Dairy Vietnam Farm Model (DAIVIE): Moc Chau dairy basin case

“Adoption of new forage technology: impact and perspectives on the socio-economic sustainability of milk production”

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Abstract

The dairy sector in Vietnam quickly evolved with the support of government and private sector, R&D organizations (NIAH, CIRAD, JICA, etc.) and ONG's. Dairy farms are actively supported not only in the interest of milk production but also for their socio-economic role. New policies and technology innovations are being proposed in order to answer the main issues related to the socio-economic and environmental sustainability of the dairy sector. The selection of orientations to be implemented requires a comprehensive analysis of their impact and eventual consequences at a multi-scale production level. Modeling appears as an interesting decision tool for the agricultural sector because it helps to assess the complex interactions found in the farm system as well as to analyze the configuration of alternative technical innovations.

Moc Chau dairy farmers face important issues related to milk production in which the availability of forage resources during winter season and the high cost of concentrated feeds are presently limiting the dairy herd development and the economic sustainability of farms. In response to these issues, researchers provide alternative solutions using new forage technologies based on temperate species. Oat species proved to be the best solution in terms of agro-ecological adaptation, high production yields, excellent nutritive value and low production costs. The adoption of oat forage by farmers started in 2004 and two years later 30% of total farmers were using this new forage resource in their farming system. The number of farmers implicated in oat production and the surface of land allocated are considered useful indicators of farmer adoption. However, some dissatisfaction opinions related to oat potentialities were addressed which may possibly influence further adoption.

In order to realize the importance of these factors we developed a multi-period farm-scale model. Four criterions were chosen to establish the farm typology (soil fertility, herd size, dairy experience and adoption behavior) and two indicators (profit and labor time) were selected to evaluate the impact of the new forage technology on the economic and social sustainability of farms. In all the tested scenarios the model selected oat production as the optimal solution to maximize farmer profits. However, farmers' adoption behavior is based not only on profitability considerations but also on other factors, such as traditional practices and cultural preferences. According to the results, the experience of farmers in dairy activity and the dimension of their herd did not seem to be the factors determining the adoption of oat technology. On the other hand, the forage yields and the additional labor needed are likely the main issues constraining the successful adoption of oat by dairy farmers. These results are in total agreement with previous field evaluation process.

The global validation of the model is currently on going. After this stage, the model can be used as support tool for discussion with farmers and local decision makers. The objective will be to valorize the positive impacts of the new agricultural practice and to scaling-up to other dairy farming regions.

1. Dairy Production in Vietnam

1.1. National context

The population of Vietnam is approximately 85 million people, more than 75% of which live in rural areas and make their living depending on agriculture. Thus, agriculture plays an important socio-economic role in Vietnam. Livestock make up about 30% of the total agricultural products and supply food (eggs, meat and dairy products) for domestic consumption and for export. Livestock development is a strategic policy of the Vietnamese government due to its potential contribution to employment creation and income generation. Animal production is expanding due to the continuous increase in demand resulting from high demographic growth and changing food habits in urban areas.

As many countries in Asia, Vietnam does not have a dairy tradition. However, with the changes of food habits, the consumption of dairy products was multiplied by twenty in the last fifteen years. It reached approximately 9 liters per year and per capita in 2006 and, at the current trend, it should continue to increase in a significant degree during next years.

The 100,000 dairy herds, 88% of which are Holstein-Friesian crossbreeds and 12% are pure Holstein-Friesian cattle, produced approximately 235,000 tons of milk in 2007. This production satisfies 30% of the domestic consumption (only 10% in 2001) and obliges Vietnam to significant milk powder imports. The Vietnamese government decided to launch a dairy national plan (2002 – 2010) to develop the domestic milk production and reach a self-sufficiency rate of about 40% in 2010. A breeding program that selects improved local cows (Lai Sind) and inseminates them with the frozen semen of the proven exotic dairy bulls was used to produce Holstein-Friesian crossbred cattle, and was considered as the main method of boosting the dairy development program in Vietnam. The first and second generation crosses cows (F1 and F2) which have milk yields of about 3,000 to 3,500 liters in 305 days lactation, are concentrated in surrounding areas of Hanoi and Ho Chi Minh City. Meanwhile, Vietnam also imported a quality dairy cow gene source from tropical countries around the world to meet the heavy demand for dairy breeds in the country. There are two major exotic dairy cattle regions in Vietnam: Son La (Moc Chau district) and Lam Dong provinces which have been importing Holstein-Friesian cattle since the 1970's. These animals produce average milk yields of between 4,200 and 4,500 liters in 305 days of lactation.

Seventy-eight percent of the total dairy herd is located in Ho Chi Minh City and the surrounding provinces; 18% is located in the north part of the country; less than 2% in the middle land and over 2% in the highlands. Dairy farms normally have a small number of cows (usually less than ten animals) and are owned by household farmers. Presently dairy farming is mainly a family business activity (near 90%), the others are state-owned business and partnership.

Even if there are real opportunities for dairy development in Vietnam, there are still major constraints for the dairy sector which are mainly linked with the relatively recent dairy experience when compared with other countries in South East Asia. Current key constraints include low technical know-how and management skills of dairy farmers, limited experience of veterinarian and extension staff and a lack of suitable forage resources for cattle ration balancing. Increasing cattle herds requires large areas of land for forage production, however, and as there is already considerable pressure on land in Vietnam, the intensification of forage production seems to be indispensable. Furthermore, the absence of an organized dairy commodity chain, the lack of capital for high initial investments and inputs costs (animal stock and feeding) and an inefficient identification and recording system also impede the expansion and the projected economic profitability of dairy cattle activity. The environmental issues gain importance in urban and peri-urban areas where numerous farmers are confronted with surpluses of manure and create a non negligible pressure on the environment. Dairy sector in Vietnam is still very young and is time now to make the required adjustments. The sustainability of dairy production sector in Vietnam will be greatly dependent on better dairy actor's know-how and to the choice of appropriate breeding and feeding strategies. Positive lessons from the past should be valorized and exchange of experiences encouraged among dairy actors.

In this context, the milk industry focuses on innovations likely to improve the technical and economic efficiency of dairy farms. Several breeding and management strategies including new technologies for feeding have been proposed in order to solve the main issues of Vietnamese milk production. The first questions are: which are the good decisions to be implemented? How to develop the dairy farm as an economic, social and environmental sustainable system? The understanding of the dairy farm in its complexity is a first complex exercise. The choices of orientations to be taken on the medium and long term are the second difficulty that farmers and decision makers must face. For this type of exercise, modeling proved to be an essential decision tool, finding the interactions between the experience, the observation and the knowledge. Bio-economic models must make possible to have ideas on the way in which the dairy farm (and the whole dairy sector) would respond to changes in the current system.

A general presentation of the selected Vietnamese dairy region (Moc Chau basin), including agro-climatic, socio-economic and political conditions is necessary to understand the choices carried out in the model and the stake of such a model. A presentation of the farm model components including the mathematical equations used is also interesting to have a better understanding of the model structure. Finally, the last section of this report will present and discuss the scenarios found by the model regarding the impact of the new forage technology adoption.

1.2. Moc Chau basin context

Moc Chau district is located in a mountainous region in the Northern part of Vietnam at around 200 km West of Hanoi City. The district is crossed by the road axis Hanoi – Lai Chau and the town of Moc Chau is 30 km distant to Laos's border. Moc Chau district counts approximately 140,000 residents (statistics December, 2006) with a multiethnic population made up mainly by Thais (34%), Kinh (30%, which is the major ethnic group in Vietnam), Muong (16%) and Hmong (14%) people.

In 1960, Beijing black-and-white dairy cows were first introduced to Vietnam for trial in Moc Chau region. Ten years latter, the Cuban Government aided Vietnam with 1,000 pure Holstein-Friesian cattle for experiments in Moc Chau. After the reunification of North and South Vietnam

(1975), the Government created the Moc Chau state dairy farm as well as the Moc Chau Milk Company and several breeding facilities. More than 1,000 ha of forage land were planted at that time. The mains purposes of the state farm were to improve the quality of the pure Holstein cows (genetic selection), to multiply cross cows with local breed and to produce milk. Since the nineties, the state farm was dismantled and the near 3,000 cows present in 1990 were distributed (sold by credit) to the farm employees according to the size of their family and management skills. On average farmers received 6 heads but the largest farm received 32 cows. However, Moc Chau Milk Company still control (or forces) the outputs to be reached: if a family raises 6 milk cows, each year they will have to deliver 20 tons of milk and provide 2 female calves to the Milk Company. In addition, farmers are entirely “attached” to Moc Chau Milk Company by a “Milk sale contract”. This contract obliges farmers to sell the totality of their production to the Company which fixes the price according to milk quality standards. Farmers do not dispose of a representative collective structure enabling them to defend their interests with respect to the Milk Company. Indeed, Moc Chau Milk Company is the only purchaser of Moc Chau region milk. The Milk Company is directly involved on all levels of the dairy sector: training of technicians and farmers, collecting and analyzing the quality of milk, hiring land and farm buildings, manufacturing concentrated feed, providing technical and veterinary services, guarantee and credits to cattle purchase, etc. Dairy farmers are entirely dependent to the Company, which is also considered as the only official technical interlocutor by the local authorities. Moc Chau Milk Company transforms the totality of milk produced in UHT and pasteurized milk, fresh yoghourts, milk concentrates and cakes, butter and cheese. The Company products are sold locally, in several sale shops in Hanoi and more recently in the whole country.

Moc Chau dairy farms are located in a plate of limestone rocks, with 900 to 1,100 m of altitude. The relief is quite flat and the soils (33% limestone and 26% sandstone soils) are generally fertile with pH close to neutrality (7.0) or slightly basic. Soils are generally very rich in carbon (45 g/kg) and in nitrogen (2.7 g/kg). The ratio C/N is quite high due to the strong percentage of carbon which is a frequent characteristic of soils used for forage production and indicates a significant level of organic matter but whit a low evolution process. The soils are generally rich in magnesium and in total phosphorus but present a low content of total potassium. The climate characteristics varied from tropical to temperate with two defined seasons: (i) rainy and hot season from April to October; (ii) dry and cold season from September to March. Total annual precipitations are up to 1,600 mm but with a heterogeneous distribution during the year. The precipitations recorded between May and October (6 months period) corresponds to approximately 85% of total precipitations. The driest months are December, January and February with levels of precipitations lower than 20 mm per month. The average annual temperature is about 19.0°C with heterogeneous distribution during the year. In summer (from May to August), the average temperatures reach 22-23°C. In winter the coldest period corresponds to December-February with monthly temperatures lower than 15°C. This climatic range involves a diversity of forage production through the year and will have significant consequences for the forage stock management from year to year. The quantity and quality of forage produced will influence significantly the milk production. However, this mountainous region is more favorable to dairy farming due to the relative availability of land for forage production and the better climatic characteristics compared to the delta zones (Red River, Mekong) in Vietnam.

Dairy cattle have been raised in Moc Chau district for more than 40 years and the eco-systemic characteristics are relatively favorable for a significant reinforcement of dairy herd in the next years. However, such animal growth will not be without consequences on the land use and management of rural surface in a context of increased land constraint and agricultural prevalence (in particular tea production and fruit trees), on the organization of the commodity chain around the Moc Chau Milk Company and on the evolution of breeding and feeding practices. At present, the mains factors blocking the dairy development in Moc Chau region includes: the low availability of land for forage production, the lack of quality forage species to balance the feeding rations, underdeveloped irrigation system, limited access to improved production technologies and the low economic profitability of dairy farms. Moc Chau farmers largely encounter forage constraints during the winter period, when temperatures are low, limiting the development of tropical forage species. In fact, low temperatures (below 15℃) inhibit the growth of the majority of tropical grasses. The cold period in Moc Chau varies from year to year, from a minimum of three months to a maximum of six months. During winter, the forage shortage is traditionally met using natural grasses (which are low in nutritive value), conserved forage (hay and silage) and a variety of agro-industrial by-products locally available. However, with large animal population these resources are insufficient, resulting in a deterioration of the physical condition of the animals, and consequently a reduction in their production milk potential. An alternative solution for forage production during winter period would be the use of forage species adapted to cold temperatures. In temperate climate countries, several forage species produce significant quantities of grass with excellent feed value when average air temperature is around 5℃. The use of temperate fodder species in the northern area of Vietnam seemed to be a good alternative to solve the fodder deficit during winter. The low economic profitability of dairy farms is the result of high input costs (especially in feeding) and low farm milk prices. More recently, the prices of internationally trade dairy commodities have became very volatile and, in some cases, almost doubled. This represents a good opportunity to the development of domestic dairy sector. For instance, in Moc Chau basin the milk price paid to the farmers increased 60% from January 2007 (0.17 €) to January 2008 (0.27 €).

1.3. Farm typology

In 2006, Moc Chau district counts 504 dairy farms with 3,300 of total dairy animals (adult cows, heifers and bulls). This number corresponds to around 4% of the national dairy herd. The oldest breeding dairy farms dating from the dismantling period of the state farm (1990). However, the average year for starting dairy activity is 1997 which means 11 years of farmer's dairy experience. The majority of farmers is engaged in dairy activity as the sole livelihood. The average size of the herd is 6 cows, 50% of which are adult lactating cows, with an average milk production of 5,000 liters per cow in 305 days of lactation. The genetic is mainly (83%) pure Holstein-Friesian cattle, 16% is HF-crossbred (F2, F3 and more) cattle and 1% is Jersey. The reproduction is entirely performed by artificial insemination (AI) without synchronization of heat, which induces a relatively homogeneous distribution of the births during the year. The first AI is applied on average at 18 months of age.

At the state farm dismantling period, the farm size was calculated according to the number of cattle distributed and the average quality of soils. At that time, farmers received from 0.3 to 0.5 ha of land per animal head. In 2006, the average size of farm land is 1.8 ha, 85% of which are occupied by perennial and annual forage species. The 15% remainder is allocated to breeding facilities (animal buildings, silos, etc.), farmer's house and other minor agricultural activities (fruit trees, vegetables, tea, etc.). Nowadays, farmers who decide to increase their herd only obtain from the Milk Company 0.2 to 0.25 ha of land per animal head. In addition, the Milk Company fixes the rules for forage land allocation: farmers must cultivate 80% of the forage surface with perennial grasses and the 20% remain must be allocated to annual fodder crops (maize, colza, cassava, etc.). For these annual crops, two successive periods are followed: March to August and then September to February. Farmers have the obligation to make maize ensilage in the first season and they are free to decide the crop sowed in the second season.

The main perennial forage crops are: *Brachiaria decumbens* (44% of fodder crop land), *Pennisetum purpureum* (30%) and *Setaria sphacelata* (6%). The annual crops are essentially maize for both silage and grain production (19% of fodder crop land) and in some farms cassava crop is sowed during the second season. The forage feeding system is almost entirely a cut-and-carry (zero-grazing) system, being grazing practically inexistent. In summer the feeding ration is composed by tropical forage species and concentrated feeds. Seventy-eight percent of farmers manufacture the concentrated themselves. In winter, due to the high forage deficit, farmers use conserved forage (silage and hay), agro-industrial by-products (cassava roots, rice straw, etc.) and greater quantities of concentrated feed. The lack of available land involves a lack of forage which is not distributed *ad libitum*. To maintain the milk production farmers have to use a significant quantity of concentrated feed (on average 10Kg/cow/day). Thus, there is a strong dependence of farmers with respect to commercial feeds which is likely to pose problems with the recent increase of the prices. The utilization of such levels of concentrated feed could also have risks to the animal health. Limited knowledge of feedstuffs quality prevents farmers from deciding how to feed cows according to the feed availability and the animal needs. Feed intake is therefore not optimized and production costs are not minimized.

Moc Chau dairy system is relatively intensive, with an average animal charge of 3.5 AU/ha. The workmanship is essentially familiar, being wife and husband occupied full-time in the farm. During few months of the year (harvest maize periods, etc.), farmers need to hire labor (1.9 people/month). The Milk Company undertakes the veterinary services and the expenses with reproduction (AI). At the calving time farmers must inform the Milk Company about the sex of the born calf; if it is a male, farmers can sell it but if it is a female they are recommended to raise it. If the land available is insufficient, farmers are allowed to sell the female calf to another farmer or directly to the Milk Company. The company proposes to farmers an insurance life for their cattle. The contribution is 4 €/head/year and if an animal dies, farmer will receive a compensation of 40 €. As it is specified in the "Milk sale contract", milk is paid according to three principal criteria: fat and dry matter content and the alcohol test result (total germs). Milk fat content in Moc Chau is surprisingly low: more than 50% of milk produced has 3.2% of fat content and only 6% of milk reaches 3.4% of fat. The price of milk paid to farmers was on average 0.13 euros in 2006.

However, from one to another farm there are some differentiations respecting to the soil quality and forage yields, the herd dimension and land available, the general breeding conditions and feeding system used. The dairy experience of farmers and the investment capacity are also factors quite different among dairy farmers in Moc Chau basin. In 2006, J.L. Warter and T.V. Tuan carried out a zoning of dairy farms using a wide questionnaire to the 504 farms and a more exhaustive assessment survey with 120 representative selected farms. The general questionnaire and the detailed survey data enabled to gather precise information about the dairy farming system and made possible to establish a farm typology. Three criterion were selected: the soil quality (measured by forage yields), the total number of dairy cattle raised (which is directly related with land surface), and the experience of farmers in dairy activity. This typology will be included and treated thereafter in the model. Simulations will be performed for an average farmer in each farm types. The main characteristics of the three farm types per selection criteria are presented in Tables 1, 2 and 3.

Table 1. Typology based on average *Pennisetum purpureum* forage yields obtained which were associated with soil fertility

Farm type 1: 60 to 80 tons of Fresh Matter/ha/year

Farm type 2: 80 to 100 tons of Fresh Matter/ha/year

Farm type 3: 100 to 120 tons of Fresh Matter/ha/year

		Farm types		
		1	**2**	**3**
Number of farmers (% of total)		52	25	23
Farmers age (years old)		42	43	41
People per family		4	4	4
Dairy experience of farmers (years)		14	11	12
Dairy herd (January 2006)	Total	10	6	7
	In lactation	4	2	3
	Dry cows	2	1	1
	Heifers	4	3	3
Animal charge (cows/ha)[1]		3.8	3.0	2.9
Workmanship (people)	Farm full-time	2.0	2.1	2.0
	Farm part-time	0.3	0.3	0.1
	Hired permanent	0.5	0.1	0.1
	Hired seasonal	2.2	1.0	1.4
People/cow		0.3	0.4	0.3
Land surface (ha)	Total	2.5	1.9	2.6
	Forage production	2.2	1.6	2.0
	Other purposes	0.3	0.3	0.6
Forage land allocation (% forage land used)	*Brachiaria decum.*	52	42	40
	Pennisetum purp.	25	32	38
	Setaria sphacel.	5	2	4
	Maize	18	24	18
Milk production	Kg milk/cow/day	13	11	12
	Kg milk/farm/day	58	36	42
Milk price (€)		0.13	0.13	0.13

The majority of farmers belong to the first farm type (lower forage yields). The farmers of this farm type have more dairy experience that those of other farm types (2 to 3 years more) and raised more dairy animals. The allocation of forage species is also influenced by the quality of soil. The other characteristics of farms are similar.

[1] Heifers = 0.6 Adult cows charge

Table 2. Typology based on average herd dimension

Farm type 1: less than 3 dairy cows

Farm type 2: 3 to 9 dairy cows

Farm type 3: more than 9 dairy cows

		Farm types		
		1	**2**	**3**
Number of farmers (% of total)		3	67	30
Farmers age (years old)		43	41	45
People per family		3	4	4
Dairy experience of farmers (years)		11	12	15
Dairy herd (January 2006)	Total	2	6	15
	In lactation	1	2	6
	Dry cows	0	1	3
	Heifers	1	3	6
Animal charge (cows/ha)[2]		1.2	3.4	3.8
Workmanship (people)	Farm full-time	2.0	1.9	2.2
	Farm part-time	0.3	0.2	0.3
	Hired permanent	0.0	0.1	0.8
	Hired seasonal	0.7	1.2	3.1
People/cow		1.5	0.4	0.2
Land surface (ha)	Total	2.2	1.7	3.9
	Forage production	1.3	1.4	3.3
	Other purposes	0.9	0.3	0.5
Forage land allocation (% forage land used)	*Brachiaria decum.*	31	47	49
	Pennisetum purp.	44	31	28
	Setaria sphacel.	4	3	4
	Maize	21	19	19
Milk production	Kg milk/cow/day	7	12	14
	Kg milk/farm/day	14	32	90
Milk price (€)		0.13	0.13	0.13

The majority of farmers belong to the second farm type (3 to 9 dairy cows). The farmers of this farm type are slightly younger, and used less workmanship to take care of the farm compared to those of other farm types. The total land surface is also lower but the allocation of forage species is similar to the farm type with greater number of heads.

[2] Heifers = 0.6 Adult cows charge

Table 3. Typology based on average experience of farmers in dairy activity

Farm type 1: less than 8 years of dairy experience

Farm type 2: 8 to 18 years of dairy experience

Farm type 3: more than 18 years of dairy experience

		Farm types		
		1	**2**	**3**
Number of farmers (% of total)		28	43	29
Farmers age (years old)		38	43	45
People per family		4	4	4
Dairy experience of farmers (years)		6	13	18
Dairy herd (January 2006)	Total	6	9	10
	In lactation	2	3	4
	Dry cows	1	2	1
	Heifers	3	4	5
Animal charge (cows/ha)[3]		3.4	3.5	3.5
Workmanship (people)	Farm full-time	1.9	2.1	2.0
	Farm part-time	0.2	0.2	0.4
	Hired permanent	0.0	0.4	0.5
	Hired seasonal	1.1	2.3	1.5
People/cow		0.4	0.3	0.3
Land surface (ha)	Total	1.9	2.5	2.6
	Forage production	1.4	2.1	2.3
	Other purposes	0.4	0.3	0.4
Forage land allocation (% forage land used)	*Brachiaria decum.*	43	46	52
	Pennisetum purp.	33	30	27
	Setaria sphacel.	4	4	2
	Maize	20	20	19
Milk production	Kg milk/cow/day	11	13	13
	Kg milk/farm/day	30	52	61
Milk price (€)		0.13	0.13	0.13

The majority of farmers belong to the second farm type (8 to 18 dairy cows). The number of cattle raised by farmers is positively related with their experience. More experience is also associated with higher animal charges, more land surface and higher milk production. The allocation of forage species seems to be also influenced by farmer's experience; higher land allocation to *Brachiaria decumbens* grass and lower allocation to *Pennisetum purpureum* when the experience increases.

[3] Heifers = 0.6 Adult cows charge

1.4. Implementation of new forage technology

CIRAD, together with Vietnamese research institutes and the Hanoi Agricultural University (as part of the PRISE platform), supports the emergent dairy sector with research and development activities which have a special focus on the feeding and nutrition of dairy cattle.

Participatory research methods were employed to conduct an analysis of local farming systems and the livestock situation in order to find out more about farmers' needs in relation to dairy cattle production. The first objective of the work was to describe the local farming system and to establish research and development priorities related to dairy cattle nutrition and feeding. This was achieved through farmer questionnaires, farm visits, meetings with farmers and consultation with local agriculture extension staff and representatives of breeding companies. These preliminary steps were crucial to the establishment of appropriate and relevant research and development activities. The questionnaire assessment survey, which was conducted with a representative number of farmers, enabled researchers to gather general information about the local farming system and the main problems farmers faced in feeding their animals. The main problem farmers identified in relation to dairy cattle production was shortage of grass during the winter season. In response to this finding, agronomic researchers set about providing new forage species (*Avena* sp., *Lolium* sp., *Medicago*, *Vicia*, etc.) and testing them under farmer-managed conditions. The establishment of close linkages among farmers, extension workers and researchers throughout the study ensured that local knowledge and new technologies were combined in practice, enabling participating farmers to better understand research results and thereby disseminate appropriate innovations more effectively amongst their peers.

Working in close collaboration with farmers, the first priority was therefore to select alternative forage plants, namely temperate species, which are resistant to cold temperatures and able to produce enough quantity and good quality grass during winter. The expansion of the cultivation area to test the best adapted species began during the second year of the project (2004/2005). The aims of this second phase were: (1) to test the adoption of these species and create awareness amongst farmers of these new forage production methods; (2) to monitor the introduction of the species within existing agricultural farming systems; (3) to confirm, under real conditions, the results of the earlier experiment; and (4) to measure the advantages offered by the new forage species in terms of animal production and feeding behavior.

The research questions were: under which conditions the temperate forage species are adapted to produce quality fodder during the winter period? Which potential of fodder production do they offer? How to better balance the dairy cattle rations?

1.5. Main experimental field results

The results obtained from the first years of experimentation on temperate forage species in Moc Chau district were variable. This was as expected and can be considered normal due to the heterogeneity of soil types across the experimental sites as well as differences in the management of the forage experiments by farmers. However, overall results suggested that the temperate species tested offer an appropriate solution to the winter forage deficit. The temperate forage *Avena* species (oats) exhibited the best adaptation to local conditions and farming systems, together with highest production levels and excellent nutritive value. Oats were quickly considered as an agronomic solution to solve the winter forage deficit. The total average forage production is about 60 tons of fresh matter/ha (around 10 tons dry matter/ha), but with significant differences among farms (from 30 to 110 tons of fresh matter/ha), according to soil fertility, irrigation availability and specially the management and care carried out by farmers. The feed value of oats forage is high; the plants are rich in protein (19% CP), energy (4,300 kcal; 0.83 UFL/kg DM) and having a low content of fibers (27%). Oat forage is well appreciated by dairy cows with an excellent ingestion rate and a high digestibility. The use of oats in the dairy ration allows a more regular production of milk throughout the lactation period. The energy and protein cost of oat forage is definitely weaker (on average 74% lower for energy and 83% lower for protein) compared to the other feed alternatives used by farmers during winter period (concentrated feed and maize silage). Even if some results of seed production are interesting (2,500 kg seeds/ha), the results are not yet conclusive in this field and research experiments are in hand to improve the technical protocol for seed production.

The majority of Moc Chau farmers (78%) having used oat forage during the winter period were very satisfied with the potentialities of this forage resource. The opinion of farmers related to the potentialities of temperate forage, in particular oats, was based on technical (sowing, harvesting, seed production, etc), nutritional and economical aspects. Globally, the reasons evoked by farmers to justify their satisfaction regarding to the production and use of oats include: easy technical procedures (sowing, harvest, etc.); valorization of available land surface during winter period; good adaptation to the local agro-climatic conditions; production of fodder during a period of serious deficit; good forage yield and high quality grass during winter; forage very well appreciated by dairy cows; avoid the use of bad quality natural grasses from mountains; stable milk production during winter; low production cost and lower than other winter crops.

On the other hand, the reasons used by farmers to justify their dissatisfaction were as follows: low growth capacity in the poor soils and in dry conditions; an insufficient number of harvest periods compared to the needs; difficulties to produce oat seeds; high input costs to obtain interesting yields; labor-intensive. For labor requirements, it is important to note that during the winter period family members are also engaged in other activities in addition to milk production. Introduction of labor-intensive technologies will result in higher costs for hiring agricultural workers to perform additional tasks and in some cases farmers are not interested to hire labor.

1.6. Farmer adoption

Farmers, in general, adopt new technologies that are appropriate with respect to their own goals, preferences and resource constraints as well as to their economic and natural environments. Farmers' decisions are governed not only by productivity and profitability considerations but also by other factors, such as available resources and their quality, family preferences and prevailing policies. For example, market instability and low milk prices will affect farmers' perception of the risk of milk production and consequently influence the technology adoption. New technologies may be adopted if they are, from the farmers' viewpoint, superior to those available traditionally. It is therefore necessary to analyze the adoption of technologies from a whole-farm perspective, rather than concentrating on costs and benefits of specific technologies. However, the analysis of costs and benefits is a useful method to assess the profitability of production activity, which is a necessary condition for adoption.

The new forage technology is being integrated in several agronomic systems in the northern part of Vietnam and appropriate technical itineraries were specifically developed to the agro-climatic conditions of these regions. The number of farmers attracted to this new forage technology and the surface of land allocated to the new temperate species can be considered useful indicators of farmer adoption. In the first year of the scaling-up experiments (2004/2005), 2.0 ha of temperate forage species were planted in Moc Chau district by 27 farmers who were mobilized for the experiment; in the second year (2005/2006) the land allocated to oat production increased up to 10 ha with the participation of 30 farmers. The following winter season (2006/2007) marked a new stage in the expansion of the new technology amongst Moc Chau farmers. The area for oat forage production was about 60 ha, a six fold increase compared to the area cultivated in the previous year and more than 140 farmers (28% of the total farmers) were involved[4]. Importantly, the acquisition of seeds in 2006 was made entirely by farmers who were willing to pay the market price in order to obtain the temperate oat seeds. Results show that the new forage technology is promising in terms of adoption by farmers.

Two challenges remain, however. Firstly, a commercial commodity chain for oat seeds needs to be implemented and maintained few years in order to allow farmers to lay out enough quantity of seeds and increase their agricultural land surface dedicated to the oat forage. Secondly, the involvement of decision-makers is needed in order to valorize the positive impacts of the new agricultural practice and to scaling-up this new technology amongst target dairy farming communities. Also, to further enhance adoption of this new technology, Milk Company policies for land allocation should be reformulated that provide incentives for farmers.

After three years of scaling-up oat experiments it is possible to classify in three farm types the adoption behavior of farmers from the beginning of the project. The main characteristics of the adoption farm types are presented in Table 4.

[4] In 2007/2008 winter season the number of farmers adopting oat forage in Moc Chau district was around 200 (39% of the total farmers) and the prospect for 2008/2009 is that the majority of farmers (55%) will adopt the new forage technology

Table 4. Typology based on oat forage adoption in the selected 120 dairy farms

Farm type 1: no adoption of oat fodder technology

Farm type 2: adopted only in 2006/2007 period

Farm type 3: adopted from the beginning (2004/2005, 2005/2006 and 2006/2007)

		Farm types		
		1	**2**	**3**
Number of farmers (% of total)		60	26	14
Farmers age (years old)		41	43	46
People per family		4	4	5
Dairy experience of farmers (years)		11	14	15
Dairy herd (January 2006)	Total	6	9	15
	In lactation	2	3	6
	Dry cows	1	2	2
	Heifers	3	4	7
Animal charge (cows/ha)[5]		3.4	3.2	4.2
Workmanship (people)	Farm full-time	1.9	2.0	2.2
	Farm part-time	0.2	0.2	0.6
	Hired permanent	0.2	0.2	1.1
	Hired seasonal	0.9	3.2	2.2
People/cow		0.4	0.3	0.3
Land surface (ha)	Total	1.8	2.8	3.5
	Forage production	1.4	2.3	2.9
	Other purposes	0.4	0.5	0.6
Forage land allocation (% forage land used)	*Brachiaria decum.*	43	50	51
	Pennisetum purp.	34	27	26
	Setaria sphacel.	3	5	3
	Maize	20	18	20
Milk production	Kg milk/cow/day	11	13	17
	Kg milk/farm/day	32	53	105
Milk price (€)		0.13	0.13	0.13
Equipments	Milking machine	NO	NO	YES
	Cut forage machine	NO	NO	YES
Animal force		YES	YES	YES

In 2006, the majority (60%) of the 120 selected farmers did not yet adopted oat forage in their farming system. Twenty-six percent have tested oat forage only in 2006/2007 and the 14% remain (farm type 3) correspond to farmers who adopted this new forage technology since the beginning of the scaling-up experiments in 2004/2005. The average data of Table 4 show that farmers adopting oat

[5] Heifers = 0.6 Adult cows charge

forage (Farm types 2 and 3) are those with more experience in dairy activity (15 *vs* 11 years in no adoption farms) and consequently those with more animals in their herd (9 to 15 *vs* 6 heads in no adoption farms). The total labor used (from farm and hired) is almost two times higher in farm type 3 (adoption) than in farm type 1 (no adoption; 3.9 and 2.3 people/month, respectively). However, this fact seems to be more related to the increase in animal herds because the number of people per cow stays almost constant (0.3 *vs* 0.4, respectively). The allocation of forage species follow the same tendency observed with more experimented farms, i.e. higher land allocation to *Brachiaria decumbens* grass and lower allocation to *Pennisetum purpureum.* The allocation of land for maize production is relatively constant (around 20%) in all farm types as well as in all other criterion used to establish the farm typology. Farmers from farm type 3 (adoption) have milking and cut forage machines in their farming equipments.

In order to better understand the impact and perspectives of the new forage technology, we decided to use the modeling approach to test the interest and constraints of oat production in the farming systems of Moc Chau dairy basin. Using this mathematical and data-processing tool, it will be possible to identify (and/or to confirm) the factors that constraint the adoption of the new forage technology and tackle the question of the socio-economic sustainability of farms. The stake in the model will be to develop the essential interrelationships between animal nutrient requirements and farm feed (nutrients) supplies related to profit maximization. This innovating method will also contribute to improve awareness about nutrients flows in dairy farms and technical and economic farmer's decisions.

2. Modeling with GAMS

2.1. Interest of modeling

The two following definitions explain well the concept of modeling. The first suggested by Magnin: "A model is a simplification of the world. We isolate a class of phenomenon and we try to understand it using a certain number of assumptions and rules". The second one is from Boussard (1970): "The mathematical programming models are simplified but quantified representations of a real phenomenon". These two definitions present conveniently the mathematical and simplified approach of a phenomenon reality which is targeted in the models. This reality approach makes possible to obtain results which could, in their turn, be useful in the real world. Simultaneously, progress in data processing allowed a fast development of data-processing modeling for natural systems (physics, chemistry, biology) or human (economy, sociology) and that allows the implementation of simulations.

The conception and the use of a model can have several advantages. One of the main specificities of mathematical programming models appears by the fact that they encourage to go beyond the simple stage of reporting and to be interested in the created dynamic, in particular trying to take into account the technical and economical dynamism of the socio-economic diversity (Louhichi, 2004). On the other hand, the translation of real phenomenon according to mathematical laws through data-processing models widened human rationality because that makes possible to consider a wide range of data, relations and nonlinear sequences (Dörner, 1989). That also helps to treat the conceptual and invisible dimensions of a given situation (Hamilton, 1995). System modeling also makes possible to detect unknown factors in a system (lack of data, etc.) and to standardize research on the biophysics processes (van Paassen, 2004).

Finally, a model allows at the same time to be concentrated on a particular problem, to compress time and space and offers an experimentation environment without dangers (Bakken *et al.*, 1994). The objective is to have access to a minimum of resource while increasing control on the precision and transparency of a model (Harris, 2002). Many hopes surround modeling. The models seem powerful tools which thanks to their systemic and holistic approach were intended to solve the contemporary problems.

Historically, the mathematical programming was used by the economists as a purely normative tool of decision. It essential property was to obtain an optimal solution and better production plans than those which would have been adopted without programming. In terms of natural resources management, territory development, sector economy and understanding biophysics process, modeling appears interesting for the agricultural sector. Indeed, agriculture activity has such an impact in time on its economic, socio-cultural and ecological environment that the complexity of the system poses a real understanding problem (Thornton and Jones, 1998). According to Boussard (1988), these models are particularly well adapted tools to the problems which are posed to the agricultural sector, due to the strong interdependence between its diverse activities. This becomes easier with the extension of these models to solve nonlinear, random, discontinuous, dynamic problems, increasingly complex, and this thanks to the development of the data-processing tools and the multiplication of resolution algorithms (Louhichi *et al.*, 2004).

Modeling considering at once the economic, biophysics and sociological interactions could allow a better analysis of agriculture as a whole. The principal interest of these models is to help the decision makers to improve the development of agriculture. But modeling is not a perfect science; the limits of the models are numerous coming either from the model conceptualization, or of the studied context. Thus, they do not bring solutions to all the problems. A nuance was brought about the objectives given to the models but without deny their main interests. However, that will be responsible to the fact that modeling remains a tool essentially used by research.

2.2. Different types of model

The classification of the different types of model can be carried out by different manners. First of all, we can consider two types of modeling approach:

- From the model towards the reality: the predictive models

These mathematical models are used to anticipate events or situations. In predictive models, the known variables, called "explanatory", will be used to determine unknown variables, called "to explain". This type of models can also be named empirical (Jansen and van Ittersum, 2007) or diagnostic (Bouman *et al.*, 2000, van Paassen, 2004) models.

- From the reality towards the model: the descriptive models

In this case, the models are used to represent known systems; the objective is to treat, in an interpretable way, a mass of information. The data used are known, called "historical data". The other terms used to name these models are mechanists (Jansen and van Ittersum, 2007) or explorative (van Paassen, 2004) models.

Jansen and van Ittersum (2007) also present another classification related to the objective of a model where two approaches are possible:

- The normative approach which corresponds to an optimization or alternative objective to find a solution to a given problem;
- The positive approach which seeks to translate the real behavior of a system for better understanding it.

Then, we can more precisely categorize the models according to their conceptualization type. Tedeschi *et al*. (2005), propose four points which characterize a model and which will be the base of its conceptualization.

- Static (time is not taken into account in the model) *vs* dynamic;
- Stochastic (the results obtained are tended by probabilities) *vs* deterministic (only one solution by data file);
- Continuous (time is taken into account over the duration) *vs* discrete (time is taken into account punctually);
- Spatially homogeneous (explicit in the space representation) *vs* heterogeneous (space is not essential).

These categories can be developed, as on the notion of the model temporal approach. The time consideration can be for example, recursive, inter-temporal, dynamic recursive (Jansen and van Ittersum, 2007) according to the sequence of the functionalities of the model over its realization duration.

Finally, a model can be apprehended from the mathematical point of view since it can be linear if it comprises only linear relation equations or the opposite, non-linear when the mathematical approach is more complex. The categories presented below are not independent the ones compared to the others. A model can gather several approaches. According to Delagarde and O'Donovan (2005), the majority of the models called mechanists should however be considered as at the same time empirical and mechanists. Many equations, parameters or assumptions in the mechanists' models are based on expertise or partial data comes from literature and can for this reason be regarded as empirical. In addition, the categories can be associated according to the will of the programmer and the model objectives.

2.3. Contributions of modeling

G. Harris, 2002, summarize well one of the stakes for research vis-à-vis modeling questions: "The development and research sector has to produce systems connecting science to the economic innovations and economic policy, to the environmental problems and regional development".

Modeling called upon science but does not limit itself to a particular branch. It is a first difficulty of modeling which demand the participation and cooperation of several fields. Pittroff and Cartwright (2002), explain that the bio-economic models are mainly led by socio-economists or economists or even by agronomists, without interdisciplinary work. Consequently, a lack of data precision can involve the no-validity of the model. For that reason, modeling requires a close cooperation between researchers. Then, another difficulty is that a model greatly depends on its creator. This means that a model is intrinsically related to the theories, values, interests and aspirations of the modeler (David, 2001). There is thus certain subjectivity in a model which can exploit on the value of the model but also in its facility of use. A model is not always comprehensible for external people to the model itself or to the programming in general. Consequently, the models are mainly used by people making the effort to understand the model in order to recover the results for their own activities. For example, very few farmers directly use agronomic models which they find generally difficult to understand (van Paassen, 2004; Leeuwis, 1993).

Finally, after the hopes of the beginnings of modeling, it was recognized that a model does not give "the solution" of a problem and will never represent reality but is first of all a tool to widen human rationality (Dörner, 1997). The majority of the models are now regarded as tools to support discussion which should be used advisedly, by knowing well the limits for each model. First of all, the models are very used within research to advance knowledge but they do not find always a practical utility on the field.

2.4. Modeling under GAMS

There are many data-processing programs allowing the creation of models. The choice carried out for this model was to use the software GAMS whose bookshops, technical advantages and the development context entirely justified this selection.

GAMS is the acronym for "General Algebraic Modeling System". It is a high level programming language which makes possible to solve models with a formulation of concise algebraic statements which can be read easily by the computer and by the programmer. At the beginning, this language was intended to the programming of economic models but it can be just as easily used for other topics of modeling.

This language is easy to use and can be imported easily from a data-processing environment to another. We can work in a DOS environment (PC) and then transfer the program written in ASCII characters to an UNIX environment and vice versa. Any kind of text editors can be used (e.g. VPLUS, Norton desktop, DOS editor, WP, Word). MINOS (Modular In-core Non-linear Optimization System) which is the resolution algorithm used accepts very complex statements of non-linear programming in GAMS. Different types of models can be managed by GAMS: linear, non-linear, models of optimization or search for economic equilibrium etc.

GAMS language is organized according to the following elements:

- Sets: a collection of elements (labels). Basic building blocks of a GAMS model, corresponding exactly to the indices in the algebraic representations of models;
- Parameters: exogenous data defined at the beginning of modeling. A constant or group of constants that may be a scalar, a vector, or a matrix of two or more dimensions;
- Variables: endogenous data to the model;
- Equations: symbolic algebraic relationships that will be used to specify required relationships (and generate the constraints in the model) between activity levels of variables;
- The "Model": simply a collection of equations;
- The statement "Solve": causes GAMS to use a solver to optimize the model named immediately after the Solve statement. The solve statement tells the solver to maximize and/or minimize a defined variable.

The direction and the restrictions given to these elements will form the syntax of the model. GAMS language is similar in the form with the programming languages commonly use. It is thus familiar to the people with knowledge in this field. It also requires good practices of modeling in terms of exactitude and concision of the structure. GAMS language has several advantages. First of all, this language allows a compact representation for the particularly complex models. Then the algebraic relations are clearly presented and thus the changes in a model are easy to realize and especially the risks are limited since the damage of the model is not possible. Finally, for the facility of results treatment, the description of the model is presented independently of the solutions. In addition of its facility of use, GAMS language is particularly well adapted to an economic modeling of a given sector.

After the methodological choices carried out, it is important to explain which stakes are considered to create a bio-economic farm model.

2.5. Bio-economic modeling on a farm scale

The conceptualization of bio-economic modeling started since the Seventies on the idea to integrate a biological modeling component into economic models when the technical choices are strongly subjected to the influence of the biological factors, which makes possible to better realize the technical decisions. The purpose of this idea was not to analyze the impacts of the policies in agricultural economics, but rather from a normative point of view to find the optimal solution to a natural resources management problem. Today, this type of model is also used to estimate objectives.

The bio-economic approach is based on the combination of an economic model (often using mathematical programming) modeling the farmers' decisions in resources management to a biophysics model estimating, according to several technical choices, the engineer production and externalities functions, generated by the modes and practices of production (Louhichi *et al.*, 2005). The great interest of the bio-economic approach is its capacity to simultaneously generate economic (defined in terms of income), labor force mobilization, input consumption and ecological results apprehended like physical realities, measured like such, while escaping arbitrary from a monetary evaluation.

The bio-economic models can be divided into three classes according to their objectives:

- Models analyzing the configuration of alternative systems or technical innovations;
- Models seeking to envisage the effects of political or economic changes which are mainly intended to be support tools for discussion;
- Models intended to improve the bio-economic modeling aspects.

The bio-economic models can allow at the same time an economic and environmental approach. On the other hand, if we are interested in the sustainability of a system as a whole, the social approach still poses problems of conceptualization. No bio-economic exploration models were found which incorporates the impacts of the farmer' social background (Jansen and van Ittersum, 2007).

The application of bio-economic models can be located at different scales going from the farm level "farm model" up to the continental level passing by the regional, sector, country level, etc. (Ghali, 2007). The best approach level for modeling a system depends on the type of solution than we wish to obtain as well as the purpose of the model. The farm level approach has been extensively used to model decision-making behavior of farmers and to assess likely effects on policy measures on land-use decisions and farmer welfare (Singh *et al.*, 1986). The approach explicitly models the farm household's objectives, available resources and activities, and its other biophysical and socio-economic circumstances. It has been applied in various studies to assess the impact of new technologies and of policy instruments such as price stabilization, reduction of transaction costs and increases in credit availability on farm household' welfare and sustainability indicators (Barlow *et al.*

1983; Schipper, 1996; Shiferaw *et al.*, 2001). Farm level approach is also suitable to assess the complex interactions found in the farmer dairy system and to encompass the temporal scale. The farm model simulates how farmers as individual agents, respond to production opportunities in relation to their given context with regards to the new technology introduction. Farmer decisions concerning land use and management are simulated using the linear optimization model. However, in farm scale approach, each farm type is optimizing its own objective function in complete isolation of the other farm types.

The presentation of the Moc Chau dairy basin context must allow to understand the main problems to which farmers will have to face in an immediate or remote future. The effects of forage deficit during winter or the amplified price of raw materials which consequently increase the prices of concentrates are examples of situations affecting presently the sustainability of dairy farms.

Changes at farm level and also in the whole dairy system are necessary but the decisions to be taken are not always obvious, the long-term consequences of those being difficult to evaluate. There is an interest for dairy actors, and in particular extension workers and Milk Company managers, to have a tool making possible to have an idea of the possible evolutions of farms according to new technologies proposed. The farm model is an approach which makes possible to take into account the local availability and constraints for certain production factors in order to visualize the evolution of the farm and to measure the repercussions of external changes over the labor and the economy inside the different farm types. It is thus a question of having a relatively fine representation of dairy farms structure and the behaviors and strategies of their actors.

3. DAIVIE Farm Model

3.1. Type of model

DAIVIE Model is a mechanistic (or descriptive) model since it is built from theories and scientific knowledge mathematically conceptualized within the model for the long-term simulation of extrapolations and forecasts. The model follows a normative approach because it seeks to find an optimal solution and possible alternatives to the problem of feeding management and allocation of fodder surfaces in the farm. Concerning its conceptualization the model is dynamic (time is taken into account), deterministic (the results obtained are not associated with probabilities), continuous (time is taken into account over the model duration) and spatially homogeneous (explicit in the space representation).

The structure of the model is based on linear programming and allows the optimization of one or several objectives. Like all linear optimization models, it includes the three necessary components:

- A description of the activities and resources within the system considered (dairy farms);
- A number of constraints which define the realization conditions, the activities and the model limits;
- An objective function which minimizes or maximizes a specific function among the various activities.

3.2. Model objectives

DAIVIE focuses on the introduction of new forage technology in a dairy farm. This farm-level model must make possible to evaluate the impact, the adoption behavior and perspectives of the use of oat forage during winter, over the profit, labor time and more generally on sustainability of dairy farms in Moc Chau district. These questions are in the center of the interests with regard to the agricultural development in Vietnam. The model must consequently take into account the interactions between the different components of the farm system: the forage and feeding systems, the livestock system, the market as well as the heterogeneity of farming systems (farm types) and the changes (land allocation, herd evolution, etc.) within the model period. Indeed, the progress of a dairy farm depends on complex interactions between the past and present decisions in which effects will have an impact in the future (Alary, 2000). The farms are dynamic and especially codetermined by the socio-economic conditions of their environment. Two indicators are selected to evaluate the impact of the new forage technology on the economic and social sustainability of farms:

- The profit (income minus costs);
- Labor time.

The profit is defined like the "objective" function and will be the factor to be maximized. The labor time is fixed at 30 days per month.

In terms of utilization objective, this model is initially intended to carry out individual analyses of the dairy farms in Moc Chau district, but once validated it will be used like a support tool for discussion with farmers, extension staff, Milk Company managers and local decision makers.

3.3. Transferability

The legibility of the model is essential if improvements must be made but also for a possible transferability of the model. Indeed, as Jansen and van Ittersum (2007) explain, a lack of transferability prevents the use of the model apart from the research field which in general makes it less interesting for research. This concept of transferability joins the suggestions of Sinclair and Seligman (2000) on the need for clearness and transparency at the time of model presentation.

The next subsections of this report have as main objective to improve the legibility and the understanding of DAIVIE farm model. Detailed explanations for each component as well as for data and their sources are provided. A simplified presentation of all the programming steps is available.

This implement, necessary for a future use of the model, is also important to detect possible errors. The structuring of data in several file interface Excel sheets makes possible to apprehend each model component and understand its significance. In addition, a simplified presentation allows a rapid assimilation of the model which makes discussions more effective and also facilitates the comprehension of the results.

3.4. Model structure and components

Crop-livestock farms, especially dairy farms, are very complex systems. However, we can schematize a dairy farm as made of four interconnected subsystems (forage crops, feeds, the herd and fertilizers), each comprising several elementary stocks. The main biomasses circulating within the system are forages, concentrated feeds, milk, animals, and manures.

Figure 1 gives a simple conceptual representation of the model structure and components. A detailed mathematical description is given in appendix 1.

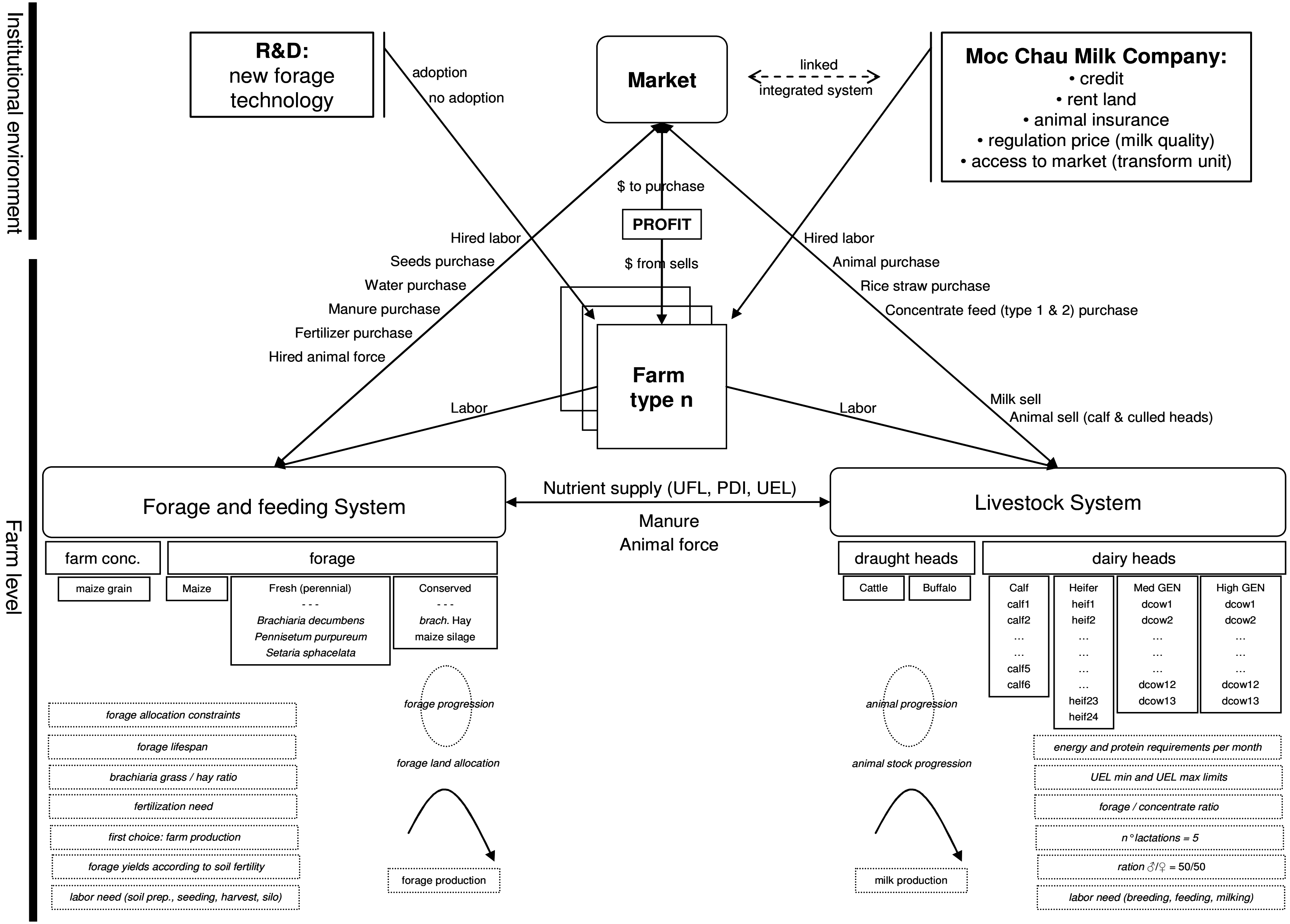

Figure 1. Structure and components of DAIVIE farm model

The model includes four main components (forage, feeding, livestock and market) and a certain number of assumptions and constraints used for conceptualization needs. The Period 1 of the model corresponds to January 2006. The initial (starting) situation of each farm type was described thanks to the questionnaires carried out in 2006. For the simulations, each model run consisted of 8 years, considered to be the maximum lifetime of dairy cow in Moc Chau district. We used a monthly time step because the degree of detail suffices the purposes of our study. The model dynamically simulates the herd composition and forage land allocation according the breeding and agricultural parameters. The herd demography is a key element to estimate the variation in forage and feed consumption and in production of milk (and manure).

3.4.1. Forage component

Land surface and allocation

The available land surface varies according to certain limits which depend on the farm type (initial surface) and the availability of fallow land in the neighboring of farms (maximum surface). Farmers who wish to increase their dairy herd can rent land from the Milk Company at an average rate of 0.25 ha/head. However, as the availability of land in Moc Chau dairy basin starts to be restricted, we fixed in the model a maximum of additional surface at 0.5 ha.

Land allocation refers to the surfaces used by each forage crop type (perennial and annual) and crop species. The forage surface production must be able to cover a great part (or if possible the total) of the nutritional requirements of animals. Land allocation also influences the economic level due to the variable costs of inputs. As we saw in the first section of the report (Moc Chau dairy farm typology) the allocation of forage surfaces follows certain rules imposed by the Milk Company. The farmers are obliged to plant at least 80% of their forage surface with perennial forage species (*Brachiaria decumbens*, *Pennisetum purpureum*, *Setaria sphacelata*). This constraint is taken into account in the model. According to data resulting from zoning, we observed that the majority of farmers uses three (or in few cases more) perennial forage species in their farm system. This is usually justified by the will of more diversified feed for the animals and by a better agro-climatic adaptation of certain species to different type of soils in the farm and to annual climatic variations. However, as the model does not take into account the climatic occurrences, the variability of soil fertility inside the farm or the farmer’s preference concept for a more diversified feed, we "force" the model to select at least two forage species (*Brachiaria decumbens* and another*)*. Thus, we fix the surface allocation of *Brachiaria* grass between 35 and 60% of the farm total forage surface. This range corresponds to the average of *Brachiaria* grass allocation in the 500 dairy farms.

The period of use for each allocated surface varies from 12 months/year for the perennial forage species to 5-6 months/year for the annual species. The starting dates for forage crops correspond to the plantation time (perennial plants) or sowing time (annual plants). For the perennial forage species, in each 12 months period, the age of the plant increases one year. The lifespan of perennial forage species is variable between species but constant during the whole simulation period.

Labor need

The labor need (days/ha/month) for the forage system is calculated for the activities of soil preparation (manually performed or using animal force), plantation or sowing, fertilization (mineral or organic), irrigation, cut of forage, seeds or plants harvest, silage process and weed control. For certain agricultural activities the labor need is the same for all forage species (e.g. soil preparation), but for other activities the time necessary depends on the forage specie considered.

Inputs

The inputs considered for forage system are: seeds or seedlings, fertilizers and water for the irrigation. Estimates of the inputs needs for each species are derived from the questionnaires and assessment surveys carried out in Moc Chau in 2006 (average data).

The seedlings used to replant perennial forage surfaces result from the farm. Due to lack of accurate data, we do not take yet into account the reduction in the field forage production due to the "removal" of those seedling materials. The seeds for the annual crops result from the market. The type and quantity of fertilizer is fixed for each forage species type according to the stage of crop development (sowing or cuts). Usually, farmers use two types of fertilizers, the complete NPK and the nitrogenous (urea with 46% nitrogen). The model does not take into account the different formulas available in the market for NPK fertilizer because the specific requirements for N, P and K of forage crops are not specified. The quantities of fertilizers used for the three types of soils (farm types) are the same. However, a coefficient could be applied according to the zone considered. The needs for organic fertilization (manure) vary according to the species and the stage of development considered.

The requirements of water for irrigation do not take into account the contribution of the monthly rainfall which is variable from year to year. Herbicides and pesticides inputs are not taken into account in the model.

Animal force need

The requirements for animal force (days/ha/month) for the forage system are calculated for the activities of soil preparation and forage transportation.

Forage productions

Forages, source of nutrients for animals, are apprehended according to their nature (species), their age, the harvest type (fresh or conserved) and their yield (variable according to the farm type). We consider that Moc Chau farms have forage autonomy since only in very rare cases (period of strong deficit) farmers purchase forage coming from others districts. The choice made by the model to select forage species (and surface allocated) is linked to the nutritional needs of animals and the nutritional values of forage. As farmers do not cultivate rice on their fields, the totality of rice straw needed is bought in the market. Rice straw is mainly used to meet the animal requirements of fibers. Generally, maize crop has two objectives: (1) production of grains to make maize meal which constitutes part of the requirements of concentrated feed for the herd and (2) production of silage like a method to stock forage for the winter period. According to the nutritional needs of animals and the costs of concentrated feed in the market, part of the surface allocated with maize (maximum 20% of total forage surface) will be split (or not) between the production of maize for grain and maize for silage.

Annual forage yields data are obtained from questionnaires carried out with farmers and remain constant during the whole simulation period. However, in some cases we observe high variability in average yields among farmers. The differences in forage yields in each region (farm type) are assumed to be mainly associated with soil fertility since climatic conditions are quite similar among regions. Factors affecting biomass production including: plant maturity, water stress, thee effects of temperature on photosynthesis efficiency, and the fertilization effect on growth were not taken into account. The monthly growth potential of perennial forage species is calculated according to the growth curve observed with *Pennisetum purpureum*. Even if we consider a weak growth (< 7%) of perennial species during winter period, there are no cuts of these species during January, February, March (except for *Pennisetum purpureum*), November and December. At the time of the planting year (first year) of perennial crops (except for *Pennisetum purpureum*) the forage production is assumed as being 75% of the total production; at the time of the last year of lifespan for perennial crops the forage production is assumed as being 90% of the total production. The production of hay from *Brachiaria decumbens* is only performed in July and August because these two months usually correspond to the period with forage surplus. The quantity of hay produced (in % of the grass production) is fixed by the user (or by the farmer behavior) but remains constant during the whole simulation period. The dry matter content and the nutritional value (energy, protein, UEL) of forage species (fresh and conserved) remain constant during the whole year. Conserved forage (hay and silage) can be used for a 12-months period after the harvest time (1 month later in the case of silage).

3.4.2. Livestock component and feeding

The herd management

The dairy herd is divided in three groups: calves (from 1 to 6 months of age), heifers (from 7 to 30 months of age) and adult dairy cows (from 31 to 92 months of age; around 7.5 years of age). The animal genetic potential for milk production is taken into account according with two categories: cows producing on average 4,000 liters of milk per lactation (in 305 days) and those producing 7,000 liters per lactation. We observe that this genetic potential is normally present in the majority of Moc Chau dairy farms. The progression of the animals in the herd is carried out per month periods. After five years of milk production, cows are obligatorily reformed.

The male calves are automatically sold as well as the female calves resulting from the group of medium milk production potential (4,000 liters/lactation). The female calves resulting from the high milk production cows (7,000 liters/lactation) are sold or remain in the farm for the herd replacement. The male/female birth ratio (50/50) is taken into account by considering that the first, third and fifth calving periods of the cows of medium milk potential give place to a male and the second and fourth calving periods give place to a female born. In the case of the high milk potential cows, the female calves born result from the first, third and fifth calving periods and the male calves from the second and fourth calving periods. Mortality and fecundity rates of animals are not taken into account in the model due to the small scale of farm herds.

The number of animals present in the farm will varies according to feed availabilities, milk production potential and lifetime. However, we can fix a minimum and a maximum of animals to be present in the farm in each period.

The draught herd corresponds to the cattle and/or buffaloes which are used for agricultural activities and transport of forage from the field to the dairy herd housing. The lifetime of draught animals is fixed to 10 years. The renewal of draught herd is made with animals bought in the market or rented by day-length periods.

Labor need

The labor need (days/ha/month) for livestock component is calculated to the following activities: general breeding (observation of animals, changes among buildings, cleanness and other care, treatments and vaccinations, etc.), feeding and milking (manually performed or mechanized). The requirements in labor vary according to the age (young and adult) and the type of animals (dairy or draught).

Livestock nutritional needs and feeding

The animal feeding aspect is a key part of the model since it gathers at the same time the milk production and the management of forage resources. It is thus in the center of DAIVIE model and requires a detailed attention. Moreover, this aspect strongly influences the adoption of farmers regarding the new forage technology. Indeed, the intense forage deficit observed during the winter period obliges farmers to adopt oat forage as being the only available forage resource to feed the animals in this period of the year.

Feeding values are defined according to the UFL/PDI feeding value system (Jarrige, 1989). The UFL is the forage unit characterizing the energy value of a considered feed to allow milk production. The energy value of feeds and the animal requirements are expressed in UFL. Protein truly digestible in the small intestine (PDI) has two origins: dietary (PDIA) and microbial (PDIN and PDIE). The last two are synthesized in the rumen respectively from degraded dietary N and dietary energy. The protein value of feeds and the animal requirements are expressed in kg PDI.

The approach used by the model is based on the total cover (fulfill) of energy needs for the herd. The energy needs are calculated according to the expenditures for maintenance, growth (calves, heifers and first calving cows), gestation, moving, animal body condition (loss or gain weight) and for milk production. Monthly nutrient requirements are calculated to the total herd (young and adult dairy and draught animals). These requirements are met by both forage resources (first priority but under a certain number of nutritional or physiological constraints defined by modeler) and concentrated feed. The calculation of energy intake does not take into account the depressive effects of concentrate-forage interactions in the rumen (Vermorel *et al.*, 1987). However, the amount of concentrated feed allowed in the daily ratio is fixed to a maximum of 40% on an UEL basis (*Unités d'Encombrement Lait*; Volume Units for Milk production). The energy requirements for lactation are calculated for a fixed milk production level (according to the month of lactation and genetic type) and will have obligatorily to be met by the energy supply of the ration. Animals are never considered as in under-nutrition situation.

The protein needs for the herd are calculated according to the expenditures for maintenance, growth, gestation and milk production. They are covered by the protein contributions of the ration. Since the model does not have as first purpose to be a program of feed rationing or ratio formulation, the accurate balance of energy and protein contributions compared to the needs remains difficult to formulate. The intake of energy from forage and concentrated feed is always associated with a combined intake of proteins from these feedstuffs. The model guarantees at least the supply of the minimum quantity of protein necessary to meet the animal protein requirements but will be able to exceed this minimal limit and to involve an excess of protein consumption by animals.

The requirements (minimum and maximum) of fiber elements (cellulose, etc.) in the animals feed ration are taken into account using the French concept of *Unités d'Encombrement Lait* (UEL). The approach used by the model is based on the maximum capacity intake (UEL) of animals which is limited by rumen volume and the minimal quantity of intake required to avoid problems of digestive physiology of ruminants. The maximum capacity intake is calculated using coefficients to body weight, milk potential (kg/day), animal body condition, weeks of lactation, weeks of gestation and animal age. The quantity of minimum intake is fixed to 75% of the maximum capacity intake. Rice straw is mainly used to meet the minimal fiber requirements of animals. The daily intake of certain feed like maize grain (maize meal), maize silage and *Brachiaria* hay are limited to maximum quantities.

The energy and protein needs and the UEL (minimal and maximum) for the draught herd (cattle and buffalos) are not particularly detailed considering the relatively low influence in the feed management of a dairy farm in Moc Chau. An approximate value for each requirement is given and remains constant throughout the whole simulation period.

Livestock productions

The milk production of adult cows is calculated according to their genetic potential (medium and high), their rank of lactation (first calving and others calving) and the month of lactation (following the theoretical optimal milking curve). The milk production level remains constant throughout the whole simulation period because we declared that the energy and protein contributions of the ration will always cover the totality of requirements for milk production. The lactation period is fixed at 10 months and the dry period is fixed at 3 months. The calving interval in Moc Chau dairy farms is generally 13 month with few exceptions which are not taken into account by the model. The herd reproduction performances are kept constant. To improve the model accuracy, a mathematical function could be designed to allow the calving interval to be dynamically calculated, depending on forage availability for instance.

The manure production of milk cows is calculated using an equation which takes into account the body weight, the weeks of lactation and the milk production. The model dynamically calculates the stock of manure produced (and/or bought) and the manure used in the farm. The manure production resulting from the draught herd (cattle and buffaloes) is not taken into account because these animals are almost permanently in displacement or divagation.

The animal force production is fixed at 30 days per month and per animal and we do not make any differentiation between the activities carried out by cattle (weaker) or by buffaloes (stronger).

3.4.3. Initial stocks

The initial stocks for feed (*Brachiaria* hay, maize silage, maize grain) existing in the farm to face the first periods of the model, the initial herd size and their ages, the quantity of manure available on the farm, the initial budget of farmers, the size of available surface as well as the perennial crops allocation surfaces are imposed to the model according to data obtained in the questionnaires (January 2006).

The farm labor is mainly from family origin with an average from 2 to 4 people depending on the farm type. The working time considered is 10 hours per day throughout the year. However, the majority of farmers wish to decrease this working period with less hours of work per day. This factor represents the social character which will be taken into account in the model. There is no differentiation between the activities (and the working times) carried out by the man and the woman. When the required labor for forage and livestock activities exceeds the family labor potential, the model uses hired labor available in the market.

3.4.4. Economic approach

The model economic approach results in the combination of costs and incomes. The costs include all the inputs for livestock and forage components (concentrated feed, rice straw, manure, water for irrigation, seeds, etc.), human labor and animal force needed for all activities, the rent of agricultural surfaces and the depletion costs of equipments and buildings. Over the whole simulation period, the farm's equipments and facilities are assumed to be invariant with neither acquisition nor disposal of new durable assets. The family labor cost (opportunity cost) is considered in the model but remains lower than the hired labor cost to force the model using firstly the family labor resources. The model does not take into account the refunding of loans carried out by farmers due to the absence of accurate data.

The incomes come from the sale of milk, calves and culled animals (dairy and draught). The initial costs prices as well as the milk selling price are fixed over the whole simulation period. The model also considers the incomes resulting from other activities of breeding (pigs, poultries, etc.), agriculture (fruit trees, tea, etc.) or other nonagricultural activities (shop, teaching, etc.) of family members. There are no constraints in terms of liquidity. The model calculates the animal inheritance (patrimony) of farms throughout the whole simulation period.

With regard to the optimized profit, we expect a slight over-estimation because of the absence of some costs which are not taken into account due to the absence of accurate data or due to the complexity to analyze it. In addition, given the fact that the profit is the factor to optimize, the model will not always seek to increase the production investing in animals but will precisely limit the expenses. For example, a stop on herd renewal (keeping heifers) is noted as from a certain period of the model with the aim to reduce costs and consequently increase the profit. Indeed, as from a certain moment of the model the heifers which would entry in the system would be only a source of expenditure (feeding, labor, etc.) and would not bring any benefit to the final income because their milk production will not be effective (or very little) until the end of the simulation period.

3.5. Sensitivity analysis of the model

Saltelli (2000) defines sensitivity analysis as “the study of the relationship between information flowing in and out of the model”. Sensitivity analysis is generally used to characterize and understand model behavior or to ensure that the way in which the model operates resembles the phenomena being modeled. A sensitivity analysis of a linear model makes possible to situate the effect of several parameters on the optimized result. In addition, this analysis makes possible to locate the coefficients which could have little effect on the realization of the objectives but nevertheless can lead to a change in the type of activities chosen by the process of optimization (Jansen and van Ittersum, 2007).

Several scenarios varying certain criteria of the farm (price of milk, available surfaces, etc.) will be compared with a reference scenario according to the method of the "bench marking" (comparative analyzes) presented by Louhichi *et al.* (2004). This method initially makes possible to note the sensitivity of the model for the selected factors.

The sensitivity analysis of DAIVIE model is currently on going. However, we already noted that market prices and costs exploit a dominating role in the profit. The land surface available which is a constraint for the expansion of farms has an impact on the forage supply potential. The forage output has significant consequences because the nutrient requirements for the animals are fixed and the supplies must absolutely meet these needs. Other factors have not a very strong impact on the final profit result but if we drastically change their values, the model can not converge any more towards one optimal solution. The few scenarios tested until now are not sufficient, numerous other scenarios must be tested to be certain that the behavior of the model remains coherent. These scenarios will be then compared with a reference scenario to judge the changes caused by each change of factors. According to expert statements, if a model remains sensitive for many parameters this is regarded as a sign of good precision of the model. The analysis of sensitivity of the model is founded on logic and on good perception during the result analysis. Generally the analyses of sensitivities call upon statistical tests but when the factors of a model vary too much, their impact could not be analyzable any more with statistics. It is thus a global analysis with expertise-based opinions who allows targeting the sensitivity of the model.

After testing scenarios to analyze the coherence of the model, it is interesting to show in what the model can be useful using oriented scenarios. This means scenarios whose results can be exploited by the local actors. The response of the model to a question, with significant stakes, can make possible to really bring trails of discussion to farmers and to the local decision makers. These results remain indicators of evolution which must be considered by knowing the limits of the model.

3.6. Validation of the model

The validation of a model is one of the key stages in the realization of a model and is obligatory to allow a future use of the model. The validation represents the principal stake but the questions concerning the methods of validation and the necessary approach according to the type of model, remain sometimes an obstacle for the good realization of this step.

Concerning the validation approach, two ideas are proposed. The first approach presented by Jansen (1997), consists in considering that the principal method to prove the reliability of a model is obtaining results which are closest possible to reality. This approach is largely widespread (Aggarwal *et al*., 2006, Hazell and Norton, 1986, Thornton and Jones, 1998) and is the base for the majority of the validation methods. It is accordingly that the calibration of a model is carried out. The calibration of the coefficients, according to experiments and literature, consists in adjusting them in order to have results close to reality (Aggarwal *et al*., 2006). As well as in the "bench marking" method the validation consists in defining one reference year for the source data. The results of this year must be close to reality, which will allow a comparison between the results of simulation and this reference year. The analysis of scenarios consists in detecting the reactions of the endogenous variables of the model following the changes of exogenous parameters. The goal of this analysis is to study the impact of various assumptions related to these parameters on the behavior and the outputs of the model. The results of each scenario are compared with those of the reference scenario to isolate the economic effects of the exogenous changes introduced into the scenario (Louhichi *et al*., 2004). This comparison between the results obtained by modeling and the results observed in reality will also permit a statistical analysis of the results. That allows a reliable validation of the results with recognized statistical methods.

On the other hand, some authors refute this method to compare the simulated results with the reality. A mathematical programming model cannot be validated by comparing its solutions with reality because the model gives a better solution than in reality (Morrison *et al*., 1986) and than apart from the limits of the model, they do not correspond to reality (Magnin, 2006). An argument also quoted by Herrero *et al.* (1999), is that the model gives an optimal solution which a priori will never be able to correspond to reality. They are thus opposed to a validation only with one comparison: simulation *vs* reality which seems to them to be quite little realist. For example, it is difficult to compare the profit obtained by the model and reality because it is precisely the factor which should not remain close to reality. The important is to have a coherence of results which as much as possible remain in an acceptable scale for the farm. But this first approach is not enough to validate the model. Many tests should be realized to evaluate the way in which the model reacts to the changes of exogenous variables. In the second time, the comparative analysis must ensure that the model does not create endogenous effects, and the technical and economic results must be confronted with expertise-based forecasts. Finally a possible scenario must be built to identify the effects due to the exogenous changes (Nidumolu, 2007).

Nevertheless, the solutions of the model can be compared with reality to ensure itself at least of the feasibility of the model. Concrete methods suggested for precisely going further a simple comparison from the results consist in for example the expertise-based validation (Nidumolu, 2007).

These two approaches seem opposite at first view but are in fact complementary since it is interesting to have the two types of validation. The opinions of experts (scientists and technical advisers) are always necessary to validate the form and the structure of the model. The analysis of the results with if possible a correct reference is also necessary to test the reliability of the model, while always remaining within the limits of the model.

In conclusion, to obtain a valid and calibrated model, it is necessary that the model produces results sufficiently representative of reality which result to consider as optimal the model operation. Then, we can use the model in a predictable way. The global validation of DAIVIE model is currently on going.

3.7. Limits of the model

The first consideration we should not forget concerning the models is that being a simplification, any model has its limits, its validity domain (Magnin, 2006). It is within this domain that the results should be considered. The results make possible to highlight the coherence of the model but the range of these results is limited by several factors.

First of all, the logic and coherence of the model can be evaluated but the validation of both stochastic and predictive model remainder difficult. The results are thus to prudently and thoroughly analyze and to not seeking reality but a tendency in the observed evolutions. A coherence of the results and a correct internal operation of the model should not lead to a final and absolute confidence in the results. The validation of the model is never really finished, each new scenario can confirm or to serve the validation and it is by carrying out many scenarios that we will improve the realism of the model outputs.

Then, the choices of conceptualization pose others limits to the model. Certain parameters, as animal intake or milk production are very simplified to be globally used. We can thus wonder until where this simplification will not disturb the results. Other parameters needed to be reviewed in order to obtain the appropriate level of complexity to represent with realism the functioning of the dairy farms. In addition, the objective of the model is the optimization of the income which is not inevitably the objective of all farmers. In reality decisions of farmers are motivated by multiple, often conflicting, objectives, among which profit maximization is only one (McCown, 2001; Wallace and Moss, 2002).

On the other hand, each factor has a higher or a lower limit which when it is exceeded, will make the model unfeasible. This means that no solution objectifies will be defined. These limits are not definite because they are dependents on the variations of other variables. The risk to reach a limit during a scenario realization always exists but it can be limited by making scenarios which remain logical and using coherent data.

Lastly, the model remains a linear model of optimization. In spite of a very good logic in the organization of the different sections and reasoning, the model remains in the field of the possibilities. It does not give results true or false, it is necessary to know advisedly how to use the results without forgetting that they are, first of all, a support tool to discussion and they do not try to get always “the solution”.

3.8. The user interface

The objective of the interface is to allow the use of the model by an uninitiated person to programming under GAMS. The model must thus be activated from a simple use interface, accessible to all, thanks to which it is not necessary to interact directly with the programming software. This interface will have to manage at the same time the compilation of the model and the results.

The simplicity of the interface to both user and modeler is a significant objective. The modeler must build a functional interface without spending too much time on presentation design, as other questions about the quality of the model are more significant. The user, who will be a priori a dairy actor of Moc Chau milk basin, will have to be able to use this tool in a specific way.

In agreement with this objective, the choice carried out for the interface design consists of an Excel file which was improved using Visual BASIC for Applications (VBA). The file is connected to the model under GAMS and allows its activation. The user has thus only to handle an Excel file made up of simple tables as well as menus allowing to facilitate navigation between the various sheets and tables.

The optimized results of the model are also presented under Excel. This software being known for a great number of users, avoid special training. The interface is also useful to facilitate the access to the results and accordingly to this, the interface appears satisfactory. The presentation of the results is improved thanks to the interface but their interpretation remains difficult for certain scenarios. The interface facilitates the use of the model from the technical point of view but does not bring structural solutions. In addition, it is important to know a minimum the initial assumptions and the conceptualization choices to have a better comprehension of the results.

4. Scenarios and discussion

This section presents the main results of several scenarios tested with the DAIVIE model. The model focuses on the introduction of *Avena* grass during the winter period in a dairy farm. The farm level approach makes possible to take into account the availability of this production factor and allows to visualize the evolution of the farm and to measure the effects over the economy, labor time and other variables inside the different farm types. Using this modeling tool, it will be possible to evaluate the impact of *Avena* grass utilization and to identify the main factors constraining its adoption by farmers. The annual profit (total income – total costs) and the labor time were selected as indicators to evaluate this impact on the economic and social sustainability of dairy farms.

The multi-period linear programming model was developed for each farm type using data and coefficients derived from questionnaires and assessment surveys in 2006. Farm types (1, 2 and 3) were based on an average farm from each typology criterion (soil fertility, farmers' dairy experience, dimension of herd and adoption behavior). The farm structure is put in an optimization setting where farm profit is maximized over the multi-year planning period. The multi-period nature of the model allows it to capture the dynamics of adjustment processes, which is far more enlightening than the alternative methodology of comparative static.

When we used the model without any restriction concerning the number of animals in the herd and the possibility to use *Avena* grass, we observed that in all the obtained scenarios the dairy herd increased compared to the initial situation and *Avena* was selected like forage resource for all the winter periods. This indicates that the optimal solution found by the model to maximize the profit of farmers passes by an increase in the number of dairy animals and by the adoption of oats in winter. However, the results are variable according to the specific characteristics of each firm type. According to the current situation in Moc Chau, the increase in the dairy herd is not always an objective of farmers because that represents a more significant labor time for the family or because there are land constraints in the farm. To take into account this condition, we carried out two options of scenarios (S and S'); the first one with a number of animals stabilized compared to the initial herd and the second option with the possibility of increasing the dairy herd. To test the impact of oat forage utilization, we made scenarios with and without the possibility for the model to select this forage resource. The results obtained for the annual profit and the labor time in each of the typologies are presented in Tables 5, 6, 7 and 8.

4.1. Typology based on soil fertility (*Pennisetum purpureum* yields)

In the case of scenarios carried out with a stable dairy herd we must note that the model cannot strictly respect, as maximum, the number of existing adult animals during the first period (January 2006) because at this period, other young animals (calves females and heifers) are already presents in the system and will join the adult herd in the following periods. The model does not have the possibility to eliminate animals which are already presents in the initial situation of farms. Thus, we limited the model between a minimum adult herd which corresponds to the initial herd and a maximum adult herd required by the structure of the initial dairy herd.

In the scenarios with a stable dairy herd, the impact of oat forage utilization on the farm economy leads to an increase in the total profit (8 years) of 8, 11 and 18% for farm types 1, 2 and 3, respectively. The increase in the profit of a dairy farm is directly related to an increase in the incomes (milk and young animals sell) and/or on a reduction in the production costs. When farmers use oat forage during winter, they have additional forage resources to feed their animals and the number of productive animals present in the farm likely increase (even in the case of a stable animal herd). Generally, the costs related to feeding dairy cows correspond to 60-70% of the total production costs, and a significant part is due to the purchase of concentrated feed. As we can observe in Table 9 (appendix 2), the use of oat forage during winter decreases (25 % on average) the concentrated feed consumption in this period. This confirms our observations and feeding experiments concerning the possibility of using oat forages like alternative to replace, from a nutritional point of view, the concentrated feeds. Moreover, from an economic point of view, the energy and protein cost of the oat forage is 75 and 82% lower, respectively, compared to concentrated feed.

However, the increase in the profit with the use of oat forages was variable according to the farm type. The farm which has a better soil quality (type 3) corresponds to that where the increase in the profit was higher (18%; S6). This is directly related to higher oat forage yields in the case of farm type 3. The production potential of oat forage is 30 tons of fresh matter/ha in the case of farm type 1, 60 tons FM/ha for type 2 and 100 tons FM/ha for type 3. This result confirms one no-satisfaction reason declared by certain farmers related to the use of oat forage, which estimates that in poor soils the interest of oat forage is rather limited due to low re-growth capacity. Even if an increase in total profit (8%) is observed in the farm with the poor soils (type 1), this slight increase is probably not sufficient to the adoption of oats as an alternative forage resource.

Labor time data is calculated to the whole dairy farm activities (livestock and forage) during the period of oat forage production (from September to February). The impact of oat forage utilization over the labor time of farmers leads to an increase of 35% on average for the three farm types. This result quantifies the comments of certain farmers related to the increase in labor time due to the production of oat forages during winter. However, in any case the additional labor need caused by oat forage production exceeds the farm labor availability (60 days/month on average). Nevertheless, for certain farmers, this time of the year "culturally" corresponds to a period of rest related to the agricultural activities, and the additional labor required by oat forage production is not very well accepted to allow the adoption of the new technique.

In the case of scenarios carried out with a variable dairy herd ("free"), the impact of oat forage utilization on the total profit and the labor time was similar to that previously observed. The great difference relates to the farm type 3 which obtains an increase in the profit of about 40% compared to the scenario without oats. This is mainly related to the increase in the incomes with milk production because the number of adult animals increased until a maximum of 11 and also thanks to significant reductions of the quantity of concentrated feed used (20%; cf. Table 9, appendix 2). In conclusion, the results show that the oat forage yields (related with soil fertility) seems to be an important issue for the adoption of the new forage technology, especially if it requires significant amount of additional labor.

Table 5. Scenarios based on *Pennisetum purpureum* yields (associated with the soil fertility of farms)

herd fixed			farm type	scenario	use of *Avena*	indicator	years								total / average	%
In.	min	max					1	2	3	4	5	6	7	8		
6	6	8	1	S1	N	Profit	819	1613	2819	2950	2590	2494	3168	3925	20 378	
						Labor	33	31	27	29	30	31	29	31	30	
				S2	Y	Profit	772	1671	3064	3367	2800	2697	3601	4109	22 081	+ 8
						Labor	42	40	36	38	40	40	39	42	39	+ 30
3	3	6	2	S3	N[6]	Profit	968	1263	2364	2064	2606	2490	3059	2304	17 118	
						Labor	18	22	17	20	21	21	18	21	20	
				S4	Y	Profit	873	1756	2488	2317	2855	2774	3481	2450	18 994	+ 11
						Labor	25	29	24	27	28	28	25	28	27	+ 35
4	4	6	3	S5	N	Profit	902	1817	2533	2303	2654	2521	3234	3097	19 060	
						Labor	23	25	21	23	24	24	23	26	24	
				S6	Y	Profit	1109	2580	3110	3304	3415	3126	3910	3969	22 522	+ 18
						Labor	32	33	28	32	34	34	33	37	33	+ 38
herd "free"																
In.	min	max														
6	5	11	1	S1'	N	Profit	797	1 364	2 056	2 477	3 551	3 688	3 868	3 808	21 607	
						Labor	33	33	30	31	32	31	28	29	31	
	6	12		S2'	Y	Profit	830	1 161	2 020	3 083	3 929	3 979	4 204	4 295	23 504	+ 9
						Labor	43	44	40	44	44	43	39	41	42	+ 35
3	3	8	2	S3'	N[6]	Profit	896	1272	1909	1597	3140	2881	3402	2761	17 859	
						Labor	18	23	19	22	24	24	21	22	22	
		9		S4'	Y	Profit	895	1606	1939	1842	3398	3497	3668	3206	20 052	+ 12
						Labor	25	30	27	30	33	34	30	32	30	+ 36
4	4	8	3	S5'	N	Profit	922	1818	2393	1929	2691	3160	3745	3488	20 145	
						Labor	23	25	23	25	26	28	25	28	25	
		11		S6'	Y	Profit	1156	2316	2638	2898	4339	4845	4923	4797	27 916	+ 39
						Labor	32	36	34	38	41	42	38	41	38	+ 52

In.: initial herd (adult cows) in January 2006; **min:** minimum number of adult cows considered by the model; **max:** maximum number of adult cows considered by the model;
Farm type 1: *Pennisetum purpureum* yields between 60 – 80 tons FM/ha/year;
Farm type 2: *Pennisetum purpureum* yields between 80 – 100 tons FM/ha/year;
Farm type 3: *Pennisetum purpureum* yields between 100 – 120 tons FM/ha/year;
Profit: Total income – total costs;
Labor: monthly labor need for crop and livestock system during the months of *Avena* production (Septembre to February; 6 months)

[6] No bound for Maize silage maximum intake per day (5.0 kg FM) when *Avena* grass is not used

4.2. Typology based on dairy experience of farmers

In the case of scenarios based on the experience of farmers related to dairy activity (Table 6), the impact of oat forage utilization on the profit was similar for the two options of the model about the herd (stable or variable). On average, the increase in the profit was 18% in the case of scenarios with a stable adult herd and 20% for scenarios with a "free" adult herd. The reasons for this profit increase are similar to those presented in the typology based on soil fertility; i.e. an increase in the incomes resulting from the sale of milk and young animals, as well as a reduction of the concentrated feed expenditure when farmers use oat forage during the winter period. In Table 10 (appendix 2) we observe that the reduction in the use of concentrated feed was 18% in the case of scenarios with a stable adult herd and about 8% for scenarios with a variable adult herd. The increase in the profit in the case of the scenarios with variable dairy herd was less significant compared to the expectations because the reduction in concentrated feed quantities was only 8%.

The results of these scenarios demonstrate that the experience of farmers in dairy activity is not a required condition to obtain good economic results with the adoption of oat technology. Almost all farmers declared that the technical protocol for oat production is rather simple and do not pose difficulties even for farmers with less experience in dairy breeding. The similarity of the profit increases with oats among the three farm types (1, 2 and 3) is also influenced by the oat forage yields which were relatively comparable, about 60 tons FM/ha, for the three farm types.

The impact of oat forage utilization over the labor time was paradoxically more significant for farmers with further experience in dairy breeding compared to those with less experience. This could be partly explained by the higher oats surface sowed by farmers with more experience (0.44 ha) compared to the less experienced farmers (0.28 ha). In conclusion, the results show that the experience of farmers in dairy production does not seem to be a factor determining the adoption of the new fodder technology.

Table 6. Scenarios based on farmer’ experience in dairy activity

herd fixed			farm type	scenario	use of *Avena*	indicator	Years								total / average	%
In.	min	max					1	2	3	4	5	6	7	8		
3	3	6	1	S1	N[7]	Profit	716	1186	1516	1915	2270	2153	2751	2214	14 722	
						Labor	19	22	16	20	21	21	18	20	20	
				S2	Y	Profit	811	1476	2161	2162	2649	2533	3055	2656	17 504	+ 19
						Labor	25	28	22	26	27	27	24	27	26	+ 30
5	4	8	2	S3	N	Profit	978	1434	2621	2873	3271	3067	3886	3497	21 627	
						Labor	28	30	24	27	28	29	26	27	27	
				S4	Y	Profit	961	1850	3167	3391	3868	3614	4476	3995	25 321	+ 17
						Labor	38	39	33	37	38	38	35	37	37	+ 37
5	5	9	3	S5	N	Profit	943	1447	2349	2884	3311	3301	3588	3121	20 945	
						Labor	31	32	26	30	30	29	27	29	29	
				S6	Y	Profit	899	1657	2851	3898	3315	3554	4262	4050	24 485	+ 17
						Labor	42	42	37	41	41	41	38	40	40	+ 38
herd “free”																
In.	min	max														
3	3	8	1	S1’	N[7]	Profit	702	898	1226	1388	2683	2552	3004	2580	15 033	
						Labor	19	24	18	22	24	24	20	22	22	
				S2’	Y	Profit	775	1324	1723	1830	3246	3030	3316	2976	18 220	+ 21
						Labor	25	30	24	28	30	30	27	29	28	+ 27
5	5	9	2	S3’	N	Profit	1015	1435	2422	2679	3590	3513	3792	3447	21 893	
						Labor	28	30	25	28	30	30	26	27	28	
		12		S4’	Y	Profit	1135	1735	2217	2956	4273	4530	4871	4732	26 450	+ 21
						Labor	38	42	37	42	45	46	42	43	42	+ 50
5	5	10	3	S5’	N	Profit	1037	1508	2583	2223	2956	3798	3606	3358	21 070	
						Labor	30	32	27	29	30	30	26	28	29	
		12		S6’	Y	Profit	999	1330	2069	3369	4301	4313	4451	4305	25 137	+ 19
						Labor	42	45	40	44	45	44	40	42	43	+ 48

A: actual herd (adult cows) in January 2006; **min:** minimum number of adult cows considered by the model; **max:** maximum number of adult cows considered by the model;
Farm type 1: dairy experience lower than or equal to 8 years;
Farm type 2: dairy experience from 9 to 17 years;
Farm type 3: dairy experience greater than or equal to 18 years;
Profit: Total income – total costs;
Labor: monthly labor need for crop and livestock system during the months of *Avena* production (Septembre to February; 6 months)

[7] No bound for Maize silage maximum intake per day (5.0 kg FM) when *Avena* grass is not used

4.3. Typology based on dairy herd dimension

In the case of scenarios based on the dairy herd dimension (Table 7), the impact of oat forage utilization on the profit was slightly higher in the farm with fewer animals (≤ 2). The increase in the profit (+ 23%) of this farm type is the result of a considerable reduction (65%) in the concentrated feed consumption (Table 11, appendix 2) when farmers opt to use oats during winter period. This reduction in the quantities of concentrated feed was less significant (17% on average) in the case of farms with more animals (> 3). This result indicates that in spite oats are an excellent solution for feeding animals during winter (in alternative to the use of concentrated feed), the quantities produced (linked to allocated surface) by farms with greater dimension are still insufficient to suitably feed large dairy herds. In the case of farms with small size (type 1), the oats surface per animal head is 0.17 ha, for farms of type 2 and 3, oats surfaces per animal head are 0.06 ha and 0.08 ha, respectively. The land allocation for annual forage species (maize and oats) is fixed by the rules of the Milk Company of Moc Chau. Farmers cannot cultivate more than 20% of their total surface with annual species because the remainders 80% of surface is occupied by perennial forage species. However, as the production of tropical forage species is almost non-existent during winter months, some farmers started to cultivate oats in the spaces between-lines used by perennial species. Thus, they can use more than 20% of their forage surface with oats and the first results from the field are very optimistic.

In the case of scenarios carried out with a variable dairy herd, the impact of oat forage utilization on the profit is higher thanks to the increase in the incomes of milk and young animals' sale. The maximum number of adult animals increased by 150% for farm type 1, by 33% for farm type 2 and by 55% for farm type 3. The differences of oat forage impact on the benefit of farmers were higher in the case of scenarios with variable dairy herd.

The impact of oat forage utilization over the labor time was similar, about 36% on average, for the three farm types with stable dairy herd, and a little more significant and differentiated when the scenarios were carried out with a variable dairy herd. The impact over the labor time is rather consequent (50%) for the farms with few animals. In conclusion, the results show that the dimension of the dairy herd does not seem to be an essential factor determining the adoption of oat technology. However, the results seem to be more interesting for farmers with small herd size even if in the farms with bigger herds, the impact of oat forage utilization is also considerable. However, the significant impact over the labor time in the small size farms can represent a major constraint to the successful adoption of the technique by farmers in this farm type.

Table 7. Scenarios based on dairy herd dimension

herd fixed			farm type	scenario	use of *Avena*	indicator	Years								total / average	%
In.	min	max					1	2	3	4	5	6	7	8		
1	1	2	1	S1	N	Profit	417	310	808	905	603	973	939	1053	6 012	
						Labor	11	11	13	11	11	11	11	12	11	
				S2	Y	Profit	459	388	960	1257	742	1196	1140	1229	7 372	+ 23
						Labor	14	15	18	14	17	17	16	13	15	+ 36
3	3	6	2	S3	N[8]	Profit	782	1101	1804	1724	2404	1963	2896	2184	14 859	
						Labor	17	21	16	20	20	21	18	19	19	
				S4	Y	Profit	696	1467	2134	2117	2643	2425	3021	2506	17 009	+ 14
						Labor	23	27	22	26	26	27	24	26	25	+ 32
9	6	11	3	S5	N	Profit	2274	3060	4042	4170	4196	4667	5514	5465	33 388	
						Labor	39	40	38	38	38	37	34	38	38	
	7			S6	Y	Profit	2255	3848	4996	5398	4461	5460	6016	6469	38 902	+ 17
						Labor	55	55	53	53	53	52	51	53	53	+ 39
herd "free"																
In.	min	max														
1	1	3	1	S1'	N[9]	Profit	367	244	667	1280	1130	1396	1388	1469	7 944	
						Labor	11	12	14	12	13	13	14	14	13	
		5		S2'	Y[9]	Profit	402	486	884	1398	997	1985	2093	2403	10 649	+ 34
						Labor	16	17	20	20	21	23	24	25	20	+ 54
3	3	8	2	S3'	N[8]	Profit	783	833	1502	1322	2565	2548	3038	2503	15 095	
						Labor	17	22	18	22	23	24	20	21	21	
				S4'	Y	Profit	824	1265	1729	1686	2989	2983	3239	2753	17 470	+ 16
						Labor	23	28	24	28	29	30	26	28	27	+ 29
9	9	15	3	S5'	N	Profit	2295	3038	3710	3839	3977	5953	5678	5758	34 249	
						Labor	40	41	41	39	40	40	37	41	40	
		17		S6'	Y	Profit	2165	3387	3361	4998	6304	6957	6655	7275	41 101	+ 20
						Labor	55	59	59	59	61	58	55	60	58	+ 45

A: actual herd (adult cows) in January 2006; **min:** minimum number of adult cows considered by the model; **max:** maximum number of adult cows considered by the model;
Farm type 1: lower than or equal to 2 animals;
Farm type 2: from 3 to 9 animals;
Farm type 3: greater than or equal to 10 animals;
Profit: Total income – total costs;
Labor: monthly labor need for crop and livestock system during the months of *Avena* production (Septembre to February; 6 months)

[8] No bound for Maize silage maximum intake per day (5.0 kg FM) when *Avena* grass is not used
[9] Bound for *Brachiaria* hay was increased from 4 kg FM maximum intake per day to 6 kg FM maximum intake per day

4.4. Typology based on *Avena* adoption behavior

In the case of scenarios based on the farmers' behavior related to the adoption oat forage (Table 8), the impact of the new forage technology on the profit and the labor time was similar in the three farm types and in the two dairy herd options (stable or variable). The increase in the profit was about 17% and 23% and the increase in the labor time was about 35% and 42% for scenarios with stable and variable dairy herd, respectively. Apparently, the reasons to the no-adoption of forage technology in the case of farmers in the farm type 1, does not seem to be related to the economic or social indicators selected. Other reasons such as, for instance, the lack of information concerning the availability of this new technology, the lower reactivity of farmers related to technical innovations, the lack of motivation to increase the labor charge during this time of the year, were probably the explanations to the behavior of farmers in 2006. However, according to more recent data of adoption behavior in the following year (2007/2008), the number of adherent farmers increased considerably, passing from 28% of the total Moc Chau dairy farmers in 2006/2007 to 39% in 2007/2008. The forecasts for next winter season (2008/2009) are that the majority of farmers (55% of the total) adopt oat forage in their farming production system.

The DAIVIE model was not tested yet with a great number of situations. However, according to the first uses the results are coherent and the scenarios obtained seem to represent correctly the field observations. Moreover, the model answers to a certain questions of scientific interest like the relative importance of animal feeding strategies imposed by nutritional constraints and allocation of forage crops for productivity of dairy farms. The model achieves the main fixed objectives but many questions remain in suspends, in particular concerning the global validity of the model. Indeed only certain factors are validated but the performance of a model must also be evaluated on its critical components throughout compilation (Sinclair and Seligman, 2000).

Table 8. Scenarios based on *Avena* adoption behavior

herd fixed			farm type	scenario	use of *Avena*	indicator	years								total / average	%
In.	min	max					1	2	3	4	5	6	7	8		
3	3	6	1	S1	N[10]	Profit	648	979	1630	1863	2218	2022	2741	2239	14 340	
						Labor	19	23	17	20	21	21	18	20	20	
				S2	Y	Profit	629	1261	2093	2097	2606	2438	3127	2592	16 843	+ 17
						Labor	25	29	23	26	27	28	25	27	26	+ 30
5	4	9	2	S3	N	Profit	1387	1814	2207	3119	3704	3775	3941	3394	23 341	
						Labor	31	33	25	29	30	29	27	30	29	
				S4	Y	Profit	1239	2272	2921	4134	3902	4200	4656	4452	27 778	+ 19
						Labor	42	43	37	40	41	41	38	43	41	+ 41
8	6	12	3	S5	N	Profit	1290	1903	3477	3612	4445	3965	5425	4845	28 962	
						Labor	36	37	35	36	37	36	33	35	36	
				S6	Y	Profit	1285	2263	4088	4739	4924	4861	5898	5341	33 399	+ 15
						Labor	49	50	48	50	50	49	46	46	48	+ 33
herd "free"																
In.	min	max														
3	3	7	1	S1'	N[10]	Profit	650	735	1537	1574	2578	2440	2797	2285	14 596	
						Labor	19	23	18	21	22	22	18	20	20	
		8		S2'	Y	Profit	732	1193	1635	1712	3140	2951	3189	2892	17 444	+ 20
						Labor	25	30	25	28	30	30	27	29	28	+ 40
5	5	10	2	S3'	N	Profit	1433	2162	2810	2454	2512	3862	3935	3635	22 804	
						Labor	30	31	26	28	27	29	26	31	29	
		13		S4'	Y	Profit	1368	1994	2156	3190	4857	4957	5096	4997	28 615	+ 25
						Labor	42	45	40	44	47	46	43	47	44	+ 52
8	6	15	3	S5'	N	Profit	1242	1795	2728	3449	4266	4545	5031	4913	27 970	
						Labor	36	39	38	40	41	41	39	43	39	
		16		S6'	Y	Profit	1338	2134	3183	4077	5744	5635	6162	6039	34 312	+ 23
						Labor	49	53	52	54	55	54	49	52	52	+ 33

A: actual herd (adult cows) in January 2006; **min:** minimum number of adult cows considered by the model; **max:** maximum number of adult cows considered by the model;
Farm type 1: no adoption;
Farm type 2: adopted only in 2006;
Farm type 3: adopted from beginning of experiments;
Profit: Total income – total costs;
Labor: monthly labor need for crop and livestock system during the months of *Avena* production (Septembre to February; 6 months)

[10] No bound for Maize silage maximum intake per day (5.0 kg FM) when *Avena* grass is not used

Conclusion and perspectives

In Moc Chau dairy basin the low availability of forage resources during winter period and the high cost of concentrated feeds are causing big concerns to dairy farmers with respect to the economic sustainability of their production system. Temperate forage species, in particular oats, are excellent alternatives, in an agronomic and nutritional point of view, to solve the forage winter deficit. Since 2004 oat forages are being experimented in demonstration sites and under farmer-managed fields and in 2006 around 30% of Moc Chau farmers cultivate oats in their farm. The adoption process is on going and the interest demonstrated by new farmers with respect to this new technology is significantly increasing in the last years. The adoption behavior of farmers related to new technologies deals with several factors. We used a modeling approach in order to represent the interactions of main components of a Vietnamese dairy farm, to measure the impact of the new forage technology and to better understand the adoption behavior of farmers. The scenarios obtained from several farm types showed coherent results and logical representations of adoption behaviors. According to the scenario results, the experience of farmers in dairy activity and the dimension of their herd did not seem to be crucial factors determining the adoption behavior of farmers to the new forage technology. However, the oat forage yields obtained and the additional labor time needed to implement this activity are likely the main issues affecting oat adoption in Moc Chau.

The complexity of a dairy farm system makes that there are always certain simplified or ignored factors and the model is thus always likely to be improved. Certain parameters, as fertilizer management, animal progression, milk production variability, labor gender differentiation, etc. are not yet conveniently developed by the model and needed to be reviewed to obtain a better representation of Moc Chau dairy farms. In addition, DAIVIE model was applied at a single farm scale in one specific region of Vietnam. This can only shed partial light on solutions to the dairy sector problems which are essentially of a multi-scale nature. A new modeling approach at a regional-level should be realized to evaluate the effect of political choices, to determine the impact of WTO agreements on the Vietnamese dairy sector, to analyze the possible trajectories of the production systems making possible to pre-empt the awaited evolutions, and to propose indicators of environment impacts. A regional approach is more complex because of the many hierarchical levels which are necessarily taken into account. It is a real stake for the research because of the methodological questions which a regional modeling project involves.

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Appendix 1. Description of DAIVIE GAMS equations and mathematical formula

The model formulation of DAIVIE is presented here. The model is linear and can be solved using linear programming (LP) software, but needs to include integer variables for animal variables resulting in a mixed integer programming (MIP) model.

Further indices used are land available for forage production [index *init* and *max*] (initial and maximum), 96 model periods [index *p*] (in a monthly basis which correspond to 8 years), 12 months of the year [index *m*] (from January to December), 9 crop types [index *ct*] (*Brachiaria decumbens* grass, *Brachiaria decumbens* hay, *Pennisetum purpureum*, *Setaria Sphacelata*, Maize grain, Maize silage, *Avena* grass non irrigated, *Avena* grass irrigated, *Avena* for seed production), 5 crop ages [index *ca*] (1 to 5 years old), 3 forage allocation constraints [index *per_min*, *bra_max*, *bra_min*] (minimum land for perennial grasses, minimum and maximum land for *Brachiaria* grass, respectively), dry matter content of feeds [index *bh_DM*, *mg_DM*, *ms_DM*] (dry matter content of *Brachiaria* hay, Maize grain and Maize silage, respectively), energy content of feeds [index *bh_E*, *mg_E*, *ms_E*] (energy content of *Brachiaria* hay, Maize grain and Maize silage, respectively), protein content of feeds [index *bh_P*, *mg_P*, *ms_P*] (protein content of *Brachiaria* hay, Maize grain and Maize silage, respectively), UEL content of feeds [index *bh_UEL*, *mg_UEL*, *ms_UEL*] (UEL content of *Brachiaria* hay, Maize grain and Maize silage, respectively), dairy cattle age [index *da*] (from 1 to 92 months which correspond to 7.6 years old), draught cattle age [index *dca*] (from 1 to 120 months which correspond to 10 years old), draught buffalo age [index *dba*] (from 1 to 120 months which correspond to 10 years old), calving ages of dairy cattle [index *cma*, *cfa*] (for calving male age and for calving female age, respectively), feed intake bounds [index *MgMax*, *MgMin*, *BhMax*, *BhMin*, *MsMax*, *MSMin*] (maximum and minimum dry matter intake for Maize grain, *Brachiaria* hay and Maize silage, respectively), 2 types of concentrated feed [index *cft*] (type 1 and 2).

The objective functions in DAIVIE are: 1) maximizing farm profit; 2) minimizing costs. The sets that define the different activities are: forage land available (initial and maximum), periods (month), number of crop cycles, crop types, crop ages, animal ages, calving periods, concentrated feed type and market prices. In the formulation, multiple summations over different indices are indicated by a single sigma (e.g. $\sum_{a,b,c}$), equivalent to a series of sigmas, separately for each index ($\sum_a \sum_b \sum_c$).

This section presents the equations used for formulating the constraints, the auxiliary variables, the balances and the objective functions.

<u>Land available, crop allocation and progression</u>

No crop allocation

No land area allocated to a particular crop, if the crop is not present in the crop calendar, or if it exceeds the lifespan.

$$vFX_{p,m,ct,ca} = 0 \qquad \forall\, p$$

Where:

- vFX: land area allocated
- p: period
- m: month
- ct: crop type
- ca: crop age

Land available

The land available in each period, is lower than or equal to the initial land available (if the period is equal to 1) <u>more</u> the land available in the previous period (if the period is greater than 1). Initial land available is a constraint defined by the farm type.

$$vLand\_AV_p \leq Land\_AV_{init} \qquad p=1$$

$$vLand\_AV_p \leq Land\_AV_{init} + vLand\_AV_{p-1} \qquad \forall\, p>1$$

Where:

vLand_AV:	land available
Land_AV:	land available
init:	initial

Land available
If the period is greater than 1, the land available in each period is greater than or equal to the land available in the previous period.

$$vLand\_AV_p \geq vLand\_AV_{p-1} \qquad \forall_{p>1}$$

Where:

vLand_AV:	land available

Land available
The land available in each period is lower than or equal to the maximum of land available. Maximum land available is a constraint defined by the Milk Company.

$$vLand\_AV_p \leq Land\_AV_{\max} \qquad \forall_p$$

Where:

vLand_AV:	land available
Land_AV:	land available
max:	maximum

Crop allocation
The sum of land area allocated for each crop type and crop age is lower than or equal to the land available in each period.

$$\sum_{ct,ca} vFX_{p,m,ct,ca} \leq vLand\_AV_p \qquad \forall_p$$

Where:

vFX:	land area allocated
vLand_AV:	land available

Perennial crop allocation
The land allocated for perennial grasses in each period is equal to the land available <u>multiplied</u> by the minimum area fixed for perennial grasses. This constraint is defined by the Milk Company.

$$vLand\_PGrass_p = vLand\_AV_p \times Area\_Const_{per\_\min} \qquad \forall_p$$

Where:

vLand_PGrass:	land allocated for perennial grasses
vLand_AV:	land available
Area_Const:	area constraint
per_min:	minimum for perennial grasses

Perennial crops allocation
The land allocated for perennial grasses in each period is equal to the sum of land area allocated for each crop type and crop age, if the crop is present in the crop calendar and if the crop type belongs to the perennial grasses (which corresponds to the first four grasses in the crop_type set).

$$vLand\_PGrass_p = \sum_{ct,ca} vFX_{p,m,ct\leq 4,ca} \qquad \forall_p$$

Where:

vLand_PGrass:	land allocated for perennial grasses
vFX:	land area allocated
ct≤4:	crop type = first 4 crop types (perennial grasses)

Brachiaria maximum allocation
The sum of land area allocated for each age of Brachiaira grass is lower than or equal to the land available <u>multiplied</u> by the maximum area fixed for Brachiaria grass. This constraint is defined by the model user.

$$\sum_{ca} vFX_{p,m,ct=1,ca} \leq vLand\_AV_p \times Area\_Const_{bra\_\max} \qquad \forall_p$$

Where:

vFX:	land area allocated
vLand_AV:	land available
ct=1:	crop type = *Brachiaria* grass
Area_Const:	area constraint
bra_max:	maximum for *Brachiaria* grass

Brachiaria minimum allocation

The sum of land area allocated for each age of Brachiaira grass is greater than or equal to the land available multiplied by the minimum area fixed for Brachiaria grass. This constraint is defined by the model user.

$$\sum_{ca} vFX_{p,m,ct=1,ca} \geq vLand\_AV_p \times Area\_Const_{bra\_\min} \qquad \forall\, p$$

Where:

vFX:	land area allocated
vLand_AV:	land available
ct=1:	crop type = *Brachiaria* crop
Area_Const:	area constraint
bra_min:	minimum for *Brachiaria* grass

Annual crop allocation

The land allocated for annual grasses in each period is equal to the sum of land area allocated for each crop type, if the crop is present in the crop calendar and if the crop type belongs to the annual grasses (which corresponds to the grasses with a position higher than four in the crop_type set).

$$vLand\_AGrass_p = \sum_{ct} vFX_{p,m,ct\geq 4,ca=1} \qquad \forall\, p$$

Where:

vLand_AGrass:	land allocated for annual grasses
vFX:	land area allocated
ct>4:	crop type = except the first 4 crop types (annual grasses)
ca=1:	crop age = 1 year (annual grasses)

Initial crop allocation

In period 1, the land area allocated for each crop type and crop age, if the period and the month are equal to 1, if the crop is present in the crop calendar and if the crop age is lower than or equal to the lifespan, is equal to the initial crop allocation. This parameter is defined by the farm type.

$$vFX_{p,m,ct,ca} = I\_Land_{ct,ca} \qquad p=1$$

Where:

vFX: land area allocated

I_Land: initial crop allocation

Crop allocation

If the period and the month are greater than 1, if the period is not the "start month" for the crop, if the crop is present in the crop calendar and if the crop age is lower than or equal to the lifespan, the land area allocated in each period and month for each crop type and crop age, if the crop is present in the crop calendar, is equal to the land area allocated in the previous period and in the previous month, if the crop is present in the crop calendar in the previous month.

$$vFX_{p,m,ct,ca} = vFX_{p-1,m-1,ct,ca} \qquad \forall\, p>1$$

Where:

vFX: land area allocated

Crop allocation

If the month is equal to 12 (December), if the crop is present in the crop calendar, if the period is not the "start month" for the crop, if the crop is present in the crop calendar in the month equal to 1 (January) and if the crop age is lower than or equal to the lifespan, the land area allocated in the next period and in month 1 for each crop type and crop age is equal to the land area allocated in the period and month.

$$vFX_{p+1,m=1,ct,ca} = vFX_{p,m,ct,ca} \qquad m=12$$

Where:
vFX: land area allocated
m=1: month = January

Perennial crop allocation
If the month is equal to 12 (December), if the crop is present in the crop calendar, if the period is the "start month" for the crop, if the crop type belongs to the perennial grasses (which corresponds to the first four grasses in the crop_type set), if the crop is present in the crop calendar in the month equal to 1 (January) and if the crop age is lower than or equal to the lifespan, the land area allocated in the next period and in month 1 for each crop type and crop age 1 year older is equal to the land area allocated in the period and month.

$$vFX_{p+1,m=1,ct,ca+1} = vFX_{p,m,ct,ca} \qquad m=12$$

Where:
vFX: land area allocated
ca+1: crop age = 1 more year old

Perennial crop allocation
If the period is the "start month" for the crop, if the crop type belongs to the perennial grasses (which corresponds to the first four grasses in the crop_type set), if the crop age is lower than or equal to the lifespan, if the crop is present in the crop calendar and if the crop is present in the crop calendar in the previous month, the land area allocated in the period and month for each crop type and crop age 1 year older is equal to the land area allocated in the previous period and in the previous month.

$$vFX_{p,m,ct,ca+1} = vFX_{p-1,m-1,ct,ca} \qquad p=\text{start month}$$

Where:
vFX: land area allocated
ca+1: crop age = 1 more year old

<u>**Crop production**</u>

Green forage dry matter production
The green forage dry matter production in each period is equal to the sum of land area allocated for each crop type and crop age, if the crop type corresponds to the non-stored grasses, <u>multiplied</u> by the forage dry matter yields.

$$vF\_DMP_p = \sum_{ct,ca,m} vFX_{p,m,ct,ca} \times F\_Y_{ct,ca,m} \qquad \forall\, p$$

Where:
vF_DMP: green forage dry matter production
vFX: land area allocated
F_Y: forage dry matter yields

Initial Brachiaria hay dry matter
If the period is equal to 1, the Brachiaria hay dry matter is equal to the initial stock of Brachiaria hay dry matter. This parameter is defined by the farm type (or by the user).

$$vBh\_DMP_p = I\_Fs_{bh\_DM} \qquad p=1$$

Where:
vBh_DMP: *Brachiaria* hay dry matter production
I_Fs: initial stock
bh_DM: *Brachiaria* hay dry matter

Brachiaria hay dry matter production (produced in July and August but used from August only)
If the period is greater than 1, the Brachiaria hay dry matter production per period is equal to the sum of land area allocated in month 8 (August) with Brachiaria grass of each age, if the month is equal to 7 (July) <u>multiplied</u> by the Brachiaria grass yield in July and <u>divided</u> by the % of Brachiaria hay produced in July <u>more</u> the sum of land area allocated in month 8 (August) with Brachiaria grass of each age, if the month is equal to 8 (August) <u>multiplied</u> by the Brachiaria grass yield in August and <u>divided</u> by the % of Brachiaria hay produced in August. The % of Brachiaria hay produced is defined by the farm type (or by the user).

$$vBh\_DMP_p = \sum_{ct,ca,m=7}(vFX_{p,m=8,ct=1,ca} \times F\_Y_{ct,ca,m} \div Hp_{july}) + \sum_{ct,ca,m=8}(vFX_{p,m=8,ct=1,ca} \times F\_Y_{ct,ca,m} \div Hp_{august}) \quad \forall_{p>1}$$

Where:

vBh_DMP:	*Brachiaria* hay dry matter production
vFX:	land area allocated
F_Y:	forage dry matter yields
Hp_{july}:	% of Brachiaria hay produced in July
Hp_{august}:	% of Brachiaria hay produced in August
ct=1:	crop type = *Brachiaria* crop

Initial Maize grain dry matter
If the period is equal to 1, the Maize grain dry matter is equal to the initial stock of Maize grain dry matter. This parameter is defined by the farm type (or by the user).

$$vMg\_DMP_p = I\_Fs_{mg\_DM} \quad p=1$$

Where:

vMg_DMP:	Maize grain dry matter production
I_Fs:	initial stock
mg_DM:	Maize grain dry matter

Maize grain dry matter production (produced in August and used from September)
If the period is greater than 1, the Maize grain dry matter production per period is equal to the land area allocated in the previous period and in month 8 (August) with Maize grain <u>multiplied</u> by the Maize grain dry matter yield.

$$vMg\_DMP_p = vFX_{p-1,m=8,ct=5,ca=1} \times F\_Y_{ct=5,ca=1,m=9} \quad \forall_{p>1}$$

Where:

vMg_DMP:	Maize grain dry matter production
vFX:	land area allocated
F_Y:	forage dry matter yields
ct=5:	crop type = Maize grain crop

Initial Maize silage dry matter
If the period is equal to 1, the Maize silage dry matter is equal to the initial stock of Maize silage dry matter. This parameter is defined by the farm type (or by the user).

$$vMs\_DMP_p = I\_Fs_{ms\_DM} \quad p=1$$

Where:

vMs_DMP:	Maize silage dry matter production
I_Fs:	initial stock
ms_DM:	Maize silage dry matter

Maize silage dry matter production (produced in August and used from October)
If the period is greater than 1, the Maize silage dry matter production per period is equal to the land area allocated in the two previous periods and in month 8 (August) with Maize silage <u>multiplied</u> by the Maize silage dry matter yield.

$$vMs\_DMP_p = vFX_{p-2,m=8,ct=6,ca=1} \times F\_Y_{ct=6,ca=1,m=10} \quad \forall_{p>1}$$

Where:

vMs_DMP:	Maize silage dry matter production
vFX:	land area allocated
F_Y:	forage dry matter yields
ct=6:	crop type = Maize silage crop

Total dry matter production (all crops)
The total dry matter production per period is equal to the green forage dry matter production per period <u>more</u> the Brachiaria hay dry matter production per period <u>more</u> the Maize grain dry matter production per period <u>more</u> the Maize silage dry matter production per period.

$$vTot\_DMP_p = vF\_DMP_p + vBh\_DMP_p + vMg\_DMP_p + vMs\_DMP_p \quad \forall_p$$

Where:

vTot_DMP:	Total dry matter production
vF_DMP:	green forage dry matter production
vBh_DMP:	*Brachiaria* hay dry matter production
vMg_DMP:	Maize grain dry matter production
vMs_DMP:	Maize silage dry matter production

Green forage energy production
The green forage energy production in each period is equal to the sum of land area allocated for each crop type and crop age, if the crop type corresponds to the non-stored grasses, multiplied by the forage energy yields.

$$vF\_EP_p = \sum_{ct,ca,m} vFX_{p,m,ct,ca} \times F\_E_{ct,ca,m} \qquad \forall\ p$$

Where:

vF_EP:	green forage energy production
vFX:	land area allocated
F_E:	forage energy yields

Initial Brachiaria hay energy
If the period is equal to 1, the Brachiaria hay energy is equal to the initial stock of Brachiaria hay energy. This parameter is defined by the farm type (or by the user).

$$vBh\_EP_p = I\_Fs_{bh\_E} \qquad p=1$$

Where:

vBh_EP:	*Brachiaria* hay energy production
I_Fs:	initial stock
bh_E:	*Brachiaria* hay energy

Brachiaria hay energy production (produced in July and August but used from August only)
If the period is greater than 1, the Brachiaria hay energy production per period is equal to the sum of land area allocated in month 8 (August) with Brachiaria grass of each age, if the month is equal to 7 (July) multiplied by the Brachiaira energy yield in July and divided by the % of Brachiaria hay produced in July more the sum of land area allocated in month 8 (August) with Brachiaria grass of each age, if the month is equal to 8 (August) multiplied by the Brachiaira energy yield in August and divided by the % of Brachiaria hay produced in August. The % of Brachiaria hay produced is defined by the farm type (or by the user).

$$vBh\_EP_p = \sum_{ct,ca,m=7} (vFX_{p,m=8,ct=1,ca} \times F\_E_{ct,ca,m} \div Hp_{july}) + \sum_{ct,ca,m=8} (vFX_{p,m=8,ct=1,ca} \times F\_E_{ct,ca,m} \div Hp_{august}) \qquad \forall\ p>1$$

Where:

vBh_EP:	*Brachiaria* hay energy production
vFX:	land area allocated
F_E:	forage energy yields
Hp_{july}:	% of Brachiaria hay produced in July
Hp_{august}:	% of Brachiaria hay produced in August
ct=1:	crop type = *Brachiaria* crop

Initial Maize grain energy
If the period is equal to 1, the Maize grain energy is equal to the initial stock of Maize grain energy. This parameter is defined by the farm type (or by the user).

$$vMg\_EP_p = I\_Fs_{mg\_E} \qquad p=1$$

Where:

vMg_EP:	Maize grain energy production
I_Fs:	initial stock
mg_E:	Maize grain energy

Maize grain energy production (produced in August and used from September)
If the period is greater than 1, the Maize grain energy production per period is equal to the land area allocated in the previous period and in month 8 (August) with Maize grain multiplied by the Maize grain energy yield.

$$vMg\_EP_p = vFX_{p-1,m=8,ct=5,ca=1} \times F\_E_{ct=5,ca=1,m=9} \qquad \forall\ p>1$$

Where:

vMg_EP:	Maize grain energy production
vFX:	land area allocated
F_E:	forage energy yields
ct=5:	crop type = Maize grain crop

Initial Maize silage energy
If the period is equal to 1, the Maize silage energy is equal to the initial stock of Maize silage energy. This parameter is defined by the farm type (or by the user).

$$vMs\_EP_p = I\_Fs_{ms\_E} \qquad p=1$$

Where:

vMs_EP:	Maize silage energy production
I_Fs:	initial stock
ms_E:	Maize silage energy

Maize silage energy production (produced in August and used from October)
If the period is greater than 1, the Maize silage energy production per period is equal to the land area allocated in the two previous periods and in month 8 (August) with Maize silage multiplied by the Maize silage energy yield.

$$vMs\_EP_p = vFX_{p-2,m=8,ct=6,ca=1} \times F\_E_{ct=6,ca=1,m=10} \qquad \forall\ p>1$$

Where:

vMs_EP:	Maize silage energy production
vFX:	land area allocated
F_E:	forage energy yields
ct=6:	crop type = Maize silage crop

Total energy production (all crops)
The total energy production per period is equal to the green forage energy production per period more the Brachiaria hay energy production per period more the Maize grain energy production per period more the Maize silage energy production per period.

$$vTot\_EP_p = vF\_EP_p + vBh\_EP_p + vMg\_EP_p + vMs\_EP_p \qquad \forall\ p$$

Where:

vTot_EP:	Total energy production
vF_EP:	green forage energy production
vBh_EP:	*Brachiaria* hay energy production
vMg_EP:	Maize grain energy production
vMs_EP:	Maize silage energy production

Green forage protein production
The green forage protein production in each period is equal to the sum of land area allocated for each crop type and crop age, if the crop type corresponds to the non-stored grasses, multiplied by the forage protein yields.

$$vF\_PP_p = \sum_{ct,ca,m} vFX_{p,m,ct,ca} \times F\_P_{ct,ca,m} \qquad \forall\ p$$

Where:

vF_PP:	green forage protein production
vFX:	land area allocated
F_P:	forage protein yields

Initial Brachiaria hay protein
If the period is equal to 1, the Brachiaria hay protein is equal to the initial stock of Brachiaria hay protein. This parameter is defined by the farm type (or by the user).

$$vBh\_PP_p = I\_Fs_{bh\_P} \qquad p=1$$

Where:

vBh_PP:	*Brachiaria* hay protein production
I_Fs:	initial stock

bh_P: *Brachiaria* hay protein

Brachiaria hay protein production (produced in July and August but used from August only)
If the period is greater than 1, the Brachiaria hay protein production per period is equal to the sum of land area allocated in month 8 (August) with Brachiaria grass of each age, if the month is equal to 7 (July) multiplied by the Brachiaira protein yield in July and divided by the % of Brachiaria hay produced in July more the sum of land area allocated in month 8 (August) with Brachiaria grass of each age, if the month is equal to 8 (August) multiplied by the Brachiaira protein yield in August and divided by the % of Brachiaria hay produced in August. The % of Brachiaria hay produced is defined by the farm type (or by the user).

$$vBh\_PP_p = \sum_{ct,ca,m=7}(vFX_{p,m=8,ct=1,ca} \times F\_P_{ct,ca,m} \div Hp_{july}) + \sum_{ct,ca,m=8}(vFX_{p,m=8,ct=1,ca} \times F\_P_{ct,ca,m} \div Hp_{august}) \qquad \forall_{p>1}$$

Where:

vBh_PP:	*Brachiaria* hay protein production
vFX:	land area allocated
F_P:	forage protein yields
Hp_{july}:	% of Brachiaria hay produced in July
Hp_{august}:	% of Brachiaria hay produced in August
ct=1:	crop type = *Brachiaria* crop
ca:	crop age

Initial Maize grain protein
If the period is equal to 1, the Maize grain protein is equal to the initial stock of Maize grain protein. This parameter is defined by the farm type (or by the user).

$$vMg\_PP_p = I\_Fs_{mg\_P} \qquad p=1$$

Where:

vMg_PP:	Maize grain protein production
I_Fs:	initial stock
mg_P:	Maize grain protein

Maize grain protein production (produced in August and used from September)
If the period is greater than 1, the Maize grain protein production per period is equal to the land area allocated in the previous period and in month 8 (August) with Maize grain multiplied by the Maize grain protein yield.

$$vMg\_PP_p = vFX_{p-1,m=8,ct=5,ca=1} \times F\_P_{ct=5,ca=1,m=9} \qquad \forall_{p>1}$$

Where:

vMg_PP:	Maize grain protein production
vFX:	land area allocated
F_P:	forage protein yields
ct=5:	crop type = Maize grain crop

Initial Maize silage protein
If the period is equal to 1, the Maize silage protein is equal to the initial stock of Maize silage protein. This parameter is defined by the farm type (or by the user).

$$vMs\_PP_p = I\_Fs_{ms\_P} \qquad p=1$$

Where:

vMs_PP:	Maize silage protein production
I_Fs:	initial stock
ms_P:	Maize silage protein

Maize silage protein production (produced in August and used from October)
If the period is greater than 1, the Maize silage protein production per period is equal to the land area allocated in the two previous periods and in month 8 (August) with Maize silage multiplied by the Maize silage protein yield.

$$vMs\_PP_p = vFX_{p-2,m=8,ct=6,ca=1} \times F\_P_{ct=6,ca=1,m=10} \qquad \forall_{p>1}$$

Where:

vMs_PP:	Maize silage protein production

vFX: land area allocated
F_P: forage protein yields
ct=6: crop type = Maize silage crop

Total protein production (all crops)
The total protein production per period is equal to the green forage protein production per period more the Brachiaria hay protein production per period more the Maize grain protein production per period more the Maize silage protein production per period.

$$vTot\_PP_p = vF\_PP_p + vBh\_PP_p + vMg\_PP_p + vMs\_PP_p \qquad \forall\, p$$

Where:
vTot_PP: Total protein production
vF_PP: green forage protein production
vBh_PP: *Brachiaria* hay protein production
vMg_PP: Maize grain protein production
vMs_PP: Maize silage protein production

Green forage UEL production
The green forage UEL production in each period is equal to the sum of land area allocated for each crop type and crop age, if the crop type corresponds to the non-stored grasses, multiplied by the forage UEL yields.

$$vF\_UELP_p = \sum_{ct,ca,m} vFX_{p,m,ct,ca} \times F\_UEL_{ct,ca,m} \qquad \forall\, p$$

Where:
vF_UELP: green forage UEL production
vFX: land area allocated
F_UEL: forage UEL yields

Initial Brachiaria hay UEL
If the period is equal to 1, the Brachiaria hay UEL is equal to the initial stock of Brachiaria hay UEL. This parameter is defined by the farm type (or by the user).

$$vBh\_UELP_p = I\_Fs_{bh\_UEL} \qquad p=1$$

Where:
vBh_UELP: *Brachiaria* hay UEL production
I_Fs: initial stock
bh_UEL: *Brachiaria* hay UEL

Brachiaria hay UEL production (produced in July and August but used from August only)
If the period is greater than 1, the Brachiaria hay UEL production per period is equal to the sum of land area allocated in month 8 (August) with Brachiaria grass of each age, if the month is equal to 7 (July) multiplied by the Brachiaira UEL yield in July and divided by the % of Brachiaria hay produced in July more the sum of land area allocated in month 8 (August) with Brachiaria grass of each age, if the month is equal to 8 (August) multiplied by the Brachiaira UEL yield in August and divided by the % of Brachiaria hay produced in August. The % of Brachiaria hay produced is defined by the farm type (or by the user).

$$vBh\_UELP_p = \sum_{ct,ca,m=7} (vFX_{p,m=8,ct=1,ca} \times F\_UEL_{ct,ca,m} \div Hp_{july}) + \sum_{ct,ca,m=8} (vFX_{p,m=8,ct=1,ca} \times F\_UEL_{ct,ca,m} \div Hp_{august}) \qquad \forall\, p>1$$

Where:
vBh_UELP: *Brachiaria* hay UEL production
vFX: land area allocated
F_UEL: forage UEL yields
Hp_{july}: % of Brachiaria hay produced in July
Hp_{august}: % of Brachiaria hay produced in August
ct=1: crop type = *Brachiaria* crop

Initial Maize grain UEL
If the period is equal to 1, the Maize grain UEL is equal to the initial stock of Maize grain UEL. This parameter is defined by the farm type (or by the user).

$$vMg\_UELP_p = I\_Fs_{mg\_UEL} \qquad p=1$$

Where:

vMg_UELP: Maize grain UEL production
I_Fs: initial stock
mg_UEL: Maize grain UEL

Maize grain UEL production (produced in August and used from September)
If the period is greater than 1, the Maize grain UEL production per period is equal to the land area allocated in the previous period and in month 8 (August) with Maize grain multiplied by the Maize grain UEL yield.

$$vMg\_UELP_p = vFX_{p-1,m=8,ct=5,ca=1} \times F\_UEL_{ct=5,ca=1,m=9} \qquad \forall\ p>1$$

Where:

vMg_UELP: Maize grain UEL production
vFX: land area allocated
F_UEL: forage UEL yields
ct=5: crop type = Maize grain crop

Initial Maize silage UEL
If the period is equal to 1, the Maize silage UEL is equal to the initial stock of Maize silage UEL. This parameter is defined by the farm type (or by the user).

$$vMs\_UELP_p = I\_Fs_{ms\_UEL} \qquad p=1$$

Where:

vMs_UELP: Maize silage UEL production
I_Fs: initial stock
ms_UEL: Maize silage UEL

Maize silage UEL production (produced in August and used from October)
If the period is greater than 1, the Maize silage UEL production per period is equal to the land area allocated in the two previous periods and in month 8 (August) with Maize silage multiplied by the Maize silage UEL yield.

$$vMs\_UELP_p = vFX_{p-2,m=8,ct=6,ca=1} \times F\_UEL_{ct=6,ca=1,m=10} \qquad \forall\ p>1$$

Where:

vMs_UELP: Maize silage UEL production
vFX: land area allocated
F_UEL: forage UEL yields
ct=6: crop type = Maize silage crop

Total UEL production (all crops)
The total UEL production per period is equal to the green forage UEL production per period more the Brachiaria hay UEL production per period more the Maize grain UEL production per period more the Maize silage UEL production per period.

$$vTot\_UELP_p = vF\_UELP_p + vBh\_UELP_p + vMg\_UELP_p + vMs\_UELP_p \qquad \forall\ p$$

Where:

vTot_UELP: Total UEL production
vF_UELP: green forage UEL production
vBh_UELP: *Brachiaria* hay UEL production
vMg_UELP: Maize grain UEL production
vMs_UELP: Maize silage UEL production

Crop needs

Labor
The labor need for the crop system in each period is equal to the sum of land area allocated for each crop type and crop age multiplied by the crop labor requirements.

$$vC\_LN_p = \sum_{ct,ca,m} vFX_{p,m,ct,ca} \times F\_LN_{ct,ca,m} \qquad \forall\ p$$

Where:

vC_LN:	labor need for crop system
vFX:	land area allocated
F_LN:	crop labor requirements

Seedlings and/or seeds

The seedlings and/or seeds need for the crop system in each period is equal to the sum of land area allocated for each crop type and crop age multiplied by the crop seedlings and/or seeds requirements.

$$vC\_SSN_{p,m,ct} = vFX_{p,m,ct,ca=1} \times F\_SSN_{ct,m} \qquad \forall\, p$$

Where:

vC_SSN:	seedlings and/or seeds need for crop system
vFX:	land area allocated
F_SSN:	crop seedlings and/or seeds requirements

NPK fertilizer

The NPK fertilizer need for the crop system in each period is equal to the sum of land area allocated for each crop type and crop age multiplied by the crop NPK fertilizer requirements.

$$vC\_NPKN_p = \sum_{ct,ca,m} vFX_{p,m,ct,ca} \times F\_NPKN_{ct,ca,m} \qquad \forall\, p$$

Where:

vC_NPKN:	NPK fertilizer need for crop system
vFX:	land area allocated
F_NPKN:	crop NPK fertilizer requirements

N fertilizer

The N fertilizer need for the crop system in each period is equal to the sum of land area allocated for each crop type and crop age multiplied by the crop N fertilizer requirements.

$$vC\_NN_p = \sum_{ct,ca,m} vFX_{p,m,ct,ca} \times F\_NN_{ct,ca,m} \qquad \forall\, p$$

Where:

vC_NN:	nitrogenous fertilizer need for crop system
vFX:	land area allocated
F_NN:	crop nitrogenous fertilizer requirements

P fertilizer

The P fertilizer need for the crop system in each period is equal to the sum of land area allocated for each crop type and crop age multiplied by the crop P fertilizer requirements.

$$vC\_PN_p = \sum_{ct,ca,m} vFX_{p,m,ct,ca} \times F\_PN_{ct,ca,m} \qquad \forall\, p$$

Where:

vC_PN:	phosphorus fertilizer need for crop system
vFX:	land area allocated
F_PN:	crop phosphorus fertilizer requirements

K fertilizer

The K fertilizer need for the crop system in each period is equal to the sum of land area allocated for each crop type and crop age multiplied by the crop K fertilizer requirements.

$$vC\_KN_p = \sum_{ct,ca,m} vFX_{p,m,ct,ca} \times F\_KN_{ct,ca,m} \qquad \forall\, p$$

Where:

vC_KN:	potassium fertilizer need for crop system
vFX:	land area allocated
F_KN:	crop potassium fertilizer requirements

Manure

The manure need for the crop system in each period is equal to the sum of land area allocated for each crop type and crop age multiplied by the crop manure requirements.

$$vC\_MaN_p = \sum_{ct,ca,m} vFX_{p,m,ct,ca} \times F\_MaN_{ct,ca,m} \qquad \forall\ p$$

Where:

vC_MaN: manure need for crop system
vFX: land area allocated
F_MaN: crop manure requirements

Water for irrigation

The water for irrigation need for the crop system in each period is equal to the sum of land area allocated for each crop type and crop age multiplied by the crop water for irrigation requirements.

$$vC\_WiN_p = \sum_{ct,ca,m} vFX_{p,m,ct,ca} \times F\_WiN_{ct,ca,m} \qquad \forall\ p$$

Where:

vC_WiN: water for irrigation need for crop system
vFX: land area allocated
F_WiN: crop water for irrigation requirements

Animal labor

The animal labor need for the crop system in each period is equal to the sum of land area allocated for each crop type and crop age multiplied by the crop animal labor requirements.

$$vC\_ALN_p = \sum_{ct,ca,m} vFX_{p,m,ct,ca} \times F\_ALN_{ct,ca,m} \qquad \forall\ p$$

Where:

vC_ALN: animal labor need for crop system
vFX: land area allocated
F_ALN: crop animal labor requirements

Livestock progression

Initial dairy herd

If the period is equal to 1, the dairy herd structure is equal to the initial herd stock. This parameter is defined by the farm type.

$$vDX_{p,da} = I\_Ds_{da} \qquad p=1$$

Where:

vDX: dairy herd structure
I_Ds: initial dairy herd stock
da: dairy age

Dairy herd

If the period is greater than 1, the dairy herd structure per period and per cow age is equal to the high potential cows (Age set between 1 and 92) present in the previous period and previous age more the medium potential cows (Age set between 94 and 155) present in the previous period and previous age more the female heifers born in this period less the female heifers sold, if the females born belong to the high potential cows group.

$$vDX_{p,da} = vDX_{p-1,da-1} + vDXfb_p - vDXfs_p \qquad \forall\ p>1$$

Where:

vDX: dairy herd structure
vDXfb: dairy female born
vDXfs: dairy female sold

Heifers and adult dairy cows

The number of heifers (age greater than 6 months) and adult dairy cows per period is equal to the sum of the dairy herd structure if their ages are comprised between 7 and 92 (for the high potential cows) and between 94 and 155 (for the medium potential cows).

$$vDXha_p = \sum_{da} vDX_{p,da\geq 7} \qquad \forall\ p$$

Where:

vDXha:	total heifers and adult dairy cows
vDX:	dairy herd structure
da≥7:	dairy age = greater than or equal to 7 months

Adult dairy herd

The adult dairy herd per period is equal to the sum of the dairy herd structure if their ages are comprised between 30 and 92 (for the high potential cows) and between 94 and 155 (for the medium potential cows).

$$vDXta_p = \sum_{da} vDX_{p,da>30} \qquad \forall p$$

Where:

vDXta:	total adult dairy herd
vDX:	dairy herd structure
da>30:	dairy age = more than 30 months

Total number of ruminants

The total numbre of ruminants per period is equal to the sum of the dairy herd structure if their ages are comprised between 7 and 92 (for the high potential cows) and between 94 and 155 (for the medium potential cows) more the sum of the draught cattle herd structure more the sum of the draught buffalo herd structure.

$$vTRX_p = \sum_{da} vDX_{p,da>6} + \sum_{dca} vCX_{p,dca} + \sum_{dba} vBX_{p,dba} \qquad \forall p$$

Where:

vTRX:	total ruminant herd
vDX:	dairy herd structure
vCX:	draught cattle herd structure
vBX:	draught buffalo herd structure
da>6:	dairy age = more than 6 months
dca:	draught cattle age
dba:	draught buffalo age

Dairy herd culled

The dairy herd culled per period is equal to the dairy herd structure in the previous period having age 92 (for the high potential cows) <u>more</u> the herd structure in the previous period having age 155 (for the medium potential cows).

$$vDXcu_p = vDX_{p-1,da=92} + vDX_{p-1,da=155} \qquad \forall p$$

Where:

vDXcu:	culled dairy cows
vDX:	dairy herd structure
da=92:	dairy age = 92 months (high milk potential cows)
da=155:	dairy age = 155 months (medium milk potential cows)

Dairy male calves born

The dairy male calves born per period is equal to the sum of dairy herd structure when the age corresponds to the male calving period.

$$vDXmb_p = \sum_{da=cma} vDX_{p,da} \qquad \forall p$$

Where:

vDXmb:	dairy male calves born
vDX:	dairy herd structure
da=cma:	dairy age = calving male age

Dairy male calves sold

The dairy male calves sold per period is equal to the the dairy male calves born per period.

$$vDXms_p = vDXmb_p \qquad \forall p$$

Where:

vDXms:	dairy male calves sold

vDXmb: dairy male calves born

Dairy female calves born
The dairy female calves born per period is equal to the sum of dairy herd structure when the age corresponds to the female calving period.

$$vDXfb_p = \sum_{da=cfa} vDX_{p,da} \qquad \forall\, p$$

Where:
vDXfb: dairy female calves born
vDX: dairy herd structure
da=cfa: dairy age = calving female age

Dairy female calves introduced in the herd
The dairy herd structure with cows of age 1 (female calves introduced in the herd) per period is lower than or equal to the dairy female calves born per period.

$$vDX_{p,da=1} \leq vDXfb_p \qquad \forall\, p$$

Where:
vDX: dairy herd structure
vDXfb: dairy female calves born
da=1: dairy age = 1 month

Dairy female calves sold from high potential cows
The dairy female calves of group 1 sold per period is lower than or equal to the sum of the dairy female calves born per period if they belong to the high potential cows, which means D_Age equal to 31, 57 and 83 (when high potential cows give birth a female calve).

$$vDXfsG1_p \leq \sum_{da} vDX_{p,da=31,57,83,} \qquad \forall\, p$$

Where:
vDXfsG1: dairy female calves sold from high potential cows
vDX: dairy herd structure

Dairy female calves sold from medium potential cows
The dairy female calves of group 2 sold per period is equal to the sum of the dairy female calves born per period if they belong to the medium potential cows, which means D_Age equal to 107 and 133 (when medium potential cows give birth a female calve).

$$vDXfsG2_p = \sum_{da} vDX_{p,da=107,133} \qquad \forall\, p$$

Where:
vDXfsG2: dairy female calves sold from medium potential cows
vDX: dairy herd structure

Dairy female calves sold
The dairy female calves sold per period is equal to the dairy female calves of group 1 sold more the dairy female calves of group 2 sold.

$$vDXfs_p = vDXfsG1_p + vDXfsG2_p \qquad \forall\, p$$

Where:
vDXfs: dairy female calves sold
vDXfsG1: dairy female calves sold from high potential cows
vDXfsG2: dairy female calves sold from medium potential cows

Maximum dairy female calves sold
The maximum dairy female calves sold per period is lower than or equal to the dairy female calves born per period.

$$vDXfs_p \leq vDXfb_p \qquad \forall\, p$$

Where:
vDXfs: dairy female calves sold
vDXfb: dairy female calves born

Initial draught cattle herd
If the period is equal to 1, the draught cattle herd structure is equal to the initial herd stock. This parameter is defined by the farm type.

$$vCX_{p,dca} = I\_Cs_{dca} \qquad p=1$$

Where:
vCX: draught cattle herd structure
I_Cs: initial draught cattle herd stock

Draught cattle herd
If the period is greater than 1, the draught cattle herd structure per period is equal to the draught cattle herd structure in the previous period and previous age, if the age is greater than 1.

$$vCX_{p,dca} = vCX_{p-1,dca-1} \qquad \forall\ p>1$$

Where:
vCX: draught cattle herd structure

Draught cattle herd culled
The draught cattle culled per period is equal to the draught cattle herd structure in the previous period having age 120.

$$vCXcu_{p} = vCX_{p-1,dca=120} \qquad \forall\ p$$

Where:
vCXcu: culled draught cattle
vCX: draught cattle herd structure
dca=120: draught cattle age = 120 months of age

Initial draught buffalo herd
If the period is equal to 1, the draught buffalo herd structure is equal to the initial herd stock. This parameter is defined by the farm type.

$$vBX_{p,dba} = I\_Bs_{dba} \qquad p=1$$

Where:
vBX: draught buffalo herd structure
I_Bs: initial draught buffalo herd stock

Draught buffalo herd
If the period is greater than 1, the draught buffalo herd structure per period is equal to the draught buffalo herd structure in the previous period and previous age, if the age is greater than 1.

$$vBX_{p,dba} = vBX_{p-1,dba-1} \qquad \forall\ p>1$$

Where:
vBX: draught buffalo herd structure

Draught buffalo herd culled
The draught buffalo culled per period is equal to the draught buffalo herd structure in the previous period having age 120.

$$vBXcu_{p} = vBX_{p-1,dba=120} \qquad \forall\ p$$

Where:
vBXcu: culled draught buffalo
vBX: draught buffalo herd structure
dba=120: draught buffalo age = 120 months of age

Total number of animal heads (dairy more draught)
The total number of animal heads per period is equal to the sum of the dairy herd structure more the sum of the draught cattle herd structure more the sum of the draught buffalo herd structure.

$$vDXtot_{p} = \sum_{da} vDX_{da} + \sum_{dca} vCX_{dca} + \sum_{dba} vBX_{dba} \qquad \forall\ p$$

Where:
vDXtot: total number of animal heads (dairy more draught)

	vDX:	dairy herd structure
	vCX:	draught cattle herd structure
	vBX:	draught buffalo herd structure

Livestock production

Milk

The milk production per period is equal to the sum of the dairy herd structure multiplied by the milk potential.

$$vMilkP_p = \sum_{da} vDX_{p,da} \times Milk\_P_{da} \qquad \forall\, p$$

Where:

	vMilkP:	milk production
	vDX:	dairy herd structure
	Milk_P:	milk potential

Manure

The manure production per period is equal to the sum of the dairy herd structure multiplied by the manure potential.

$$vManuP_p = \sum_{da} vDX_{p,da} \times Manu\_P_{da} \qquad \forall\, p$$

Where:

	vManuP:	manure production
	vDX:	dairy herd structure
	Manu_P:	manure potential

Cattle animal force

The cattle animal force production per period is equal to the sum of the draught cattle herd structure multiplied by the cattle animal force potential.

$$vCafP_p = \sum_{dca} vCX_{p,dca} \times Caf\_P_{dca} \qquad \forall\, p$$

Where:

	vCafP:	cattle animal force production
	vCX:	draught cattle herd structure
	Caf_P:	cattle animal force potential

Buffalo animal force

The buffalo animal force production per period is equal to the sum of the draught buffalo herd structure multiplied by the buffalo animal force potential.

$$vBafP_p = \sum_{dba} vBX_{p,dba} \times Baf\_P_{dba} \qquad \forall\, p$$

Where:

	vBafP:	cattle buffalo force production
	vBX:	draught buffalo herd structure
	Baf_P:	buffalo animal force potential

Livestock needs

Labor for dairy herd

The labor need for the dairy herd in each period is equal to the sum of the dairy herd structure multiplied by the dairy herd labor requirements.

$$vDX\_LN_p = \sum_{da} vDX_{p,da} \times DX\_LN_{da} \qquad \forall\, p$$

Where:

	vDX_LN:	labor need for dairy herd
	vDX:	dairy herd structure
	DX_LN:	dairy herd labor requirements

Energy for dairy herd
The energy need for the dairy herd in each period is equal to the sum of the dairy herd structure multiplied by the dairy herd energy requirements.

$$vDX\_EN_p = \sum_{da} vDX_{p,da} \times DX\_EN_{da} \qquad \forall p$$

Where:

vDX_EN:	energy need for dairy herd
vDX:	dairy herd structure
DX_EN:	dairy herd energy requirements

Protein for dairy herd
The protein need for the dairy herd in each period is equal to the sum of the dairy herd structure multiplied by the dairy herd protein requirements.

$$vDX\_PN_p = \sum_{da} vDX_{p,da} \times DX\_PN_{da} \qquad \forall p$$

Where:

vDX_PN:	protein need for dairy herd
vDX:	dairy herd structure
DX_PN:	dairy herd protein requirements

Maximum UEL intake for dairy herd
The maximum UEL intake for the dairy herd in each period is equal to the sum of the dairy herd structure multiplied by the dairy herd maximum intake requirements.

$$vDX\_UELMax_p = \sum_{da} vDX_{p,da} \times DX\_UELMax_{da} \qquad \forall p$$

Where:

vDX_UELMax:	maximum UEL intake for dairy herd
vDX:	dairy herd structure
DX_UELMax:	dairy herd maximum UEL intake

Minimum UEL intake for dairy herd
The minimum UEL intake for the dairy herd in each period is equal to the sum of the dairy herd structure multiplied by the dairy herd minimum intake requirements.

$$vDX\_UELMin_p = \sum_{da} vDX_{p,da} \times DX\_UELMin_{da} \qquad \forall p$$

Where:

vDX_UELMin:	minimum UEL intake for dairy herd
vDX:	dairy herd structure
DX_UELMin:	dairy herd minimum UEL intake

Labor for draught cattle herd
The labor need for the draught cattle herd in each period is equal to the sum of the draught cattle herd structure multiplied by the draught cattle herd labor requirements.

$$vCX\_LN_p = \sum_{dca} vCX_{p,dca} \times CX\_LN_{dca} \qquad \forall p$$

Where:

vCX_LN:	labor need for draught cattle herd
vCX:	draught cattle herd structure
CX_LN:	draught cattle herd labor requirements

Energy for draught cattle herd
The energy need for the draught cattle herd in each period is equal to the sum of the draught cattle herd structure multiplied by the draught cattle herd energy requirements.

$$vCX\_EN_p = \sum_{dca} vCX_{p,dca} \times CX\_EN_{dca} \qquad \forall p$$

Where:

vCX_EN:	energy need for draught cattle herd
vCX:	draught cattle herd structure

CX_EN: draught cattle herd energy requirements

Protein for draught cattle herd
The protein need for the draught cattle herd in each period is equal to the sum of the draught cattle herd structure multiplied by the draught cattle herd protein requirements.

$$vCX\_PN_p = \sum_{dca} vCX_{p,dca} \times CX\_PN_{dca} \qquad \forall p$$

Where:
- vCX_PN: protein need for draught cattle herd
- vCX: draught cattle herd structure
- CX_PN: draught cattle herd protein requirements

Maximum UEL intake for draught cattle herd
The maximum UEL intake for the draught cattle herd in each period is equal to the sum of the draught cattle herd structure multiplied by the draught cattle herd maximum intake requirements.

$$vCX\_UELMax_p = \sum_{dca} vCX_{p,dca} \times CX\_UELMax_{dca} \qquad \forall p$$

Where:
- vCX_UELMax: maximum UEL intake for draught cattle herd
- vCX: draught cattle herd structure
- CX_UELMax: draught cattle herd maximum UEL intake

Minimum UEL intake for draught cattle herd
The minimum UEL intake for the draught cattle herd in each period is equal to the sum of the draught cattle herd structure multiplied by the draught cattle herd minimum intake requirements.

$$vCX\_UELMin_p = \sum_{dca} vCX_{p,dca} \times CX\_UELMin_{dca} \qquad \forall p$$

Where:
- vCX_UELMin: minimum UEL intake for draught cattle herd
- vCX: draught cattle herd structure
- CX_UELMin: draught cattle herd minimum UEL intake

Labor for draught buffalo herd
The labor need for the draught buffalo herd in each period is equal to the sum of the draught buffalo herd structure multiplied by the draught buffalo herd labor requirements.

$$vBX\_LN_p = \sum_{dba} vBX_{p,dba} \times BX\_LN_{dba} \qquad \forall p$$

Where:
- vBX_LN: labor need for draught buffalo herd
- vBX: draught buffalo herd structure
- BX_LN: draught buffalo herd labor requirements

Energy for draught buffalo herd
The energy need for the draught buffalo herd in each period is equal to the sum of the draught buffalo herd structure multiplied by the draught buffalo herd energy requirements.

$$vBX\_EN_p = \sum_{dba} vBX_{p,dba} \times BX\_EN_{dba} \qquad \forall p$$

Where:
- vBX_EN: energy need for draught buffalo herd
- vBX: draught buffalo herd structure
- BX_EN: draught buffalo herd energy requirements

Protein for draught buffalo herd
The protein need for the draught buffalo herd in each period is equal to the sum of the draught buffalo herd structure multiplied by the draught buffalo herd protein requirements.

$$vBX\_PN_p = \sum_{dba} vBX_{p,dba} \times BX\_PN_{dba} \qquad \forall p$$

Where:

vBX_PN:	protein need for draught buffalo herd
vBX:	draught buffalo herd structure
BX_PN:	draught buffalo herd protein requirements

Maximum UEL intake for draught buffalo herd
The maximum UEL intake for the draught buffalo herd in each period is equal to the sum of the draught buffalo herd structure multiplied by the draught buffalo herd maximum intake requirements.

$$vBX\_UELMax_p = \sum_{dba} vBX_{p,dba} \times BX\_UELMax_{dba} \qquad \forall\, p$$

Where:

vBX_UELMax:	maximum UEL intake for draught buffalo herd
vBX:	draught buffalo herd structure
BX_UELMax:	draught buffalo herd maximum UEL intake

Minimum UEL intake for draught buffalo herd
The minimum UEL intake for the draught buffalo herd in each period is equal to the sum of the draught buffalo herd structure multiplied by the draught buffalo herd minimum intake requirements.

$$vBX\_UELMin_p = \sum_{dba} vBX_{p,dba} \times BX\_UELMin_{dba} \qquad \forall\, p$$

Where:

vBX_UELMin:	minimum UEL intake for draught buffalo herd
vBX:	draught buffalo herd structure
BX_UELMin:	draught buffalo herd minimum UEL intake

Total labor need for livestock system (dairy more draught)
The total labor need for livestock system in each period is equal to the labor need for the dairy herd more the labor need for the draught cattle herd more the labor need for the draught buffalo herd.

$$vTot\_LN_p = vDX\_LN_p + vCX\_LN_p + vBX\_LN_p \qquad \forall\, p$$

Where:

vTot_LN:	total labor need for livestock
vDX_LN:	labor need for dairy herd
vCX_LN:	labor need for draught cattle herd
vBX_LN:	labor need for draught buffalo herd

Total energy need for livestock system (dairy more draught)
The total energy need for livestock system in each period is equal to the energy need for the dairy herd more the energy need for the draught cattle herd more the energy need for the draught buffalo herd.

$$vTot\_EN_p = vDX\_EN_p + vCX\_EN_p + vBX\_EN_p \qquad \forall\, p$$

Where:

vTot_EN:	total energy need for livestock
vDX_EN:	energy need for dairy herd
vCX_EN:	energy need for draught cattle herd
vBX_EN:	energy need for draught buffalo herd

Total protein need for livestock system (dairy more draught)
The total protein need for livestock system in each period is equal to the protein need for the dairy herd more the protein need for the draught cattle herd more the protein need for the draught buffalo herd.

$$vTot\_PN_p = vDX\_PN_p + vCX\_PN_p + vBX\_PN_p \qquad \forall\, p$$

Where:

vTot_PN:	total protein need for livestock
vDX_PN:	energy protein for dairy herd
vCX_PN:	energy protein for draught cattle herd
vBX_PN:	energy protein for draught buffalo herd

Total maximum UEL intake for livestock system (dairy more draught)
The maximum UEL intake for livestock system in each period is equal to the maximum UEL intake for the dairy herd more the maximum UEL intake for the draught cattle herd more the maximum UEL intake for the draught buffalo herd.

$$vTot\_UELMax_p = vDX\_UELMax_p + vCX\_UELMax_p + vBX\_UELMax_p \qquad \forall\ p$$

Where:

vTot_UELMax: maximum UEL intake for livestock
vDX_UELMax: maximum UEL intake for dairy herd
vCX_UELMax: maximum UEL intake for draught cattle herd
vBX_UELMax: maximum UEL intake for draught buffalo herd

Total minimum UEL intake for livestock system (dairy more draught)
The total minimum UEL intake for livestock system in each period is equal to the minimum UEL intake for the dairy herd more the minimum UEL intake for the draught cattle herd more the minimum UEL intake for the draught buffalo herd.

$$vTot\_UELMin_p = vDX\_UELMin_p + vCX\_UELMin_p + vBX\_UELMin_p \qquad \forall\ p$$

Where:

vTot_UELMin: minimum UEL intake for livestock
vDX_UELMin: minimum UEL intake for dairy herd
vCX_UELMin: minimum UEL intake for draught cattle herd
vBX_UELMin: minimum UEL intake for draught buffalo herd

Farm nutrients used and balance

Maize grain dry matter used (associated with the maize grain energy used)
The maize grain dry matter used in each period is equal to the maize grain energy used in each period divided by the UFL content of maize grain divided by 1000 to convert kg of DM in tons of DM.

$$vMg\_DMU_p = vMg\_EU_p \div Mg\_Ec \div 1000 \qquad \forall\ p$$

Where:

vMg_DMU: maize grain dry matter used
vMg_EU: maize grain energy used
Mg_Ec: maize grain energy content
1000: to convert kg DM in tons DM

Maize silage dry matter used (associated with the maize silage energy used)
The maize silage dry matter used in each period is equal to the maize silage energy used in each period divided by the UFL content of maize silage divided by 1000 to convert kg of DM in tons of DM.

$$vMs\_DMU_p = vMs\_EU_p \div Ms\_Ec \div 1000 \qquad \forall\ p$$

Where:

vMs_DMU: maize silage dry matter used
vMs_EU: maize silage energy used
Ms_Ec: maize silage energy content
1000: to convert kg DM in tons DM

***Brachiaria* hay dry matter used** (associated with the maize silage energy used)
The *Brachiaria* hay dry matter used in each period is equal to the *Brachiaria* hay energy used in each period divided by the UFL content of *Brachiaria* hay divided by 1000 to convert kg of DM in tons of DM.

$$vBh\_DMU_p = vBh\_EU_p \div Bh\_Ec \div 1000 \qquad \forall\ p$$

Where:

vBh_DMU: *Brachiaria* hay dry matter used
vBh_EU: *Brachiaria* hay energy used
Bh_Ec: *Brachiaria* hay energy content
1000: to convert kg DM in tons DM

Balance between total crop energy supply and total livestock energy requirements
The farm energy balance (positive or negative variable) in each period is equal to the total energy production per period <u>less</u> the total energy need for livestock system in each period.

$$vFEBal_p = vTot\_EP_p - vTot\_EN_p \qquad \forall\ p$$

Where:

vFEBal:	farm energy balance
vTot_EP:	total energy production
vTot_EN:	total energy need for livestock

Forage energy used per period (associated with the forage UEL used)
The forage energy used in each period is equal to the forage UEL used in each period divided by the UEL content of forage (average) multiplied by the energy (UFL) content of forage (average).

$$vF\_EU_p = vF\_UELU_p \div F\_UELc \times F\_Ec \qquad \forall\ p$$

Where:

vF_EU:	green forage energy used
vF_UELU:	green forage UEL used
F_UELc:	forage UEL content (average)
F_Ec:	forage energy content (average)

Maize grain energy used per cycle
The sum of the maize grain energy used per period, in each cycle, is equal to the sum of the maize grain energy production per period, in each cycle.

$$\sum_p vMg\_EU_p = \sum_p vMg\_EP_p \qquad \forall\ p$$

Where:

vMg_EU:	maize grain energy used
vMg_EP:	maize grain energy production

Maize silage energy used per cycle
The sum of the maize silage energy used per period, in each cycle, is equal to the sum of the maize silage energy production per period, in each cycle.

$$\sum_p vMs\_EU_p = \sum_p vMs\_EP_p \qquad \forall\ p$$

Where:

vMs_EU:	maize silage energy used
vMs_EP:	maize silage energy production

***Brachiaria* hay energy used per cycle**
The sum of the *Brachiaria* hay energy used per period, in each cycle, is equal to the sum of the *Brachiaria* hay energy production per period, in each cycle.

$$\sum_p vBh\_EU_p = \sum_p vBh\_EP_p \qquad \forall\ p$$

Where:

vBh_EU:	*Brachiaria* hay energy used
vBh_EP:	*Brachiaria* hay energy production

Balance between total crop protein supply and total livestock protein requirements
The farm protein balance (positive or negative variable) in each period is equal to the total protein production per period <u>less</u> the total protein need for livestock system in each period.

$$vFPBal_p = vTot\_PP_p - vTot\_PN_p \qquad \forall\ p$$

Where:

vFPBal:	farm protein balance
vTot_PP:	total protein production
vTot_PN:	total protein need for livestock

Forage protein used per period (associated with the forage UEL used)
The forage protein used in each period is equal to the forage UEL used in each period divided by the UEL content of forage (average) multiplied by the protein (PDI) content of forage (average).

$$vF\_PU_p = vF\_UELU_p \div F\_UELc \times F\_Pc \qquad \forall\ p$$

Where:

vF_PU: green forage protein used
vF_UELU: green forage UEL used
F_UELc: forage UEL content (average)
F_Pc: forage protein content (average)

Maize grain protein used (associated with the maize grain energy used)
The maize grain protein used in each period is equal to the maize grain energy used in each period divided by the UFL content of maize grain multiplied by the PDI content of maize grain.

$$vMg\_PU_p = vMg\_EU_p \div Mg\_Ec \times Mg\_Pc \qquad \forall\ p$$

Where:

vMg_PU: maize grain protein used
vMg_EU: maize grain energy used
Mg_Ec: maize grain energy content
Mg_Pc: maize grain protein content

Maize silage protein used (associated with the maize silage energy used)
The maize silage protein used in each period is equal to the maize silage energy used in each period divided by the UFL content of maize silage multiplied by the PDI content of maize silage.

$$vMs\_PU_p = vMs\_EU_p \div Ms\_Ec \times Ms\_Pc \qquad \forall\ p$$

Where:

vMs_PU: maize silage protein used
vMs_EU: maize silage energy used
Ms_Ec: maize silage energy content
Ms_Pc: maize silage protein content

***Brachiaria* hay protein used** (associated with the *Brachiaria* hay energy used)
The *Brachiaria* hay protein used in each period is equal to the *Brachiaria* hay energy used in each period divided by the UFL content of *Brachiaria* hay multiplied by the PDI content of *Brachiaria* hay.

$$vBh\_PU_p = vBh\_EU_p \div Bh\_Ec \times Bh\_Pc \qquad \forall\ p$$

Where:

vBh_PU: *Brachiaria* hay protein used
vBh_EU: *Brachiaria* hay energy used
Bh_Ec: *Brachiaria* hay energy content
Bh_Pc: *Brachiaria* hay protein content

Balance between total crop UEL production and livestock minimum UEL intake
The farm UEL balance (positive or negative variable) in each period is equal to the total UEL production per period less the minimum UEL intake for livestock system in each period.

$$vFUELBal_p = vTot\_UELP_p - vTot\_UELMin_p \qquad \forall\ p$$

Where:

vFUELBal: farm UEL balance
vTot_UELP: Total UEL production
vTot_UELMin: minimum UEL intake for livestock

Forage UEL used
The forage UEL used in each period is lower than or equal to the forage UEL produced in each period.

$$vF\_UELU_p \leq vF\_UELP_p \qquad \forall\ p$$

Where:

vF_UELU: green forage UEL used
vF_UELP: green forage UEL production

Maize grain UEL used (associated with the maize grain energy used)
The maize grain UEL used in each period is equal to the maize grain energy used in each period divided by the UFL content of maize grain multiplied by the UEL content of maize grain.

$$vMg\_UELU_p = vMg\_EU_p \div Mg\_Ec \times Mg\_UELc \qquad \forall\ p$$

Where:

vMg_UELU: maize grain UEL used
vMg_EU: maize grain energy used
Mg_Ec: maize grain energy content
Mg_UELc: maize grain UEL content

Maize silage UEL used (associated with the maize silage energy used)
The maize silage UEL used in each period is equal to the maize silage energy used in each period divided by the UFL content of maize silage multiplied by the UEL content of maize silage.

$$vMs\_UELU_p = vMs\_EU_p \div Ms\_Ec \times Ms\_UELc \qquad \forall\ p$$

Where:

vMs_UELU: maize silage UEL used
vMs_EU: maize silage energy used
Ms_Ec: maize silage energy content
Ms_UELc: maize silage UEL content

***Brachiaria* hay UEL used** (associated with the *Brachiaria* hay energy used)
The *Brachiaria* hay UEL used in each period is equal to the *Brachiaria* hay energy used in each period divided by the UFL content of *Brachiaria* hay multiplied by the UEL content of *Brachiaria* hay.

$$vBh\_UELU_p = vBh\_EU_p \div Bh\_Ec \times Bh\_UELc \qquad \forall\ p$$

Where:

vBh_UELU: *Brachiaria* hay UEL used
vBh_EU: *Brachiaria* hay energy used
Bh_Ec: *Brachiaria* hay energy content
Bh_UELc: *Brachiaria* hay UEL content

Feed bounds

Maximum DM maize grain used by ruminants
The maximum maize grain DM used by the total number ruminants is lower than or equal to the feed bound (maximum) defined by the user multiplied by the total number of ruminants present in each period.

$$vMg\_DMU_p \le FB_{MgMax} \times vTRX_p \qquad \forall\ p$$

Where:

vMg_DMU: maize grain dry matter used
FB: Feed bound
vTRX: total ruminant herd
MgMax: Maximum of Maize grain DM intake per day

Minimum DM maize grain used by ruminants
The minium maize grain DM used by the total number ruminants is greater than or equal to the feed bound (minimum) defined by the user multiplied by the total number of ruminants present in each period.

$$vMg\_DMU_p \ge FB_{MgMin} \times vTRX_p \qquad \forall\ p$$

Where:

vMg_DMU: maize grain dry matter used
FB: Feed bound
MgMin: Minimum of Maize grain DM intake per day
vTRX: total ruminant herd

Maximum DM Brachiaria hay used by ruminants

The maximum Brachiaria hay DM used by the total number ruminants is lower than or equal to the feed bound (maximum) defined by the user multiplied by the total number of ruminants present in each period.

$$vBh\_DMU_p \leq FB_{BhMax} \times vTRX_p \qquad \forall\ p$$

Where:

vBh_DMU:	Brachiaria hay dry matter used
FB:	Feed bound
BhMax:	Maximum of Brachiaria hay DM intake per day
vTRX:	total ruminant herd

Minimum DM Brachiaria hay used by ruminants

The minium Brachiaria hay DM used by the total number ruminants is greater than or equal to the feed bound (minimum) defined by the user multiplied by the total number of ruminants present in each period.

$$vBh\_DMU_p \geq FB_{BhMin} \times vTRX_p \qquad \forall\ p$$

Where:

vBh_DMU:	Brachiaria hay dry matter used
FB:	Feed bound
BhMin:	Minimum of Brachiaria hay DM intake per day
vTRX:	total ruminant herd

Maximum DM maize silage used by ruminants

The maximum maize silage DM used by the total number ruminants is lower than or equal to the feed bound (maximum) defined by the user multiplied by the total number of ruminants present in each period.

$$vMs\_DMU_p \leq FB_{MsMax} \times vTRX_p \qquad \forall\ p$$

Where:

vMs_DMU:	maize silage dry matter used
FB:	Feed bound
MsMax:	Maximum of Maize silage DM intake per day
vTRX:	total ruminant herd

Minimum DM maize silage used by ruminants

The minium maize silage DM used by the total number ruminants is greater than or equal to the feed bound (minimum) defined by the user multiplied by the total number of ruminants present in each period.

$$vMs\_DMU_p \geq FB_{MsMin} \times vTRX_p \qquad \forall\ p$$

Where:

vMs_DMU:	maize silage dry matter used
FB:	Feed bound
MsMin:	Minimum of Maize silage DM intake per day
vTRX:	total ruminant herd

<u>Farm labor used</u>

Farm labor used

The farm labor used in each period is lower than or equal to the available farm labor. This parameter is defined by the farm type.

$$vFLU_p \leq FLav_p \qquad \forall\ p$$

Where:

vFLU:	farm labor used
FLav:	farm labor available

<u>Inputs and nutrient balances</u> (Requirements – Supply + Market)

Total labor need for Crop and Livestock systems
The total labor need for the crop and the livestock systems is equal to the labor need for the crop system more the total labor need for the livestock system.

$$vCL\_LN_p = vC\_LN_p + vTot\_LN_p \qquad \forall\ p$$

Where:

vCL_LN: total labor need for crop and livestock needs
vC_LN: labor need for crop system
vTot_LN: total labor need for livestock

Total labor need during the *Avena* season (from September to February)
If the month is December, the total labor need during the *Avena* season period is equal to the total labor need for the crop and the livestock systems during September, October, November, December, January and February (the sum of each month).

$$vL\_AsN_{p,m=12} = vCL\_LN_{p-3} + vCL\_LN_{p-2} + vCL\_LN_{p-1} + vCL\_LN_p + vCL\_LN_{p+1} + vCL\_LN_{p+2} \qquad m=12$$

Where:

vL_AsN: total labor need during the *Avena* season period
vCL_LN: total labor need for crop and livestock needs

Labor
The labor need for the crop system <u>more</u> the total labor need for the livestock system is lower than or equal to the farm labor used in each period more the hired labor from market.

$$vC\_LN_p + vTot\_LN_p \leq vFLU_p + vLhi_p \qquad \forall\ p$$

Where:

vC_LN: labor need for crop system
vTot_LN: total labor need for livestock
vFLU: farm labor used
vLhi: labor hired

Initial stock of manure (in period 1)
If the period is equal to 1, the manure stock is equal to the initial stock of manure <u>more</u> the manure production in period 1. The initial stock parameter is defined by the user.

$$vManuS_{p=1} = IManuS + vManuP_{p=1} \qquad p=1$$

Where:

vManuS: manure stock
IManuS: initial manure stock
vManuP: manure production
p=1: period=1 month

Stock of manure
If the period is greater than 1, the manure stock in each period is equal to the manure production in the period <u>less</u> the crop manure need in the period <u>more</u> the manure stock in the previous period <u>more</u> the manure bought in the previous period.

$$vManuS_p = vManuP_p - vC\_MaN + vManuS_{p-1} + vManuM_{p-1} \qquad \forall\ p>1$$

Where:

vManuS: manure stock
vManuP: manure production
vC_MaN: manure need for crop system
vManuM: manure bought in market
p=1: period=1 month

Stock of manure (the manure bought correspond to the negative value of the variable manure stock (if any))
If the period is greater than 1, the manure stock in each period <u>more</u> the manure bought in each period is greater than or equal to zero.

$$vManuS_p + vManuM_p \geq 0 \qquad \forall_{p>1}$$

Where:

vManuS:	manure stock
vManuM:	manure bought in market
p=1:	period=1 month

Stock of manure (to limit the quantity of manure bought in each period)
If the period is greater than 1, the manure bought in each period is lower than or equal to the manure stock in each period.

$$vManuM_p \leq vManuS_p \qquad \forall_{p>1}$$

Where:

vManuM:	manure bought in market
vManuS:	manure stock
p=1:	period=1 month

Animal labor
The animal labor need for the crop system is lower than or equal to the cattle animal force production more the buffalo animal force production more the animal force rent from market.

$$vC\_ALN_p \leq vCafP_p + vBafP_p + vafR_p \qquad \forall_p$$

Where:

vC_ALN:	animal labor need for crop system
vCafP:	cattle animal force production
vBafP:	buffalo animal force production
vafR:	animal force rent

Energy
The total energy need for livestock system in each period is lower than or equal to the green forage energy used more the maize grain energy used more the maize silage energy used more the *Brachiaria* hay energy used more the sum of the concentrated feed types in fresh matter multiplied by the concentrated feed dry matter content multiplied by the concentrated feed energy content.

$$vTot\_EN_p \leq vF\_EU_p + vMg\_EU_p + vMs\_EU_p + vBh\_EU_p + \sum_{ct}(vkg\_Cf_{p,ct} \times Cf\_DMc \times Cf\_Ec)$$

Where: $\forall_p$

vTot_EN:	total energy need for livestock
vF_EU:	green forage energy used
vMg_EU:	maize grain energy used
vMs_EU:	maize silage energy used
vBh_EU:	*Brachiaria* hay energy used
vkg_Cf:	kg of concentrated feed bought
Cf_DMc:	concentrated feed DM content
Cf_Ec:	concentrated feed energy content

Total energy balance (supply – requirements; the result should be equal to zero)
The supply_requirement energy balance is equal to the green forage energy used more the maize grain energy used more the maize silage energy used more the *Brachiaria* hay energy used more the sum of the concentrated feed types in fresh matter multiplied by the concentrated feed dry matter content multiplied by the concentrated feed energy content less the total energy need for livestock system.

$$vsr\_Ebal_p = vF\_EU_p + vMg\_EU_p + vMs\_EU_p + vBh\_EU_p + \sum_{cft}(vkg\_Cf_{p,cft} \times Cf\_DMc \times Cf\_Ec) - vTot\_EN_p$$

Where: $\forall_p$

Vsr_Ebal:	supply-requirements energy balance
vF_EU:	green forage energy used
vMg_EU:	maize grain energy used
vMs_EU:	maize silage energy used
vBh_EU:	*Brachiaria* hay energy used
vkg_Cf:	kg of concentrated feed bought

Cf_DMc: concentrated feed DM content
Cf_Ec: concentrated feed energy content
vTot_EN: total energy need for livestock
cft: concentrated feed type

Protein
The total protein need for livestock system in each period is lower than or equal to the green forage protein used more the maize grain protein used more the maize silage protein used more the *Brachiaria* hay protein used more the sum of the concentrated feed types in fresh matter multiplied by the concentrated feed dry matter content multiplied by the concentrated feed protein content.

$$vTot\_PN_p \leq vF\_PU_p + vMg\_PU_p + vMs\_PU_p + vBh\_PU_p + \sum_{cft}(vkg\_Cf_{p,cft} \times Cf\_DMc \times Cf\_Pc)$$

Where: $\forall p$

vTot_PN: total protein need for livestock
vF_PU: green forage protein used
vMg_PU: maize grain protein used
vMs_PU: maize silage protein used
vBh_PU: *Brachiaria* hay protein used
vkg_Cf: kg of concentrated feed bought
Cf_DMc: concentrated feed DM content
Cf_Pc: concentrated feed protein content

Total protein balance (supply – requirements; the result should be equal to or greater than zero)
The supply_requirement protein balance is equal to the green forage protein used more the maize grain protein used more the maize silage protein used more the *Brachiaria* hay protein used more the sum of the concentrated feed types in fresh matter multiplied by the concentrated feed dry matter content multiplied by the concentrated feed protein content less the total protein need for livestock system.

$$vsr\_Pbal_p = vF\_PU_p + vMg\_PU_p + vMs\_PU_p + vBh\_PU_p + \sum_{cft}(vkg\_Cf_{p,cft} \times Cf\_DMc \times Cf\_Pc) - vTot\_PN_p$$

Where: $\forall p$

Vsr_Pbal: supply-requirements protein balance
vF_PU: green forage protein used
vMg_PU: maize grain protein used
vMs_PU: maize silage protein used
vBh_PU: *Brachiaria* hay protein used
vkg_Cf: kg of concentrated feed bought
Cf_DMc: concentrated feed DM content
Cf_Pc: concentrated feed protein content
vTot_PN: total protein need for livestock

Total UEL minimum balance (supply – minimum intake requirements; the result should be greater than or equal to the minimum UEL intake)
The green forage UEL used more the maize grain UEL used more the maize silage UEL used more the *Brachiaria* hay UEL used more the rice straw bought in fresh matter multiplied by the rice straw dry matter content multiplied by the rice straw UEL content is greater than or equal to the minimum UEL requirement.

$$F\_UELU_p + vMs\_UELU_p + vBh\_UELU_p + (vkg\_Rs_p \times Rs\_DMc \times Rs\_UELc) \geq vTot\_UELMin_p$$

Where: $\forall p$

vF_UELU: green forage UEL used
vMs_UELU: maize silage UEL used
vBh_UELU: *Brachiaria* hay UEL used
vkg_Rs: kg of rice straw bought
Rs_DMc: rice straw DM content
Rs_UELc: rice straw UEL content
vTot_UELMin: minimum UEL intake for livestock

Total UEL maximum balance (supply – maximum intake requirements; the result should be lower than or equal to the maximum UEL intake)
The green forage UEL used more the maize grain UEL used more the maize silage UEL used more the *Brachiaria* hay UEL used more the rice straw bought in fresh matter multiplied by the rice straw dry matter content multiplied by the rice straw UEL content is lower than or equal to the maximum UEL requirement.

$$F\_UELU_p + vMs\_UELU_p + vBh\_UELU_p + (vkg\_Rs_p \times Rs\_DMc \times Rs\_UELc) \leq vTot\_UELMax_p \quad \forall p$$

Where:

vF_UELU:	green forage UEL used
vMs_UELU:	maize silage UEL used
vBh_UELU:	*Brachiaria* hay UEL used
vkg_Rs:	kg of rice straw bought
Rs_DMc:	rice straw DM content
Rs_UELc:	rice straw UEL content
vTot_UELMax:	maximum UEL intake for livestock

Forage/concentrate ratio

Ratio between UEL forage (silage + hay + rice straw) **and UEL concentrate** (maize grain + concentrate market)
The green forage UEL used more the maize silage UEL used more the *Brachiaria* hay UEL used more the rice straw bought in fresh matter multiplied by the rice straw dry matter content multiplied by the rice straw UEL content divided by the forage concentrate ratio (defined by the user) is greater than or equal to the maize grain UEL used more the concentrated feed cost divided by the concentrate feed price multiplied by the concentrated feed dry matter content multiplied by concentrated feed UEL content.

$$(F\_UELU_p + vMs\_UELU_p + vBh\_UELU_p + (vkg\_Rs_p \times Rs\_DMc \times Rs\_UELc)) \div ratio\_FC \geq$$
$$(vMg\_UELU_p + (vCf\_\cos t_p \div \$Cf \times Cf\_DMc \times Cf\_UELc) \quad \forall p$$

Where:

vF_UELU:	green forage UEL used
vMs_UELU:	maize silage UEL used
vBh_UELU:	*Brachiaria* hay UEL used
vkg_Rs:	kg of rice straw bought
Rs_DMc:	rice straw DM content
Rs_UELc:	rice straw UEL content
Ratio_FC:	forage concentrate ratio
vMg_UELU:	maize grain UEL used
vCf_cost:	concentrated feed cost
$Cf:	price of concentrated feed
Cf_DMc:	concentrated feed DM content
Cf_UELc:	concentrated feed UEL content

Costs

Hired labor
The hired labor cost in each period is equal to the hired labor used per period multiplied by the market price for labor.

$$vLhi\_\cos t_p = vLhi_p \times \$Lhi \quad \forall p$$

Where:

vLhi_cost:	labor hired cost
vLhi:	labor hired
$Lhi:	price of labor hired

Farm labor (opportunity cost)
The farm labor cost in each period is equal to the farm labor used per period multiplied by the market price for farm labor. This parameter is defined by the user and should be lower than the price for hired labor.

$$vFL\_\cos t_p = vFLU_p \times \$FL \qquad \forall\ p$$

Where:

vFL_cost: farm labor cost
vFLU: farm labor used
$FL: price of farm labor (opportunity cost)

Seedlings and/or seeds
The seedlings and/or seeds cost in each period is equal to the seedlings needs for *Brachiaria* grass multiplied by the price of *Brachiaria* seedlings (equal to zero because seedlings come from the farm) more the seedlings needs for *Pennisetum* grass multiplied by the price of *Pennisetum* seedlings (equal to zero because seedlings come from the farm) more the seedlings needs for *Setaria* grass multiplied by the price of *Setaria* seedlings (equal to zero because seedlings come from the farm) more the seeds needs for Maize grain multiplied by the price of Maize seeds more the seeds needs for Maize silage multiplied by the price of Maize seeds more the seeds needs for *Avena* grass multiplied by the price of *Avena* seeds more the seeds needs for *Avena* seed production multiplied by the price of *Avena* seeds.

$$vSS\_\cos t_p = (vC\_SSN_{p,m,ct=1} \times \$SSbra) + (vC\_SSN_{p,m,ct=3} \times \$SSpen) + (vC\_SSN_{p,m,ct=4} \times \$SSset) +$$
$$(vC\_SSN_{p,m,ct=5} \times \$SSmai) + (vC\_SSN_{p,m,ct=6} \times \$SSmai) + (vC\_SSN_{p,m,ct=7} \times \$SSave) +$$
$$(vC\_SSN_{p,m,ct=8} \times \$SSave) + (vC\_SSN_{p,m,ct=9} \times \$SSave) \qquad \forall\ p$$

Where:

vSS_cost: seedlings and/or seeds cost
vC_SSN: seedlings and/or seeds need for crop system
$SS: price of seedlings and/or seeds
m: month
ct: crop type (1=Brachiaria grass; 3=Pennisetum grass; 4=Setaria sphacelata; 5=maize grass; 6=maize silage; 7=*Avena* grass non irrigated; 8=*Avena* grass irrigated; 9=*Avena* seeds)

Fertilizer NPK
The NPK fertilizer cost in each period is equal to the NPK fertilizer need per period multiplied by the market price of NPK fertilizer.

$$vNPK\_\cos t_p = vC\_NPKN_p \times \$NPK \qquad \forall\ p$$

Where:

vNPK_cost: NPK fertilizer cost
vC_NPKN: NPK fertilizer need for crop system
$NPK: price of NPK fertilizer

Fertilizer N
The N fertilizer cost in each period is equal to the N fertilizer need per period multiplied by the market price of N fertilizer.

$$vN\_\cos t_p = vC\_NN_p \times \$N \qquad \forall\ p$$

Where:

vN_cost: nitrogenous fertilizer cost
vC_NN: nitrogenous fertilizer need for crop system
$N: price of nitrogenous fertilizer

Fertilizer P
The P fertilizer cost in each period is equal to the P fertilizer need per period multiplied by the market price of P fertilizer.

$$vP\_\cos t_p = vC\_PN_p \times \$P \qquad \forall\ p$$

Where:

vP_cost: phosphorus fertilizer cost

vC_PN: phosphorus fertilizer need for crop system
$P: price of phosphorus fertilizer

Fertilizer K

The K fertilizer cost in each period is equal to the K fertilizer need per period multiplied by the market price of K fertilizer.

$$vK\_cost_p = vC\_KN_p \times \$K \qquad \forall\ p$$

Where:

vK_cost: potassium fertilizer cost
vC_KN: potassium fertilizer need for crop system
$K: price of potassium fertilizer

Manure

The manure cost in each period is equal to the manure need per period multiplied by the market price of manure.

$$vMa\_cost_p = vC\_MaN_p \times \$Ma \qquad \forall\ p$$

Where:

vMa_cost: manure cost
vC_MaN: manure need for crop system
$Ma: price of manure

Water for irrigation

The water cost in each period is equal to the water need for irrigation per period multiplied by the market price of water.

$$vWi\_cost_p = vC\_WiN_p \times \$Wi \qquad \forall\ p$$

Where:

vWi_cost: water for irrigation cost
vC_WiN: water for irrigation need for crop system
$Wi: price of water for irrigation

Animal labor

The animal labor cost in each period is equal to the animal labor need per period multiplied by the market price of animal labor.

$$vAL\_cost_p = vC\_ALN_p \times \$AL \qquad \forall\ p$$

Where:

vAL_cost: animal labor cost
vC_ALN: animal labor need for crop system
$AL: price of animal labor

Concentrated feed

The concentrated feed cost in each period is equal to the concentrate feed type 1 need per period multiplied by the market price of concentrate 1 more the concentrate feed type 2 need per period multiplied by the market price of concentrate 2.

$$vCf\_cost_p = (vkg\_Cf_{p,cft=1} \times \$Cftype1) + (vkg\_Cf_{p,cft=2} \times \$Cftype2) \qquad \forall\ p$$

Where:

vCf_cost: concentrated feed cost
vkg_Cf: kg of concentrated feed bought
$Cf: price of concentrated feed (type 1 and type 2)
cft=1 and 2: concentrated feed type (1 and 2)

Rice straw

The rice straw (UEL) cost in each period is equal to the rice straw need per period multiplied by the market price of rice straw.

$$vRs\_cost_p = vkg\_Rs_p \times \$Rs \qquad \forall\ p$$

Where:

vRs_cost: rice straw cost

vkg_Rs: kg of rice straw bought
$Rs: price of rice straw

Rent land

The rent land cost in each period is equal to the sum of the land allocated for perennial grasses and the land allocated for annual grasses multiplied by the market price of land.

$$vLr\_cost_p = (vLand\_PGrass_p + vLand\_AGrass_p) \times \$Lr \qquad \forall\ p$$

Where:

vLr_cost: land rent cost
vLand_PGrass: land allocated for perennial grasses
vLand_AGrass: land allocated for annual grasses
$Lr: price of land rent

Total costs

The total costs in each period is equal to the hired labor cost more the farm labor cost more the seedlings and seeds cost more de fertilizer NPK cost more de fertilizer N cost more de fertilizer P cost more de fertilizer K cost more de manure cost more the water for irrigation cost more the animal labor cost more the concentrated feed cost more the rice straw cost more the rent land cost more the depletion cost for buildings more the depletion cost for equipments.

$$vTot\_cost_p = vLhi\_cost_p + vFL\_cost_p + vSS\_cost_p + vNPK\_cost_p + vN\_cost_p + vP\_cost_p + vK\_cost_p + vMa\_cost_p + vWi\_cost_p + vAL\_cost_p + vCf\_cost_p + vRs\_cost_p + vLr\_cost_p + dep\_cost\_b + dep\_cost\_e \qquad \forall\ p$$

Where:

vTot_cost: total cost
vLhi_cost: labor hired cost
vFL_cost: farm labor cost
vSS_cost: seedlings and/or seeds cost
vNPK_cost: NPK fertilizer cost
vN_cost: nitrogenous fertilizer cost
vP_cost: phosphorus fertilizer cost
vK_cost: potassium fertilizer cost
vMa_cost: manure cost
vWi_cost: water for irrigation cost
vAL_cost: animal labor cost
vCf_cost: concentrated feed cost
vRs_cost: rice straw cost
vLr_cost: land rent cost
dep_cost_b: depletion cost for buildings
dep_cost_e: depletion cost for equipments

Income

Milk

The milk income in each period is equal to the milk production per period multiplied by the market milk price.

$$vMilk\_inc_p = vMilkP_p \times \$Milk \qquad \forall\ p$$

Where:

vMilk_inc: milk income
vMilkP: milk production
$Milk: milk price

Young dairy animal

The young dairy animals income in each period is equal to the dairy male calves born multiplied by the market dairy male price more the dairy female calves sold multiplied by the market dairy female price.

$$vCalves\_inc_p = (vDXmb_p \times \$Ymale) + (vDXfs_p \times \$Yfemale) \qquad \forall\ p$$

Where:

vCalves_inc:	calves income
vDXmb:	dairy male calves born
vDXfs:	dairy female calves sold
$Ymale:	young male price
$Yfemale:	young female price

Culled animals (dairy and draught)
The culled animals income in each period is equal to the dairy culled animals multiplied by the market dairy culled price more the draught cattle culled multiplied by the market draught cattle price more the draught buffalo culled multiplied by the market draught buffalo price.

$$vCulled\_inc_p = (vDXcu_p \times \$Cdairy) + (vCXcu_p \times \$Ccattle) + (vBXcu_p \times \$Cbuffalo) \qquad \forall_p$$

Where:

vCulled_inc:	calves income
vDXcu:	culled dairy cows
vCXcu:	culled draught cattle
vBXcu:	culled draught buffalo
$Cdairy:	culled dairy price
$Ccattle:	culled cattle price
$Cbuffalo:	culled buffalo price

Total income in period 1 (with initial budget)
If the period is equal to 1, the total income in each period is equal to the initial budget of farmers (defined by user) more the milk income more the young animal income more the culled animal income more other livestock revenue more other agricultural revenue more other non agricultural revenue.

$$vTot\_inc_{p=1} = IBudget + vMilk\_inc_p + vCalves\_inc_p + vCulled\_inc_p + O\_inc\_liv + O\_inc\_agr + O\_inc\_n\_agr \qquad p=1$$

Where:

vTot_inc:	total income
IBudget:	initial budget of farmers
vMilk_inc:	milk income
vCalves_inc:	calves income
vCulled_inc:	calves income
O_inc_liv:	other livestock revenue
O_inc_agr:	other agricultural revenue
O_inc_n_agr:	other non agricultural revenue

Total income
If the period is greater than 1, the total income in each period is equal to the milk income more the young animal income more the culled animal income more other livestock revenue more other agricultural revenue more other non agricultural revenue.

$$vTot\_inc_{p>1} = vMilk\_inc_p + vCalves\_inc_p + vCulled\_inc_p + O\_inc\_liv + O\_inc\_agr + O\_inc\_n\_agr \qquad \forall_{p>1}$$

Where:

vTot_inc:	total income
vMilk_inc:	milk income
vCalves_inc:	calves income
vCulled_inc:	calves income
O_inc_liv:	other livestock revenue
O_inc_agr:	other agricultural revenue
O_inc_n_agr:	other non agricultural revenue

Dairy cows "patrimony"
The dairy cows patrimony in each period is equal to the sum of dairy calves (age between 1 and 12) multiplied by the patrimony price of dairy calves more the sum of dairy heifers (age between 13 and 30) multiplied by the patrimony price of dairy heifers more the sum of high potential dairy cows in first lactation (age between 31 and 43) multiplied by the patrimony price of high potential dairy cows in first lactation more the sum of high potential dairy cows in middle lactations (age between 44 and 82) multiplied by the patrimony price of high potential dairy cows in middle lactations more the sum of high

potential dairy cows in last lactation (age between 83 and 92) multiplied by the patrimony price of high potential dairy cows in last lactation more the sum of medium potential dairy cows in first lactation (age between 94 and 106) multiplied by the patrimony price of medium potential dairy cows in first lactation more the sum of medium potential dairy cows in middle lactations (age between 107 and 145) multiplied by the patrimony price of medium potential dairy cows in middle lactations more the sum of medium potential dairy cows in last lactation (age between 146 and 155) multiplied by the patrimony price of medium potential dairy cows in last lactation.

$$vPat\_DX_p = \sum_{da\geq 1\&\leq 12}(vDX_{p,da}\times \$Y\_1) + \sum_{da\geq 13\&\leq 30}(vDX_{p,da}\times \$Y\_2) + \sum_{da\geq 31\&\leq 43}(vDX_{p,da}\times \$A\_hfl) + \sum_{da\geq 44\&\leq 82}(vDX_{p,da}\times \$A\_hml) + \sum_{da\geq 83\&\leq 92}(vDX_{p,da}\times \$A\_hll) + \sum_{da\geq 94\&\leq 106}(vDX_{p,da}\times \$A\_mfl) + \sum_{da\geq 107\&\leq 145}(vDX_{p,da}\times \$A\_mml) + \sum_{da\geq 146\&\leq 155}(vDX_{p,da}\times \$A\_mll) \quad \forall\, p$$

Where:

vPat_DX:	dairy cows patrimony
vDX:	dairy herd structure
$Y_1:	price for female calves
$Y_2:	price for heifers
$A_hfl:	price for adult high potential cows in first lactation
$A_hml:	price for adult high potential cows in middle lactations
$A_hll:	price for adult high potential cows in last lactation
$A_mfl:	price for adult medium potential cows in first lactation
$A_mml:	price for adult medium potential cows in middle lactations
$A_mll:	price for adult medium potential cows in last lactation

<u>Profit</u>

Profit per period

The profit per period is equal to the total income less the total costs in each period.

$$v\Pr ofit_p = vTot\_inc_p - vTot\_\cos t_p \quad \forall\, p$$

Where:

vProfit:	profit per period
vTot_inc:	total income
vTot_cost:	total cost

Profit per year

If the month is December, the profit per year is equal to the profit of the last 12 months (from January to December).

$$v\Pr ofit\_Y_{p,m=12} = v\Pr ofit\_Y_p + v\Pr ofit\_Y_{p-1} + v\Pr ofit\_Y_{p-2} + v\Pr ofit\_Y_{p-3} + v\Pr ofit\_Y_{p-4} + v\Pr ofit\_Y_{p-5} + v\Pr ofit\_Y_{p-6} + v\Pr ofit\_Y_{p-7} + v\Pr ofit\_Y_{p-8} + v\Pr ofit\_Y_{p-9} \; v\Pr ofit\_Y_{p-10} + v\Pr ofit\_Y_{p-11} \quad m=12$$

Where:

vProfitY:	profit per year
vProfit:	profit per period

Maximise profit

The maximum profit is equal to the sum of total income less total costs in all periods.

$$vMax\Pr ofit = vTot\_inc_p - vTot\_\cos t_p$$

Where:

vMaxProfit:	maximum profit
vTot_inc:	total income
vTot_cost:	total cost

Appendix 2. Quantity of concentrated feed per head and per day (during the *Avena* season)

Table 9. Scenarios based on *Pennisetum purpureum* yields (associated with the soil fertility of farms)

Herd fixed			**farm type**	**scenario**	**use of *Avena***	**indicator**	**years**								average	%
In.	min	max					**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**		
6	6	8	1	S1	N	Q. conc.	6.1	6.5	7.4	7.2	6.7	7.5	8.1	5.7	6.9	
				S2	Y	Q. conc.	5.5	6.1	6.6	6.2	5.8	6.7	6.9	4.8	6.1	- 12
3	3	6	2	S3	N[11]	Q. conc.	3.7	5.6	3.8	6.3	6.8	7.1	6.8	3.9	5.5	
				S4	Y	Q. conc.	2.8	4.8	2.8	5.3	5.9	6.2	4.5	3.7	4.5	- 18
4	4	6	3	S5	N	Q. conc.	4.1	4.9	4.5	5.6	5.7	5.6	6.5	4.7	5.2	
				S6	Y	Q. conc.	1.9	2.4	2.0	2.8	2.9	3.5	3.6	3.2	2.8	- 46
herd "free"																
In.	min	max														
6	5	11	1	S1'	N	Q. conc.	6.1	5.9	6.8	8.2	8.8	8.4	7.4	4.5	7.0	
	6	12		S2'	Y	Q. conc.	5.2	5.5	6.2	8.7	8.5	8.3	7.3	4.5	6.8	- 3
3	3	8	2	S3'	N[11]	Q. conc.	4.0	5.0	4.1	7.7	8.5	8.4	7.6	4.8	6.3	
		9		S4'	Y	Q. conc.	2.8	4.3	3.3	6.3	8.4	7.9	7.1	5.7	5.7	- 10
4	4	8	3	S5'	N	Q. conc.	4.1	4.8	4.0	5.3	6.8	7.4	7.3	5.4	5.6	
		11		S6'	Y	Q. conc.	1.9	2.6	2.2	5.1	6.7	6.9	6.2	4.7	4.5	- 20

In.: initial herd (adult cows) in January 2006; **min:** minimum number of adult cows considered by the model; **max:** maximum number of adult cows considered by the model;
Farm type 1: *Pennisetum purpureum* yields between 60 – 80 tons FM/ha/year;
Farm type 2: *Pennisetum purpureum* yields between 80 – 100 tons FM/ha/year;
Farm type 3: *Pennisetum purpureum* yields between 100 – 120 tons FM/ha/year;
Q. conc.: Quantity of concentrated feed (Maize grain + concentrated feed from Market) during the months of *Avena* production (Sept.–Feb.; 6 months)

[11] No bound for Maize silage maximum intake per day (5.0 kg FM) when *Avena* grass is not used

Table 10. Scenarios based on farmer' experience in dairy activity

herd fixed			farm type	scenario	use of *Avena*	indicator	years								average	%
In.	min	max					1	2	3	4	5	6	7	8		
3	3	6	1	S1	N[12]	Q. conc.	4.9	6.2	4.8	6.3	7.0	7.4	7.0	4.2	6.0	
				S2	Y	Q. conc.	3.7	5.3	3.1	5.8	6.0	6.3	5.3	2.5	4.8	- 20
5	4	8	2	S3	N	Q. conc.	4.5	5.4	5.5	6.6	6.9	7.3	6.7	4.1	5.9	
				S4	Y	Q. conc.	3.7	4.5	4.2	5.6	6.0	6.2	4.9	2.2	4.7	- 20
5	5	9	3	S5	N	Q. conc.	5.3	6.0	6.0	7.0	7.1	7.0	6.9	4.7	6.3	
				S6	Y	Q. conc.	4.4	5.1	5.7	5.9	6.2	6.5	6.3	3.1	5.4	- 14
herd "free"																
In.	min	max														
3	3	8	1	S1'	N[12]	Q. conc.	5.0	5.7	4.5	7.8	8.6	8.4	7.6	5.5	6.6	
				S2'	Y	Q. conc.	3.8	4.9	3.5	6.8	7.5	7.0	6.3	4.0	5.5	- 17
5	5	9	2	S3'	N	Q. conc.	4.5	5.2	5.5	6.8	7.8	7.9	7.1	4.6	6.2	
		12		S4'	Y	Q. conc.	3.9	4.4	4.6	6.7	8.2	8.1	7.0	4.8	6.0	- 3
5	5	10	3	S5'	N	Q. conc.	5.3	5.9	5.9	7.0	8.3	7.6	6.7	4.2	6.4	
		12		S6'	Y	Q. conc.	4.5	4.8	5.7	8.2	8.0	7.1	6.4	4.0	6.1	- 5

A: actual herd (adult cows) in January 2006; **min:** minimum number of adult cows considered by the model; **max:** maximum number of adult cows considered by the model;
Farm type 1: dairy experience lower than or equal to 8 years;
Farm type 2: dairy experience from 9 to 17 years;
Farm type 3: dairy experience greater than or equal to 18 years;
Q. conc.: Quantity of concentrated feed (Maize grain + concentrated feed from Market) during the months of *Avena* production (Sept.–Feb.; 6 months)

[12] No bound for Maize silage maximum intake per day (5.0 kg FM) when *Avena* grass is not used

Table 11. Scenarios based on herd dimension

herd fixed			farm type	scenario	use of *Avena*	indicator	years								average	%
In.	min	max					1	2	3	4	5	6	7	8		
1	1	2	1	S1	N	Q. conc.	3.0	3.4	5.1	2.5	5.3	5.1	4.7	0.2	3.7	
				S2	Y	Q. conc.	0.7	0.9	2.7	0.3	2.3	2.0	1.8	0.0	1.3	- 65
3	3	6	2	S3	N[13]	Q. conc.	4.6	6.3	4.7	7.1	7.6	8.0	7.7	4.7	6.3	
				S4	Y	Q. conc.	3.7	5.2	3.6	6.0	6.3	6.7	6.2	3.6	5.2	- 17
9	6	11	3	S5	N	Q. conc.	5.1	5.4	6.7	6.4	6.4	6.5	5.9	2.8	5.7	
	7			S6	Y	Q. conc.	4.1	4.7	5.5	5.1	5.2	5.4	5.8	2.2	4.8	- 16
herd "free"																
In.	min	max														
1	1	3	1	S1'	N[14]	Q. conc.	2.7	3.4	5.2	4.0	5.9	6.3	6.2	3.1	4.6	
		5		S2'	Y[14]	Q. conc.	0.6	1.0	2.8	2.4	4.0	7.0	6.7	5.0	3.7	- 20
3	3	8	2	S3'	N[13]	Q. conc.	4.6	5.7	4.8	8.4	9.2	9.2	8.3	6.0	7.0	
				S4'	Y	Q. conc.	3.7	4.9	3.9	7.3	8.2	7.9	7.1	5.1	6.0	- 14
9	9	15	3	S5'	N	Q. conc.	4.9	5.4	6.0	6.5	7.5	7.8	6.7	4.6	6.2	
		17		S6'	Y	Q. conc.	4.1	4.1	5.4	7.0	7.8	7.2	6.4	3.0	5.6	- 10

A: actual herd (adult cows) in January 2006; **min:** minimum number of adult cows considered by the model; **max:** maximum number of adult cows considered by the model;
Farm type 1: lower than or equal to 2 animals;
Farm type 2: from 3 to 9 animals;
Farm type 3: greater than or equal to 10 animals;
Q. conc.: Quantity of concentrated feed (Maize grain + concentrated feed from Market) during the months of *Avena* production (Sept.–Feb.; 6 months)

[13] No bound for Maize silage maximum intake per day (5.0 kg FM) when *Avena* grass is not used
[14] Bound for *Brachiaria* hay was increased from 4 kg FM maximum intake per day to 6 kg FM maximum intake per day

Table 12. Scenarios based on *Avena* adoption behavior

Herd fixed			**farm type**	**scenario**	**use of *Avena***	**indicator**	**years**								average	**%**
In.	min	max					**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**		
3	3	6	1	S1	N[15]	Q. conc.	4.8	6.2	4.8	6.6	6.9	7.3	7.1	4.3	6.0	
				S2	Y	Q. conc.	3.9	5.3	3.8	5.6	6.4	6.7	5.2	2.6	4.9	- 18
5	4	9	2	S3	N	Q. conc.	5.0	5.7	4.9	6.7	6.9	6.5	6.6	4.9	5.9	
				S4	Y	Q. conc.	4.3	5.1	4.7	5.7	6.0	6.6	5.4	3.3	5.1	- 14
8	6	12	3	S5	N	Q. conc.	4.6	6.0	7.0	7.5	7.3	7.2	7.1	3.7	6.3	
				S6	Y	Q. conc.	3.9	5.1	5.7	6.4	6.8	6.8	5.9	2.3	5.4	- 14
herd "free"																
In.	min	max														
3	3	7	1	S1'	N[15]	Q. conc.	4.9	6.1	4.7	7.8	7.8	7.8	6.8	3.7	6.2	
		8		S2'	Y	Q. conc.	3.9	4.9	4.1	6.8	7.5	7.2	6.5	4.2	5.6	- 10
5	5	10	2	S3'	N	Q. conc.	5.4	6.1	4.5	6.7	8	7.4	7.1	5.4	5.7	
		13		S4'	Y	Q. conc.	4.2	4.8	4.5	5.8	5.9	7.3	6.3	4.2	6.3	- 15
8	6	15	3	S5'	N	Q. conc.	4.5	5.6	6.7	7.5	8.5	8.4	7.5	5.7	5.4	
		16		S6'	Y	Q. conc.	3.9	4.9	5.5	7.6	7.8	8.0	6.9	3.0	6.0	- 12

A: actual herd (adult cows) in January 2006; **min:** minimum number of adult cows considered by the model; **max:** maximum number of adult cows considered by the model;
Farm type 1: no adoption;
Farm type 2: adopted only in 2006;
Farm type 3: adopted from beginning of experiments;
Q. conc.: Quantity of concentrated feed (Maize grain + concentrated feed from Market) during the months of *Avena* production (Sept.–Feb.; 6 months)

[15] No bound for Maize silage maximum intake per day (5.0 kg FM) when *Avena* grass is not used