut = \left(\left(TAvAnE_p - 3\,TSDAnE_p\right) - AvOutE_p\right)^2 \tag{6.36}$$

Equation 6.28 became

$$CEW1 = \left(\left(TAvAnE_p \text{ - } 3\,TSDAnE_p\right) - AvOutE_p\right) + EAC1 \tag{6.37}$$

And equation 6.29 stays the same. These will be executed many times until the value of the difference between the $TAESP1_p$ - $AESP1_p$ is met. Like in equation 6.30 the difference with the average is stored by

$$VOut = VOut + \left(CEW1 - AvOutE_p\right)^{2} \tag{6.38}$$

The same procedure is followed for the next extrapolation areas as before in the calculation of standard deviation for animals that stay in the paddock.

$$\begin{aligned}
EAC2 &= \frac{TSDAnE_p}{TAESP2_p \text{ - } 1}\\
EAC3 &= \frac{TSDAnE_p}{TAESP3_p \text{ - } 1}\\
EAC4 &= \frac{TSDAnE_p}{TAESP4_p \text{ - } 1}\\
EAC5 &= \frac{TSDAnE_p}{TAESP5_p \text{ - } 1}
\end{aligned} \tag{6.39}$$

And the counter for live weight becomes

$$\begin{aligned}
CEW2 &= \left(\left(TAvAnE_p \text{ - } 2\,TSDAnE_p\right) - AvOutE_p\right) + EAC2\\
CEW3 &= \left(\left(TAvAnE_p \text{ - } TSDAnE_p\right) - AvOutE_p\right) + EAC3\\
CEW4 &= \left(\left(TAvAnE_p + TSDAnE_p\right) - AvOutE_p\right) + EAC4\\
CEW5 &= \left(\left(TAvAnE_p + 2\,TSDAnE_p\right) - AvOutE_p\right) + EAC5
\end{aligned} \tag{6.40}$$

The difference with the average is stored.

$$VOut = VOut + \left(CEW2 - AvOutE_p\right)^2$$

$$VOut = VOut + \left(CEW3 - AvOutE_p\right)^2$$

$$VOut = VOut + \left(CEW4 - AvOutE_p\right)^2 \quad \textbf{6.41}$$

$$VOut = VOut + \left(CEW5 - AvOutE_p\right)^2$$

Therefore, the standard deviation for animals that were removed from the paddock is calculated by

$$SDOutE_p = \sqrt{\frac{VOut}{(AnOutE_p - 1)}} \quad \textbf{6.42}$$

The discharge by highest live weight follows the same equations describe above except that the animals are taken out from right to left. Therefore, the animals are taken out from $AESP5_p$ to $AESP1_p$.

6.1.1.2.2. Randomised removal.

When the farmer does not consider live weight to remove animals from the paddock, animals are removed at random. The model considers the probability of animals from each genetic group to be removed is proportional to the number of animals in each group in the paddock. Therefore,

$$AnOutE_p = truncate\left(\frac{NAnE_p}{NAn_p} AnOutRand_p\right)$$

$$AnOutM_p = truncate\left(\frac{NAnM_p}{NAn_p} AnOutRand_p\right) \quad \mathbf{6.43}$$

$$AnOutL_p = truncate\left(\frac{NAnL_p}{NAn_p} AnOutRand_p\right)$$

The variable $AnOutRand_p$ is an input from the farmer decision-maker model. If the difference between the $AnOutRand_p$ and the sum of $AnOutE_p$+ $AnOutM_p$ + $AnOutL_p$ is positive, that number is removed from the genetic group with largest numbers of animals.

The number of animals of the early maturing group that stay in the paddock is calculated by

$$NAnE_p = NAnE_p - AnOutE_p \quad \mathbf{6.44}$$

As animals are removed at random, the model assumes that the average live weight of animals that stay in the paddock is the same average as before the animals were removed. Also, the average live weight of the animals that were removed from the paddock is the same. Therefore, the model considers the new AvAnEp equal the $AvOutE_p$ and equals the old AvAnEp

However, the standard deviation must be calculated. To calculate the standard deviation for animals that were removed from the paddock, first the distribution in the extrapolation areas is made.

$$ASP1_p = truncate\,(AnOutE_p\ 0.03)$$

$$ASP2_p = truncate\,(AnOutE_p\ 0.13)$$

$$ASP3_p = truncate\,(AnOutE_p\ 0.68) \tag{6.45}$$

$$ASP4_p = truncate\,(AnOutE_p\ 0.13)$$

$$ASP5_p = truncate\,(AnOutE_p\ 0.03)$$

After that, the same methodology described in the section above 6.1.1.2.1 is followed. First the program consider if the number of animals in the extrapolation area (AESP1$_p$) is different from the number of animals that were removed from the paddock (ASP1$_p$). In the positive case the animals were removed from the extrapolation area, and the individual contribution is calculated by

$$EAC1 = \frac{SDAnE_p}{ASP1_p\ \text{-}\ 1} \tag{6.46}$$

The value for the gap between the live weight of the first animal and the group average is obtained by

$$VOut = \left(\left(AvAnE_p\ \text{-}\ 3\ SDAnE_p\right) - AvOutE_p\right)^{\ 2} \tag{6.47}$$

The following live weight is calculate by

$$CEW1 = \left(\left(AvAnE_p\ \text{-}\ 3\ \ SDAnE_p\right) - AvOutE_p\right) + EAC1 \tag{6.48}$$

and after that by

$$CEW1 = CEW1 + EAC1 \tag{6.49}$$

These operations will be executed many times until the value of $ASP1_p$ is met. Again, the difference with the average liveweight is stored by

$$VOut = VOut + \left(CEW1 - AvOutE_p\right)^2 \tag{6.50}$$

The same procedure is followed for the next extrapolation areas as before in section 6.1.1.2.1. Finally, the standard deviation for animals out of paddock is calculated.

$$SDOutE_p = \sqrt{\frac{VOut}{(AnOutE_p - 1)}} \tag{6.51}$$

To calculate the standard deviation for animals that stay in the paddock the same procedure is followed. Equation 6.45 is modified by charging $ASP1_p$ for $AESP1_p$ - $ASP1_p$ to represent the number of animals that stay in the paddock. Also, the individual live weight is subtracted from the paddock average. The new standard deviation for animals in the paddock is

$$SDAnE_p = \sqrt{\frac{Vstay}{(NAnE_p - 1)}} \tag{6.52}$$

6.1.1.3. Destinations of animals removed from the paddock sub-model

The destination of animals removed from a paddock is decided in the decision-maker model. Farmers can remove animals to sell them. In this case, the economic model (Chapter 7) is activated to credit the balance account and the animal's discharge reduces the stocking rate at paddock and farm level. However, if the farmer decides to move animals to another paddock, the decision-maker model asks about which paddock the animals will be allocated. At the animal model, the same procedure described in the section 6.1.1.1 for animals into the paddock is followed. In this case, the values for the number of animals into the paddock (AnInE_p), the average (AvInE_p) and the standard deviation (SDInE_p) are supplied by the animals remove sub-model (section 6.1.1.2). Therefore, the values are transferred from:

$$\begin{array}{ccc}
\text{Origin} & & \text{Destination} \\
\mathrm{AnOutE}_p & \longrightarrow & \mathrm{AnInE}_p \\
\mathrm{AvOutE}_p & \longrightarrow & \mathrm{AvInE}_p \\
\mathrm{SDOutE}_p & \longrightarrow & \mathrm{SDInE}_p
\end{array}$$

Following the same procedure described in the section 6.1.1.1 the new number of animals, average live weight and standard deviation in the paddock is obtained. Therefore, this farmer decision has an impact only on the individual paddock-stocking rate, because in this case animals remain on the farm.

The herd sub-model was developed as a consequence of the goal of the thesis to simulate a dynamic pastoral farming systems. The model simulates the general structure of the herd present in these systems. Different live weights and breeds are also considered. In addition, the model contemplates the impact of the farm management decision on these variables.

6.1.2. Individual animal sub-model

To simulate the individual animal performance two sub-models are considered. The first sub-model simulates the intake and digestion of food. It uses an hour time-step and produces daily outputs of the amount of metabolic energy ($\mathrm{MESupply}_{ga}$) and protein ($\mathrm{MPSupply}_{ga}$) supplied for production. The second sub-model considers these outputs to predict the live weight change of the animal. The subscript $_a$ represents the animal simulation point (1 to 5) and the subscript $_g$ represents the genetic group (early, medium and late) in each paddock.

The first sub-model following the model described by Herrero (1997), was based on the models of Illius & Gordon, (1991) and Sniffen et al. (1992). Modifications were made in the intake model to put in effects of environment and availability of pasture. The second sub-model, that was made to simulate the growing and fattening processes in beef cattle, was developed considering models and data from ARC (1980), AFRC (1993), CSIRO (1990) and NRC (1996). The intake and predicted gain sub-model are described below.

6.1.2.1. Intake sub-model

The daily intake by the animal is simulated as sums of individual meals eaten by the animal. To simulate the meal the maximum rumen capacity is considered. The model works on hour time-step and the meal happens when the rumen dry matter content is less than 70% of capacity following Illius and Gordon (1991). The manner in which rumen dry matter content is obtained and the variables associated with the digestion processes can be found in Illius and Gordon (1991) and Herrero (1997).

These models consider only physical dietary constraints to intake. This is acceptable in our case, because the main goal is to simulate animal performance in a pastoral farming system. In this system, as explained in Chapter 2, the diet is basically composed of forages of low digestibility (natural pasture) and the use of concentrate as a proportion of the diet is low. Consequently, the digestibility of dry matter is expected to be below the constrained metabolic point (Van Soest, 1994). However, in situations where this constraint may operate the metabolic constraint can be incorporated, e.g., Illius & Jessop, (1996). However, the environmental and food allowance effects need to be considered in the animal intake in pastoral system.

To simulate the environmental effects, the NRC (1981) review of the environmental effects on domestic animals was considered. The temperature effect is considered when mean daily temperature is out of the range between 15 to 25°C. Temperature above 25°C reduces the animals' intake. CSIRO (1990) considers 1% of reduction for each degree above 25°C. The same assumption is assumed in the model. Temperatures below 15°C in dry conditions stimulate animal intake. NRC (1981) estimates variation of 2 to 5% between 5 to 15°C and increases of up to 10% at -15°C. Considering this fact, the model considers intake increases of 1% for each 3°C below 15°C. However, low temperatures associates with rain cause depression of 10 to 30% in intake (NRC, 1981). The double effect of low temperature and rain are also considered in the model and the intake is reduced in 1% for each degree below 15°C on rainy days.

The forage allowance (FA_p) is another important constraint on intake in a grazing system and the approach adopted by NRC (1996) is followed.

6.1.2.2. Live weight changes sub-model

To simulate animal conditions in the field, the model has to consider different levels of energy and protein that the animals may experience during the growing and fattening processes. Therefore, six situations are considered in the model.

a) Supply of energy and protein below maintenance.
b) Supply of protein below maintenance.
c) Supply of energy below maintenance.
d) Supply of energy and protein in equilibrium above maintenance.
e) Supply of energy and protein above maintenance, with protein limiting the maximum gain.
f) Supply of energy and protein above maintenance, with energy limiting the maximum gain.

The flow of decisions is represented in figures 6.2 and 6.3. The inputs of metabolic energy and protein produce the live weight change (LWC) and fat content (FAT) as outputs.

To consider, which food level the animal is submitted, the static sub-model calculated the amount of metabolic energy and protein necessary for animal maintenance. The amount of metabolic protein (MPm_{ga}), g/day, and the energy (EM_{ga}), MJ/day, required for maintenance is calculated, considering the animal live weight (W_{ga}) following AFRC (1993).

These equations consider animals maintained in a housed environment. To simulate additional energy expenditure by animals in grazing conditions ($Egraze_{ga}$), MJ/day, the CSIRO (1990) approach is considered. Therefore, the total of energy necessary for maintenance (TEM_{ga}), MJ/day, is obtained by

$$TEM_{ga} = EM_{ga} + Egraze_{ga} \qquad \textbf{6.53}$$

After the calculations of requirements of energy and protein for maintenance are made, the model begins to test which level of performance is supplied by the diet.

6.1.2.2.1. Supply of energy and protein below maintenance

This situation occurs when energy and protein supply by the diet is less than the minimum required for animal maintenance. Therefore, the requirements for maintenance are met from tissue catabolism. In this case, the model calculates first the amount of protein and energy supplied by each gram of tissue utilised considering the body weight composition (fat:protein).

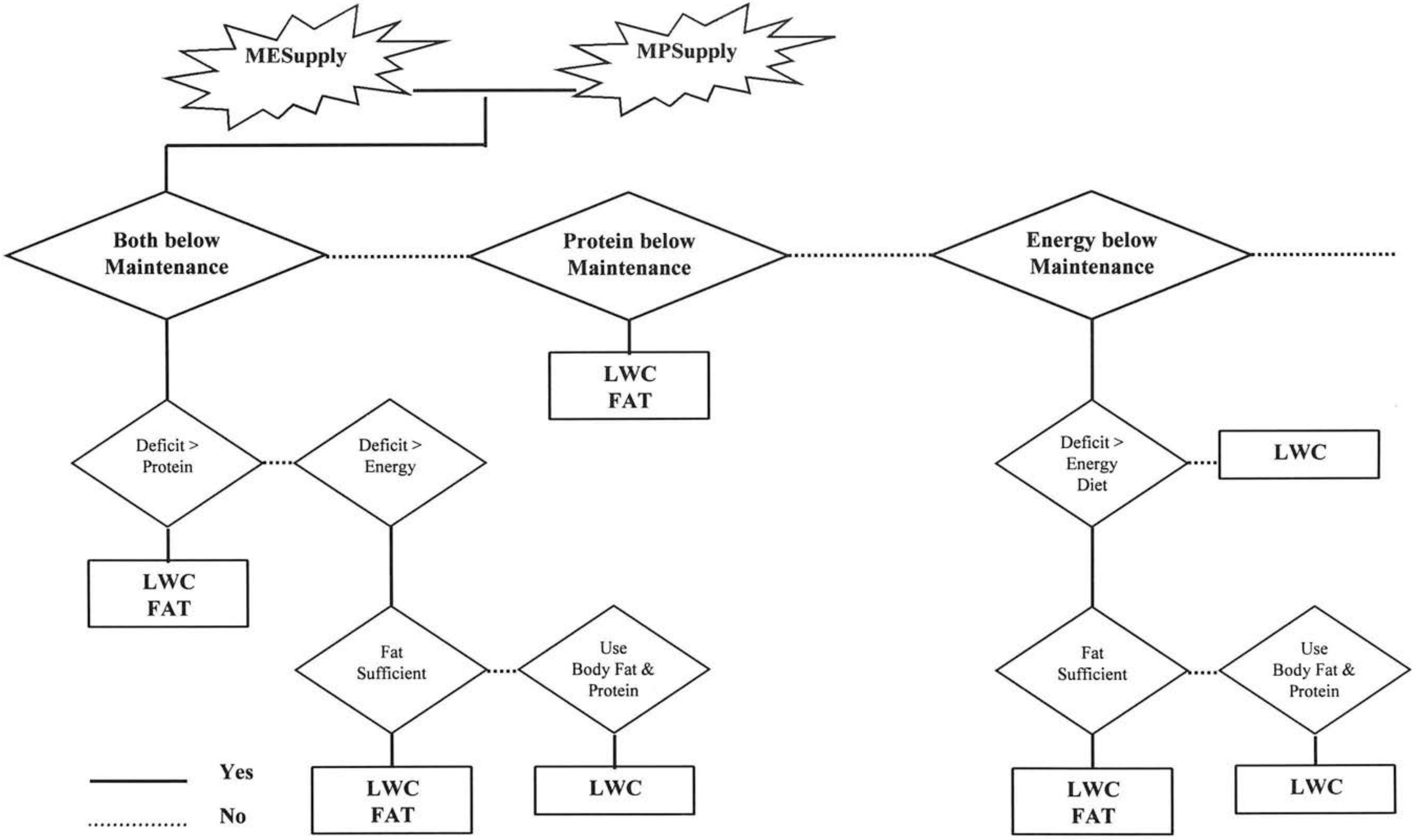


Figure 6.2. Decision flow in the prediction model: negative supply.

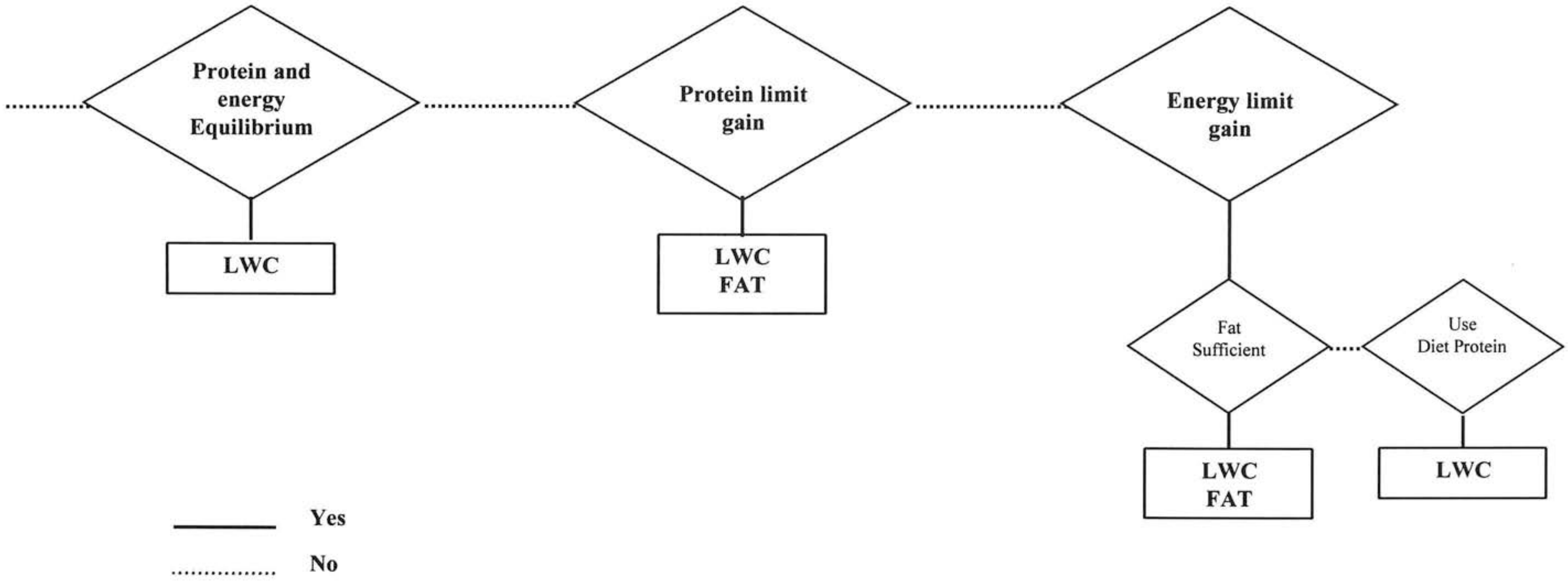


Figure 6.3. Decision flow in the prediction model: positive supply.

The amount of protein ($ProtComp_{ga}$), g/kg, and fat in the empty body ($FatComp_{ga}$), g/kg, is obtained respectively by

$$ProtComp_{ga} = factorC2\left(309.93\left(\frac{W_{ga}}{1.08}\right)^{-0.1085}\right) \qquad \mathbf{6.54}$$

$$FatComp_{ga} = factorC2\left(2.1972\left(\frac{W_{ga}}{1.08}\right)^{0.7883}\right) \qquad \mathbf{6.55}$$

The factor C2 is the correction factor for energy value content of live weight gain in cattle (AFRC, 1993). The rest of the equations are derived from ARC (1980), table 1.21, p. 31. The value of 1.08 converts empty bodyweight to live bodyweight (ARC, 1980) and the value 0.001 is used in all formulas which need to convert kilograms to grams.

The amount of metabolic protein from body tissue (MPBody), g/day, is obtained by

$$MPBody_{ga} = MPm - MPsupply \qquad \mathbf{6.56}$$

After that, the potential amount of protein to be lost by body tissue ($PotProL_{ga}$), g/day, to meet maintenance level is calculated

$$PotProtL_{ga} = \frac{MPBody_{ga}}{ProtComp_{ga}\ 0.001}\ 1.08 \qquad \mathbf{6.57}$$

The supply of metabolic energy from each gram of live weight ($Ener_{ga}$), MJ/g, is calculated by

$$Ener_{ga} = FatComp_{ga}\ (0.001)(0.8)(0.0393)\ (1.08) \tag{6.58}$$

The value 0.8 represents the efficiency of energy used for maintenance from live weight loss following CSIRO (1990) and the value 0.0393 is the amount of energy (MJ) per gram of fat (ARC, 1980;Blaxter, 1989; NRC, 1996).

At this level, the model tests the amount of metabolic energy from the body ($MEBody_{ga}$), MJ/day, that is obtained considering the amount of grams loss to satisfy the protein requirements ($PotProL_{ga}$).

$$MEBody_{ga} = TEM_{ga} - MEsupply_{ga} - \left(Ener_{ga}\ PotProL_{ga}\right) \tag{6.59}$$

Negative value for $MEBody_{ga}$ indicates that the protein deficit is larger than the energy deficit. In this case, the model assumes excess of energy is storage in the fat compartment (FAT_{ga}), kg. This compartment represents in the model an energetic reserve that has priority use when a situation of a negative energetic balance occurs.

$$FAT_{ga} = \frac{MEBody_{ga}\ 0.96}{39.3}\ (-1) \tag{6.60}$$

The value 0.96 represents the efficiency of using lipids for body fat (Blaxter, 1989) and 39.3 is the amount of energy content in MJ per kilogram of body fat. Therefore, the live weight change (LWC_{ga}), kg, is represented by

$$LWC_{ga} = PotProL_{ga}\ (-0.001) \tag{6.61}$$

A positive value for MEBody_{ga} represents that the energy deficit is larger than the protein deficit. In this case, the model first considers the fat reserve (FAT_{ga}) and the amount of metabolic energy stored in the FAT_{ga} compartment (MeF_{ga}), MJ, is calculated by

$$MEF_{ga} = FAT_{ga} \left(39.3\right)\left(0.96\right) \tag{6.62}$$

After that, the model obtains the amount of MEF_{ga} from MEBody_{ga}. Negative results of MEF_{ga} indicates that the amount of reserve is sufficient to supply the diet energetic deficit and the new value of FAT_{ga} is calculated by

$$FAT_{ga} = \frac{FAT_{ga}\ 39.3 - MEBody_{ga}}{39.3} \tag{6.63}$$

The live weight change (LWC_{ga}) is represented as such in equation 6.61. However, positive result evidences that the loss of live weight must be larger than the loss estimates to protein supply. The extra potential amount of energy loss ($\mathrm{PotEnerL}_{ga}$), MJ/day, is calculated by

$$PotEnerL_{ga} = \frac{MEBody_{ga} - MEF_{ga}}{\left(ProtComp_{ga}\left(0.0236\right)\left(0.8\right)\left(1.08\right)\right) + Ener_{ga}} \tag{6.64}$$

At this time, all the bodyweight loss was used for energy. The live weight change (LWC_{ga}), kg/day, is represented by the sum of $\mathrm{PotEnerL}_{ga}$ plus $\mathrm{PotProtL}_{ga}$.

$$LWC_{ga} = \left(PotProtL_{ga} + PotEnerL_{ga}\right)\left(-0.001\right) \tag{6.65}$$

6.1.2.2.2. Supply of protein below maintenance

Diets that supply animals with protein below requirements of maintenance can happen mainly in dry season or during the winter. The extension of the deficit is calculated following equation 6.59 and the amount of live weight loss (LWC_{ga}) is obtained by equation 6.60 and 6.64. The amount of energy that is stored in the fat comportment (FAT_{ga}) is calculated by

$$FAT_{ga} = \frac{\left(MESupply_{ga} + \left(Ener_{ga}\ PotProL_{ga}\right) - TEM_{ga}\right) 0.96}{39.3} \qquad \textbf{6.66}$$

6.1.2.2.3. Supply of energy below maintenance

The metabolic energy supply sometimes is not sufficient to meet the minimum requirements for animal maintenance. However, in this situation the excess protein available above maintenance level can be used to produce energy. In this case, the model considers the energy is below maintenance but the diet has sufficient energy for animal maintenance or to obtain low bodyweight gains through the conversion of excess protein to energy. First, the model tests the energy content in the diet ($EDiet_{ga}$), MJ/day,

$$EDiet_{ga} = TEM_{ga} - MESupply_{ga} - \left(\left(MPSupply_{ga} - MPm_{ga}\right) 0.0236\right) \qquad \textbf{6.67}$$

Negative results indicate that diet energy is above maintenance. The amount protein in the diet available to convert to energy ($EnerProt_{ga}$), g/day, is calculated by

$$EnerProt_{ga} = \frac{\left(\left(MPSupply_{ga} - MPm_{ga}\right) 0.0236\right) + MESupply_{ga} - TEM_{ga}}{0.0236} \qquad \textbf{6.68}$$

However, the animal converts protein to energy only the amount necessary to maintain the equilibrium between protein and energy for a determined gain. The next step is the calculation of the amount of metabolic protein (MPf_{ga}), g/day, and metabolic energy (Ef_{ga}), MJ/day, needs for each gram of live weight gain. The value 0.001 in the equations is to transform kilograms to grams.

$$MPf_{ga} = factorC6\left(168.07 - 0.16869\,W_{ga} + 0.0001633\,W_{ga}^{2}\right)\left(1.12 - (0.1223)(0.001)\right)(1.695)(0.001) \tag{6.69}$$

$$Ef_{ga} = 0.001\left(\frac{factorC2\left(4.1 + 0.0332\;W_{ga} - \left(0.000009\,W_{ga}^{2}\right)\right)}{1 - factorC3\,(0.1474)(0.001)}\right) \tag{6.70}$$

FactorC2 and factorC3 were described before and factorC6 is the correction factor for net protein from the fattening process table3.1, pg.36, AFRC (1993). After that, the live weight change (LWC_{ga}), kg/day, is calculated by

$$LWC_{ga} = \frac{EnerProt_{ga}}{MPf_{ga} + \left(\dfrac{EF_{ga}}{0.0236}\right)}0.001 \tag{6.71}$$

In this way, the equilibrium between protein and energy to determined gain is obtained.

When $EDiet_{ga}$ is positive this indicates that the amount of energy supplied by the excess of protein is insufficient to supply the minimum requirements of energy for animal maintenance. Therefore, the energy for maintenance must came from body catabolism. The model assumes that the extra fat reserve (FAT_{ga}) is first used to try to meet the energy requirements, so

$$EDietFat_{ga} = EDiet_{ga} - \left(Fat_{ga}\,(39.3)(0.96)\right) \tag{6.72}$$

Negative value of $EDietFat_{ga}$ denotes that the amount of excess fat in the body is sufficient to supply the energy deficit in the diet. Then, the new Fat_{ga} value is calculated by

$$Fat_{ga} = \frac{EDietFat_{ga}}{39.3}(-1) \tag{6.73}$$

In contrast, positive value for $EDietFat_{ga}$ indicates that the tissue catabolism is needed to supply the energy requirements for maintenance. The amount of live weight loss is calculate by

$$LWC_{ga} = \frac{EDietFat_{ga}}{((0.0393)\,(0.96) + (0.0236)(0.8))}(-1) \tag{6.74}$$

6.1.2.2.4. Supply of energy and protein in equilibrium above maintenance

Diets that supply energy and protein above maintenance are treated in the model to identify the equilibrium of the diet. As protein can be converted into energy, but energy cannot be converted into protein the model considers the protein of diet as limiting to maximum gain. Therefore, the prediction of maximum gain obtained by dietary protein must be calculated. The amount of metabolic protein in the diet available to gain (MPf_{ga}), g/day, is calculated by

$$MPf_{ga} = MPsupply_{ga} - MPm_{ga} \tag{6.75}$$

To calculate the potential gain obtained with available MPf_{ga} the equation 93, pg.36, AFRC (1993) had to be modified. The potential gain ($PotProtG_{ga}$), kg/day, can be calculated by the lower root of the quadratic equation.

$$PotProtG_{ga} = \frac{-(-1.8984) - \sqrt{-1.8984 - (4 \;\; 0.2073\, CTerm_{ga})}}{2\,(0.02073)} 0.95 \tag{6.76}$$

$$CTerm_{ga} = \frac{MPf_{ga}}{factorC6((168.7) \;\; (0.1687\, W_{ga}\;)(0.0001633\, W_{ga}{}^{2}))} \tag{6.77}$$

The value 0.95 in equation 6.76 is the security margin following AFRC (1993).

After the potential gain is estimated, the amount of energy necessary for maintenance and production ($MEmp_{ga}$), MJ/day, at this level is calculated by

$$MEmp_{ga} = \frac{TEM_{ga}}{factorK_{ga}} ln\left(\frac{factorB_{ga}}{factorB_{ga} - R_{ga} - 1}\right) 1.05 \tag{8.78}$$

The value 1.05 is the security margin following AFRC (1993). $FactorK_{ga}$, $FactorB_{ga}$ and R_{ga} are calculated by the AFRC (1993), equations 13, 14 and 15, pg. 5.

After that, the model tests the relation between the amount of $MEsupply_{ga}$ and $MEmp_{ga}$. A result between 0.95 and 1.05 indicates the diet is in equilibrium and the LWC_{ga} is assumed to be the $PotProtG_{ga}$ calculated in equation 6.76.

6.1.2.2.5. Supply of energy and protein above maintenance, with protein limiting the maximum gain

When the relation between the amount of MEsupply_{ga} and MEmp_{ga}, calculated following section 6.1.2.2.5, results above 1.05 indicates that protein is a limiting factor to gain. Therefore, the LWC_{ga} is assumed to be the PotProtG_{ga} calculated in equation 6.76 and the excess energy is stored as fat in the fat compartment (FAT_{ga}).

$$FAT_{ga} = \frac{MESupply \text{ - } MEmp_{ga}}{39.3}\ 0.96 \tag{6.79}$$

6.1.2.2.6. Supply of energy and protein above maintenance, with energy limiting the maximum gain

The relationship between the amount of MEsupply_{ga} and MEmp_{ga} below 0.95 indicates that the diet contains less energy than protein to obtain a determined gain. In this case, the model assumes that the first available energy to be used is the FAT_{ga} to counteract energy deficiency of diet.

$$MEmpFAT_{ga} = MEmp_{ga} - MESupply \text{ - } \left(Fat_{ga}\ (39.3)(0.96)\right) \tag{6.80}$$

A negative result of metabolic energy from diet and fat (MEmpFAT_{ga}), MJ/day, denotes that the amount of energy from fat is sufficient to supplement energetic deficit in the diet. Therefore, the PotProtG_{ga} is assumed as the LWC_{ga} and the FAT_{ga} is calculated by

$$MEmpFAT_{ga} = \frac{MEmpFAT_{ga}\ (\text{- } 1)}{39.3} \tag{6.81}$$

A positive result for $MEmpFAT_{ga}$, determines that the energy gap must be filled by the protein of the diet. First, the metabolic protein per gram of gain ($MPfGG_{ga}$),g/day, and the metabolic energy per gram of gain ($MEmpGG_{ga}$) ,MJ/day, are calculated

$$MPfGG_{ga} = \frac{MPf_{ga}}{PotProtG_{ga}\ 1000} \tag{6.82}$$

$$MEmpGG_{ga} = \frac{MEmp_{ga}}{PotProtG_{ga}\ 1000} \tag{6.83}$$

Therefore, the equilibrium of protein:energy from available energy to gain ($PotEnerG_{ga}$), Kg/day, is obtained by

$$PotEnerG_{ga} = \frac{MESupply_{ga} + \left(Fat_{ga}\ (39.3)\ (0.96)\right)}{MEmpGG_{ga}}\ 0.001 \tag{6.84}$$

Following the same approach adopted in section 6.1.2.2.3 the amount of excess protein available that has to be converted to energy is calculated and the effective LWC_{ga} is obtained by

$$LWC_{ga} = PotEnerG_{ga} + \left(\frac{MPf_{ga} - \left(PotEnerG_{ga}\ 1000\ MPfGG_{ga}\right)}{MPfGG_{ga} + \dfrac{MEmnGG_{ga}}{0.0236}}\ 0.001 \right) \tag{6.85}$$

Where, the first term of the equation is the live weight gain when protein and energy are at equilibrium and the right term is the additional gain, obtained from the excess of protein in the diet.

The individual animal intake and digestion sub-model is based on the Herrero (1997) model. The main modification was to make the model dynamic in order to be able to simulate the effects of continuos growth of animals on their intake and digestion processes. Also, feed allowance following NRC (1996), and environmental effects following NRC (1996) and CSIRO (1990), were incorporated to make the model useful for pastoral farming systems.

The live weight change sub-model was developed based on the formulas presents in AFRC (1993). The daily production of metabolic energy and protein in pastoral farming systems change during the year and consequently the energy:protein equilibrium is also modified. Modifications in the formulas were needed to simulate energy:protein balance conditions that occurs in these systems.

6.2. Simulations

Similar to the plant and soil sub-models, the outputs produced by the animal sub-model were contrasted against data collected in an experiment with supplemented steers at a farm level, in Bagé, RS. After weaning, 12 crossbreed Hereford x Nelore males were allocated to a natural pasture paddock of 10 hectares and supplemented twice daily. The supplement was composed of rice bran (± 50%), industrial residues of the rice crop (± 35%) and wheat bran, sorghum or maize (± 15%). The variation of pasture quality and supplement during the year is showed in table 6.1. The substantial variations in the availability and quality of natural pasture between months are clearly perceived and confirm the discussion in Chapter 2. The variation of quality in the supplement can be explained mainly due to the variation of the composition of the industrial residues from the rice crop (Gonçalves & Saccol, 1995).

The value for the Neutral Detergent Fibre (NDF) in the concentrate was estimated based on the individual components. Rice bran contains in average 33 % of NDF according to NRC, (1996). MAFF (1992) gives values of 10.7 % and 11.7 % for

Table 6.1. Nutritional characteristics of forage and concentrate used in the experiment.

Date	CP	NDF	ADF	IVD	EE	P	Availability
		---------	% DM	---------			-- Kg/Ha --
			Forage				
10/03/93	6.56	75.40	45.41	46.23	1.00*	0.08	976.00
07/04/93	5.19	76.20	41.17	55.28	1.00*	0.08	1304.00
05/05/93	4.94	76.30	46.50	42.40	1.00*	0.07	1638.00
02/06/93	7.81	76.10	45.89	40.77	1.00*	0.07	1840.00
30/06/93	6.81	75.40	44.63	39.10	1.00*	0.07	2180.00
28/07/93	6.63	78.80	46.88	38.96	1.00*	0.08	1571.00
25/08/93	7.88	78.10	41.58	32.75	1.00*	0.04	1130.00
22/09/93	7.81	75.50	49.36	29.23	1.00*	0.03	742.00
20/10/93	6.19	74.00	42.03	46.44	1.00*	0.05	1468.00
17/11/93	9.00	74.00	42.36	46.55	1.00*	0.07	963.00
07/12/93	10.50	74.90	42.90	45.63	1.00*	0.10	981.00
			Concentrate				**Availability - Kg/Head -**
10/03/93	18.31	37.40*	18.62	59.04	10.87	1.32	2.00
19/05/93	19.88	37.40*	16.88	61.86	11.00	1.40	2.50
11/08/93	18.66	37.40*	14.79	69.95	9.09	1.36	3.00
08/10/93	20.06	37.40*	15.43	67.00	9.05	1.34	3.00

CP, Crude Protein; **NDF**, Neutral Detergent Fibre; **ADF**, Acid Detergent Fibre; **IVD**, In Vitro Digestibility; **EE**, Ether Extract; **P**, Phosphorus.

* Assumed values see text for details

sorghum and maize respectively. The NDF of the industrial residues varies from 40% to 60%, in the model a value of 50 % was considered.

The amount of concentrate given to the animals was adjusted according to the forage availability and quality during the year. The concentrate was fed to the animals in a trough. An area of 0.5 m was available per animal. (Silveira et al., 1992). To simulate the competition between animals for feed that occurs in this situation, the model considers the following adjustment by simulation point (SP). In the SP1, animals ate 80% of the average concentrate supply and the animals in SP2 90%. The same assumptions were made for animals above the average. The model assumes that animals in SP4 and SP5 ate respectively 110% and 120% of average concentrate supply.

Tables 6.2 and 6.3 contain the forage and concentrate parameters used in the model. The parameters linked with protein (aCPForage, bCPForage, uCPForage, aCPConcentrate, bCPConcentrate, uCPConcentrate) were obtained from AFRC (1993), table 4.1, pg. 48, that contains the mean values of N degradability by class of feed. The values assumed for the forage parameters for most of the year were those for fresh forage. However, during the winter, grass hay values were used. The reason for this assumption is the standing hay strategy adopted by farmers as explained in Chapter 2.

The cell content in the forage (CCForage), that is wholly or largely digestible (Van Soest, 1994), was calculated by the difference of total dry matter (DM) less the amount of NDF. To calculate the digestible cell wall in the forage (DCWForage), the *in vitro* digestible (IVD) and CCForage were considered. We assume that the degradable protein (aCPForage plus bCPForage versus CPForage) was present in the CCForage. Therefore, the DCWForage was calculated by the IVD less CCForage and the fraction of degradable protein.

The cell wall digestion rate declines significantly with the plant's maturity (Illius and Gordon, 1991; Hoffman et al., 1993; NRC, 1996; Doane et al., 1997; Coblentz et al., 1998). Illius & Gordon (1991) reported rates for *Dactylis glomerata* from 0.128 h^{-1} in vegetative stage to 0.046 h^{-1} in the mature stage. Coblentz et al., (1998) compared four physiological stages for a natural grass found in Kansas, USA, and reported digestion rates from 0.056 h^{-1} to 0.032 h^{-1} at maturity. In the model, the value for the cell wall digestions rate (K2Forage) considers the physiological stage of the natural pasture, with a minimum value during winter and maximum value during autumn and spring.

De Peters et al. (1997) gave values of 0.07 h^{-1} for the cell wall digestion rate in rice bran, while NRC (1996) gave values of 0.08 h^{-1}. Maize, sorghum and rice grain cell wall degradation rate range from 0.05 h^{-1} to 0.08 h^{-1} (Sniffen et al., 1992; Krishnamorthy et al., 1995; NRC, 1996). In the model a value of 0.07 h^{-1} for the parameter cell wall degradation rate in the concentrate (K2Forage) is assumed.

To calculate the amount of starch in the no structural carbohydrate (NSC), the starch content of rice bran, sorghum and maize was considered as 90% of NSC (NRC, 1996). Starch in residues was considered as 50% of NSC, because the residue was a mixture of seeds, broken grains and straw as described in Chapter 2. Seeds and grains have around 90 % of starch and straw only 5% of starch in the NSC (NRC, 1996). Therefore, it was assumed that 65% of concentrate contains 90% of starch in the NSC and the rest contains 50% of starch. Consequently, the model considers the value of 60.25 % of starch in the NSC. The DCWConcentrate was obtained in the same way of DCWForage.

Figure 6.4 shows the values for the forage *in vitro* digestibility. These values have a small difference when compared values presented in the table 6.1 because they represent the average values per period. Illius & Gordon (1991) and Herrero (1997) validated the intake and digestion of food sub-models with data available in the literature.

Table 6.2. Forage parameters used in the model.

Date	Parameters					
	K2Forage	aCPForage	bCPForage	uCPForage	CCForage	DCWForage
10/03/93	0.05	0.24	0.67	0.09	0.25	0.28
07/04/93	0.05	0.24	0.67	0.09	0.24	0.37
05/05/93	0.05	0.24	0.67	0.09	0.24	0.24
02/06/93	0.04	0.24	0.67	0.09	0.24	0.25
30/06/93	0.03	0.22	0.60	0.18	0.25	0.21
28/07/93	0.03	0.22	0.60	0.18	0.21	0.24
25/08/93	0.04	0.24	0.67	0.09	0.22	0.19
22/09/93	0.05	0.24	0.67	0.09	0.25	0.13
20/10/93	0.05	0.24	0.67	0.09	0.26	0.27
17/11/93	0.05	0.24	0.67	0.09	0.26	0.30
07/12/93	0.04	0.24	0.67	0.09	0.25	0.31

K2Forage, Cell wall digestion rate of forage (h^{-1}); **aCPForage**, Proportion of soluble CP in the total protein of forage; **bCPForage**, Proportion of potentially degradable CP in the total protein of forage; **uCPForage**, Proportion of completely undegradable CP in the total protein of forage; **CCForage**, Proportion of cell contents in the forage; **DCWForage**, Proportion of digestible cell wall in the forage.

Table 6.3. Concentrate parameters used in the model.

Date	K2Concentrate	aCPConcentrate	bCPConcentrate	uCPConcentrate	Starch	DCWConcentrate	FatConcentrate
10/03/93	0.07	0.36	0.55	0.09	0.75	0.18	108.70
07/04/93	0.07	0.36	0.55	0.09	0.75	0.18	108.70
05/05/93	0.07	0.36	0.55	0.09	0.75	0.18	108.70
02/06/93	0.07	0.36	0.55	0.09	0.75	0.24	110.00
30/06/93	0.07	0.36	0.55	0.09	0.75	0.24	110.00
28/07/93	0.07	0.36	0.55	0.09	0.75	0.23	110.00
25/08/93	0.07	0.36	0.55	0.09	0.75	0.28	90.90
22/09/93	0.07	0.36	0.55	0.09	0.75	0.28	90.90
20/10/93	0.07	0.36	0.55	0.09	0.75	0.28	90.90
17/11/93	0.07	0.36	0.55	0.09	0.75	0.26	90.50
07/12/93	0.07	0.36	0.55	0.09	0.75	0.26	90.50

K2Concentrate, Cell wall digestion rate of concentrate (h^{-1}); **aCPConcentrate**, Proportion of soluble CP in the total protein of concentrate; **bCPConcentrate**, Proportion of potentially degradable CP in the total protein of concentrate; **uCPConcentrate**, Proportion of completely undegradable CP in the total protein of concentrate; **Starch**, Proportion of starch in the no structural carbohydrate (NSC); **DCWConcentrate**, Proportion of digestible cell wall in the concentrate; **FatConcentrate**, Amount of fat in the concentrate (g/Kg).

Modifications were introduced to make these models dynamic, and some effects were introduced in the intake sub-model as described in section 6.1.2.1. The average, maximum and minimum value of forage digestibility simulated by the model represents the dynamic behaviour expected for the forage digestion by the animal.

The average value simulated is close to that obtained by the *in vitro* procedure. The reason for the average value not reaching the *in vitro* value may be associated with the feeding level that these animals were subjected to. The model simulates that increase in the feeding level increases the passage rate, and consequently reduces the digestibility of the feed. In contrast, mainly in the period from 29/07 to 20/10, when the quality of pasture (Table 6.1.) was low, the improvement of rumen environment through the concentrate supplementation increases the forage digestibility. These results agree with results described by Caton & Dhuyvetter, (1996) that supplementation can increase or reduce the digestibility of forage, according with the quality of forage and the amount and quality of the supplement in the diet.

The animal's average live weight are presented in figure 6.5. Three simulations were made to compare the real data with the model outputs. The first simulation uses the standard values parameters from tables 6.1, 6.2 and 6.3. The other simulations consider the animal selectivite capacity during grazing. Therefore, increases for protein (CPForage) and the proportion of digestible cell wall (DCWForage) were considered. In the first graph, in Figure 6.5, the output produced by the model has a good agreement with the field data. However, the live weight gain during spring was faster than the one simulated by the model. An increase of 5% in the quality of the diet reduces this difference in the spring, but a small difference in favour of the simulated gain could be perceived during winter. This difference is larger when an increase of 10% in the quality of diet is considered. However, at this level of diet quality, the prediction of the final mean live weight of the animals is excellent.

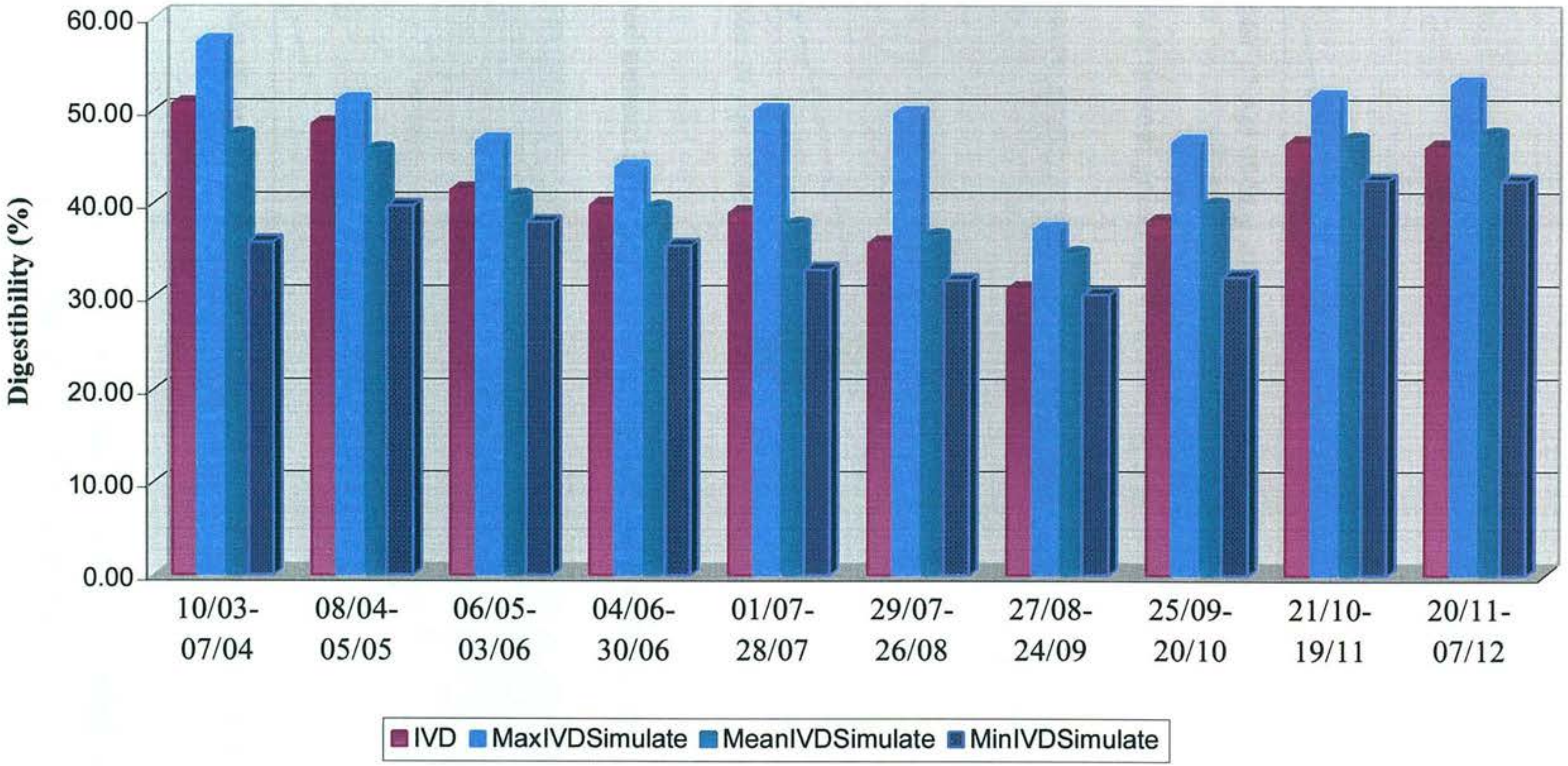
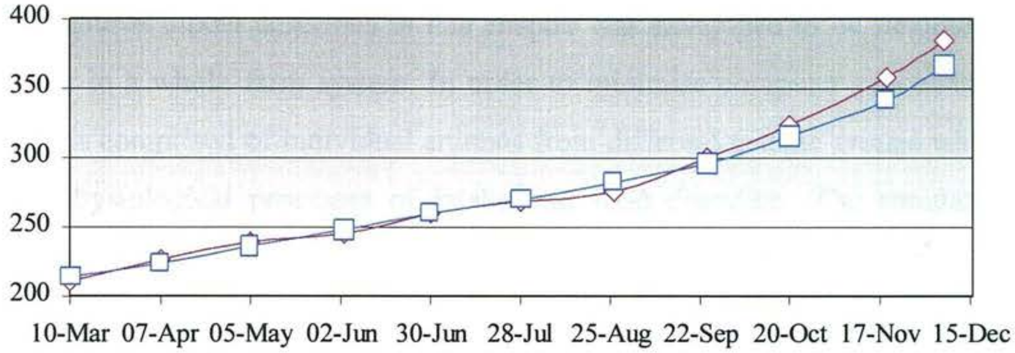
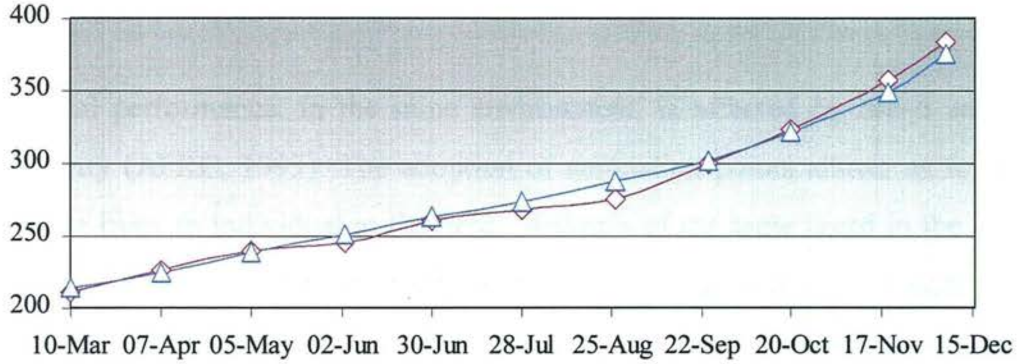


Figure 6.4. Forage in vitro digestibility (IVD) and maximum, mean and minimum values simulated for in vivo digestibility.

(a) Simulated animal gain (kg) without diet selection



(b) Simulated animal gain (kg) considering 5% of diet selection



(c) Simulated animal gain (kg) considering 10% of diet selection

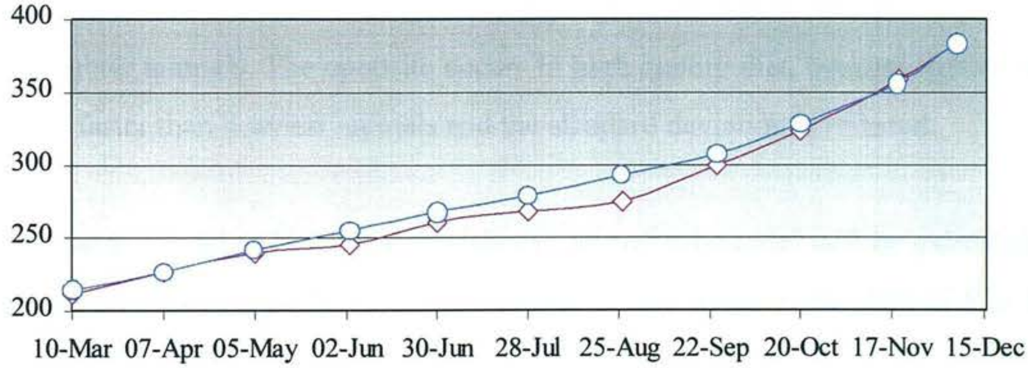


Figure 6.5. Experimental and simulated gains with variations in diet quality (– Actual, – Simulated).

6.3. Concluding Remarks

The animal model described in this chapter was developed to be flexible enough to use it in a whole farm system. In order to minimise computer processing time the herd is comprised of individual animals from different genetic groups which operate the physiological processes of intake and food digestion. The simulation results presented in section 6.2 show that the model works in a satisfactory way.

The herd sub-model permits the simulation of the real situation of a beef cattle finishing system. When farmers buy animals, they normally consider both price and quality. Consequently, a paddock may contain animals from different breeds.

Animal performance, in the same environment, is affected by breed and stage of maturity (AFRC, 1993). The adoption of simulation points allows us to link these effects from an individual to the herd. Animals of the same breed in the left side of the normal curve (Figure 6.1) utilise metabolic energy and protein more efficiently than animals on the right side, due the stage of maturity. In contrast, because of the rumen capacity, heavier animals are more capable of digesting poor quality diet (Illius & Gordon, 1991). Animal simulations with poor diet increase the standard deviation. This means that daily live weight gain for heavier animals is greater than for lighter animals. The opposite occurs in high quality diet, because lighter animals grow faster than heaviest animals and the standard deviation is reduced.

Similar to the other biological models the animal sub-model will be validated when the whole system model is tested in the field at farm level in the state of Rio Grande do Sul.

CHAPTER 7

RICE AND ECONOMIC MODEL

The remaining two components to be considered in the simulation of the rice-beef cattle finishing system are the economic factors and rice production. How these two components are treated in this work is the main goal of this chapter.

7.1. Rice model

As discussed in Chapter 2, rice models have been developed in the last decades and they are available in the literature (Ritchie, 1995). However, for these models to be included in this work some modifications were required. The rice model included in the DSSAT shell developed by Allocilja & Ritchie (1988), works like the other crop models in a continuous growing season. Modifications in the level of fertiliser or number of plants per square metre need to be made at the outset. Consequently, only tactical decisions can be considered. This approach is helpful for conditions where water and inputs used in the crop-growing season are not limiting. This situation generally occurs in single crop commercial farms. However, when the farm is multi-enterprise, the farmer deals with other variables in the whole farm system and sometimes tactical decisions are made at the time of execution. Castelán-Ortega et al. (1998) found this situation using the Ceres-maize model to simulate the campesino system in Mexico. For example, the number of plants at the start of the growing season are not the same as at the end because farmer uses some plants to feed animals during the growing season.

In Rio Grande do Sul, the water used for the rice crop may come from a river and/or dam (Chapter 2). Sometimes the areas cultivated with rice are larger than the irrigation capacity of the dam. In this case, the rice farmer responds to the amount of that rain can fall during the growing season. The same occurs with rice farmers who depend on water from rivers for irrigation. Therefore, in years with low precipitation rice farmers leave areas fallow to keep other areas in conditions to produce. This factor is an example of decision making that occurs during the growing season and that must be contemplated in an adaptive model.

As the main goal of this work is the demonstration of the simulation of a rice-beef cattle finishing system considering the cattle farmer management only, we adopted a simplified way to simulate rice yield. The production per hectare considered is based on the historical production. However, in the future when the model will be transposed to a more powerful language, interactive adaptations of crop models need to be made.

7.2. Economic model

The income of a beef cattle farmer derives from selling animals and the payment received for the land rented by the rice farmer. This payment generally is made by the rice farmer in product (rice) and the farmer sells it according to his needs. The economic outcomes are related with procedures to maintain the improved pasture production and animal health. In addition, transport, employee salary and family expense are considered. The monetary unit adopted in the model is the American dollar.

7.2.1. Income sub-model

The decision of a farmer to sell animals has a direct impact on pasture production and the stocking rate. This decision also produces input for the economic model. Couto (1997) developed an economic model to simulate meat prices in Brazil, which is adopted here. The model is based on historical data and considers price fluctuations, the beef pluriannual cycle (6 years in Brazil) and seasonal variability. The model considers also the effects of the price of chicken meat and the exchange rate of American dollar. The simulated prices for January 1999 to July 2000 are demonstrated in Figure 7.1. The results predicted by the model are higher than the historic average (figure 2.7, chapter 2). These can be justified, due to a linear and ascending tendency of prices and the ascendant stage of pluriannual cycle in 1999 and 2000.

The income associated with the land rented for rice production is directly linked with the yield per hectare. Generally, the land is rented for 15% of the yield, but if a beef cattle farmer provides the water as well, the price increases to 22%-25%, according the quality of the land and the type of road available to reach the rice field (FEARROZ, 1998). The value of the rent is one of the question in the farmer management model (Chapter 8).

Table 7.1 contains the minimum, median and maximum monthly values received by the farmer for a ton of rice. These values were used to calculate the triangular distribution of the forecast for rice prices. This is an effective tool for rapid subjective estimation of the probabilities involved in price estimates. The single-point forecast is replaced by minimum, maximum and most likely values (Fawcett et al., 1993).

Table 7.1. Prices considered in the calculation of triangular distribution forecast.

Month	US$/Ton		
	Minimum	Median	Maximum
January	255.80	263.05	277.60
February	224.40	235.35	250.40
March	193.20	212.05	239.60
April	173.00	213.65	254.40
May	182.60	202.75	222.20
June	179.00	204.90	217.80
July	213.00	215.15	218.60
August	216.00	233.45	244.60
September	227.40	253.40	276.60
October	225.00	259.85	290.40
November	241.20	265.95	285.80
December	253.20	269.05	282.40

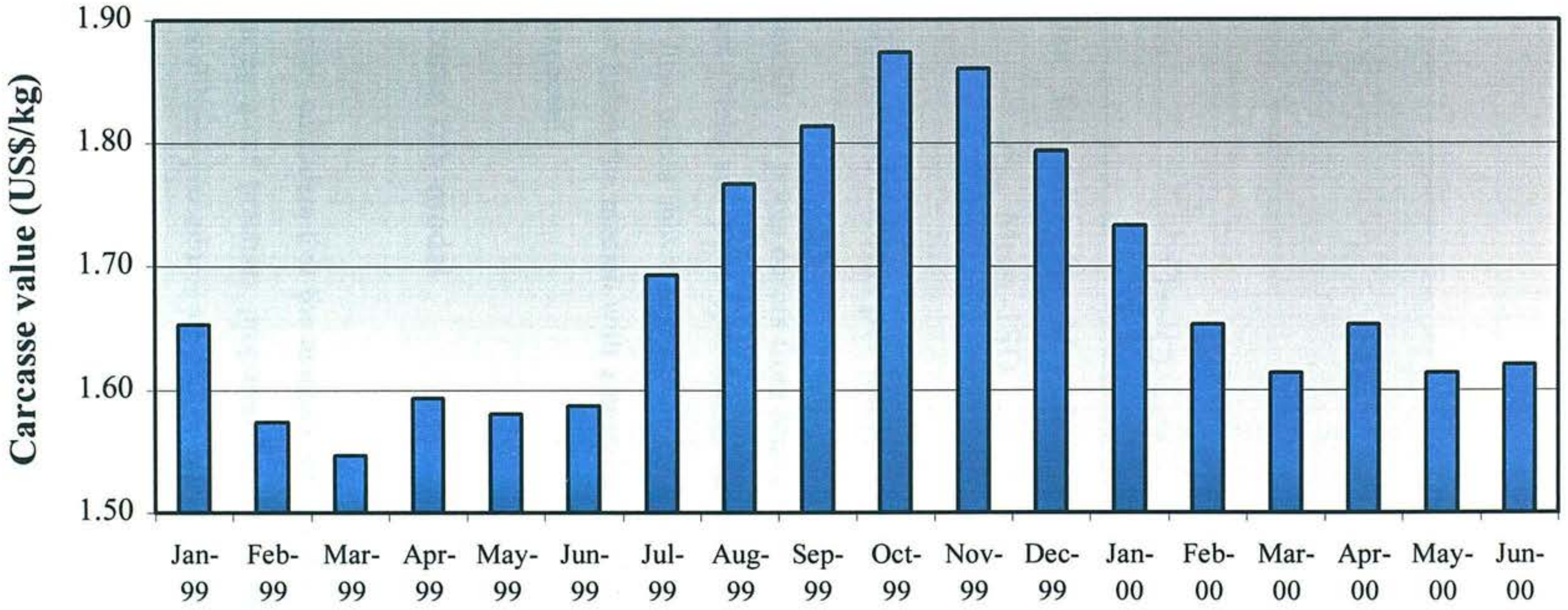


Figure 7.1. Simulated meat price in Brazil for 1999/2000.

The covariance effect of yield on price was studied using the underlying correlation coefficients. The adjusted expectated value and the variability considering one standard deviation are showed in Figure 7.2.

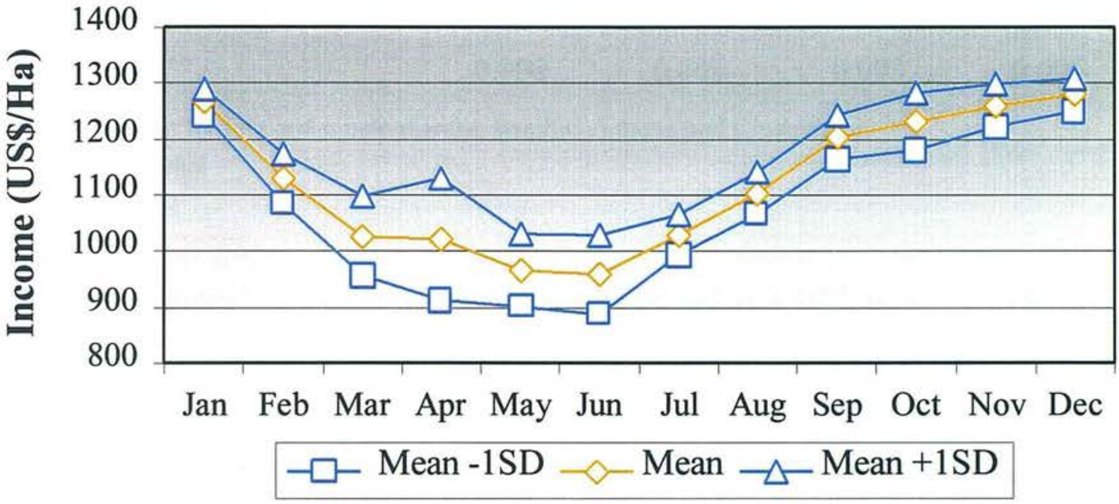


Figure 7.2. Expected income per hectare of rice (US$/Ha).

The main variability of prices occurs from March to June, which coincides with the time of harvest (yield and price speculation, farmers sell rice to pay back bank loans). After June prices shown less variability and the harvest yield indicates the values above or below the median with a negative correlation between harvest yield and price, as expected.

7.2.2. Outcome sub-model

The animal model considers that the animals are healthy, consequently, it assumes the health management practises proposed by Alves-Branco et al. (1997). The economic costs of these procedures are shown in table 7.2.

Table 7.2. Cost of health procedures.

Activity	Month				
	January	**February**	**May**	**September**	**November**
Vaccination*+	0.36	0.09	-	0.45	-
De-Worm++	-	0.006	0.006	0.003	0.006

*Immunisation for foot and mouth disease, Bacillus Anthrax and Clostridium.

+ Price per animal

++ Price per Kg

When the farmer has a debit to pay, the model considers a 10% annual interest rate. This value was used last year in Brazil. The monthly variation in the value for salaries, price of urea, triple phosphate, concentrate and fuel considered in the model is presented in table 7.3. The values were obtained from a database available at the Centre for Cattle research for the Southern Brazilian Grasslands (CPPSUL), a unit of the Brazilian Agricultural Research Corporation (EMBRAPA).

Table 7.3. Prices considered in the model.

Month	Salary	Urea	Phosphate Triple	Concentrate	Fuel
January	180.75	0.12	0.22	0.12	0.67
February	179.85	0.12	0.21	0.12	0.67
March	178.95	0.25	0.26	0.12	0.66
April	178.05	0.24	0.25	0.12	0.66
May	190.03	0.23	0.26	0.13	0.65
June	189.09	0.21	0.22	0.14	0.65
July	188.14	0.26	0.27	0.15	0.65
August	187.20	0.27	0.29	0.16	0.64
September	186.27	0.28	0.28	0.15	0.64
October	185.34	0.26	0.26	0.15	0.63
November	184.41	0.14	0.24	0.14	0.63
December	183.49	0.13	0.25	0.13	0.63

Therefore, for each decision taken by the farmer with an associated economic cost the value in the table is considered. The prices are dynamic in nature as seen in the table. For example, concentrate prices have a maximum value in winter-early spring as a consequence of high demand during that time of the year.

The farm enterprise generated expected daily cash flow and the monthly balance is calculated. This represents the economic environment in the model. The model only considers a limited set of seasonally variable prices, but the inclusion of fixed costs and depreciation have to be addressed in the future.

7.3. Concluding remarks

A simple approach was used to deal with rice production and the economic impact in the system. However, the main inputs and outputs are considered to represent the real economic environment that affected decisions taken by the beef cattle farmer in a dynamic way. Future work is necessary to incorporate other variables of the economic environment to improve the model accuracy, mainly in more complex systems found in the region. The inclusion of land taxation in the economic model is one of the priorities in the next step. This is a key factor to simulate the real profit of farmers.

An adaptation of the rice model from DSSAT will allow farmer management intervention during the growing season. This approach is needed mainly when the same decision-maker manages both the crop and the animals. Situations where the water availability became a constraint for rice production allow the animals to go into the rice area. The rice model needs to deal with these situations, which produce an impact in the whole system.

Similar adaptations can be extended to other crop models present in the DSSAT shell, this would facilitate the simulation of other alternative systems not only the beef cattle-rice systems.

CHAPTER 8

FARM DECISION MODEL

The farm decision model is the last model necessary to complete the diagram proposed in Chapter 3. The decisions are grouped in activities such as management of animals, pasture/soil, land use and finance. These are the generic questions made in the model.

8.1. General structure

The model stops at a determined time-step (e.g. week) and prompts for answers to questions on specific topics. This feedback generates a matrix of decisions. The scenario generated for a determined period of time (e.g. bi-annual) is a consequence of the interaction between the farmer and the environment and has in this matrix a memory. In this way farmers can use the model to learn about the impact of individual decisions on the farm and help in their future decisions.

Figure 8.1 shows the flow of questions to the decision-maker. The model works through the rules and the questions with yes/no answers to simulate farmer behaviour. Some of the basic rules are generated inside the model and others are decided by the farmer.

Decisions can be made weekly, bi-monthly or monthly, and can be changed during the run. This flexibility is important because at some times of year decisions are be made less frequently, but at other times (e.g. winter) farmers take decisions more frequently. Other specific constraints (e.g. level N in the soil to fertilise) will be described later in each decision sub-model.

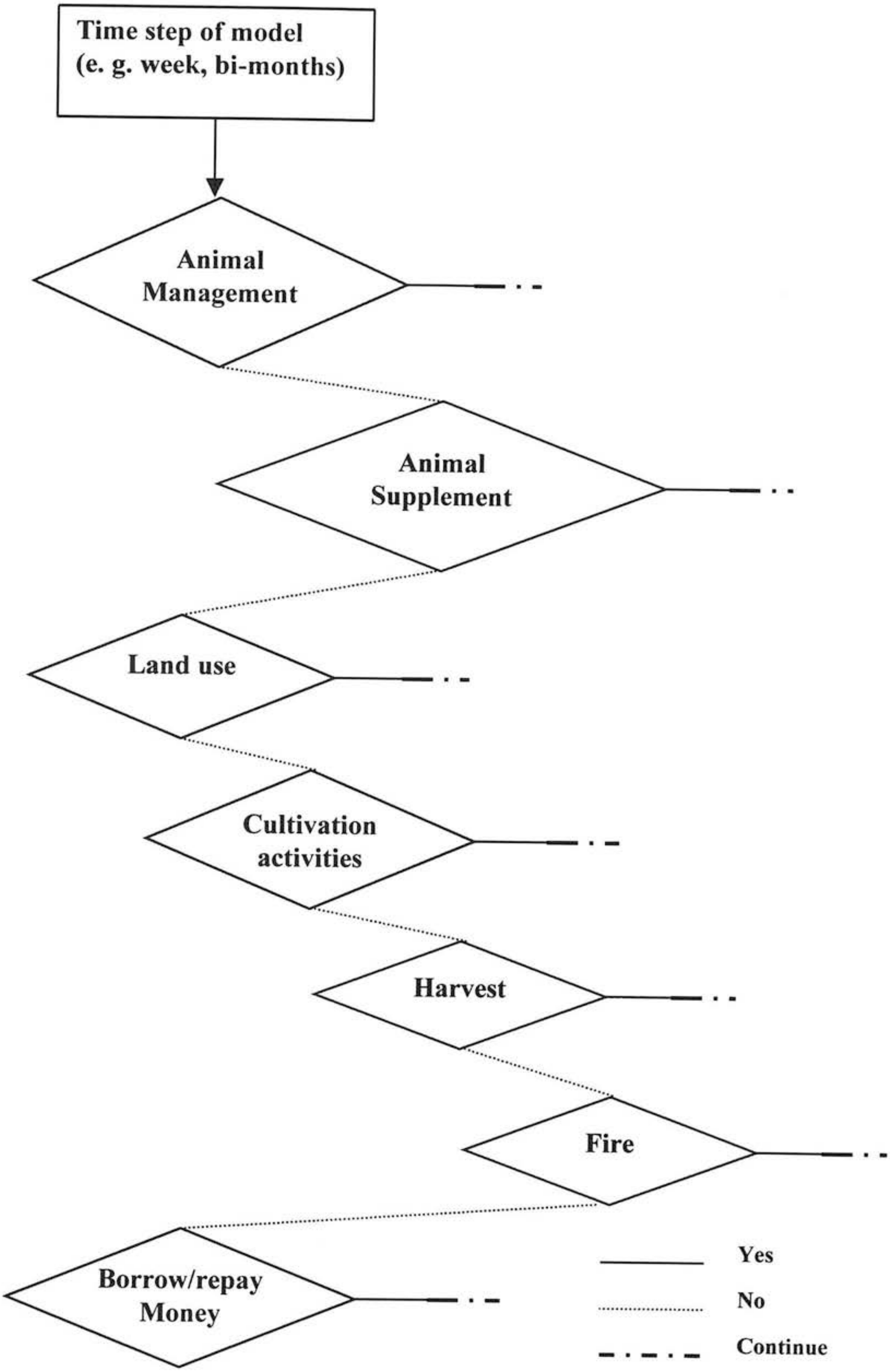


Figure 8.1. Flow of question made in the decision maker model.

8.2. Animal decision sub-model

Farmers have three main types of decisions in a finishing beef cattle pastoral farm system: economic (buy and sell animals), nutritional (supplementation and/or move animals between paddocks) and health (vaccination, deworm and cattle-dip). The model assumes a fixed set of animal health procedures according to the recommendations of Alves-Branco et al. (1997) for the studied region. However, future work should explore this factor in the animal sub-model and consequently in the farmer decision model.

Decisions about management of animals in the paddocks are represented in Figure 8.2 and only the time-step constraint is considered. The first question is about management of animals in the farm. In the case of a positive answer the next question is what the management will be in paddock 1? If the answer is negative, the farmer will be questioned about paddock 2 and in front of a new negative the model follows to the next paddock until paddock N. When a positive answer occurs at this level, the program asks if the farmer bought animals and wants to put then in this paddock. The positive replies determines which genetic maturity group (see Chapter 6) these animals will join in the paddock. First, the question is about the group of early maturity after the medium and finally the late maturity (AFRC, 1993). The number of animals, average, and standard deviation are required as inputs to link with the animal sub-model (Chapter 6). After that or in case of a negative response the model inquires about the removal of animals from the paddock. All animals can be removed from a paddock, or animals can be removed according to their liveweight (lowest or highest) or at random.

When animals are removed from a paddock a question about their new allocation is made. The first question yes/no refers to sale animals. A negative answer means the animals stay in the farm, so the next question is about which paddock the animals will be allocated to. When the allocation of animals from paddocks that had animals removed finish, the program goes to the question about supplementation.

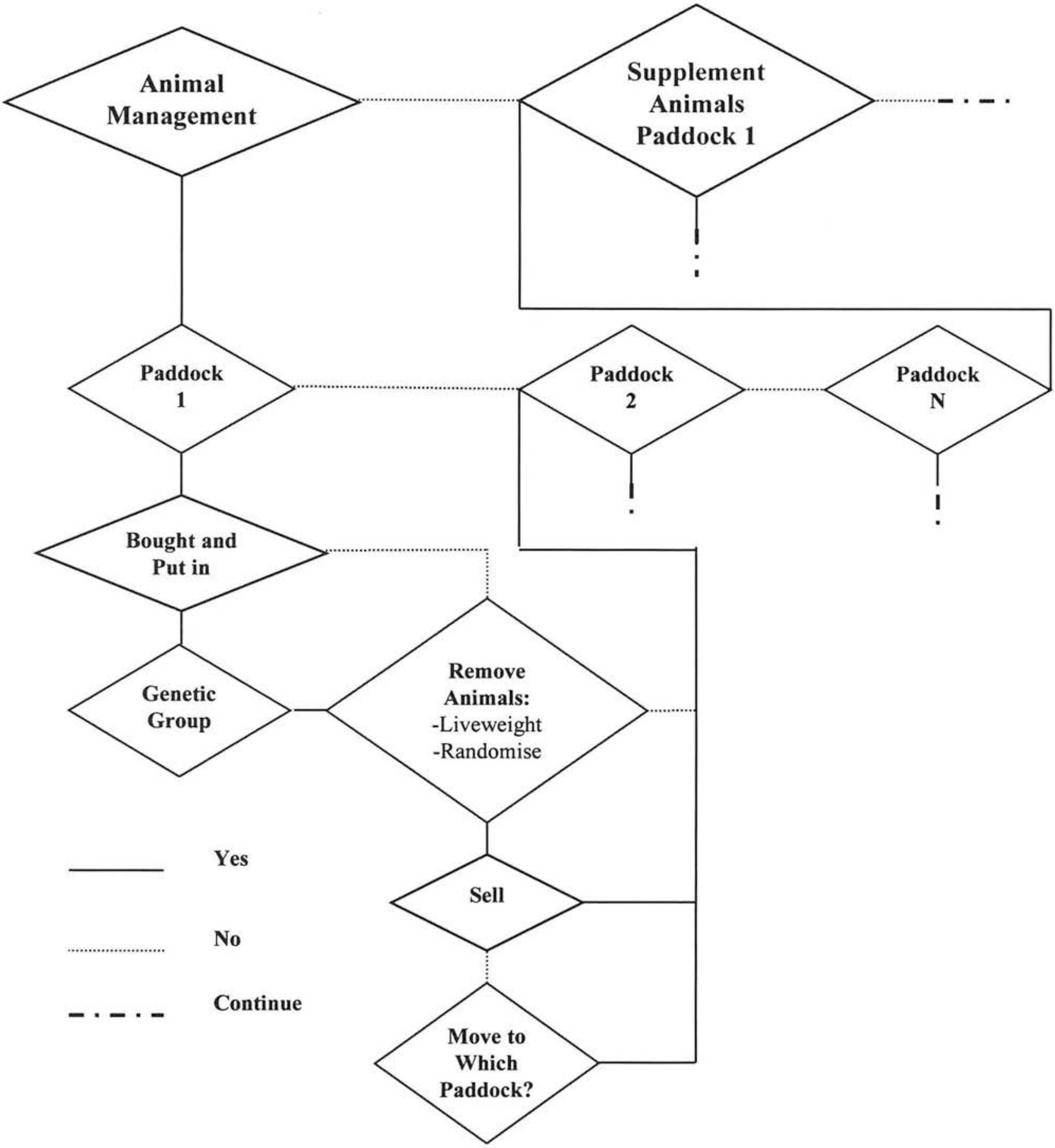


Figure 8.2. Flow of questions made about animal management.

Supplementation is an example in the model of a mix between a decision rule and a yes/no question. The model starts and questions the farmer below which level of daily animal gain he wants to be alerted to use supplement. Therefore, question about supplementation occurs only when the daily animal gain, which is an output produced by the animal sub-model, meets the level established by the farmer. The flowchart for the supplementation sub-model is presented in Figure 8.3. The first question refers to whether or not the farmer wants to start supplementation for animals in the paddock. Positive answers induce to questions about the management used as such as how many times per day? The following steps refer to the amount and quality of supplement. After all answers are obtained, the model follows to question about pasture management.

The next time that the model stops and the animals are in a supplementation regime, a new question will be made about changes in the management of supplementation (e.g. times) and changes in the amount and quality of concentrate (Figure 8.4). This option is a key factor in the model to simulate the real farmer environment. Sometimes farmers use residues to supplement animals that they have in limited stock. When these residues finish another residue or supplement is used or the supplementation is suspended.

8.3. Pasture and soil decision sub-model

The pasture and soil sub-models are treated together in the decision framework because of the close link between them. The decision about pasture-soil change depends on the type of pasture that grows in the paddock. Fertilisers are not used in natural pastures but it is a normal procedure for improved pastures. In contrast, farmers cut the excess of dead material of natural pasture in early spring and sometimes they use fire. The main decisions considered for paddocks with natural pasture are stocking rate, burning, cutting or to leave standby in the paddock. Questions about burning pasture are made when the variable amount of dead shoot remaining after winter is more

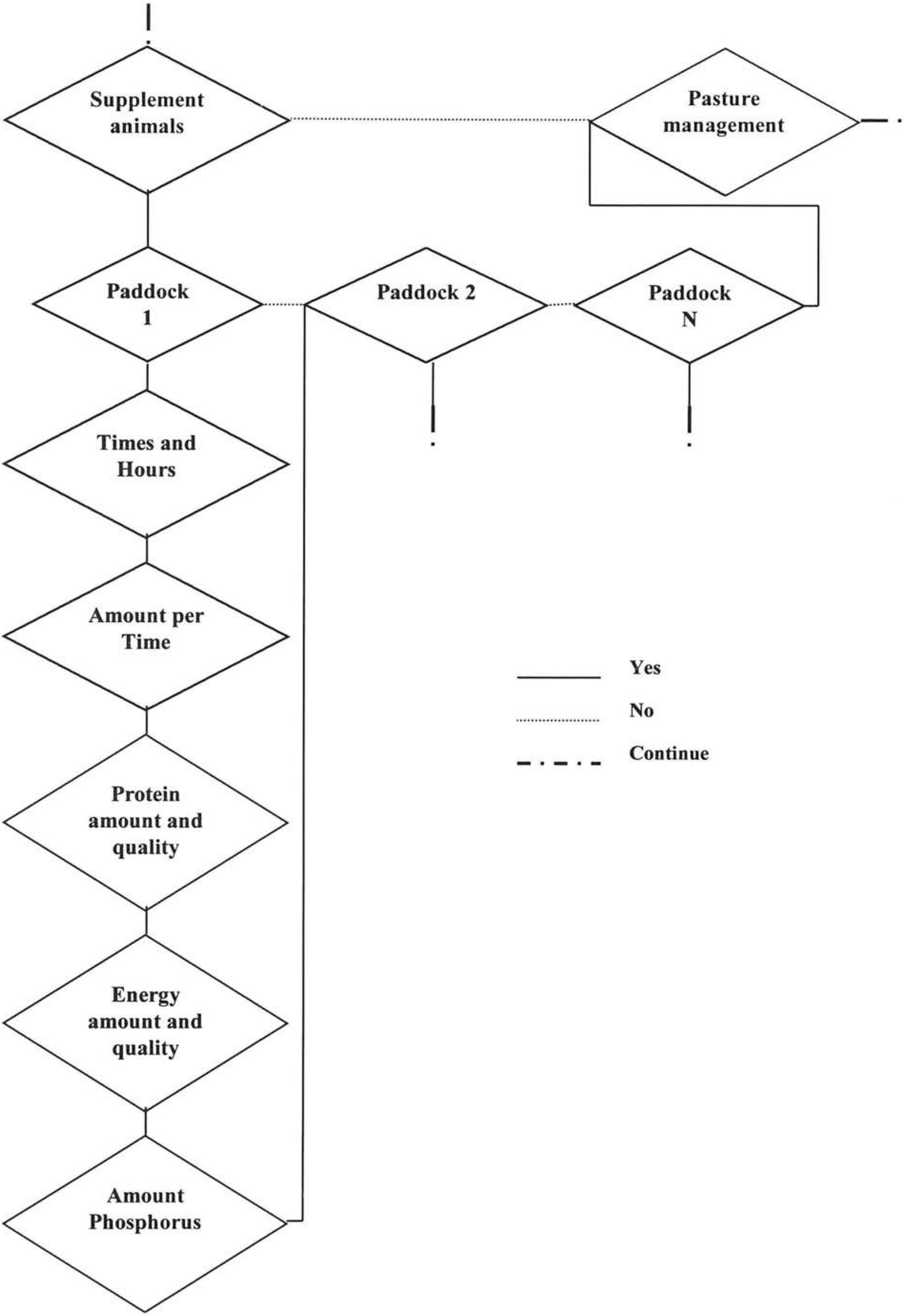


Figure 8.3. Flow of questions made about animal supplementation.

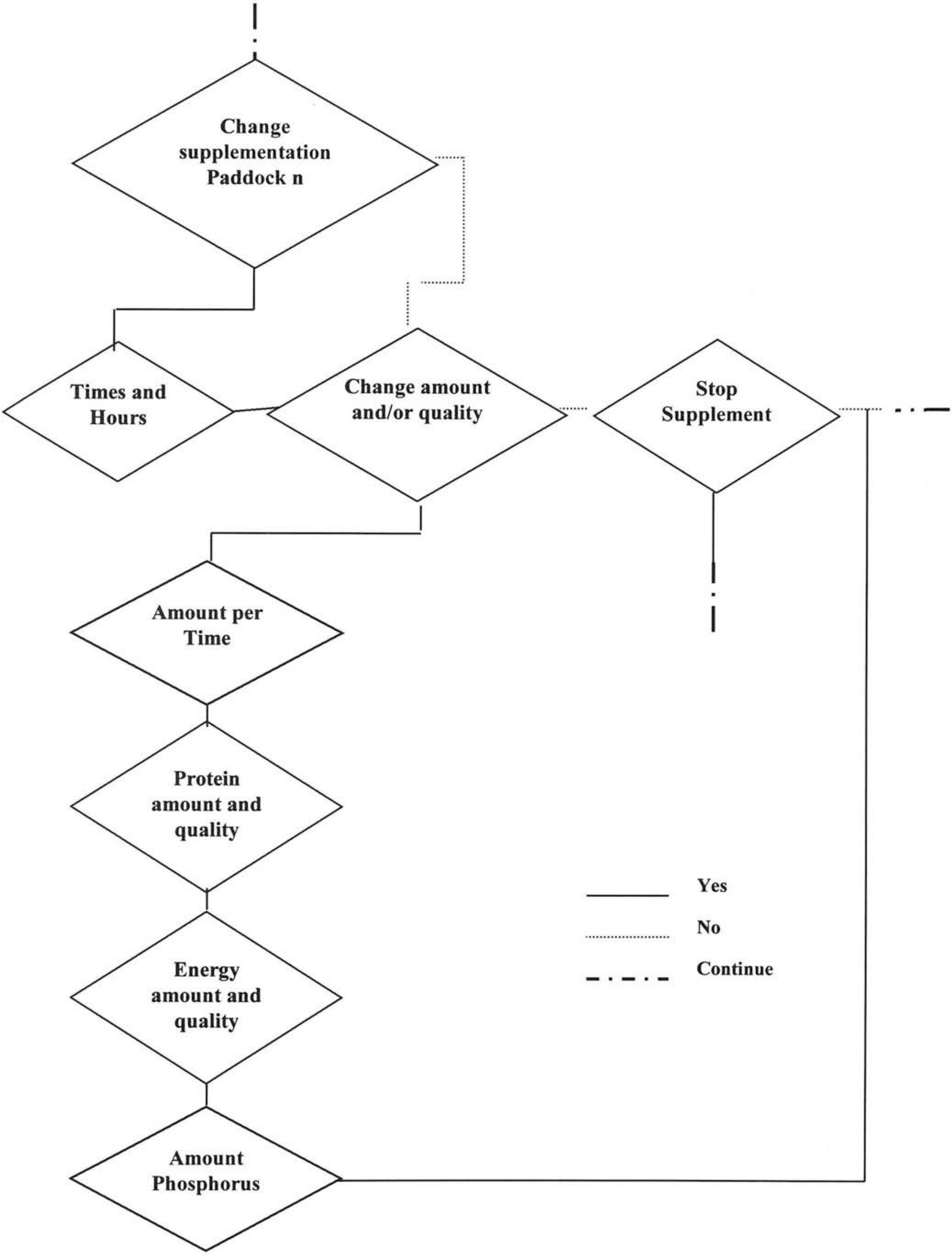


Figure 8.4. Flow of questions to change animal supplementation.

than 1000 kg/ha ($ShDead_s$, equation 4.39, Chapter 4). This is the simplest way to include this fact in the model; in the future this could be better represented when the model is linked as a spatial model. Also, paddocks can be compartmentalised and accept treatment in sequence.

Management in paddocks with improved pasture includes other options to harvest pasture as hay/silage or seed production. In addition, questions about fertiliser with N or P can be made. This happens when N or P available to the plant in the soil affect the plant growing (parameter $MNSoil_s$ and $MPSoil_s$, equation 4.22, Chapter 4).

8.4. Economic decision sub-model

The numbers of employees are treated dynamically inside the model. Every time the model stops questions about changes in the number of employees are made. Farmers with credit or debit are asked if they have received or spent money. After the rice harvest, questions about the amount of rice to be sold start. The sale of rice and animals are the main economic inputs of the system (Chapter 7).

8.5. Concluding remarks

The main goal of this chapter was to describe the main questions made by FIDM. The matrix of decisions generated by the farm decision model is a key factor to learn about the system. These outputs can be used as important tools to help farmers and extension workers in a way that the efficiency of the system increases according to their socio-bio-economic objectives.

The farm decision sub-model is a key model for the achievement of FIDM. Questions made to the farmer will need to be updated directly with the farmer's participation. These questions are the link between "natural" and "simulated" information. Consequently, the FIDM performance will be better if the questions made capture the decision-maker behaviour and introduce it into the whole model.

In this sub-model the adaptive level proposed by Jones et al. (1997) for decision models can be noticed. The adoption level of technology by the farmer is clearly noticed by the answers of the questions formulated in the farm decision sub-model.

CHAPTER 9

SIMULATIONS USING INTEGRATED SOCIO-BIO-ECONOMIC MODEL

This chapter describes the simulation of the main farm decisions in a finishing beef cattle pastoral farming system. Some simulations were made and the results of proposed methodology described in chapter 3 are presented. The main goal of this chapter is to demonstrate the potential use of this approach in generating different scenarios for the farmer. Case studies with hypothetical farmer behaviour are presented.

9.1. Simulated physical farm

In the case studies, the farming systems are based on growing and finishing beef cattle together with rice production. The human agents involved are described in chapter 2 as the cattle farmer (Gaúcho) who leases land to the rice farmer. The model considers the cattle farmer, who is the landowner, to be the decision-maker. The model simulates the biological phases of the system (soil-plant-animal). The animals in this case are represented by male growing beef cattle and the plant by native or improved pasture. The rice model simulates yield from historic data. The main goal of the rice model was to produce an economic input to the system. The economic model incorporates attitudes to risk in a subjective way through the farmers decision options in the extensive beef cattle production system. The Figure 9.1 shows a theoretical farm situation and the models involved using the farm integrated decision model (FIDM).

The simulated farms (100 ha) have de facto three paddocks with 20, 50 and 30 hectares respectively. The first paddock is rented to rice production from October to April.

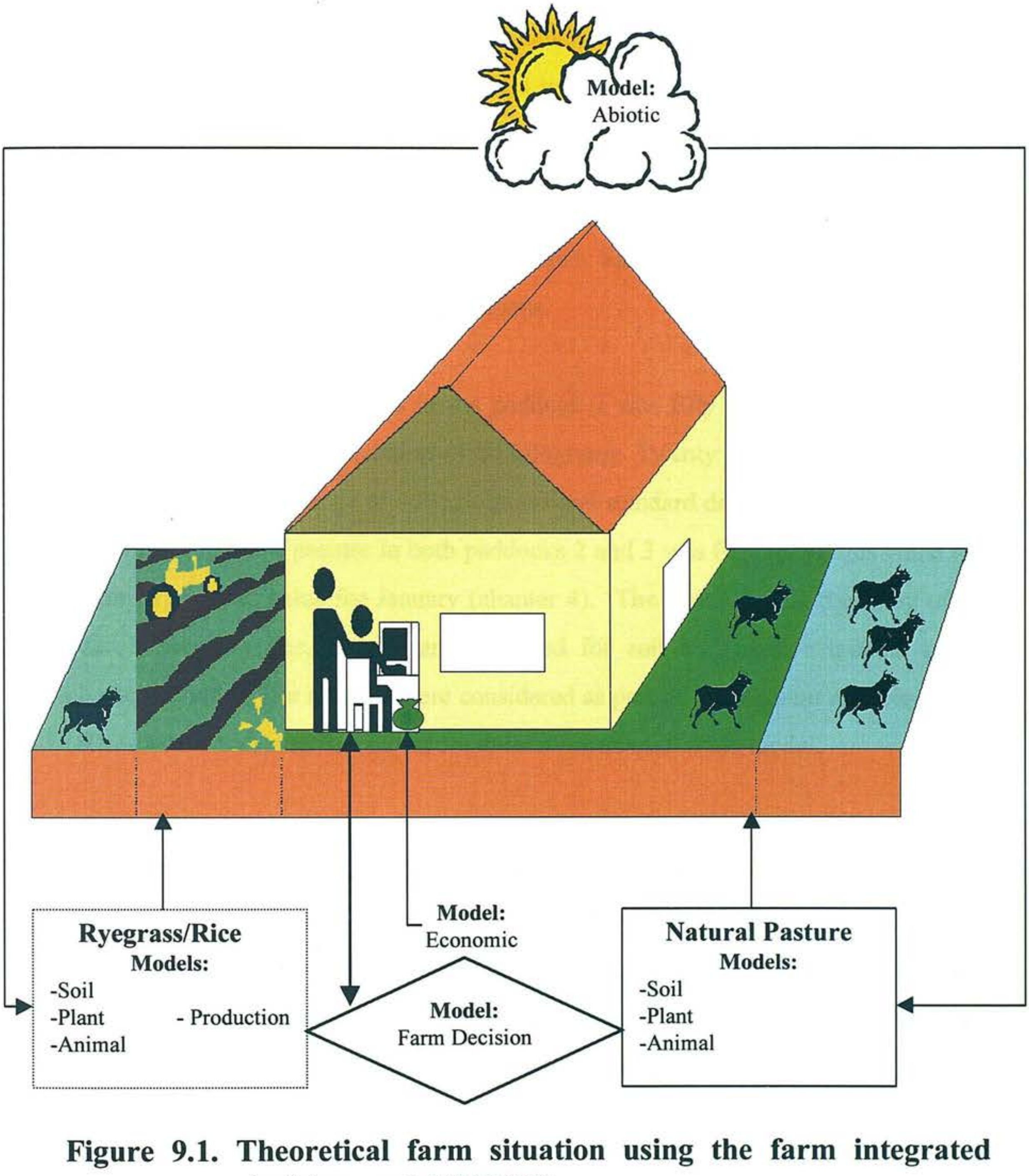


Figure 9.1. Theoretical farm situation using the farm integrated decision model (FIDM).

The rice farmer surrenders 15% of the total harvest and sows Italian Ryegrass in the paddock, as per the lease agreement. The two paddocks growing natural pasture contain grazing cattle:

(i) The paddock number 2 is used to keep the growing animals and it is considered as the growing paddock.

(ii) The paddock number 3 is used to keep animals in the final stage of the fattening process.

The farmer's family spends US$ 200 per month and the farmer has one employee (wages listed table 7.1, chapter 7). The farmer had US$ 1000 in the bank account and a debt of US$ 2000 as initial conditions.

The initial number of animals in the paddock 2 was fifty with an average of 300 kilograms and standard deviation of 20 kilograms. Twenty animals were grazing in paddock 3 with an average of 400 kilograms and standard deviation of 10 kilograms. The total amount of pasture in both paddocks 2 and 3 was 620 kg/ha, this value was assumed as mean value for January (chapter 4). The paddock 1 at this time of the year is growing rice. The parameters used for soil and pasture models follow chapters 4 and 5. The animals were considered as part of the medium maturity group (Hereford). These were the initial conditions considered in the model.

9.2. Simulated psychological farmer behaviour

To demonstrate the potential use of FIDM two farmers (FARMER1 and FARMER2) with the same farm initial condition (section 9.1) were simulated. The main "natural" information used by the farmers in the decision process is described below and it is summarised in table 9.1.

The time intervals between decisions are variable. In general, decisions are made twice per month in summer and late autumn. In winter and early spring, the interval was weekly so animal performance could be monitored closely. Both farmers consider the advice given by extension worker and adopt the research recommendations to keep animals healthy (chapter 7, section 7.2.2).

Table 9.1. Pre conceived action plan based on previous experience of farmers.

		Month											
		J	F	M	A	M	J	J	A	S	O	N	D
Farm1	Decision interval ,weeks*	3	3	3	3	2	1	1	1	2	2	3	3
	Minimum average weight to sell animals (kg)	460	460	460	460	460	460	460	450	450	450	460	460
	Supplement animals	no	no	no	no	no	no	no	no	no	no	no	no
	Fertilise paddock1	no	no	no	no	no	no	no	no	no	no	no	no
	Leave paddocks empty	no	no	no	no	no	no	no	no	no	no	no	no
	Sell Rice	no	no	no	no	no	yes	yes	no	no	no	no	no
	Minimum weight to buy animals (kg)	250	250	250	250	250	250	250	250	250	250	250	250
Farm2	Decision interval ,weeks*	3	3	3	3	2	1	1	1	2	2	3	3
	Minimum average weight to sell animals (kg)	**450**	**450**	**450**	**450**	**450**	**450**	**450**	**420**	**420**	**420**	**450**	**450**
	Supplement animals	no	no	no	no	**yes**	**yes**	**yes**	**yes**	no	no	no	no
	Fertilise paddock1	no	no	no	no	no	no	no	no	no	no	no	no
	Leave paddocks empty	no	no	no	no	no	no	no	**yes**	**yes**	**yes**	no	no
	Sell Rice	no	no	no	no	**yes**	**yes**	**yes**	**yes**	**yes**	**yes**	no	no
	Minimum weight to buy animals (kg)	250	250	250	250	250	250	250	250	250	250	250	250

*1=each week,2=every two-weeks,3=every four-weeks.

To sell animals, the FARMER1 used an approach that considers a security margin over the minimum acceptable liveweight while FARMER2 targets the minimum acceptable weight. In so doing FARMER2 assumes a higher risk than FARMER1, because a carcass that does not meet the minimum weight is penalised with a reduction in the price per kilogram.

FARMER2's strategy is to sell two groups of animals during the period of high prices. This goal can be achieved using three tactics in combination.

(i) Supplementation of animals on natural pasture.
(ii) Selling animals at the minimum weight accepted by the market.
(iii) Leaving paddock3 empty in late winter-early spring to obtain more pasture for animals moved from the improved pasture when closed for rice production.

The supplementation of animals in natural pasture is adopted as a tactical decision to begin when animals are losing live weight in paddock 3. Therefore, the model asks the farmer to begin supplementation as an operational decision when animal liveweight change (chapter 6) is less than zero.

In relation to rice received from the rented land, FARMER1 does not like to be involved in the rice market. He waits for a small increase in the rice price to sell and then buys animals. In contrast, FARMER2 deals in the rice market.

To replace animals sold, both farmers adopted the same strategy, they buy animals with an average live weight of 250 kg. Also, they try to buy animals in the winter when the demand and price for growing animals are low.

9.3. Simulated farm results and discussion

The "simulated" biological and economic information is supplied, at each time step to the decision-maker sub-model, for all the variables described in Chapters 4 to 7.

These sub-models can produce too much information for the decision-maker. An example of the subset of state variables supplied for farm2 is demonstrated in Figure 9.2.

The state variables supplied by the "simulated" information are the physical results that steer the decision-maker towards his/her goals. Some of the "simulated" information about animal conditions and the economic environment at the time of the farmer made decisions are presented in table 9.2 and table 9.3. The simulated amount of pasture available is demonstrated in figure 9.3. The names of variables are described in the respective sub-model (e.g. NAnPad1 from chapter 6).

In these hypothetical case studies, the farmers' decisions were the same until day 106 and the "simulated " information supplied to both farmers were the same derived from the same decisions taken before. One of the state variables supplied was the average animal liveweight in paddock3 (AvAnMPad3, tables 9.2 and 9.3). FARMER2 following his pre-conceived plan (Table 9.1) sold the animals. He also set the time step for 1 week to decide when to buy animals to put in paddock 3 or move animals from paddock2. In contrast, FARMER1 set the time step for two weeks to gain the safety margin live weight to sell the animals. The decisions were based on the estimated live weight of the animals and the rate of daily liveweight change (LWC variable, section 6.1.2.2 in chapter 6).

In the next step for FARMER2, he decides to move the heaviest animals from paddock2 to paddock3. FARMER1's forecast was confirmed and the average animal liveweight in paddock3 was above 460 kg (table 9.1) so he sells the animals.

The description above is an example of how the FIDM works at each time step. First, the model shows the simulated economic and biological environment generated by the sub-models. Second, questions are asked of the decision-maker following the farmers pre-conceived plan. Third, the decision-maker answers the question (his/her decision) based on both the "simulated" and "natural" information. Fourth the model

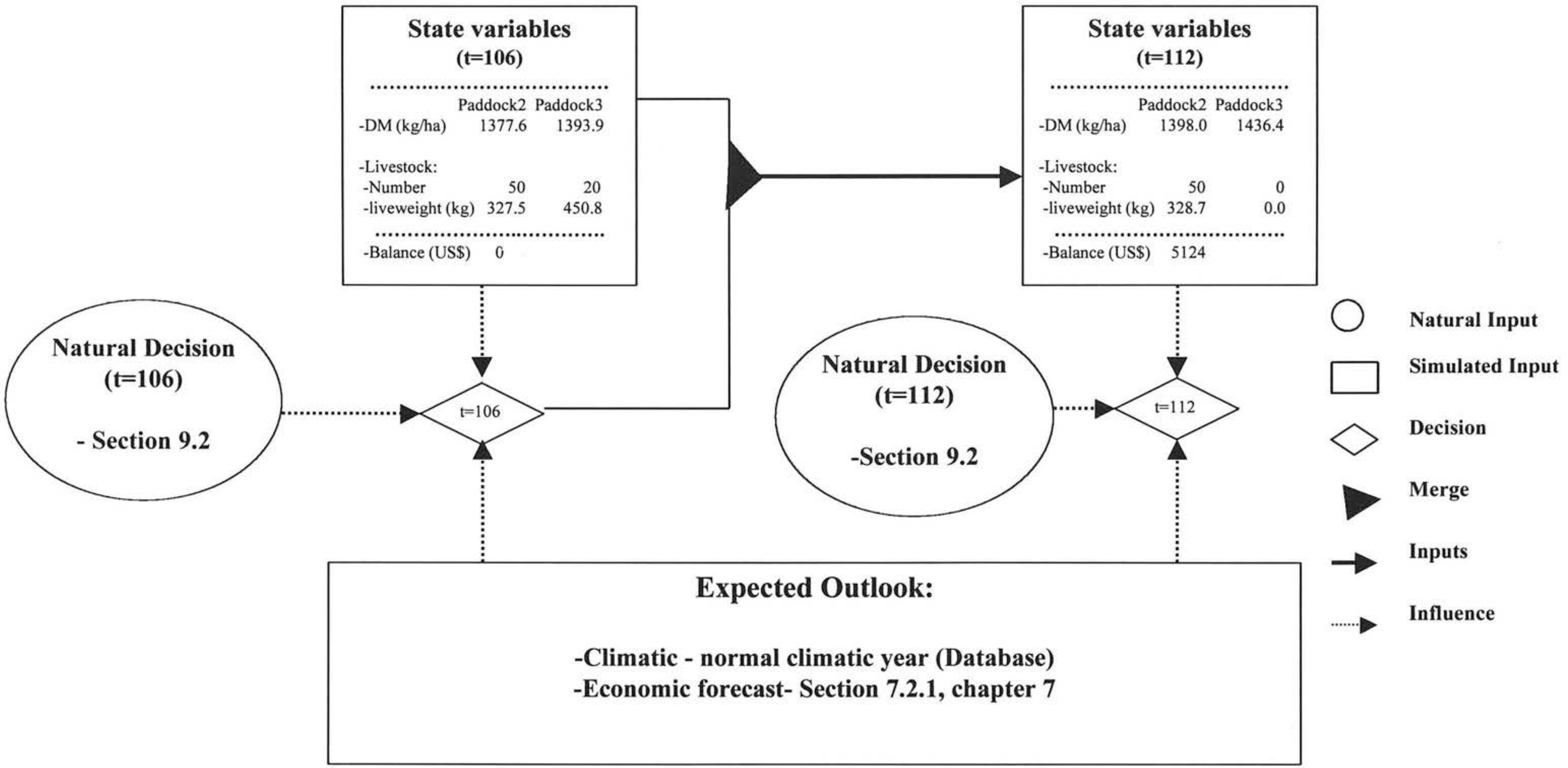


Figure 9.2. The dynamic decision approach at Farm2.

Table 9.2. Farm1 - Animal condition and economic environment at decision making time.

Month	Julian Day	NAnMPad1	AvAnMPad1 (Kg)	NAnMPad2	AvAnMPad2 (Kg)	NAnMPad3	AvAnMPad3 (Kg)	Rice (Ton)	Debit (US$)	Balance (US$)
Jan	**1**	0	0.00	50	300.12	20	400.06	0	2000.00	1000.00
Jan	**28**	0	0.00	50	304.63	20	409.74	0	2000.00	1000.00
Feb	**54**	0	0.00	50	311.37	20	424.65	0	2016.00	586.29
Mar	**80**	0	0.00	50	318.55	20	440.19	0	2032.13	47.70
Apr	**106**	**0**	**0.00**	**50**	**326.16**	**20**	**450.79**	**0**	**2392.94**	**0.00**
Apr	**119**	**0**	**0.00**	**50**	**333.91**	20*	462.21	**0**	**0.00**	**0.00**
May	**125**	**0**	**0.00**	**50**	**335.24**	**0**	**0.00**	**0**	**0.00**	**4880.17**
May	**132**	0	0.00	30	324.72	20	368.80	0	0.00	4880.17
May	**146**	0	0.00	30	325.86	20	372.19	0	0.00	4880.17
Jun	**158**	0	0.00	30	324.37	20	373.21	15	0.00	4346.36
Jun	**172**	0	0.00	30	321.64	20	371.83	15	0.00	4346.71
Jul	**184**	0	0.00	30	318.19	20	370.76	15	0.00	3934.55
Jul	**190**	20	379.98	30	317.40	0	0.00	15	0.00	3934.40
Jul	**197**	20	392.49	10	291.41	20	324.08	15	0.00	3934.23
Jul	**203**	20	410.36	10 20**	290.56 250.00	20	320.77	0	0.00	3934.23
Jul	**210**	20	428.45	30	259.56	20	317.97	0	0.00	3350.34
Aug	**223**	20	440.10	30	256.43	20	314.77	0	0.00	2954.30
Aug	**236**	20	472.78	30	255.35	20	314.03	0	0.00	2954.30
Sep	**249**	20	483.22	**30**	**257.62**	**20**	**317.19**	**0**	**0.00**	**2559.30**
Sep	**255**	**0**	**0.00**	**30** 20	**257.95** 250.00	**20**	**317.98**	**0**	**0.00**	**11790.30**
Sep	**262**	**20**	**341.95**	**50**	**260.85**	**0**	**0.00**	**0**	**0.00**	**7894.80**
Sep	**268**	20	350.38	50	264.01	0	0.00	0	0.00	7894.80
Oct	**275**	20	362.05	50	271.94	0	0.00	0	0.00	7408.35
Oct	**281**	0	0.00	50	278.64	20	373.18	0	0.00	7408.35
Oct	**294**	0	0.00	50	287.78	20	388.01	0	0.00	7408.35
Nov	**318**	0	0.00	50	296.45	20	402.73	0	0.00	7015.22
Dec	**339**	0	0.00	50	299.74	20	410.75	0	0.00	6484.11
Dec	**365**	0	0.00	50	304.13	20	417.17	0	0.00	6092.72

*animals sold, ** animals bought

Table 9.3. Farm2 - Animal condition and economic environment at decision making time.

Month	Julian Day	NAnMPad1	AvAnMPad1 (Kg)	NAnMPad2	AvAnMPad2 (Kg)	NAnMPad3	AvAnMPad3 (Kg)	Rice (Ton)	Debit (US$)	Balance (US$)
Jan	1	0	0.00	50	300.12	20	400.06	0	2000.00	1000.00
Jan	28	0	0.00	50	304.63	20	409.74	0	2000.00	1000.00
Feb	54	0	0.00	50	311.37	20	424.65	0	2016.00	586.29
Mar	80	0	0.00	50	318.55	20	440.19	0	2032.13	47.70
Apr	**106**	**0**	**0.00**	**50**	**327.52**	20*	450.79	**0**	**2392.94**	**0.00**
Apr	**112**	**0**	**0.00**	**50**	**328.66**	**0**	**0.00**	**0**	**0.00**	**5124.75**
Apr	**119**	**0**	**0.00**	**30**	**322.46**	**20**	**366.01**	**0**	**0.00**	**5124.75**
May	132	0	0.00	30	325.54	20	372.97	0	0.00	4726.61
May	146	0	0.00	30	326.31	20	376.32	0	0.00	4726.61
Jun	158	0	0.00	30	324.17	20	377.45	15	0.00	4192.24
Jun	172	0	0.00	30	321.76	20	377.44	15	0.00	4168.05
Jul	184	0	0.00	30	318.97	20	383.12	15	0.00	5686.97
Jul	197	0	0.00	30	314.18	20	392.30	5	0.00	5505.99
Jul	203	20	413.29	30	313.29	0	0.00	5	0.00	5479.53
Jul	210	20	431.27	10	286.43	20	326.76	5	0.00	5327.98
Aug	223	20	443.60	10	282.25	20	336.84	5	0.00	4818.56
Aug	229	0	0.00	10	280.80	20	347.18	5	0.00	12977.90
Aug	236	20	364.83	10 40**	280.54 250.00	0	0.00	5	0.00	12914.80
Aug	242	20	376.43	50	257.67	0	0.00	0	0.00	6509.81
Sep	268	20	404.15	50	263.59	0	0.00	0	0.00	6114.86
Oct	281	20	409.27	50	274.46	0	0.00	0	0.00	5625.24
Oct	288	0	0.00	50	281.49	20	428.58	0	0.00	5625.24
Oct	294	0	0.00	50	290.25	20	432.24	0	0.00	5625.24
Oct	301	0	0.00	50	292.90	0	0.00	0	0.00	14123.00
Nov	307	0	0.00	30 20	286.62 250.00	20	339.58	0	0.00	13730.00
Nov	314	0	0.00	50	282.83	20	347.47	0	0.00	9623.64
Dec	340	0	0.00	50	286.92	20	353.63	0	0.00	9103.73
Dec	365	0	0.00	50	291.01	20	358.60	0	0.00	8712.34

*animals sold, ** animals bought

runs until the next time step defined by the decision-maker. The importance of biological and economic models to supply the "simulated" information to the decision-maker is clearly perceived.

In table 9.2, another example of "simulated" information supplied by the model, which interferes in the pre-conceived plan of FARMER1. As a consequence of a good climatic year, animals from paddock1 were ready for slaughter at day 249 and FARMER1 sold them. At day 255, FARMER1 according to the pre-conceived plan bought animals to replace the ones sold. Paddock 1 was empty and rice cultivation does not start for at least 20 days. FARMER1 had five options to deal with for animal allocation in the farm:

- Leaves paddock 1 empty.
- Put bought animals in paddock 1.
- Put bought animals plus animals from paddock2 in paddock 1, and leaves paddock 2 empty.
- Transfer animals from paddock2 to paddock 1 and put bought animals in paddock 2.
- Put bought animals in paddock 2 and transfer animals from paddock3 to paddock 1 and leave paddock3 empty.

The option taken was to move animals from paddock 3 and leave paddock 3 empty. Leave paddock 3 empty, was not considered in the pre-conceived plan (table 9.1), but the farmer makes his as a response to the "simulated" information supplied by the model. This option considers the main goal of FARMER1 who allocates the best pasture to animals in the fattening process.

The final scenarios generated by the model in these two hypothetical cases simulated are different even though they both started with the same conditions. This demonstrates the capacity of the model to incorporate "natural" information and the goals of the farmer to reach an output. FARMER2 sold 60 animals during the year and achieved the goal of selling two groups during the season of high cattle price. To realise this goal one of the conditions was to keep pasture availability in paddock3 high during early spring. The animal management permitted achievement of this goal (figure 9.3).

Table 9.4 contains a summary of final dry matter generated by the model for the two farms. Table 9.4 shows the dry matter produced in each paddock and the total intake by the animals.

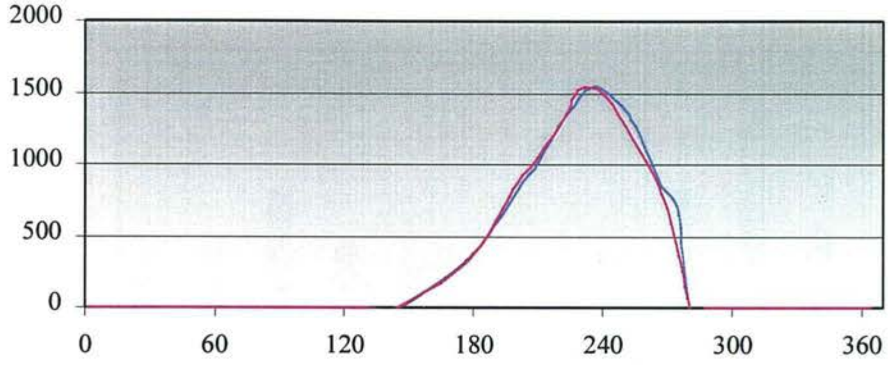
Table 9.4. Simulated dry matter (DM) produced and utilised per paddock for the two farms.

Paddock	Farm	Produced DM/Ha/Year	Intake DM/Ha/Year	Utilisation %
Paddock1	Farm1	2948.4	666.1	22.6
	Farm2	2818.2	601.4	21.4
Paddock2	Farm1	6088.1	1530.2	25.1
	Farm2	6071.6	1489.1	24.5
Paddock3	Farm1	5992.8	1371.4	22.8
	Farm2	5825.2	1198.6	20.6

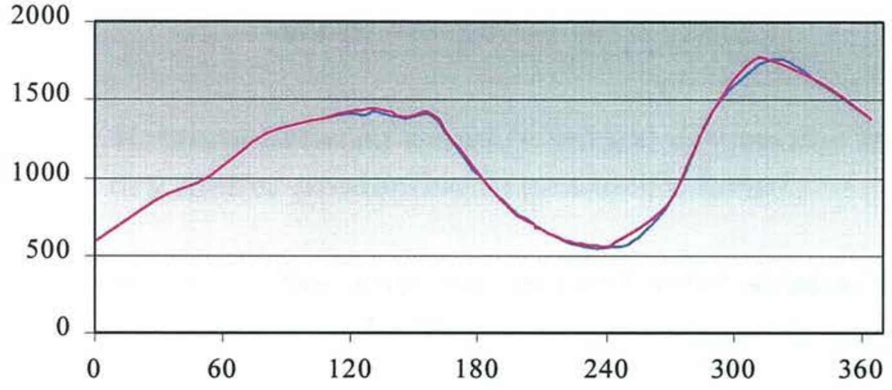
This output allows the analysis of the annual rate of pasture utilised by the animals. However, this output alone hides the seasonal variation that occurs in natural pastures. Figure 9.4 shows, as an example, the variation that occurred in farm1 paddock3. The bimodal production of natural pasture is clearly seen. During the winter, pasture production is very low as discussed in chapter 2. Consequently, the intake rate in June was four times higher than the monthly pasture production and it was also higher in July. During the other months, intakes are always lower than the production of dry matter.

The main economic output for the finishing beef cattle farmer is the amount of meat produced per hectare per year. To achieve this goal the "natural" information is used in the strategy of buying and selling animals as described in section 9.2.

(a) Dry matter production (kg/ha) in paddock1.



(b) Dry matter production (kg/ha) in paddock2.



(c) Dry matter production (kg/ha) in paddock3.

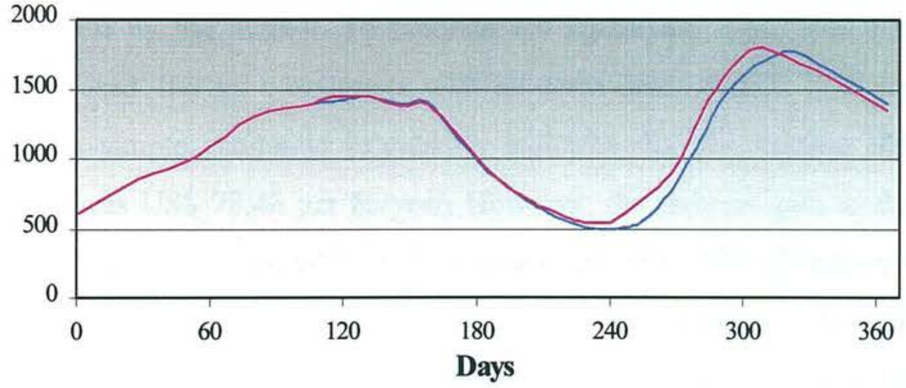


Figure 9.3. Simulated pasture available in the paddocks for two farms (– Farm1, – Farm2).

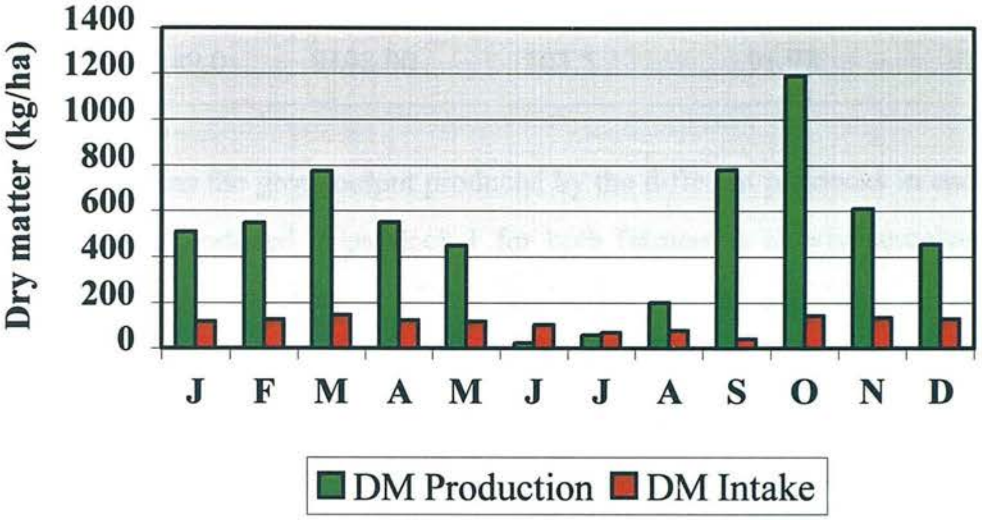


Figure 9.4. Relation between monthly animal dry matter intake and dry matter production in paddock3, farm1.

Table 9.5 summarises the live weight and economic output produced by the two farms. The price per kilogram obtained by FARMER1 was higher than that made by FARMER2. In contrast, the income per hectare obtained by FARMER2 was higher as a result of the goal to sell more animals during the year with the minimum live weight request by the market. To produce 8.9 kg/ha/year more than FARMER1, FARMER2 used 104 kg concentrate with an extra cost of US$ 13,5 per hectare. Therefore, a simple economic calculation indicates that the income obtained by FARMER2 was US$ 78,48 per ha/year. However, the indirect gain to the farm as reduction of nutrients extracted from the system (reduction DM utilisation, table 9.4) and residual nutrients incorporated to the soil must be evaluated in the future. Also, the indirect impact on industrial labour outside farm environment (e.g. manufacturing employee) needs to be evaluated.

Table 9.5. Simulated liveweight and gross economic output.

Farm	Live weight Kg/Year	Produced US$/Year	Live weight Kg/Ha/Year	Income US$/Ha/Year	Income US$/Kg
Farm1	9457.0	8839,00	94.6	88,39	0,93
Farm2	10349.0	9198,00	103.5	91,98	0,89

Table 9.6 contains the gross output produced by the different paddocks in each farm. The high value produced in paddock 1 for both farmers is clearly perceived. This happens due to the contribution of rice production and the possibility of increased animal live weight produced per hectare on improved pastures. This fact is clearer in farm1. The difference between paddocks in farm2, is reduced by strategies such as animal supplementation on natural pasture. The income produced by rice in farm1 was US$ 162.5 per hectare and US$ 163.8 per hectare in farm2. These values are twice that obtained with animal on natural pasture. This fact and the increase animal live weight produced per hectare on improved pastures, emphasises the importance of investigating the beef cattle-rice integration process in Rio Grande do Sul.

Table 9.6. Gross economic output produced per each paddock.

Paddock	Farm	Liveweight Kg/Ha/Year	Rice* Kg/Ha/Year	Gross US$/Ha/Year
Paddock1	Farm1	141.0	750	293.6
	Farm2	113.4	750	264.7
Paddock2	Farm1	80.78	-	75.1
	Farm2	95.14	-	84.7
Paddock3	Farm1	77.13	-	71.7
	Farm2	96.21	-	85.6

* 15% of harvest 5 Ton/ha/year

9.4. Simulated scenarios for farm1

To demonstrate the potential use of FIDM as scenario generator, the FARMER1 "natural" information was used as described in section 9.2., and a new climatic database (Database2) was used to compare the final scenario generated by the model. The average daily temperatures (°C) are presented in figure 9.5.

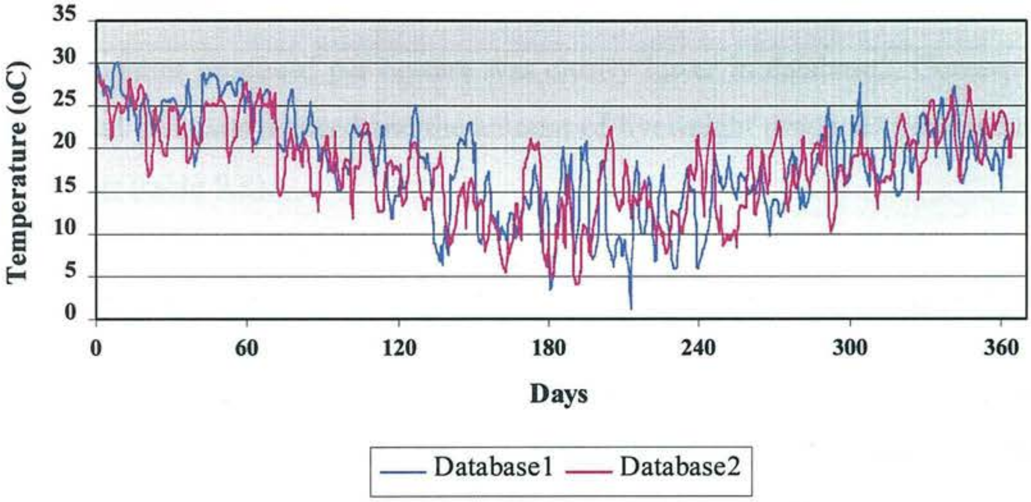


Figure 9.5. Average temperature obtained from two different databases.

Database1 was used in the previous section and considered here as a good climatic year was compared with database2, which represents a bad year. The average temperature for database2 was lower during 120 of the first 180 days of the year. During the rest of the year, the number of days with low average temperature was similar to that in database1.

The dry matter scenario generated according to the two climatic databases is shown in table 9.7.

Table 9.7. Simulated dry matter (DM) produced per paddock with two different climatic databases.

Paddock	Database	Produced DM/Ha/Year	Intake DM/Ha/Year	Utilisation %
Paddock1	Database1	2948.4	666.1	22.6
	Database2	2673.8	641.6	23.9
Paddock2	Database1	6088.1	1530.2	25.1
	Database2	5599.1	1432.2	25.6
Paddock3	Database1	5992.8	1371.4	22.8
	Database2	5522.5	1371.2	24.3

The dry matter produced per hectare was clearly lower in database2. Consequently, the animal gain was reduced and the amount of liveweight produced per hectare was also lower (table 9.8).

Table 9.8. Simulated liveweight and gross economic output for two different climatic databases.

Farm	Live weight Kg/Year	Produced US$/Year	Live weight Kg/Ha/Year	Income US$/Ha/Year	Income US$/Kg
Database1	9457.0	8839,00	94.6	88,39	0,93
Database2	7668.0	7156,82	76.7	71,57	0,93

Although, the price received per kilogram was the same, the amount of money received per hectare was reduced by US$ 16.8 using database2 as a direct effect of animal production per hectare.

In this section, how the FIDM generated scenarios for the farmer, considering climatic changes was shown. The sub-models components of FIDM allow the generation of other scenarios considering other variables as such as fertiliser, feed supplementation, and price variation. This flexibility is considered important as a tool to help the farmer in future decisions in a constantly changing socio-bio-economic environment as seen in the present.

9.5. Concluding remarks

The main goal of this chapter was to describe how the FIDM works at the farm level. The integrated approach for the socio-bio-economic model was presented. The hypothetical behaviour of farmers was used as "natural" information and the main "simulated" information available at the time of decision was presented. Finally, the flexibility of the model construction can be observed. Future work in the field will generate the feedback necessary to improve the quality of the model as a tool to help farmers in their decisions.

The levels of details in the component sub-models of FIDM are linked with the importance that they represent for the whole system. Some mechanistic models can be replaced by stochastic models, when this component is treated superficially in the whole system. The rice production model in this work uses the stochastic approach to deal with rice yield. This was accepted in this case because the rice production was used as input to the whole system. However, clear indication has been made in Chapter 7 to use a mechanistic model, which will allow farmer intervention during the growing season.

CHAPTER 10

GENERAL CONCLUSIONS

The main goal of the work developed in this thesis was to produce a methodology to incorporate the farmer as a variable within the farming system. In the past systems research was approached by studying physical models. The cost and the unreal conditions created by the research environment in these models were the main criticism made to this physical approach.

Over the last decade, researchers have produced models to help farmers in their decisions from simple ones such as how to improve supplement profitability, to complex decisions in crop management. In the literature, single function models are more abundant than complex integrated ones.

Whole system models have to deal with the interactions within the system. At present researchers have powerful computers and languages to mimic the real environment of farms. The physical links can be simulated in a satisfactory way as can be seen in the literature (e.g. DSSAT shell). The challenge is to put the psychological link (human behaviour) into whole system models. As discussed in Chapters 2 and 3, the available models (e.g. DSSAT, SPUR) still fail when trying to incorporate farmer behaviour as an important component of the system. Some reasons are:

(i) Modellers adopted the same procedures as researchers in their "physical models" as manager of the system. Consequently, the behaviour of the farmer remains outside of the "farmer system model".

(ii) The gravity of this error is directly linked to the complexity of the system. Commercial farms with a few crops are less susceptible than the animal-crop enterprise, because of the importance of human behaviour in the animal systems (decision-maker).

To escape the "research manager" approach, the methodology developed put the individual farmer as the main agent of the system. To demonstrate the methodology a simple system was simulated. In next step more research is needed to extend the models described in this thesis and produce new ones adapted to different systems existent in the south of the state of Rio Grande do Sul.

Mechanistic models allow the researchers to deal with the impact of new technologies on the whole system. The main goal of the mechanistic grassland model developed in this thesis was to quantify the influence of environmental conditions on each sub-system (soil, plant or animal) and thereby the whole system. The possibility of simulating the impact of technologies on the whole system under different environmental conditions is the main contrast between the "physical model" and the "simulated model".

Partial conclusions and recommendations linked with each chapter were made. Chapter 2 emphasises the economic and social importance of beef cattle and rice production in the Southwest of Rio Grande do Sul. In this chapter, a brief description of production systems was made, so that the complexity could be perceived. Technological advice has been given to farmers throughout the last decades to try to increase productivity and to help with their decisions on the farm. Traditional research and extension methods have been questioned mainly due to the cost and time of providing solutions for problems experienced by farmers. Considering their characteristics, computer models are an important tool in supporting technological advice and in improving agricultural system performance in the Southwest of Rio Grande do Sul.

Chapter 3 introduced the approach adopted in the thesis. The framework supplied farmer behaviour as a sub-model inside the whole model. This sub-model is flexible to capture the individual reactions of farmer in the socio-bio-economic environment by which he or she is affected.

To simulate grassland production from single species, the sub-model described in chapter 4 has shown consistent outputs when contrasted with data from the literature. A lot of work is still needed, in case of multispecies simulations. This is to be expected because of the complex relationships and the lack of information on some parameters for natural species. Parameters needed to simulate photosynthesis for the main species of natural pasture must be obtained in future experiments. The identification of these knowledge gaps are important results from the pasture model. Future research on natural species present in the Rio de la Plata grassland ecosystem must address this lack of knowledge. In this way, knowledge of physiological processes can increase the performance of models and consequently the output in support of decision systems used by farmers and policy makers.

The soil sub-model simulates soil N, P and water available for plants in a simple but mechanistic way. It combines equations from different soil models and includes original equations, mainly in the animal excreta decomposition sub-model.

In the animal model, described in chapter 6, representative individuals from a normal distribution of animals within the herd, represents the physiological process of intake and food digestion, minimising the machine time required.

In chapter 7, a simple approach was used to deal with rice production and its economic impact in the system. However, the main inputs and outputs are considered to represent the real economic environment that affects decisions taken by the beef cattle farmer in a dynamic way. Existing economic models adapted from the Brazilian economic reality can be used without modifications. Further work is necessary to increase the representation of the economic environment, mainly in more complex systems found in the region. The crop models available from the DSSAT shell need to be adapted to permit the farmer to interact at real time during the growing process. This interaction will permit for example modification of the number of plants/m^2.

Chapter 8 described the main questions asked by FIDM. The matrix of decisions generated by the farm decision model is a key factor in learning about the system. In chapter 9 the integrated approach to the socio-bio-economic model was presented. The hypothetical behaviour of farmers was used as "natural" information and the main "simulated" information available at the time of decision was presented. The flexibility of the model could be observed and future work at the field level will generate the necessary feedback to improve the quality of the model as a tool to help farmers in their decisions.

The FIDM is a whole farm model that incorporates the socio-bio-economic environment of the farm. Although the biological models have been developed more deeply, clear indications were made regarding the climatic, economic and farm behaviour models, which need to be addressed in the next step of development, when this prototype will be translated to a powerful language (e.g. Java, Delphi).

The main goal of this work was to develop a tool to use in the beef cattle/rice enterprise in south of Rio Grande do Sul. The approach of FIDM permits the incorporation of a sub-model that deals with activities developed by farmers outside of the farm, a common fact in small farms in Latin America.

As the outputs generated by the FIDM originated at farm level the FIDM can be used at the institutional level as a tool to classify farmers by their technological stage of development. Also, it indicates the likely level of adoption of the individual technology into the whole system (e.g. silage/hay supplementation).

Finally, the individual response in front of each situation is unique. The decision taken is the result of individual's lifetime beliefs. Therefore, the outputs generated by the FIDM are the results of the farmer's beliefs, and the scenario generated, is the solution for him/her. To consider new technology, farmers must replace some beliefs, and this must be considered by researchers and extension workers who aim to improve the adoption of technology by farmers. The final scenario generated at the first modelling session represents the initial technological stage of the farmer. Dialogue between extension workers and farmers permit the interactive evaluation of existing technologies. Flexibility in model construction permits incorporation of new technologies as and when information becomes available.

Further development of the decision model is best done in a user group partnership with real farmers and their advisors.

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APPENDICES

Appendix 4.1. Variables used in the plant sub-model.

State variables

$Leaffo_s$	Senescing leaves	$g\ m^{-2}$
$Leaff_s$	Growing leaves	$g\ m^{-2}$
$Leafs_s$	First fully expanded leaves	$g\ m^{-2}$
$Leaft_s$	Second fully expanded leaves	$g\ m^{-2}$
$Propagule_s$	Plant propagule	$g\ m^{-2}$
$Racfo_s$	Fourth live active root compartment	$g\ m^{-2}$
$Racf_s$	First live active root compartment	$g\ m^{-2}$
$Racs_s$	Second live active root compartment	$g\ m^{-2}$
$Ract_s$	Third live active root compartment	$g\ m^{-2}$
$RDead_s$	Root dead compartment	$g\ m^{-2}$
$Rstfo_s$	Fourth live structural root compartment	$g\ m^{-2}$
$Rstf_s$	First live structural root compartment	$g\ m^{-2}$
$Rsts_s$	Second live structural root compartment	$g\ m^{-2}$
$Rstt_s$	Third live structural root compartment	$g\ m^{-2}$
SC_s	Substrate carbon	$g\ m^{-2}$
$Seedpro_s$	Seed compartment	$g\ m^{-2}$
$ShDead_s$	Shoot stand dead compartment	$g\ m^{-2}$
SN_s	Substrate nitrogen	$g\ m^{-2}$
SP_s	Substrate phosphorus	$g\ m^{-2}$
$Stemfo_s$	Senescing sheath-stem	$g\ m^{-2}$
$Stemf_s$	Growing sheath-stem	$g\ m^{-2}$
$Stems_s$	First fully expanded sheath-stem	$g\ m^{-2}$
$Stemt_s$	Second fully expanded sheath-stem	$g\ m^{-2}$

Rate variables

ϕN_s	Recyclable fraction of N	$g\ m^{-2}$
ϕP_s	Recyclable fraction of P	$g\ m^{-2}$
γR_s	Dimensional function that determine the relative partitioning to root	-
γSh_s	Dimensional function that determine the relative partitioning to shoot	-
$AlloCProp_s$	C allocated to the propagule	$g\ m^{-2}$
$AlloSeedPhy_s$	Allocation of nutrients from seed to phytomass	$g\ m^{-2}$
BTL_s	Biomass trampled by livestock	$g\ m^{-2}$
$CAlloSeed_s$	C allocation to seed	$g\ m^{-2}$

$\mathrm{Cbalance}_s$	C balance in the plant	-
CGMax_s	C needed to maximum growth	g m^{-2}
CInput_s	Daily input of C from photosynthesis	g m^{-2}
DDTG_s	Degree-day from germination to emergence	^{O} days
$\mathrm{Emergcont}_s$	Counter start after emergence of plant	-
$\mathrm{ENplant}_s$	Effect of N in the plant (scalar)	-
ENSoil_s	Effect of N in the soil (scalar)	-
$\mathrm{EShHarv}_s$	Effective shoot harvest	g m^{-2}
$\mathrm{EShHarv}_s$	Effective harvest by plant or functional group	g m^{-2}
ESMPP_s	Effect of soil moisture on plant processes (scalar)	-
ETPP_s	Effect of temperature on plant processes (scalar)	-
FCDR_s	Flows of C from live root to dead root	g m^{-2}
FCDSH_s	Flows of C from live shoot to dead shoot	g m^{-2}
FCShD_s	Fractions of C in dead shoot material	g m^{-2}
Flam_s	Fraction of new shoot growth partitioned to lamina.	-
FNDR_s	Flows of N from live root to dead root	g m^{-2}
FNDSH_s	Flows of N from live shoot to dead shoot	g m^{-2}
FNShD_s	Fractions of N in dead shoot material	g N (g structure)$^{-1}$
$\mathrm{FOLeaffo}_s$	Fluxes out of the fourth leaf compartment	g m^{-2}
$\mathrm{FORAcfo}_s$	Fluxes out of the fourth active root compartment	g m^{-2}
FORfo_s	Total flux out of the live root compartment	g m^{-2}
$\mathrm{FORStfo}_s$	Fluxes out of the fourth structural root compartments	g m^{-2}
FOShfo_s	Total flux out of the live shoot compartment	g m^{-2}
$\mathrm{FOStemfo}_s$	Fluxes out of the fourth sheath-stem compartments	g m^{-2}
FPDR_s	Flows of P from live root to dead root	g m^{-2}
FPDSH_s	Flows of P from live shoot to dead shoot	g m^{-2}
$\mathrm{FPropSeed}_s$	Flow from propagule to seed	g m^{-2}
FPShD_s	Fractions of P in dead shoot material	g P (g structure)$^{-1}$
Gc_s	Growth coefficient	g m^{-2}
GR_s	Synthesis of growth root structural dry matter	g m^{-2}
GSh_s	Synthesis of growth shoot structural dry matter	g m^{-2}
HarvSh_{si}	Harvest shoot dry weight	g m^{-2}
LAI_{si}	Leaf area index	-
$\mathrm{LeafReFo}_s$	Proportion of material in the fourth leaf compartment that remain on the field	g (g structure)$^{-1}$
$\mathrm{LeafReT}_s$	Proportion of material in the third leaf compartment that remain on the field	g (g structure)$^{-1}$

Meff	Mycorrhizal effect (scalar)	-
MProp$_s$	Propagule maintenance respiration rate	$g\ m^{-2}$
NAlloSeed$_s$	NC allocation to seed	$g\ m^{-2}$
NGMax$_s$	N needed to maximum growth	$g\ m^{-2}$
NP$_s$	Effective amount of N uptake by the plant	$g\ m^{-2}$
PGMax$_s$	P needed to maximum growth	$g\ m^{-2}$
PGR$_s$	Potential growth rate	$g\ m^{-2}$
PhStage$_s$	Plant phenological stage index	-
Plig$_s$	Percentage of lignin (Plig$_s$)	g (g structure)$^{-1}$
PNUGR$_s$	Potential N uptake per gram of roots	$g\ m^{-2}$
PNU$_s$	Potential N uptake by roots	$g\ m^{-2}$
PSAPropagule$_s$	Rate of synthesis of new structural dry matter in shoot allocated to propagule.	$g\ m^{-2}$
RDC$_s$	C dead root compartment	$g\ m^{-2}$
RDN$_s$	N dead root compartment	$g\ m^{-2}$
RDP$_s$	P dead root compartment	$g\ m^{-2}$
Rg$_s$	C loss by substrate pool to growth	$g\ m^{-2}$
Rm$_s$	C loss by substrate pool to maintenance	$g\ m^{-2}$
Rmug$_s$	C loss by substrate pool to mineral uptake	$g\ m^{-2}$
R$_s$	Live structural root	$g\ m^{-2}$
SCSR$_s$	C supplied from recycled roots	$g\ m^{-2}$
SCS$_s$	Supply of C from plant recycling	$g\ m^{-2}$
SCS$_s$	Rates of supply C from senescence	$g\ m^{-2}$
SCSSh$_s$	C supplied from recycled shoots	$g\ m^{-2}$
SeedAvGerm$_s$	Seed available to germination from sowing or bank of seeds in the soil	$g\ m^{-2}$
SeedBank$_s$	Bank of seeds in the soil	$g\ m^{-2}$
ShDC$_s$	C dead shoot compartment	$g\ m^{-2}$
ShDN$_s$	N dead shoot compartment	$g\ m^{-2}$
ShDP$_s$	P dead shoot compartment	$g\ m^{-2}$
ShHarvTot	Total sward harvest	$g\ m^{-2}$
Sh$_s$	Live structural shoot	$g\ m^{-2}$
SNSR$_s$	N supplied from recycled roots	$g\ m^{-2}$
SNS$_s$	Supply of N from plant recycling	$g\ m^{-2}$
SNS$_s$	Rates of supply N from senescence	$g\ m^{-2}$
SNSSh$_s$	N supplied from recycled shoots	$g\ m^{-2}$
SPSR$_s$	P supplied from recycled roots	$g\ m^{-2}$
SPS$_s$	Rates of supply P from senescence	$g\ m^{-2}$

$SPSSh_s$	P supplied from recycled shoots	$g\ m^{-2}$
$StemReFo_s$	Proportion of material in the fourth stem compartment that remain on the field	g (g structure)$^{-1}$
$StemReT_s$	Proportion of material in the third stem compartment that remain on the field	g (g structure)$^{-1}$
$TEFL_s$	Time to end the first leaf as growing leaf	days^{-1}
$TEFoL_s$	Time to end the senescing leaf	days^{-1}
$TEFoR_s$	Time to end the fourth compartment root	days^{-1}
$TEFR_s$	Time to end the first compartment root	days^{-1}
$TEmerg_s$	Time needed for the seed to appear at the surface of the soil	days^{-1}
$TESL_s$	Time to end as first fully expanded leaf	days^{-1}
$TESR_s$	Time to end the second compartment root	days^{-1}
$TETL_s$	Time to end the second fully expanded leaf	days^{-1}
$TETR_s$	Time to end the third compartment root	days^{-1}

Appendix 4.2 Parameter used in the Italian ryegrass sub-model.

Parameters	Description	Unit	Value	Origin
Alpha_s	Leaf photosynthetic efficiency	$g\ CO_2\ J^{-1}$	10^{-5}	Johnson & Thornley, 1985
AlphaM_s	Respiration costs of mineral uptake	$g\ C\ (g\ mineral)^{-1}$	0.5	Johnson & Thornley, 1985
Aswfrep_s	Available soil water threshold below which the reproductive phenostage can end	-	0.05	Moore et al., 1997
DDcflow_s	Degree-day for start flowering	° days	120	-
DDcrep_s	Degree-day for start reproduction	° days	0	-
DDcsen_s	Degree-day for start senescence	° days	900	-
DDpcs_s	Degree-day need for centimetre of seed depth in the soil	° days	15	Alocija & Ritchie, 1988
DecayR_s	Decay rate from dead root to litter	-	0.12	-
DecaySh_s	Decay rate from dead shoot to litter	-	0.1	-
DLcrep_s	Day length for commencement of reproduction	h	13	-
DTC_s	Drought tolerance coefficient	-	0.6	-
Etamslm_s	Incremental specific leaf area parameter	$m^2\ (g\ structural\ dry\ matter)^{-1}$	0.025	Johnson & Thornley, 1985
FC_s	Fractional carbon content of live plant structure	$g\ C\ (g\ structure)^{-1}$	0.45	Johnson & Thornley, 1985
FCR_s	Fractional carbon content of degradable structure	$g\ C\ (g\ structure)^{-1}$	0.4	Johnson & Thornley, 1985
FCS_s	Fractional carbon content of seed	$g\ C\ (g\ structure)^{-1}$	0.7	-
FLamrep_s	Fraction of new shoot growth partitioned to lamina in reproductive stage	-	0.3	-
FLamveg_s	Fraction of new shoot growth partitioned to lamina in vegetative stage	-	0.7	-

$FLigFlow_s$	Fraction lignin in pre-flowering stage	-	0.15	-
$FLigRep_s$	Fraction lignin in reproductive stage	-	0.2	-
$FLigSen_s$	Fraction lignin in senescence stage	-	0.29	-
$FLigVeg_s$	Fraction lignin in vegetative stage	-	0.03	-
FN_s	Fractional nitrogen content of live plant structure	g N (g structure)$^{-1}$	0.0225	-
FNR_s	Fractional nitrogen content of degradable structure	g N (g structure)$^{-1}$	0.135	-
FNS_s	Fractional nitrogen content of seed	g N (g structure)$^{-1}$	0.014	-
FP_s	Fractional phosphorus content of live plant structure	g P (g structure)$^{-1}$	0.002	-
FPR_s	Fractional phosphorus content of degradable structure	g P (g structure)$^{-1}$	0.01	-
FPS_s	Fractional phosphorus content of seed	g P (g structure)$^{-1}$	0.0017	-
$Frostresist_s$	Plant frost resistence	° C	-6.0	-
$GammarOpt_s$	Rate parameter for root turnover at optimum temperature	day^{-1}	0.03	Johnson & Thornley, 1985
$GammashOpt_s$	Rate of leaf appearance at optimum temperature	day^{-1}	0.15	Johnson & Thornley, 1985
$GProp_s$	Proportion of seed germination to phytomass	-	0.8	-
K_s	Canopy extinction coefficient	-	0.63	Ludlow, 1985
$LePhoto_s$	Light saturated leaf gross photosynthetic rate parameter	(g CO2 /m2 (leaf)/sec.).	0.0006	Johnson & Thornley, 1985
$LSeedGerm_s$	Light available for seed germination	m^2 leaf m^2 ground	0.5	-
$MaxT_s$	Maximum temperature for plant activity	° C	37.0	Hanson et al., 1988
MC	Molecular mass of substrate carbon (sucrose) relative to ^{12}C	-	28.5	Johnson & Thornley, 1985
$MinT_s$	Minimum temperature for plant activity	° C	3.0	Hanson et al., 1988
$MLArep_s$	Minimum leaf area to start flowering	m^2 leaf m^2 ground	0.5	-
MN	Molecular mass of substrate nitrogen (nitrate) relative to ^{14}N	-	62	Johnson & Thornley, 1985
$MNSoil_s$	Minimum N soil without affect mobility	g m^2	8.0	-

MP	Molecular mass of substrate phosphorus (phosphate) relative to ^{15}P	-	95	-
$MPSoil_s$	Minimum P soil without affect mobility	$g\ m^2$	0.6	-
$MrOptf_s$	Maintenance coefficient of first root structural component	day	0.02	Johnson & Thornley, 1985
$MrOpts_s$	Maintenance coefficient of second root structural component	day	0.02	Johnson & Thornley, 1985
$MrOptt_s$	Maintenance coefficient of thirst root structural component	day	0.015	Johnson & Thornley, 1985
$MrOptfo_s$	Maintenance coefficient of fourth root structural component	day	0.01	Johnson & Thornley, 1985
$MshOptf_s$	Maintenance coefficient of first shoot structural component	day	0.02	Johnson & Thornley, 1985
$MshOpts_s$	Maintenance coefficient of second shoot structural component	day	0.02	Johnson & Thornley, 1985
$MshOptt_s$	Maintenance coefficient of thirst shoot structural component	day	0.015	Johnson & Thornley, 1985
$MshOptfo_s$	Maintenance coefficient of fourth shoot structural component	day	0.01	Johnson & Thornley, 1985
$OptT_s$	Optimum temperature for plant activity	° C	20.0	Johnson & Thornley, 1985
$PAlProp_s$	Proportion of growth structure allocated to propagule	-	0.4	-
$PAlProSeed_s$	Proportion of propagule allocated to seed	-	0.04	-
$PMfrost_s$	Proportion of mortality by frost	-	0.1	-
$PSeedHarv_s$	Proportion of seed harvested	-	0	-
SdN_s	Structural N degradation parameter	-	0.002	Johnson & Thornley, 1985
SdP_s	Structural P degradation parameter	-	0.0002	-
$Seed_s$	Amount of seed sowing	$g\ m^2$	2.5	-
SGR_s	Maximum growth rate	-	0.11	-
$Sowdepth_s$	Sowing depth	cm	2.0	-
$SRact_s$	Structural root activity	-	0.5	-
Tau_s	Leaf transmission coefficient	-	0.1	Johnson & Thornley, 1985

Theta$_s$	Leaf photosynthesis parameter	-	0.95	Johnson & Thornley, 1985
TMaxTGerm$_s$	Temperature maximum threshold to start germination	° C	20.0	-
TMinTGerm$_s$	Temperature minimum threshold to start germination	° C	5.0	-
Y$_s$	Yield factor for structural growth	-	0.75	Johnson & Thornley, 1985
Zetaslm$_s$	Incremental specific leaf area parameter	-	2.5	Johnson & Thornley, 1985

The subscript $_s$ means species.

Appendix 4.3. Parameter used in the natural pasture sub-model.

Parameters*	C_3 Species	C_4 Species
Alpha_s	10^{-5}	10^{-5}
AlphaM_s	0.5	0.5
Aswfrep_s	0.05	0.05
DDcflow_s	120	50
DDcrep_s	0	0
DDcsen_s	900	300
DDpcs_s	15	15
DecayR_s	0.03	0.03
DecaySh_s	0.075	0.075
DLcrep_s	12.5	10.5
DTC_s	0.6	0.35
Etamslm_s	0.025	0.025
FC_s	0.45	0.45
FCR_s	0.4	0.4
FCS_s	0.7	0.7
FLamrep_s	0.3	0.3
FLamveg_s	0.7	0.7
FLigFlow_s	0.15	0.15
FLigRep_s	0.2	0.2
FLigSen_s	0.29	0.29
FLigVeg_s	0.03	0.03
FN_s	0.017	0.014
FNR_s	0.087	0.072
FNS_s	0.0096	0.0096
FP_s	0.0008	0.0008
FPR_s	0.0048	0.0048
FPS_s	0.0007	0.0007
Frostresist_s	-6.0	0
GammarOpt_s	0.03	0.03
GammashOpt_s	0.15	0.15
GProp_s	0.8	0.8
K_s	0.5	0.5
LePhoto_s	0.0006	0.0006
LSeedGerm_s	1	1
MaxT_s	37.0	45
MC	28.5	28.5

MinT$_s$	3.0	5.0
MLArep$_s$	0.5	0.4
MN	62	62
MNSoil$_s$	7.0	6.0
MP	95	95
MPSoil$_s$	0.5	0.4
MrOptf$_s$	0.02	0.02
MrOpts$_s$	0.02	0.02
MrOptt$_s$	0.015	0.015
MrOptfo$_s$	0.01	0.01
MshOptf$_s$	0.02	0.02
MshOpts$_s$	0.02	0.02
MshOptt$_s$	0.015	0.015
MshOptfo$_s$	0.01	0.01
OptT$_s$	20.0	27.0
PAlProp$_s$	0.4	0.05
PAlProSeed$_s$	0.04	0.04
PMfrost$_s$	0.1	0.3
PSeedHarv$_s$	0	0
SdN$_s$	0.002	0.002
SdP$_s$	0.0002	0.0002
Seed$_s$	2.5	2.5
SGR$_s$	0.06	0.12
Sowdepth$_s$	2.0	2.0
SRact$_s$	0.5	0.5
Tau$_s$	0.1	0.1
Theta$_s$	0.95	0.95
TMaxTGerm$_s$	15	27.0
TMinTGerm$_s$	5.0	15.0
Y$_s$	0.75	0.75
Zetaslm$_s$	2.5	2.5

* Description and units see appendix 4.2. The subscript $_s$ means functional group C_3 and C_4.

Appendix 5.1. Variables used in the soil sub-model.

State variables

Mineral sub-model

$CMet_{sl}$	C metabolic from surface litter	$g\ m^{-2}$
$CMet_{rl}$	C metabolic from root litter	$g\ m^{-2}$
NApl	N available to plant	$g\ m^{-2}$
NMfaeces	N metabolic from faeces	$g\ m^{-2}$
NMetsl	N metabolic from surface litter	$g\ m^{-2}$
NMetrl	N metabolic from root litter	$g\ m^{-2}$
PApl	P available to plant	$g\ m^{-2}$
PIfaeces	P inorganic from faeces	$g\ m^{-2}$
PMetsl	P metabolic from surface litter	$g\ m^{-2}$
PMetrl	P metabolic from root litter	$g\ m^{-2}$
SecP	Secondary P	$g\ m^{-2}$

Water sub-model

W_1	actual soil moisture content in surface layer	$cm^3 H_2O\ cm^{-2} soil$
W_z	actual soil moisture content in layer z (2 ... n)	$cm^3 H_2O\ cm^{-2} soil$

Rate variables

Mineral sub-model

CFsl	C flow from metabolic surface litter to soil organic matter	-
CFrl	C flow from metabolic root litter to soil organic matter	-
CNsl	Content of N immobilized from structural surface litter	$g\ m^{-2}$
CNrl	Content of N immobilized from root surface litter	$g\ m^{-2}$
CPsl	Content of P immobilized from structural surface litter	$g\ m^{-2}$
CPrl	Content of P immobilized from root surface litter	$g\ m^{-2}$
Csl	C in surface litter	$g\ m^{-2}$
Crl	C in root litter	$g\ m^{-2}$
ETBDf	Effect of temperature in breakdown of faeces	-
EMD	Effect of moisture on decomposition	-
ETD	Effect of temperature on decomposition	-
EMDf	Effect of moisture in faeces degradation	-
ETDf	Effect of temperature in faeces degradation	-
ETMFavol	N losses through ammonium gas in fertiliser	-
ETMUavol	N losses through ammonium gas in urine	-

Fmrl	Metabolic fraction of root litter	-
Fmsl	Metabolic fraction of surface litter	-
ISP	Flow from SecP to PApl	-
NL	Leaching N from root zone	g m^{-2}
PL	Leaching P from root zone	g m^{-2}
Lrl	Lignin in root litter	g m^{-2}
Lsl	Lignin in surface litter	g m^{-2}
Nlvaf	N loss through ammonium volatilization	g m^{-2}
Msoil	Moisture in soil (scalar)	-
Nfaeces	N from faeces	g m^{-2}
NImrl	N immobilised from metabolic root litter	g m^{-2}
NImsl	N immobilised from metabolic surface litter	g m^{-2}
NFa	N mineralization from faeces	g m^{-2}
NFe	N mineralization from fertiliser	g m^{-2}
NSOM	N mineralization from SOM	g m^{-2}
NStrusl	N structural from surface litter	g m^{-2}
NStrurl	N structural from root litter	g m^{-2}
NMrl	N mineralization from metabolic root litter	g m^{-2}
NMsl	N mineralization from metabolic surface litter	g m^{-2}
NSsl	N Imobilization from structural surface litter	g m^{-2}
NSrl	N Imobilization from structural root litter	g m^{-2}
Nsl	N in surface litter	g m^{-2}
NR	N from rain	g m^{-2}
Nrl	N in root litter	g m^{-2}
NU	N mineralization from urine	g m^{-2}
Nurine	N from urine	g m^{-2}
OclP	Flow from SecP to Oclude P	-
OSP	Flow from PApl to SecP	-
PFe	P from fertiliser to PApl	g m^{-2}
Pfaeces	P from faeces	g m^{-2}
PiFaeces	Inorganic fraction of P in faeces	-
PImsl	P from metabolic surface litter	g m^{-2}
PImrl	P from metabolic root litter	g m^{-2}
PFa	P mineralization from faeces	g m^{-2}
PMrl	P from metabolic root litter	g m^{-2}
PMsl	P from metabolic surface litter	g m^{-2}
PminSOM	P mineralization from SOM	g m^{-2}
PR	P from rain	g m^{-2}

Prl	P in root litter	$g\ m^{-2}$
PSecfe	P from fertiliser to SecP	$g\ m^{-2}$
Psl	P in surface litter	$g\ m^{-2}$
PStrusl	P structural from surface litter	$g\ m^{-2}$
PStrurl	P structural from root litter	$g\ m^{-2}$
Tsoil	Soil mean temperature	^{o}C

Water sub-model

a_1	dimensionless soil moisture number	-
Beva	reduction factor accounting for the influence of soil moisture content of the surface layer on evaporation	-
$Btra_z$	reduction factor to account the effect of soil moisture on transpiration in layer z	-
ETO	potential evapotranspiration	$mm\ day^{-1}$
EVA	total actual soil evaporation	$cm^3H_2O\ cm^{-2}soil\ day^{-1}$
EVA_z	actual soil evaporation in layer z	$cm^3H_2O\ cm^{-2}soil\ day^{-1}$
EVAmp	potential bare soil evaporation	$cm^3H_2O\ cm^{-2}soil\ day^{-1}$
EVAp	potential soil evaporation	$cm^3H_2O\ cm^{-2}soil\ day^{-1}$
INF_z	infiltration in layer z=1, n-1 percolation in layer z=n	$cm^3H_2O\ cm^{-2}soil\ day^{-1}$
IRR	irrigation	$cm^3H_2O\ cm^{-2}soil\ day^{-1}$
LAI	leaf area index	-
RUN	runoff	$cm^3H_2O\ cm^{-2}soil\ day^{-1}$
TRA_z	actual plant transpiration in layer z	$cm^3H_2O\ cm^{-2}soil\ day^{-1}$
TRAmp	potential transpiration for a closed canopy	$cm^3H_2O\ cm^{-2}soil\ day^{-1}$
TRAp	potential plant transpiration	$cm^3H_2O\ cm^{-2}soil\ day^{-1}$
$RDef_z$	weighing factor accounting for withdrawn of moisture due to transpiration in layer z	-

Appendix 5.2. Parameters used in the soil sub-model.

Parameters	Description	Unit	Value	Origin
Mineral sub-model				
CN	C:N ratio soil type dependence	-	10	-
CP	C:P ratio soil type dependence	-	110	-
DBD	Dry bulk density	g cm^3	1.0	Rowell, 1994
ESNo	Estimates of soil N mineralization potential	ppm	32.1	Parentoni et al., 1988
Kas	Maximum decomposition to secondary P	-	0.0016	Parton et al., 1987
Kfbd	Maximum faeces breakdown	-	0.024	-
Kfn	Maximum rate of N metabolic faeces decomposition	-	0.024	-
Krl	Maximum rate of metabolic root litter decomposition	-	0.05	-
Ksa	Maximum decomposition to available P	-	7.2^{-5}	Parton et al., 1987
Ksl	Maximum rate of metabolic surface litter decomposition	-	0.04	-
Kso	Maximum decomposition from secondary P to occluded P	-	3.3^{-8}	Parton et al., 1987
MinRate	Mineralization rate constant at 35 °C	-	0.09	Parentoni et al., 1988
NP	N:P ratio soil type dependence	-	11	-
RAE	Relative agronomic effectiveness	-	0.8	Leon et al., 1986
Water sub-model				
aa	aa is a constant adjusted so $\sum Wf_z=1$	-	1.3185	-
alpha	albedo reflection coefficient surface	-	0.2	Supit et al., 1994

CN_I	dry antecedent moisture condition curve number	-	75	Springer & Lane, 1987
d_z	thickness of layer z	cm	4;4;4;4;4	-
db_z	depth to bottom of soil layer z	cm	4;8;12;16;20	-
dm_z	mean depth of soil layer z	cm	2;6;10;14;18	-
dn	density of water	cm^3 H_20 cm^3	1.0	-
ds	depth of soil to bottom of last layer	cm	20.0	-
Frt	fraction of roots in the soil profile	-	0.9999	Verberne, 1992
Kdf	extinction coefficient for diffuse radiation	-	0.6	Verberne, 1992
km	extinction coefficient for moisture withdrawal	-	0.25	Verberne, 1992
srl_z	specific root length in soil layer z	m g^{-1}	100;100;100;150;200	Verberne, 1992
tdt_z	depth of the upper boundary layer z	cm	0;4;8;12;16; 20	-
$Wair_z$	water content at air dryness in layer z	cm^3 H_2O cm^2 soil	0.04	Rowell, 1994
Wfc_z	water content at field capacity in layer z	cm^3 H_2O cm^2 soil	0.313	Rowell, 1994
Wsat	Water content at saturation	cm^3 H_2O/cm^3 soil	0.49	Rowell, 1994
Wwp_z	water content at wilting point in layer z	cm^3 H_2O cm^2 soil	0.127	Rowell, 1994

Appendix 6.1. Variables used in the animal sub-model.

Rate variables

$AESP1_p$	Number of animals in the extrapolation area 1 from early maturing breed	-
$AESP2_p$	Number of animals in the extrapolation area 2 from early maturing breed	-
$AESP3_p$	Number of animals in the extrapolation area 3 from early maturing breed	-
$AESP4_p$	Number of animals in the extrapolation area 4 from early maturing breed	-
$AESP5_p$	Number of animals in the extrapolation area 5 from early maturing breed	-
$AnInE_p$	Number of animals incorporated to the early maturing breed	-
$AnOutE_p$	Number of animals removed from the early maturing breed	-
$AnOut_p$	Number of animals removed from the paddock	-
$AvAnE_p$	Average of animals in the early maturing breed	kg
$AvAnL_p$	Average of animals in the late maturing breed	kg
$AvAnM_p$	Average of animals in the medium maturing breed	kg
$AvAn_p$	Average of animals in the paddock	kg
$AvInE_p$	Average of animals incorporated to the early maturing breed	kg
$AvOutE_p$	Average of animals removed from the early maturing breed	kg
CEW1	Value of individual live weight calculate for each animal inside of extrapolation area 1 for early maturing breed	kg
CEW2	Value of individual live weight calculate for each animal inside of extrapolation area 2 for early maturing breed	kg
CEW3	Value of individual live weight calculate for each animal inside of extrapolation area 3 for early maturing breed	kg
CEW4	Value of individual live weight calculate for each animal inside of extrapolation area 4 for early maturing breed	kg
CEW5	Value of individual live weight calculate for each animal inside of extrapolation area 5 for early maturing breed	kg
EAC1	Individual live weight animal contribution inside of extrapolation area 1 for early maturing breed	kg

EAC2	Individual live weight animal contribution inside of extrapolation area 2 for early maturing breed	kg
EAC3	Individual live weight animal contribution inside of extrapolation area 3 for early maturing breed	kg
EAC4	Individual live weight animal contribution inside of extrapolation area 4 for early maturing breed	kg
EAC5	Individual live weight animal contribution inside of extrapolation area 5 for early maturing breed	kg
$ESP1_p$	Value of simulation point 1 for animals from early maturing breed	kg
$ESP2_p$	Value of simulation point 2 for animals from early maturing breed	kg
$ESP3_p$	Value of simulation point 3 for animals from early maturing breed	kg
$ESP4_p$	Value of simulation point 4 for animals from early maturing breed	kg
$ESP5_p$	Value of simulation point 5 for animals from early maturing breed	kg
$LeftAE_p$,	Animals from early maturing breed present in the left side of the medium extrapolation area (area 3)	-
$LeftAL_p$,	Animals from late maturing breed present in the left side of the medium extrapolation area (area 3)	-
$LeftAM_p$,	Animals from mediumarly maturing breed present in the left side of the medium extrapolation area (area 3)	-
$NAnE_p$	Number of animals in the early maturing breed	-
$NAnL_p$	Number of animals in the late maturing breed	-
$NAnM_p$	Number of animals in the medium maturing breed	-
NAn_p	Number of animals in the paddock	-
$SdAnE_p$	Standard deviation for the early maturing breed	kg
$SdAnL_p$	Standard deviation for the late maturing breed	kg
$SdAnM_p$	Standard deviation for the medium maturing breed	kg
$SdAn_p$	Standard deviation for animals in the paddock	kg
$SDInE_p$	Standard deviation of animals incorporated to the early maturing breed	kg
$SDOutE_p$	Standard deviation of animals removed from the early maturing breed	kg
VE	Counter for the difference between the average at each live weight calculated	kg

VOut	Counter for the difference between the average at each live weight calculated for animal that go out from the paddock	kg
VStay	Counter for the difference between the average at each live weight calculated for animal that stay in the paddock	kg

PUBLICATIONS

An approach for simulating the soil-grassland interface in pastoral farming systems[1]

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Abstract: Recycling of nutrients from the soil is one of the key determinants for the sustainability of grazing ecosystems. In this paper, a concise soil model, which is a part of a general grazing system simulation framework, is described. The model works in conjunction with a grassland model which also interacts with animal and herd models. The objective of the model is to simulate nitrogen (N), phosphorus (P) and water available for plants in a simple but mechanistic way. The model has 14 state variables, of which the most important are the N and P available to plants and the soil water content. The model functions with daily timesteps. All degradation processes are affected by soil moisture and temperature. Easily degradable plant litter and animal excreta are simulated as inputs to a pool of minerals available to plants. Structural litter is not simulated and the input of mineral is incorporated through the potential mineralization of organic matter. Rain and fertilisation are other inputs to the pool of N and P available to plants. The water submodel treats the soil as a multi-horizon-layered system with a variable number of layers, each one with variable thickness. The content of soil moisture is calculated from the combined effect of precipitation, runoff, irrigation, soil evaporation, and transpiration by plants and downward movement. Groundwater influence is not considered. The general structure of the model and preliminary results are described in the paper.

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[1] Paper presentation at the "International congress on modelling and simulation - MODSIM 97", in Hobart-Australia. 8-11/12/1997.

The Role of the Pasture Model in the Development of the Grassland System Model to the South of Brazil[2]

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Natural pasture in the Southwest of Rio Grande do Sul is characterised by a large number of C_3 and C_4 plants with annual or perennial growth. In addition, ryegrass (*Lolium multiflorum Lam.*), which generally is the main species component of improved pasture, is an annual species. Consequently, the model has to look at both the germination and regrowth processes. Germination starts after threshold temperature (°C) and moisture (soil water-cm^3/cm^3) conditions are achieved. The traditional crop model approach is adopted to simulate emergence as related to degree-day and seed depth. Regrowth is also linked to temperature and moisture thresholds. The goal is to simulate the growth of multi-species components of natural and improved pasture. To simulate plant growths, the photosynthesis and mineral uptake sub-models supply carbon, water and minerals. The mineral uptake sub-model represents the interface between soil and plant model. The plant growth sub-model simulates the partition this nutrients to the shoot and root growing. These processes are affected by the disturbance and ontogenic sub-models. The dead material attached on the plant is simulated in the plant litter sub-model and it is the another interface between plant and soil model.

The input of carbon (C) from photosynthesis, and nitrogen (N), phosphorus (P) and water from soil are considered in the simulation of plant growth. Input of C is determined by irradiation and temperature, and restricted by leaf area index (LAI) for each species or functional group present in the canopy as demonstrated by Johnson & Thornley, (1984). Restrictions of and competition for N and P from soil are considered in the whole process of plant growth. The effective C, N and P available to plant growth can be limited by water availability represented in the model by a scalar effect from zero to one. The phenological stage of the plant is adapted from the model of Moore et al. (1997). Above ground biomass can be removed by harvest, fire or animal intake. The preference of cattle for specific species is a disturbance factor, which affects plant competition. Thus, plant growth is determined by nutrients from photosynthesis and the mineral uptake sub-model together with the influence of animals, the phenologic plant stage and water availability. The plant growth and allocation process is simulated following the general approach of Johnson & Thornley (1985). This approach has been expanded to adapt other phenological stages of the plant than just the vegetative ones.

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[2] Poster presented at "28th Annual crop simulation workshop" in Beltsville - USA. 5-8/04/1998.

The Role of the Pasture Model in the Development of the Grassland System Model to the South of Brazil.

Brazilian Agricultural Research Corporation

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Background

- The Southern part of the Rio Grande do Sul state, with an area o approximately 140.000 Km^2 is part of the Campos subregion of th Rio de La Plata temperate subhumid grasslands ecosystem. It is characterized by natural grassland, grazed by both beef cattle an sheep. Clover (*Trifolium repens* L.), lotus (*Lotus Corniculatus* L. and Italian ryegrass (*Lolium Multiflorum* L.) are the main component of improved pasture, but normally it occupies a small proportion o the farm area.
- Rain annual average is 1350 mm (34% in winter, 25% in spring, 25% in autumn and 16% in summer).
- January, with 24 °C average, is the hottest month and June, with an average of 12.5 °C is the coldest. The extreme temperatures are – 4 °C and 41°C. Frosts have happened occasionally between May and September.

Figure 1. North Campos in Rio de La Plata grassland.

Objectives:

- To develop appropriate grassland simulation models to permit a simulation study of integrated systems.
- To simulate the growth of multispecies components of natural and improved pasture
- To validate combined model framework using local data.

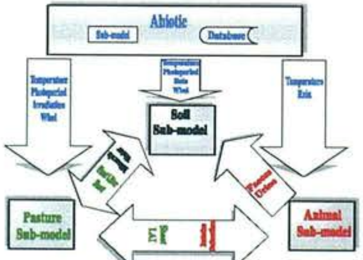

Figure 4.1. Diagram of proposed grassland biological system model

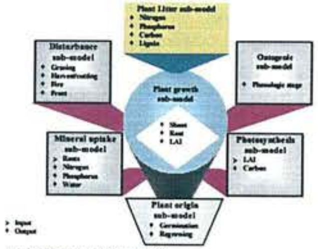

Figure 4.2 Diagram of Plant Multispecies Model

Output

- Predictions of variability in pasture supply within and among years.
- Prediction of quality of pasture supply
- Comparisons of impact of human management in pasture production.

A INTEGRAÇÃO SOCIO-BIO-ECONÔMICA ATRAVÉS DE MODELOS MATEMÁTICOS: UMA APLICAÇÃO DE ESTUDO NA REGIÃO SUDOESTE DO ESTADO DO RIO GRANDE DO SUL - BRASIL[3]

Vicente Silveira, Ana Mirtes de Sousa Trindade, Juan Busqué, Alberto Bernués, Octavio Castelan Ortega, Mário Herrero and Roy Fawcett

Resumo

O campo nativo pastejado por bovinos e ovinos é uma das principais características da região sudoeste do Rio Grande do Sul. A área ocupada por pastagem cultivada ainda é muito restrita na região, tendo geralmente o trevo branco (*Trifolium repens* L.), cornichão (*Lotus Corniculatus* L.) e o azevém anual (*Lolium Multiflorum* L.) como os seus principais componentes. Dentre as culturas de grão, a lavoura do arroz é a mais importante. O uso dos resíduos e impurezas oriundos destas culturas tem sido utilizado nos últimos anos como suplemento alimentar, principalmente para bovinos, e constituí uma via de integração entre lavoura-pecuária. Suporte tecnológico tem sido oferecido aos produtores com a finalidade de aumentar a eficiência produtiva e fornecer subsídios para as suas tomadas de decisões; entretanto, os métodos tradicionais de pesquisa e extensão estão sendo cada vez mais questionados principalmente quanto ao custo e tempo necessário para oferecer soluções aos problemas enfrentados pelos produtores. Considerando as suas características, modelos de computador são importantes ferramentas que devem ser usadas para apoiar o desenvolvimento tecnológico e aumentar a performance dos sistemas de produção.

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[3] Poster paper present at " III Simposio Latino Americano sobre Investigacion y extension en sistemas Agricolas" in Lima-Peru. 19-21/08/1998.

A INTEGRAÇÃO SOCIO-BIO-ECONÔMICA ATRAVÉS DE MODELOS MATEMÁTICOS: UMA APLICAÇÃO DE ESTUDO NA REGIÃO SUDOESTE DO ESTADO DO RIO GRANDE DO SUL-BRASIL.

Embrapa Vicente Silveira, Ana Mirtes de Sousa Trindade, Juan Busqué, Alberto Bernués, Octavio Castelan Ortega, Mário Herrero e Roy Fawcett

INTRODUÇÃO

O campo nativo continua ser a principal fonte de alimentação para ruminantes na região (Fig. 1). A pastagem cultivada tem sido utilizada como uma alternativa suplementar a baixa produção do campo nativo, no período outono-inverno, entretanto, ocupa somente 8.5% da área, estimativa do IBGE (1990). O Rio Grande do Sul produz ± 11% da carne bovina do Brasil. No inverno e início de primavera, as condições dos animais para abate são insatisfatórias; em conseqüência, os produtores vendem seus animais entre dezembro e junho, elevando a oferta de carne, causando queda de preços (Fig. 2). A ocorrência de seca limita a produção de lavouras de verão na região, entretanto, o arroz é produzido por irrigação e corresponde a aproximadamente 41% do total produzido no Rio Grande do Sul. A produção de bovinos de corte e de arroz são atividades que devem ser estudadas sob o enfoque de integração entre lavoura-pecuária na região.

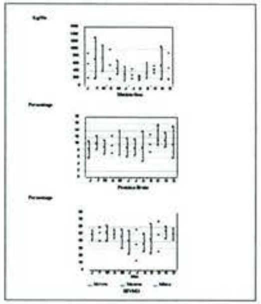

Fig. 1. Produção de Matéria seca, proteína bruta digestibilidade in vitro do campo nativo.

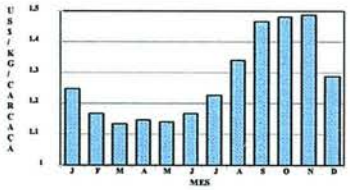

Fig.2. Preço da carne bovina no Brasil, media mensal 1975-1994.

METODOLOGIA

Etapas do Modelo Integrado de Decisões (MID):
- Reconhecimento dos sistemas praticados na região.
- Concepção teórica das vantagens e desvantagens dos sistemas.
- Desenvolvimento, adaptação/validação de modelos biológicos e econômicos.
- Geração de dados e análise dos resultados.

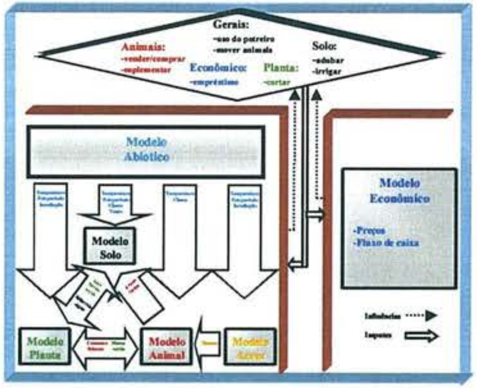

Fig.3. Diagrama do modelo integrado de Decisões (MID).

SIMULAÇÕES

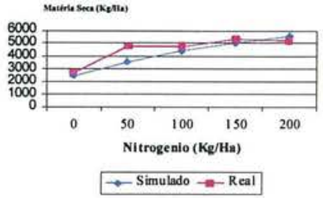

Fig.4. Produção de matéria seca de azevém anual submetido a diferentes níveis de adubação.

CONCLUSÕES

Apesar de o MID estar ainda em uma fase inicial de implementação, este tem demonstrado ser uma ferramenta importante na geração de cenários para uso, tanto a nível de produtor, quanto a níveis superiores de decisões. Logicamente, como este agrega diversos modelos bio-econômicos, indica também para pesquisadores e extensionistas prioridades de ações que possam dar respostas mais rápidas ao anseios de seus clientes.