# The TERROIR model detailed description including equations and parameters

The following document is the supplementary material of the research article entitled "**Multi-level analysis of nutrient cycling within agro-sylvo-pastoral landscapes in West Africa using an agent-based model**" in Environmental modelling & software.

This supplementary material provides an exhaustive description of the TERROIR model which was built in order to analyze nutrient recycling and spatial transfers within agro-pastoral village landscapes in a tropical context. Outlines of the model and model evaluation can be found in the main paper. In this document, the choice of the modelling platform is first explained. Then data is provided as extra information for the model overview. Model variables and parameters are then detailed, before being used in the last three sections that deal with the sub-models (biophysical processes, household decision model and livestock system).

**Content**

## 1. Modelling platform choice

The model is implemented on the GAMA platform which is often used in the domain of natural-resource management (Gaudou et al., 2014; Therond et al., 2014). It is described as a "modelling and simulation development environment for building spatially explicit agent-based simulations" (http://gama-platform.org/) (Grignard et al., 2013). Indeed the platform framework allows an explicit representation of the environment and the various stakeholders interacting within the modelled system (Taillandier et al., 2014). Even though GIS data are not currently used in this model, this possibility is offered by Gama and, indeed, it is one of its perspectives of evolution.

In the GAMA representation, the environment is an agent among others. All the agents (called "species") can be hierarchized with an inheritance scheme allowing multi-level and multi-scale modelling of complex systems as targeted for this model. The current version of the model is coded in Gama 1.7.

## 2. General overview

### 2.1. Characteristics of crop-livestock systems represented in the model

In the modeled systems, i.e. agricultural villages in West Africa, common features are often described: i) importance of crop-livestock-tree interactions in terms of biomass recycling in order to minimize economic risks (Alvarez et al., 2014; Vall et al., 2011); ii) livestock used for capital saving, animal traction and as manure provider for soil amendment and fertilization (Dugué, 1998; Powell et al., 2004); iii) landscape structure organized in four concentric rings (Manlay et al., 2004b; Ramisch, 2005) where organic matter is concentrated on the closest fields to home; iv) crop rotation with dry cereal and legume crops (Powell et al., 2004); v) a high level of farm product home consumption and the family as the main source of labor for the farming activities; vi) mono-modal rainy season, which largely determines the rhythm of farming activities as irrigation is rare (FAO, 2005). These characteristics are also taken into account in the model (Table 1).

Table 1. Characteristics of crop-livestock systems and how they were addressed in the model

| | Crop-livestock system characteristic | Source | Mean of representation in the model |
|---|---|---|---|
| 1 | Importance of crop-livestock-tree interactions in terms of biomass recycling | (Vall et al., 2011) | Plots and livestock herds are independent agents that interact. Trees are represented in the model, their leaves are used to feed livestock (and wood as fuel) |
| 2 | Livestock used for: | (Dugué, 1998; Powell et al., 2004) | |
| | Capital saving | | So far only fattened animals are traded but stochastic events can be added to simulate possible needs of destocking grazing animals |
| | Animal traction | | Equines are represented but do not contribute to farming activities (as they are not limiting) |
| | Manure provider for soil amendment and fertilization | | Paddocking is representing as well as manure spreading |
| 3 | Landscape structure organized in 4 concentric rings (i.e. land units, from the center to the periphery: housing area, home fields, bush fields, rangelands) | (Manlay et al., 2004; Ramisch, 2005) | Spatial grid with square cells representing the whole village with a grouping attribute corresponding to one of the 4 land units |
| 4 | Crop rotation with of dry cereal and legume crops | (Powell et al., 2004) | Rotation of cereal (millet) and legume (groundnut) |
| 5 | High level of farm products home consumption and family as the main source of workforce for the farming activities | (Powell et al., 2004) | High production of staple food (cereal) for home consumption; no paid labor represented |
| 6 | Mono-modal rainy season that strongly rhythms the farming activities | | One cropping season (i.e. during the rainy season); household sub-model based on the rainy season for sowing activities; vegetation growth during the rainy season only |
| 7 | High variability of rainfalls | (Perret, 2008) | Stochasticity of annual rainfalls drawn from a certain range |

### 2.2. Biomass types used in the model

Table 2. Biomass types dealt with in the model

| N° | Biomass type | | Specific biomasses | Storable by household? | Is fertilizer? | kgTNM/kgDM | kgN/kgDM | Source |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Livestock | Bovine | No | No | - | 0.034* | (Rufino et al., 2009) |
| 2 | 1 | Livestock | Small ruminant | No | No | - | 0.025* | (Rufino et al., 2009) |
| 3 | 2 | Forage | Grass (graminae) | No | No | 0.128 (rainy season) | 0.020 | (Le Thiec, 1996) |
| | | | | | | 0.039 (dry season) | 0.006 | |
| 4 | 2 | Forage | Straw | Yes | No | 0.06 | 0.010 | (Le Thiec, 1996) |
| 5 | 2 | Forage | Hay | Yes | No | 0.107 | 0.017 | (Le Thiec, 1996) |
| 6 | 2 | Forage | Leaves | No | No | 0.13 | 0.021 | (Depommier and Guérin, 1996) |
| 7 | 2 | Forage | Fresh grass | No | No | 0.128 | 0.020 | (Le Thiec, 1996) |
| 8 | 3 | Concentrate feeds | - | No | No | 0.35 | 0.056 | (Le Thiec, 1996) |
| 9 | 4 | Seed | Cereal | Yes | No | See 11. Cereal grain | | |
| 10 | 4 | Seed | Groundnut | Yes | No | See 12. Groundnut | | |
| 11 | 5 | Food | Cereal grain | Yes | No | 0.112 | 0.018 | (Le Thiec, 1996) |
| 12 | 5 | Food | Cereal pod | Yes | No | 0.153 | 0.024 | (Le Thiec, 1996) |
| 13 | 5 | Food | Cereal cob | Yes | No | - | 0.021 | (Le Thiec, 1996) |
| 14 | 5 | Food | Groundnut grain | Yes | No | - | 0.080 | (Schilling and Gibbons, 2002) |
| 15 | 5 | Food | Groundnut husk | Yes | No | 0.060 | 0.010 | (Le Thiec, 1996) |
| 16 | 5 | Food | Groundnut unhusked | Yes | No | - | 0.059 | (Le Thiec, 1996) |
| 17 | 5 | Food | Fish | No | No | 0.24 (1.2kgTNM/kg FW) | 0.038 | (Huss, 1999; Murray and Burt, 2001) |
| 18 | 5 | Food | Rice | No | No | 0.112 | 0.018 | (Le Thiec, 1996) |
| 19 | 6 | Fuels | Gathered dung | No | No | Depend on dung deposited and N losses (see section 5.2) | | |
| 20 | 6 | Fuels | Wood | Yes | No | - | 0.0076 | (Jung, 1969, p. 4) |
| 21 | 7 | Mineral fertilizer | Mineral fertilizer | No | Yes | - | 0.15 | |
| 22 | 8 | Human waste | Kitchen waste | No | Yes | Depend on household consumption (see section 5.2) | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| 23 | 9 | Livestock waste | Dung | Yes | Yes | Depend on livestock ingestion (see section ) |
| 24 | 9 | Livestock waste | Urine | No | Yes | Depend on livestock ingestion (see process) |
| 25 | 9 | Livestock waste | Feed refusals | Yes | Yes | Depend on livestock ingestion (see process) |
| 26 | 9 | Livestock waste | Manure (dung, urine, feed refusals) | Yes | Yes | Depend on livestock ingestion (see process) |

TNM = total nitrogenous matter; DM = dry matter; * kgN/250kg of live weight

### 2.3. Conceptual stock-flow models

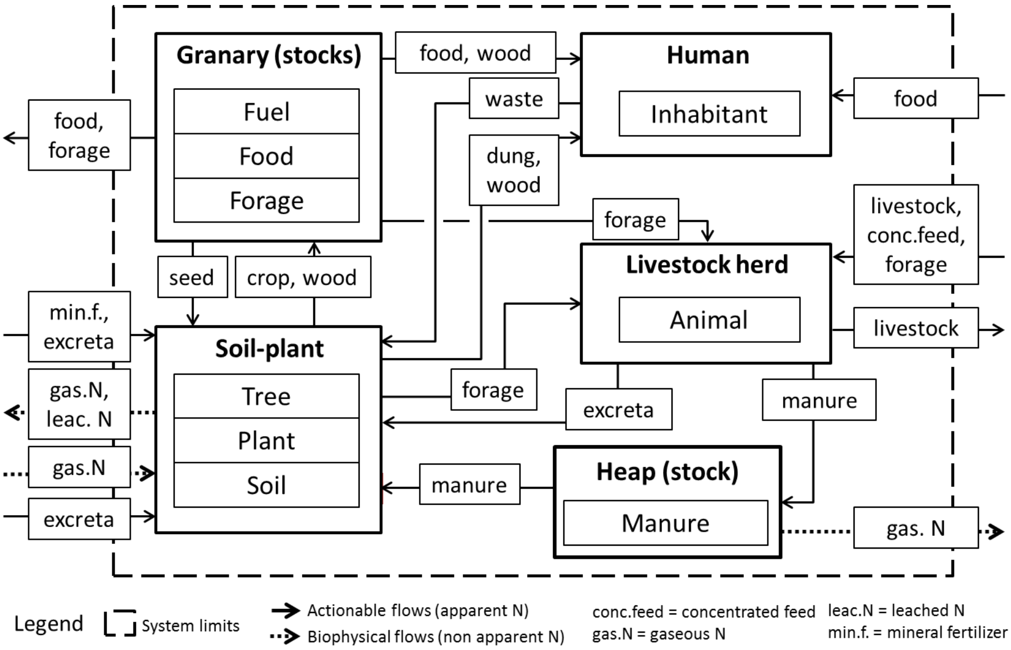


Figure 1. First conceptual stock-flow model: interaction among farming activities at village landscape level

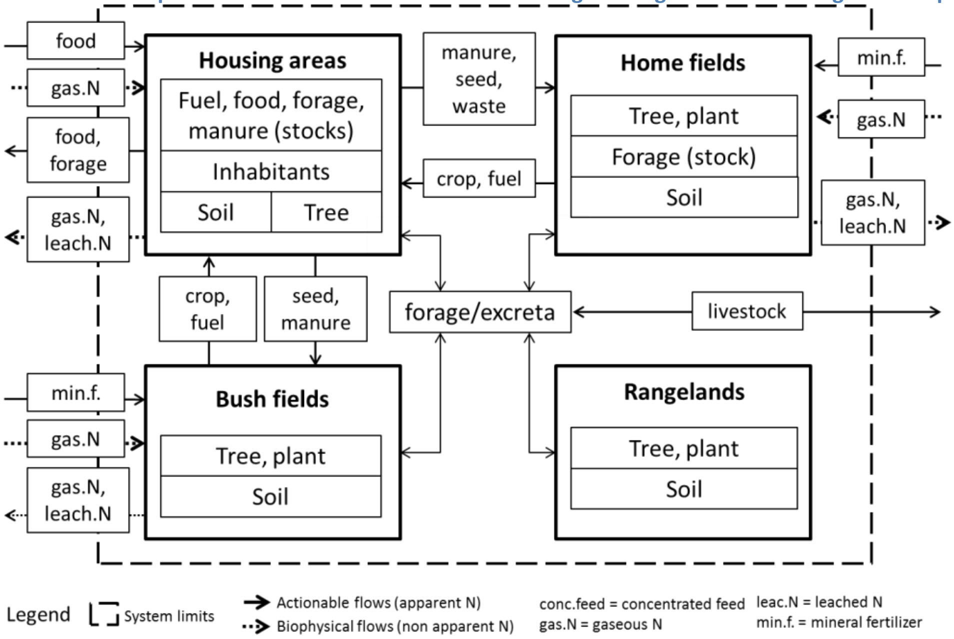


Figure 2. Second conceptual stock-flow model: interaction among land units at village landscape level

## 2.4. General sequence of action in the model

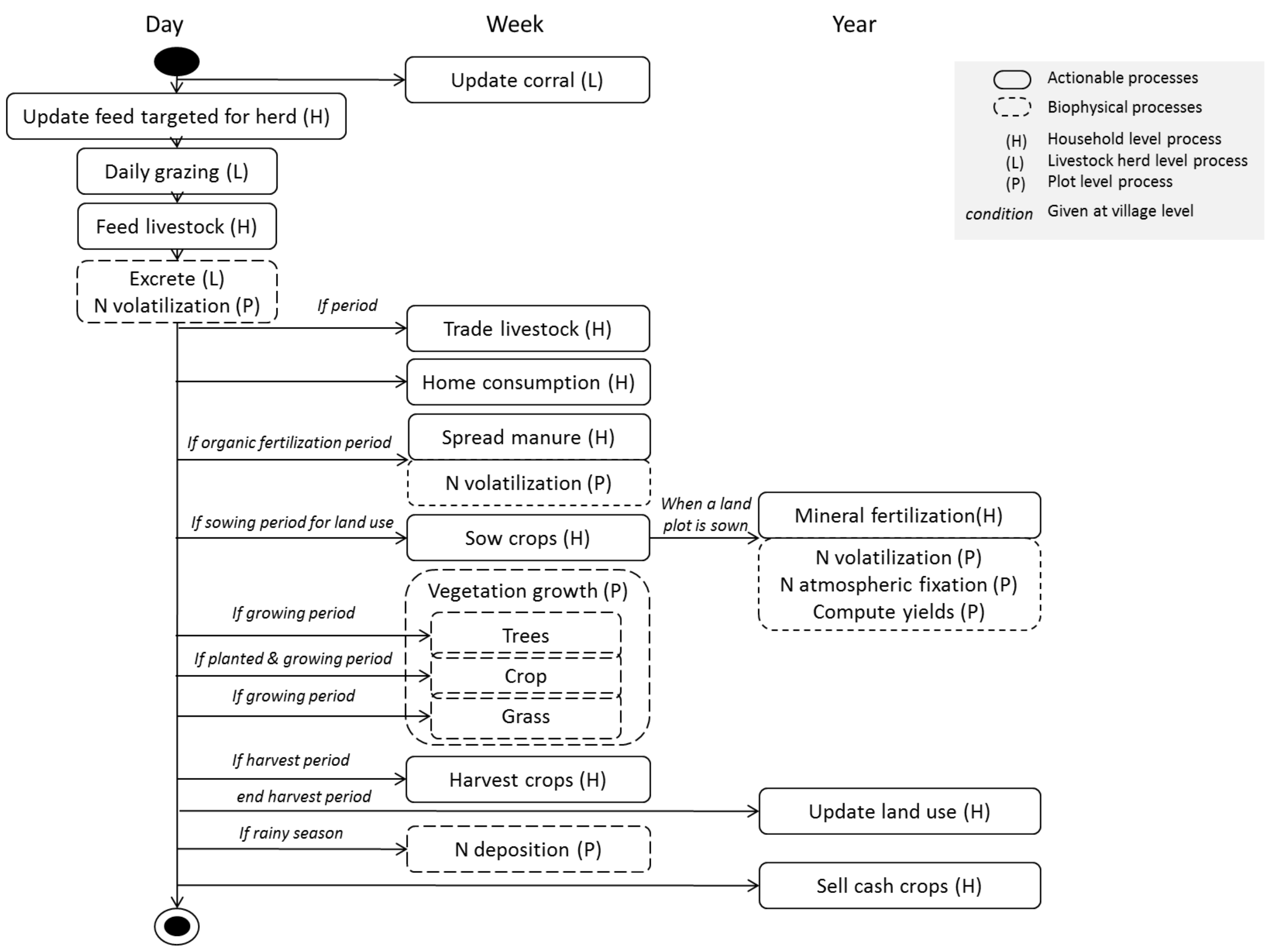


Figure 3. General sequence of actions sorted by the time scale they are performed in the model: daily, weekly or annually

Only processes relating to livestock feeding and induced excretions take place on a daily basis. Indeed, in the model livestock herds on free-grazing system interact and compete with each other through their environment while grazing. The daily time step allows reducing the bias possibly induced by the herds asynchronous biomass consumption. Most of the other processes are abstracted as weekly processes (they happen every 7 time step), as suggested by field investigations. For instance for cropping activities, it actually takes one week to harvest one hectare of dry cereal (e.g. millet) on average; for livestock management, livestock are traded once a week in the market and corral choice is made at least for a week (also described in Achard and Banouin (2003)). If the actual household food consumption is different among households each day, it is quite homogeneous on average when considered over a week. Using the week scale thus avoids the accumulation of uncertainties induced by the difficulty to model the daily heterogeneity accurately. Similarly, plot processes are modelled on a weekly basis. Mineral fertilization is the only cropping activity on an annual scale. Indeed, no fertilizer loss over time is introduced in the model (only a loss at application) and there is not any impact of the exact date of fertilization on nutrient availability.

Activities relating to tactical decisions, such as land use changes (crop rotation in agricultural plots), are undertaken every year. Cash crop sales are assumed to happen yearly, after harvest when the stocks reach their maximum level as actual markets are not represented as to influence households' decisions.

## 3. Model variables and parameters

### 3.1. Global variables and parameters

#### 3.1.1. Default parameters

Table 3. Global parameters: default values

| Type | Name | Value | Unit | Description |
|---|---|---|---|---|
| int | `daysPerStep` | 1 | day | length of a time step (day) |
| int | `weeklyActivity` | 7 | day | for activities that happen every 7 time steps |
| int | `monthlyActivity` | 30 | day | for activities that happen every 30 time steps |
| float | `year_duration` | 360 | day | length of a year (day) |
| int | `nb_year_simulated` | Defined by user (range: 1 to 20) | year | number of years simulated (year) |

* a year is 12 months of 30 days, i.e. 360 days

#### 3.1.2. Period determination

In the model the **rainy season** is a determinant period as its beginning launches the cropping season. Its beginning date and duration are global, yearly updated, variables. The rainy season is followed by two dry seasons: the hot dry season and the cold dry season which are hard to differentiate and do not determine the execution of any process in the model. In practice, during the hot one, households usually harvest crop plots for about two months plus two additional months dedicated to storage organization. Usually, the end of harvest coincides with the beginning of the cold dry season. At that period, the cropping season is over and plots can be prepared for the forthcoming one (fertilization, sowing).

Table 4. Global parameters related to model periods

| Type | Name | Description | Concerned period | Value | Unit | Source |
|---|---|---|---|---|---|---|
| int | `day_beg_rain` | date for rainy season to start | rainy season (RS) | Defined by user (default = 10) | day | - |
| int | `lengthRainySeason` | length of the rainy season | rainy season | 65 | day | |
| int | `day_beg_faidherbiaCycle` | date for tree growth to start | tree growth | 165 | day | (Depommier and Guérin, 1996) |
| int | `length_faidherbiaGrowth` | length of the tree vegetative cycle | tree growth | 100 | day | (Depommier and Guérin, 1996) |
| int | `beg_fat_after_rain` | date for fattening period to start after the end of RS | fattening period | 30 | day | |

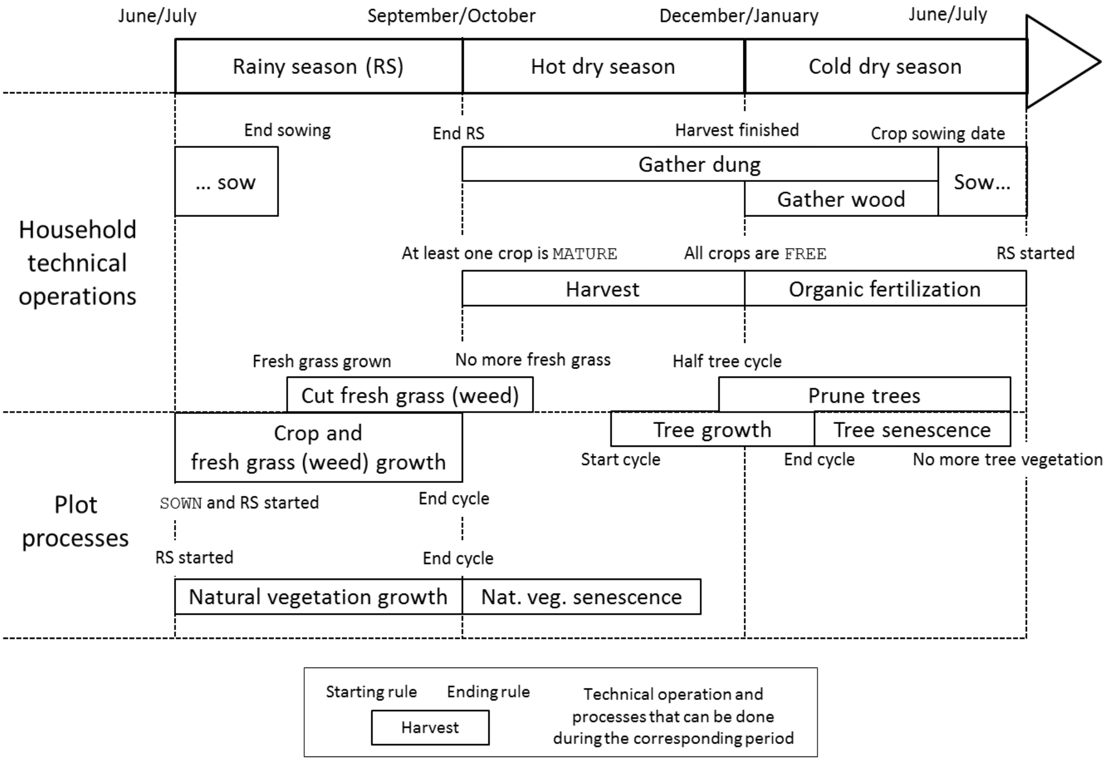


Figure 4. A typical seasonal calendar and periods for technical operations simulated in the model (for a simulation where rainfalls start in the beginning of July and end in October)

### 3.1.3. Model initialization

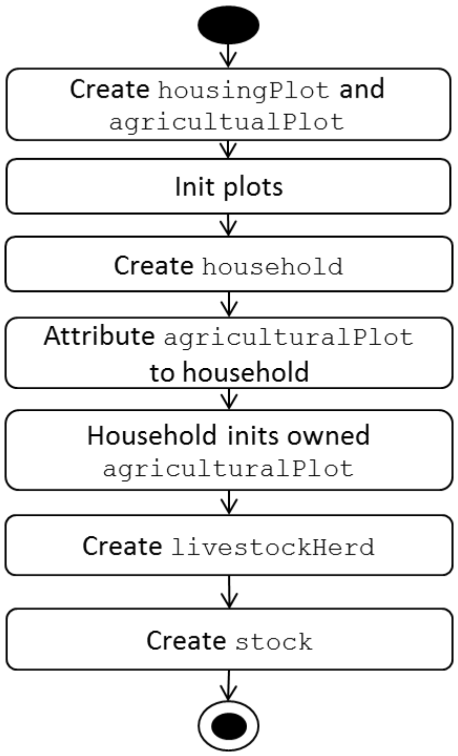


Figure 5. Initialization diagram

First the village landscape (land plot entities) is created and, depending on its structure (input data), a distinction is made between housing and agricultural plots. Then households are created. The number of households and the proportion of each type within the village population are global parameters chosen by the user according to the case study. Household structures are initialized in order to be as close as possible to the actual population of its type within the village, based on a Gaussian distribution. Each household agent sequentially and randomly chooses random plots one after the other until it reaches the area it was previously assigned for each land unit starting with home fields, then bush fields. This random distribution of plots in space mimics observations in real Senegalese villages. Due to causes such as land inheritance and strategies for adapting to climatic risks—(see Akponikpe et al. (2011)), the plots belonging to households look like they are randomly scattered all over the village landscape. Depending on the household type, household assets are instantiated differently for specific attributes such as the cropping plan for agricultural plots, livestock herd management and initial stock level (see section 3.2 for initialization data).

## 3.2. Agent parameters and variables

This section details agent parameters (i.e. constants fixed at initialization) and variables.

### 3.2.1. Land plot

#### 3.2.1.1. Parameters

Table 5. Land plots (i.e. housing and agricultural plots) constant parameters

| | Parameter | Description | Type | Unit | Initialization |
|---|---|---|---|---|---|
| 1 | `ID` | plot name | string | dimensionless | incremental numbering |
| 2 | `area_ha` | plot area | float | hectares | input from user (external file) |
| 3 | `myLandUnit` | plot land unit | string | dimensionless | input from user (external file) |
| 4 | `nb_tree` | number of trees on the plot | integer | Number of trees | input from user (external file) |
| 5 | `myOwner` (agricultural plot only) | household that owns the plot | household ID | dimensionless | initialized by the owner household |
| 6 | `croppingPlan` (agricultural plot only) | list of the various land uses year after year | list<string> | dimensionless | initialized by the owner household |

#### 3.2.1.2. Variables

Housing and agricultural plots have common variables, relating to trees (Table 6). In the model, two pruning states are distinguished, depending on whether trees were pruned during the current tree vegetative cycle (`prunedTrees`) or not (`notPrunedTrees`). For a given simulated tree vegetative cycle, each time a new tree is pruned, it shifts from the not pruned trees list to the pruned trees list. Among these pruning states, trees are clustered according to the pruning intensity. The pruning intensity refers to the last pruning year. Trees not pruned the last 2 years are indexed 0; trees pruned the year n-1 are indexed 1; trees pruned the year n-1 and year n-2 are indexed 2. Then, available tree vegetation is given for each pruning state and intensity. All trees produce wood (`deadwoodStock`) that can be collected as dead wood for fuel, for home consumption.

Unlike housing plot that does not have more variable; agricultural plots have specific variables (detailed in Table 7).

Table 6. Land plot (i.e. housing and agricultural plots) variables and time scales

<table>
<tr><th></th><th>Variables</th><th>Description</th><th>Type</th><th colspan="2">Unit</th><th>Initialization</th><th>Variation frequency</th></tr>
<tr><td rowspan="3">1</td><td rowspan="3">notPruned Trees</td><td rowspan="3">for each pruning intensity (3 types: {0,1,2}), lists the number of trees not pruned (in the current year) and the total vegetal production available</td><td rowspan="3">map<int, <int, float>></td><td>state:</td><td>dimensionless</td><td></td><td>annually</td></tr>
<tr><td>number of trees:</td><td>dimensionless</td><td></td><td rowspan="2">daily</td></tr>
<tr><td>vegetation available on trees:</td><td>kgDM</td><td></td></tr>
<tr><td rowspan="3">2</td><td rowspan="3">pruned Trees</td><td rowspan="3">for each pruning intensity (3 types: {0,1,2}), lists the number of pruned trees (in the current year) and the total vegetal production available</td><td rowspan="3">map<int,<int, float>></td><td>state:</td><td>dimensionless</td><td></td><td>annually</td></tr>
<tr><td>number of trees:</td><td>dimensionless</td><td></td><td rowspan="2">daily</td></tr>
<tr><td>vegetation available on trees:</td><td>kgDM</td><td></td></tr>
<tr><td>3</td><td>deadwood Stock</td><td>quantity of dead wood available on the plot</td><td>float</td><td colspan="2">kgDM</td><td></td><td>weekly</td></tr>
<tr><td>4</td><td>balance_ kgNapparent</td><td></td><td></td><td colspan="2">kgN/ha</td><td></td><td></td></tr>
</table>

[1]For instance: the map notPrunedTrees ([0::(2::2.3), 1::(0::0.0), 2::(4::5.2)]) means that, for the given plot and the current year, there are 2 trees not pruned with a total of 2.3 kgDM of vegetation available, with a pruning intensity of 0; 0 tree (and no vegetation) with a pruning intensity of 1; 4 trees with a total of 5.2 kgDM of vegetation available with a pruning intensity of 2.

Table 7. Agricultural plot variables and time scales (as variation frequency)

| Type of variable | N° | Variables | Description | Type | Unit | Variation frequency |
|---|---|---|---|---|---|---|
| Status | 1 | `status` | status of the plot (free, planted, on growth, mature, product harvested) and date at which it was reached | pair<integer, string> (day, status) | dimensionless | weekly |
| Biomass production (related to `croppingPlan cf. table 4`) | 2 | `planYear` | index to determine at which stage of the cropping plan the plot is (1= first year, etc.) | integer | dimensionless | annually |
| | 3 | `landUse` | use of the plot (millet, groundnut, fallow, natural vegetation) | string | dimensionless | annually |
| | 4 | `future_landUse` | land use of the plot for the next year | string | dimensionless | annually |
| Biomass production (related to `landUse`) | 5 | `product_yields_current_cropping_season` | output for the current cropping season for the various products | map<string, float> (product, quantity) | kgDM/year | annually |
| | 6 | `yieldHaPerCrop` | last yields reached for each crop | map<string, float> (crop, quantity) | kgDM/ha/year | annually |
| Biomass production (related to fertilization) | 7 | `fertilizationPriority` | | int | dimensionless | annually |
| | 7 | `organicFertilizationTargeted` | quantity of organic fertilization targeted for the current year | float | kgDM/year | annually |
| | 8 | `organicFertilizationInput` | quantity of organic fertilizer actually applied for the cropping season (i.e. starts/ends at sowing) | float | kgDM/year | weekly |
| | 9 | `fertilizerInput` | list of fertilizers applied on the plot (all types) | map<string, float> (fertilizer, quantity) | kgN/year | daily |
| | 10 | `organicFertilizationStatus` | ratio applied/targeted quantity of fertilizer for each year of the simulation | map<integer, float> (year, ratio) | dimensionless | daily |
| Resources stock | 11 | `NStock` | stock of soil nitrogen | float | kgN/year | weekly |
| | 12 | `plantStocks` | stock of live vegetation biomass | map<string, float> (product, quantity) | kgDM/year | weekly |
| Interaction with livestock | 13 | `isGrazable` | if true, livestock herd can be corralled on the plot and/or graze on it | boolean | dimensionless | bi-annually |
| | 14 | `paddockedLivestock` | ID list of livestock herds corralled on the plot | list<livestock herd ID> | dimensionless | weekly |

Table 8. Land uses and possible corresponding land units

| Land use | Land unit | Biomass type | Products | Co-products |
|---|---|---|---|---|
| Dry cereal | Home fields, bush fields | Crop | Grain | Straw |
| Legume crop | Bush fields | Crop | Grain | Hay |
| Fallow | Bush fields | Natural vegetation | Grass | Nil |
| Rangeland vegetation | Rangeland | Natural vegetation | Grass | Nil |

### 3.2.2. Household

#### 3.2.2.1. Household types

Table 9. Household types in the model

| Type name | Abbreviation |
|---|---|
| Livestock-subsistence oriented | LS |
| Livestock-market oriented | LM |
| Crop-subsistence oriented | CS |
| Crop-market oriented | CM |

#### 3.2.2.2. Parameters

Table 10. Household agent constant parameters

| | Parameters | Description | Type | Unit | Initialization |
|---|---|---|---|---|---|
| 1 | ID | household name | string | dimensionless | incremental |
| 2 | `home` | Plot where the household is located | Housing plot ID | dimensionless | any `housingPlot` |
| 3 | `myType` | Type of household (LS, LM, CS, CM) | string | dimensionless | - |
| 4 | `myAgriculturalPlots` | Agricultural plots owned by the household | list<plot> | dimensionless | depends on household type |
| 5 | `myLivestock` | livestock herds owned by the household | list<livestock Herd ID> | dimensionless | depends on household type |
| 6 | `myStocks` | Stocks of biomasses owned by the household (food, fuels, feeds, fertilizers) | list<stocks ID> | dimensionless | one stock per type of storable biomasses (list in Table 2) |
| 7 | `inhabitants` | Number of people in the household | integer | adult equivalent | depends on the household type |
| 8 | `theDump` | plot where the household disposes its wastes | plot | dimensionless | closest agricultural plot from home |

Table 14 shows the initialization figures for the creation of livestock herd agents for household agents. Each household agent gets livestock herds according to its type (based on Audouin et al. (2015)). The number of herds, the species of the herd and management are specified in Tables below. The size of every herd agent (`value_TLU` cf. Table 17) depends on the household and is based on a Gaussian distribution (mean and standard deviation) of the household type population. It is expressed in Tropical Livestock Unit (TLU) corresponding to one animal of 250kg live weight.

Table 11. Household initialization: livestock attribution to CS households (n = 92 households)

| Management | Number of herds | Specie | Average TLU | Standard deviation TLU |
|---|---|---|---|---|
| Free-grazing | 1 | small ruminant | 3.7 | 0.2 |
| **Total** | **2** | | **3.7** | |

Table 12. Household initialization: livestock attribution to CM households (n = 14 households)

| Management | Number of herds | Specie | Average TLU | Standard deviation TLU |
|---|---|---|---|---|
| Fattening | 1 | bovine | 1.0 | 0.2 |
| | 1 | small ruminant | 2.0 | 0.2 |
| Draft animals | 1 | equine | 1.0 | 0.1 |
| **Total** | **3** | | **4.0** | |

Table 13. Household initialization: livestock attribution to LS households (n = 5 households)

| Management | Number of herds | Specie | Average TLU | Standard deviation TLU |
|---|---|---|---|---|
| Free-grazing | 1 | bovine | 3.5 | 0.2 |
| | 1 | small ruminant | 3.7 | 0.2 |
| **Total** | **2** | | **7.3** | |

Table 14. Household initialization: livestock attribution to LM households (n = 3 households)

| Management | Number of herds | Species | Mean TLU | Standard deviation TLU |
|---|---|---|---|---|
| Fattening | 1 | bovine | 2.5 | 0.2 |
| | 1 | small ruminant | 3.0 | 0.2 |
| Draft animals | 1 | equine | 1.0 | 0.1 |
| **Total** | **3** | | **6.5** | |

When agricultural plots are allocated to households, households, according to their type, assign them a cropping plan that will determine the yearly rotation on the land plot. There are currently three possible cropping plans as described in Table 15.

Table 15. Agricultural plot initialization: cropping plans according to land units and types of cropping management

| Land unit | Household type | Cropping plan length (years) | Rotation (land use) |
|---|---|---|---|
| Home fields | all types | 1 | millet |
| Bush fields | LS, CS | 3 | millet, groundnut, fallow |
| Bush fields | LM, CM | 2 | millet, groundnut |

#### 3.2.2.3. Variables

Table 16. Household variables and time scales

| | Variables | Description | Type | Unit | Variation frequency |
|---|---|---|---|---|---|
| 1 | `foodNeeds` | requirements of food for the household according to its type | map<string, float> (food, quantity) | kgDM/week | weekly |
| 2 | `combustibleNeed` | requirements of firewood for the household | float | kgDM/week | weekly |
| 3 | `dungGathered` | true if dung was gathered during the current week | boolean | dimensionless | weekly |
| 4 | `activityFlows` | month flow of biomass among farming compartments (household, plot, livestock, granary, fertilizers) | map<string, map<string, map<string, float>>> (origin, destination, biomass type, quantity) | kgN/day | daily |
| 5 | `landUnitFlows` | biomass flows among land units (housing areas, home fields, bush fields, rangeland) | map<string, map<string, map<string, float>>> (origin, destination, biomass type, quantity) | kgN/day | daily |

### 3.2.3. Livestock herd

#### 3.2.3.1. Parameters

Livestock parameters described in Table 17 are provided by household agents.

Table 17. Livestock herd constant parameters

| | Parameters | Description | Type | Unit |
|---|---|---|---|---|
| 1 | `myOwner` | household that owns the herd | household | dimensionless |
| 2 | `mySpecies` | species (bovine, small ruminant or equine) | string | dimensionless |
| 3 | `management` | type of livestock management (fattening, free-grazing, draft animals) | management | dimensionless |
| 4 | `value_TLU` | quantity of animals in the herd | float | Tropical Livestock Unit (TLU)[1] |
| 5 | `stepPurchase (fattening)` | date when the herd was purchased by the household | integer | day |
| 6 | `fatteningDuration_day(fattening)` | time the herd will stay within the household before being sold | integer | day |

[1] 1 TLU is equivalent to 1 animal of 250kg live weight

#### 3.2.3.2. Variables

Table 18. Livestock herd variables and time scales

| | Variables | Description | Type | Unit | Variation frequency |
|---|---|---|---|---|---|
| 1 | forageNeed_TLU pday | forage need per day for 1 TLU | float | kgDM/TLU/ day | weekly |
| 2 | herd_forageNeed _dDay | herd forage need for the current day | float | kgDM | daily |
| 3 | previousDay Ingestions | type of biomass and quantities ingested on the previous day by the herd | map<string, float> (biomass, quantity) | kgDM | daily |
| 4 | dDayIngestions | type of biomass and quantities ingested per plot on the current day by the herd | map<plot, map<string, float>> (plot, biomass, quantity) | kgDM | daily |
| 5 | myCorral (free-grazing) | agricultural plot where the herd is corralled at night | Plot ID | dimensionless | weekly |
| 6 | concentratedFeed Need_TLUpday (fattening, draft animals) | concentrate feeds need per day for 1 TLU | float | kgDM/TLU/d ay | weekly |

Livestock variables related to feed needs are initialized according to their species and management. Forage and concentrate feeds needs are evaluated in kgDM/TLU/day and depend on the species and management of the livestock herd. Forage needs quantities are described in Table 19 according to the forage quality in terms of energy input (high or low). Low quality forages are straw while high quality forages are fresh grass and hay. Free-grazing herds mainly fulfill their forage needs with grass while grazing and do not receive concentrate feeds.

Table 19. Initialization: livestock forage need (kgDM/TLU/day)

| | bovine | | small ruminant | | equine | |
|---|---|---|---|---|---|---|
| Management \ forage quality | low | high | low | high | low | high |
| free-grazing | 3 | 0 | 2 | 0 | nil | nil |
| fattening | 3 | 2 | 2 | 1 | nil | nil |
| draft animals | nil | nil | nil | nil | 3 | 2 |

Concentrate feeds needs are detailed in Table 20.

Table 20. Initialization: livestock concentrate feeds need (kgDM/TLU/day)

| Management \ Specie | bovine | small ruminant | equine |
|---|---|---|---|
| free-grazing | 0 | 0 | nil |
| fattening | 3 | 2 | nil |
| draft animals | nil | nil | 2 |

At initialization, draft animals and fattening herds are located on their owner's home (i.e. on a `housingPlot`). Free-grazing herds are located on a corral (`myCorral`). The corral initialization is either an agricultural plot in fallow (`landUse`) that belongs to its owner or a plot from the land unit rangeland.

#### 3.2.4. Stock initialization

In this version of the model, all stock levels are initialized at 0kgDM except for the ones stocking seeds. In this case, the exact quantity of seeds required for the first year is set (equation of seed need in 5.1.1).

## 4. Biophysical processes

### 4.1. Land plot processes: tree production

Trees are represented in the model and located on land plots (i.e. `housingPlot` and `agriculturalPlot`). Modelled trees represent adult trees of the *Faidherbia albida* species. Indeed it is the dominant tree species in the studied landscape and is found highly palatable by the livestock. They are characterized by a "reverse" phenology, shedding its leaves at the peak of the rainy season, while being in full leaves throughout the dry season. The peak of production is reached in January-February (Depommier and Guérin, 1996). In the model, tree growth happens during the corresponding period (`tree_growth`) (see section 3.1.2).

Climate does not influence tree production. It seems that late rainfalls impact fruit production (CTFT, 1988) but in the studied systems, fruit production is already very low due to high pruning intensity. Thus fruit production is not accounted for in the model.

Tree production depends on the pruning intensity over years (Depommier and Guérin, 1996) as pruning practices are very common in the studied systems. Table 21 shows the average production of the various tree products in kgDM/tree/year (leaves and wood) depending on the tree pruning intensity. The production lowers if the tree has been pruned the previous years.

Table 21. Modelled tree production (*Faidherbia albida*) according to different pruning intensities

| Intensity index | Tree pruning intensity | | Leaves production (kgDM/tree/year) | Dead wood production (kgDM/tree/year) |
|---|---|---|---|---|
| | Pruning year n-1? | Pruning year n-2? | | |
| 0 | No | No | 70 | 45[1] |
| 1 | Yes | No | 50 | 22 |
| 2 | Yes | Yes | 30 | 10 |

[1] from Jung (1969, p. 6), all other figures are based on Depommier and Guérin (1996)

Annually, at the end of the tree vegetative cycle (when tree vegetation is null), the **tree pruning intensity** is updated. As described in Figure 6, first, the trees that were not pruned during the tree vegetative cycle decrease in level of pruning intensity[1]; second, pruned trees increase in level of pruning intensity. The trees that were pruned three years in a row do not reach a higher level of pruning intensity but die (i.e. `prunedTrees` with an index of 2 are deleted from the system). As a new tree vegetative cycle may start, the variable `prunedTrees` is emptied.

As *Faidherbia albida* are legumes, they fix a certain quantity of nitrogen in the soil every year, as described by Jung (1969) (`Nfixed`).

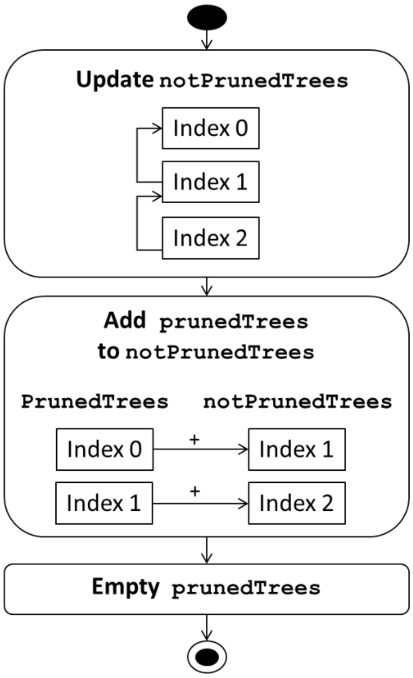


Figure 6. Update tree pruning intensity

| Type | Parameters | Description | Value | Unit | Source |
|---|---|---|---|---|---|
| float | `maxLeavesPruned Quantity` | Maximal quantity that can be pruned | 40 | kgDM/ year/tree | (Depommier and Guérin, 1996) |
| float | `ratioWoodPruned_ overLeaves` | Quantity of wood pruned over leaves quantity pruned | 1.5 | dimensionless | (Depommier and Guérin, 1996) |
| float | `Nfixed` | Quantity of nitrogen fixed per tree and per year in the soil | 4 | kgN/year/tree | (Jung, 1969)p10 |

[1] This system was inspired from the Leslie matrix (Cushing and Yicang, 1994)

## 4.2. Agricultural plots processes

### 4.2.1. Status evolution

Within a year, agricultural plots change status according to biophysical processes and/or actionable processes undertaken by households. The plot status evolution scheme depends on whether the plot land use is a crop or natural vegetation; the land use is updated annually according to a fixed cropping plan. Crop plots are first sown, i.e. seeds are destocked according to sowing density; then crop grows if it is in the growing period; then when the crop cycle is over (e.g. 90 days after the beginning of growth for millet); crops can then be harvested: first for their agricultural products, second for their co-products; then plots are freed, i.e. the livestock can graze and be corralled on it (Figure 7a). Plot with natural vegetation are only dependent on internal processes: vegetation growth and decay (Figure 7b).

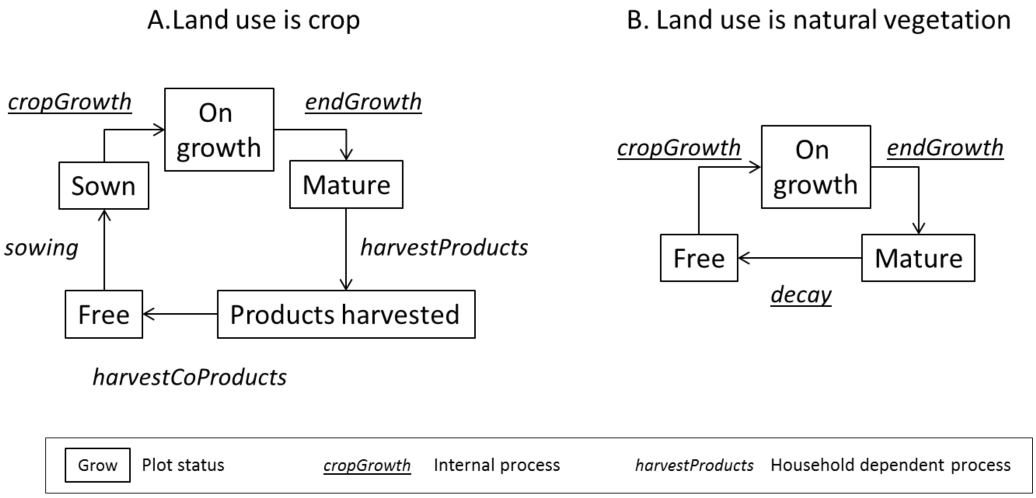


Figure 7. The various statuses for the agricultural plot agents

### 4.2.2. Yields computation

As the representation of biophysical processes is simplified in the model, when the vegetation starts growing, total final yields of products and by-products are calculated (function of the predictive rainfall, a fixed parameter and the nitrogen available provided until sowing). During vegetation growth, it is assumed that the weekly biomass gain is linear for the cycle duration; for instance, the yield of the cropped agricultural plot1 is first calculated at 1 000kgDM/ha and its whole crop cycle lasts 10 weeks, the weekly production is 100kgDM/ha.

Table 22. Land use products, co-products and cycle duration

| Land use | Product | | Co-product | | Cycle duration | Source |
|---|---|---|---|---|---|---|
| | Name | Product fraction of total vegetation biomass (kgDM/kgDM) | Name | Co-product fraction of total vegetation biomass (kgDM/kgDM) | (days) | |
| **Millet** | Grain | 0.3 | Straw | 0.7 | 90 | (Affholder, 1997) |
| **Groundnut** | Grain | 0.3 | Hay | 0.7 | 90 | Expert knowledge |
| **Fallow vegetation** | Grass (graminae) | 1.0 | - | 0 | length rainy season + 10 days | Expert knowledge |
| **Rangeland vegetation** | Grass (graminae) | 1.0 | - | 0 | length rainy season + 10 days | Expert knowledge |

The duration of the vegetation growth cycle depends on its type, as described in Table 22. As also shown in the same table, each land use can produce a product and a co-product.

#### 4.2.2.1. Vegetation yield

Crop and natural vegetation yields are dependent on rain and fertilization. As described in agricultural plot variables, land use outputs are distinguished in two types: product and co-product. Only crops produce co-products. The **yield** (Y) is calculated as described in Equation (1). The **water limited yield** (Yw) is first calculated considering water as the only limitation to crop growth. Then the **nitrogen reduction factor** (NRF) is applied to Yw.

The general equation for vegetation yield (Y in kgDM/ha) is as follows:

$$Y = Yw \text{ x } NRF \quad (1)$$

Where **Yw** is the water-limited yield (kgDM/ha) (specific for each land use)

**NRF** is the nitrogen reduction factor (dimensionless) (Equation (5))

Groundnut response to rain and fertilization does not seem linear (Garcia, 2015). It is not taken into account in the model.

#### 4.2.2.2. Water limited yield

For millet, **the water-limited yield** curve is determined using an empirical model, CELSIUS, acronym for Cereal and Legume crops Simulator Under changing Sahelian environment (Affholder et al., 2012; Garcia, 2015). CELSIUS is a dynamic crop model with a daily time-step calibrated with empirical data. The model is based on the PYE model (Affholder et al., 2013) which integrates run-off, germination delays or plant destruction in case of drought and the delivery of soil nitrogen (Garcia, 2015). The water balance module used is the one built for the SARRA model (Affholder, 1997).

Figure 8 shows the resulting yields (for millet grain in $10^3$kgDM/ha) according to the annual rainfall considering rain as the only limitation for crop growth. Below 317mm of rain, there is no millet produced. Above 805mm, the curve levels off, i.e. the yield is maximal. From these results, the following equation is drawn to calculate millet yield under rain limitation:

$$Yw\ millet = 1.8608 \ln(x) - 8.6756$$

The same equation is used for Yw natural vegetation (graminae).

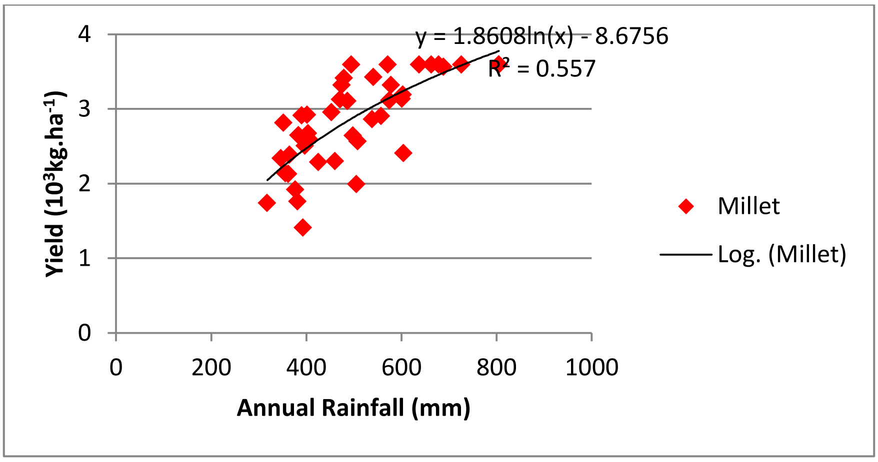


Figure 8. Water limited yield determination

#### 4.2.2.3. Nitrogen reduction factor

##### 4.2.2.3.1. Nitrogen available

In order to grow, natural and crop vegetation use nitrogen (N) drawn from the soil and external inputs applied. Only mineralized N can be used, called here **N available** (in kgN). In the model, mineralization is assumed to be undertaken during the whole year and, so, no specific time frame is determined. The most important is that every year, when yields are computed, only a certain quantity of N is mineralized which can be estimated as follows:

$$N\ available = NsoilStock + inputNmineralized + biologicalNitrogenFixation \qquad (2)$$

Where **NsoilStock** is the N mineralized from the soil organic N stock (kgN)

**inputNmineralized** is the N available from the organic fertilizer N input (kgN) (see Equation (3))

**biologicalNitrogenFixation** is the nitrogen fixed from the atmosphere (kgN)

The **soil stock of N available** (in kgN) depends on the previous inputs received. It is assumed that the annual quantity of N mineralized from the soil organic stock is higher in home fields than bush fields as home fields usually get more organic matter. The mineral nitrogen soil stock is estimated from 20 to 35 kgN/ha/year for home fields (fixed at 27.5 in the model) against 12 kgN/ha/year in bush fields (Pieri, 1989).

The quantity **of N mineralized from fertilization inputs** depends on the type of fertilizer and more especially on its nitrogen mineralization rate. Mineralization can take several years and thus there is a residual effect of fertilizers applied over years (Freschet et al., 2008).

$$inputNmineralized = \Sigma_i\ N\ input_i\ x\ ratio\_availability_i \qquad (3)$$

Where **i** the type of fertilizer (mineral, manure, waste, dung, urine)

**N input$_i$** is the quantity of fertilizer **i** input (kgN)

**ratio_mineralized$_i$** is the fraction of N mineralized of the N fertilizer i input for x100 (%)

Mineralization rates are very dependent on the environment (sun, wind, temperature, soil quality). The lack of precise data imposed simplification in the model. Table 23 shows the residual effect of organic fertilizer inputs due to nitrogen mineralization. For instance, only 60% of the nitrogen contained in manure is mineralized the first year of application and thus is available for the vegetation, the second year there is a residual effect corresponding to 40% of the input but from the 3rd year nothing remains.

Table 23. Percentage of N mineralized of organic fertilizer N applied (%)

| Year of fertilization | Mineral | Manure | Household waste | Dung | Urine |
|---|---|---|---|---|---|
| 1st | 100 | 60 | 40 | 60 | 100 |
| 2nd | 0 | 40 | 30 | 40 | 0 |
| 3rd | 0 | 0 | 30 | 0 | 0 |

**Biological nitrogen fixation** (`fixedN` in kgN/ha) is calculated as follows:

$$fixedN = Nfixation + symbioticN \qquad (4)$$

Where **Nfixation** is the nitrogen fixed by free-living micro-organisms from the atmosphere (kgN/ha) (see Table 24)

**symbioticN** is the nitrogen fixed by legumes (crops and trees) (kgN/ha) (see Table 24)

Nitrogen fixation by free-living micro-organisms (`Nfixation`) is assumed to happen linearly during the rainy season.

Table 24. Nitrogen fixation parameters

| Type | Parameters | Description | Value | Unit | Source |
|---|---|---|---|---|---|
| float | symbioticN | legume biological fixation | 20 | kgN/ha/year | (Defoer et al., 1998) |
| float | Nfixation | quantity of nitrogen fixed from the atmosphere (free-living micro-organisms fixation) | 7.5 | kgN/ha/year | (Delon et al., 2010) |

#### 4.2.2.3.2. Equation

The nitrogen reduction factor is only calculated right after the quantity of N available, i.e. once a year just before the vegetation starts its growth after the plot yield is calculated. According to Garcia (2015), the **nitrogen reduction factor** (dimensionless) is calculated as follows:

$$NRF = (\text{N available} + \text{fixedN}) x \frac{\text{kp}}{\text{Nmax}} \quad (5)$$

Where **N available** is the quantity of nitrogen mineralized during the year and available for the vegetation (kgN/ha); see Equation (2)

**fixedN** is the nitrogen fixed from the atmosphere (kgN/ha); see Equation (4)

**Kp** is a loss coefficient

**N max** is the value above which fertilization is no more limiting the vegetation growth (kgN/ha)

For millet $\frac{\text{Kp}}{\text{Nmax}}$ = 0.0105 cf. CELSIUS model (Affholder et al., 2013)

As yields cannot be indefinitely improved with nitrogen fertilizer application, in the model yields are limited above a fixed quantity of N available (kgN/ha). Conversely, a minimum yield is fixed even though no N available is low or null. Table 25 shows the bounds of the NRF under and above fixed quantities of N available.

Table 25. Minimum and maximum quantity of N input as a fertilizer and associated yields

| Vegetation | Minimum quantity of N available | Minimum Nitrogen reduction factor | Maximum quantity of N available | Maximum Nitrogen reduction factor |
|---|---|---|---|---|
| | *kgN/ha* | *dimensionless* | *kgN/ha* | *dimensionless* |
| millet | 18 | 0.25 | 83 | 1 |
| grass (graminae) | 5 | 0.25 | 83 | 1 |
| groundnut | 0 | 1 | 0 | 1 |

### 4.2.2.4. Weeds

**Fresh grass** (weed), growing along with crops, are an important source of forage for livestock herds. It is assumed that, for proximity reasons, home fields are easier to maintain and weed than bush fields. Estimations of the weed yields among a population of home fields and bush fields are shown in Table 26. Fresh grass **yield (Yfg)** is randomly drawn from a range based on these parameters assuming a normal distribution of the data. Fresh grass is only used for livestock feeding by grass cutting, and cleared at the end of harvest.

Table 26. Parameters for fresh grass growth

| | Average yield weeds (kgDM/ha) | Standard deviation (kgDM/ha) | Source |
|---|---|---|---|
| Home fields | From 75 to 125 | - | Expert knowledge, survey; |
| Bush fields | 475 | 68 | (Achard and Banoin, 2003) population = 2651 hectares |

# 5. Household decision model

## 5.1. Cropping activities parameters

### 5.1.1. Fertilization

Fertilization is the main cropping activity that will strongly impact biophysical processes on agricultural plots and in livestock activities. Each household has fertilization objectives. Even though the fertilization inputs processed in the model are computed in kgN per hectare, the household fertilization objectives are given in kgDM per hectare. Indeed, real households reason their fertilization rates rather in terms of the quantity to be spread than in terms of the N content of the manure, which is much harder to determine. As not all plots can be fertilized each year, the households determine priorities between their plots e.g.: first home fields, then bush fields with cereals, then a plot with low yield in the previous year. Plots without owners (e.g. rangeland plots) receive fertilization indirectly when the livestock moves through the village to graze and excrete at the same time.

Crop plots can receive organic or mineral fertilizers. There are two ways of fertilizing a plot with organic matter. The first is using **livestock as a conveyor** especially by night corralling of the herds in targeted plots. This daily activity is undertaken by livestock herd agents. Excreted quantities (dung and urine) depend on the feed ingested the previous day. Excreta deposits are proportional to the time spent on the plot during the day (assumed to depend on the intake on the plot). The location of corrals is determined according to household fertilization plans, but if a plot is not available (e.g. because it is still cultivated), herds are corralled on fallow. Draft and in-barn animals excrete in barns. In that case, the urine is lost but the dung is collected with feed refusals to produce manure. The second fertilization method is by **manual application** of heaped manure and waste. Manure is spread by households on their agricultural plots during a given fertilization period. The maximum quantity spread per week depends on the cart size, as real farmers usually carry one cart per week to their fields. In the current version of the model the cart size is the same for all households. One plot is targeted until organic fertilizer requirements have been fulfilled.

The quantity of nutrients available to crops depends on the quantity of organic fertilizer applied, its mineralization rate, environmental losses and nitrogen fixation. Gaseous emissions ($N_20$, $NH_3$) take place, with the organic matter being either directly excreted by the livestock excreta or spread by households. In the model, these losses are calculated based on the literature using a ratio of gaseous N emitted per kg of N applied as fertilizer. While all mineral nutrients are, for the sake of simplicity, assumed to be directly available for plant growth, it is assumed that only a part of the organic matter is mineralized the first year of application and thus becomes available for the crop. A residual effect due to organic matter mineralization the following years is included in the model. Atmospheric fixation from free-living micro-organisms and symbiotic fixation by legumes are also included. Crop and grass yields are then computed using ad hoc models such as the CELSIUS model based on the Potential Yield Estimator (Affholder et al., 2013).

In the current version of the model, organic fertilization objectives are the same for all types of cropping systems as shown in Table 27. In the model, targeted quantities are in kgDM per hectare which is easier to compare to real practices (fresh weight converted into dry matter).

Table 27. Organic fertilization objectives according to land unit

| Land unit | Targeted organic matter quantity (kgDM/ha) | Source |
|---|---|---|
| Home field | 15,500 | (Achard and Banoin, 2003; Hiernaux et al., 1997; Powell et al., 2004) |
| Bush field | | |

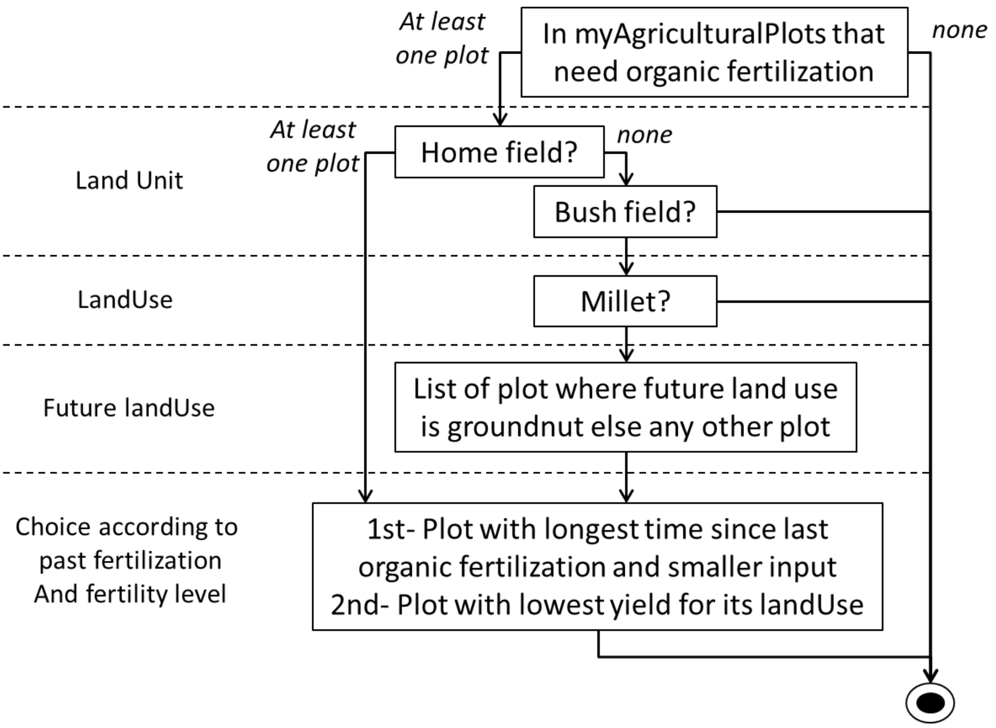


Figure 9. Household decision diagram for manure target choice (process of spreading manure)

Mineral fertilizers are assumed to be bought on an external market by households and applied right away at sowing. Purchased quantities depend on the household type (fixed by the user). There are two types of mineral fertilizers: one specific for millet and the other for groundnut. Table 28 shows the quantity of mineral fertilizer (kgDM/household/year) available annually depends on the type of household. Similarly, Table 29 shows the targeted quantities per land use and household type (in kgN/ha as available in literature, see Table 2 for conversion from DM). In the modelled systems mineral fertilizers cannot be applied on all fields mainly due to economic constraints (Andrieu et al., 2015; Powell et al., 2004). As modelled households do not have the availability to buy enough mineral fertilizers for all their agricultural plots, they have to give priority to their plots. The basic rule implemented is that for a given land use, they first try to reach the objective quantity on their least productive plot (i.e. one plot with the lowest yield for the given land use). Table 30 shows the quantity of nitrogen gaseous emissions per type of fertilizer.

Table 28. Mineral fertilizer quantity per type of household

| Household type | Millet (kgDM/household/year) | Groundnut (kgDM/household/year) | Source |
|---|---|---|---|
| Livestock-subsistence | 10.0 | 0.0 | Survey; (Audouin, 2014; Dugy, 2015; Odru, 2013; Saunier-Zoltobroda, 2015) |
| Livestock-market | 50.0 | 50.0 | |
| Crop-subsistence | 50.0 | 50.0 | |
| Crop-market | 67.0 | 50.0 | |

Table 29. Mineral fertilization objectives according to land use and household type (subsistence versus market-oriented)

| Type | Land use | Targeted mineral fertilizer quantity (kgN/ha/year) | Source |
|---|---|---|---|
| Subsistence-oriented (LS, CS) | Millet | 15 | (Akponikpè et al., 2011; Pieri, 1989, p. 92) |
| | Groundnut | 50 | Survey; (Audouin, 2014; Dugy, 2015; Odru, 2013; Saunier-Zoltobroda, 2015) |
| Market-oriented (LM, CM) | Millet | 37 | (Andrieu et al., 2015; Pieri, 1989, p. 92) |
| | Groundnut | 50 | Survey; (Audouin, 2014; Dugy, 2015; Odru, 2013; Saunier-Zoltobroda, 2015) |

Table 30. Nitrogen losses per type of fertilizer at application

| Fertilizer type | Emission factor (kgN/kgN applied) | Source |
|---|---|---|
| Dung | 0.2 | (unpublished results) |
| Urine | 0.6 | |
| Manure | 0.2 | |
| Household waste | 0.1 | |
| Mineral | 0.1 | |

### 5.1.2. Sowing

In the model, the sowing technical operation is affected by three levels of organization. First, at the village level, a general sowing period is determined as a range between the earliest sowing date and the latest sowing date ; e.g. based on Table 31, it starts when cereals can be sown (the month prior to the beginning of the rainy season) and ends when legumes are sown (after the beginning of rainy season). During this period crops can be sown if they are in their specific sowing period (see Figure 4). As described in Figure 10, during each sowing period, agricultural plots with the corresponding land use and of FREE status can be sown. Households perform the action of sowing by destocking seeds from their granaries. The destocked quantity is the sowing density for each crop (see Table 31). General equation for the required seed quantity is as follows:

$$SeedQuantity\ (kgDM) = agriculturalPlot\ area\ x\ sowing\ density\ (landUse) \tag{6}$$

Where **agriculturalPlot area** is the plot area (hectares)

**sowing density** is specific to the crop (kgDM/ha) (see Table 31)

Table 31. Crop parameters: sowing activities

| Crop type | Crop | Period | Sowing density (kgFM/ha) | Seed dry content (kgDM /kgFM) | Sowing density (kgDM/ha) | Source |
|---|---|---|---|---|---|---|
| Cereal | Millet | Month prior to the beginning of the rainy season | 5 | 0.925 (Le Thiec, 1996) | 4.6 | Survey |
| Legume | Groundnut | Week that follows the beginning of rainy season | 55 | 0.86 (Le Thiec, 1996) | 47.3 | Survey; (Schilling and Gibbons, 2002) |

Variables of sown agricultural plots change: they are not available for livestock anymore, they do not need organic fertilization and their plant stock is cleared (residual biomass is often burnt before sowing). Plots are fully sown at once in the model as the step for this technical operation is a week. Once an agricultural plot is sown, it is able to grow. It is assumed that there is no need of replanting crops in the model.

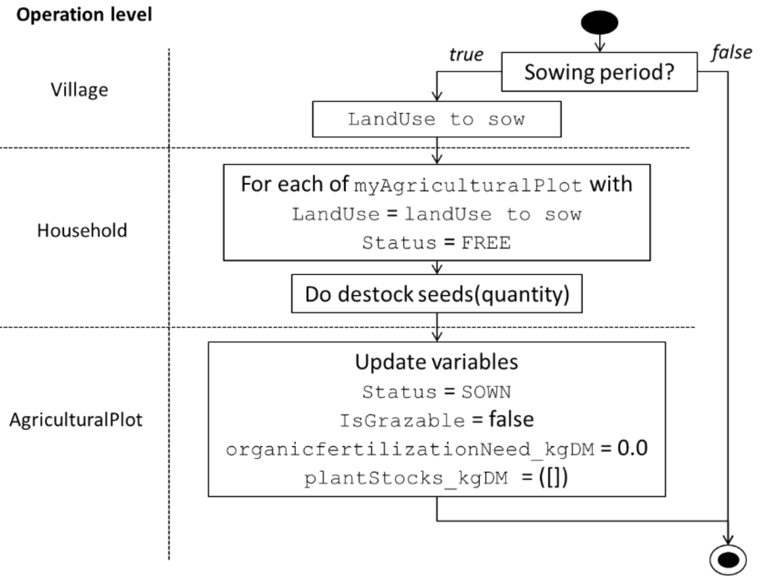


Figure 10. Activity diagram: sowing crops

### 5.1.3. Harvest

Harvest is undertaken every week during the village harvest period (`harvestPeriod`). It starts when at least one crop is of status `MATURE` and lasts until all agricultural plots are of status `FREE`. As described in Figure 11, during this period, crop products and co-products are harvested sequentially. First the main products of all agricultural plots are harvested. The harvested quantity is the total product of the plot stock. It is removed at once as the time scale for harvest is the week. Then, when there are no more products left in the household's fields, co-products are harvested, i.e. removed from the plot plant stock.

In the studied villages, coproducts are not systematically harvested. This choice depends on many factors such as the labor availability, distance to the plot, family constraints, fertilization applied, etc. On average, only half of the coproducts are harvested, the rest is left on the plot. Thus, in the model, depending on the owner type, there is a quantity of coproducts not harvested. Total yield produced is memorized by the plot and accessible for the household owner, if needed (e.g. in order to determine the less productive plot when deciding fertilization plan).

| | **Livestock-subsistence** | **Livestock-market** | **Crop-subsistence** | **Crop-market** |
|---|---|---|---|---|
| Quantity of residues left/total quantity (kgDM/kgDM) | 0.80 | 0.0 | 0.65 | 0.5 |

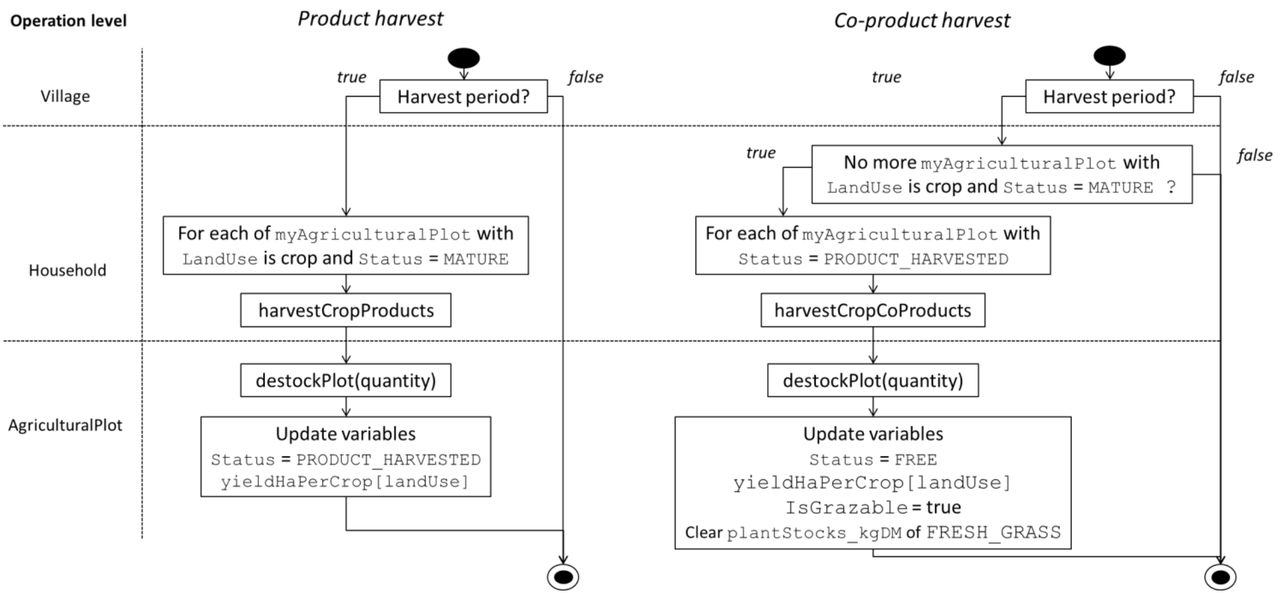


**Figure 11. Activity diagram: harvest crop products (left side) and crop co-products (right side)**

## 5.2. Home consumption parameters

Weekly operations aiming at feeding all the household members are defined in the model. As regards the two conceptual models (section 2.3), these operations are directly related to the HUMAN compartment and the households' home (HOUSING AREA).

### 5.2.1. Fuel

First of all, in order to cook, households need fuels. The required quantity is based on average firewood needs, function of the number of inhabitants within the households as described in Table 32. A conversion factor of wood into dung is used to obtain the dung needs. Fuels are collected on plots and either used directly (dung) or stored (wood). Wood and dung are only collected during specific periods, i.e. out of the rainy season (all places are accessible) and out of the harvest period (workload is too high). The target plot for wood gathering depends on the availability of dead wood on land plots; first households seek on their own plots then on any other plot. During wood gathering, households can also collect dung to fulfill their weekly needs. When wood gathering is not possible or when gathered dung does not fulfill the fuel needs, households must undertake other activities, as long as there is still a need. First if possible — i.e. in dung gathering period —, dung is gathered; then stored wood is used; then wood is purchased from another household; finally wood can possibly be bought on the market. During dry seasons, dung remains a few weeks on the surface of the plot and can possibly be gathered as fuel by any household; during the rainy season, dung decays too fast to be gathered because of humidity and high microbial activity.

$$FirewoodNeed\ (kgDM) = inhabitants\ x\ firewoodNeed\_pInhabitant \quad (7)$$

Where **inhabitants** is the number of inhabitants of the household (adult equivalents)

**firewoodNeed_pInhabitant** is the firewood need (kgDM/inhabitant/week)

Table 32. Home consumption parameters

| Type | Parameters | Description | Value | Unit | Source |
|---|---|---|---|---|---|
| float | `firewoodNeed` | Need for firewood | 0.1 | kgDM/ inhabitant/ day | Survey (Audouin, 2014; Dugy, 2015; Odru, 2013; Saunier-Zoltobroda, 2015) |
| float | `dungOverWood` | Conversion rate for firewood need into dung as a fuel | 0.33 | dimensionless | (Assouma, 2016; Lemmens et al., 2012) |

### 5.2.2. Food needs and household waste production

Households have several **food needs** that depend on the type of food and number of inhabitants (Table 33). In the model, home consumption is a source of kitchen wastes, depending on the number of inhabitants within the household. These **kitchen wastes** are gathered weekly with **yard wastes** (dust, leaves) (0.25 kgDM/inhabitant/day, based on surveys). It results in a conglomeration of waste: household waste (see Equation (8)) dumped on the closest agricultural plot they own.

Table 33. Food needs and kitchen waste production

| Food | Need (kgDM/inhabitant/day) | Source | Kitchen waste (kgDM/kgDM) | Source |
|---|---|---|---|---|
| Millet grain | 0.5 | (Andrieu et al., 2015); Survey; (Audouin, 2014; Dugy, 2015; Odru, 2013; Saunier-Zoltobroda, 2015) | 0.03 | (Audouin, 2014; Dugy, 2015; Odru, 2013; Saunier-Zoltobroda, 2015) |
| Groundnut grain | 0.05 | Survey; (Audouin, 2014; Dugy, 2015; Odru, 2013; Saunier-Zoltobroda, 2015) | 0.02 | (Audouin, 2014; Dugy, 2015; Odru, 2013; Saunier-Zoltobroda, 2015) |
| Rice | 0.17 (0.19 x 0.880 kgFW/kgDM ) | Survey; (Audouin, 2014; Dugy, 2015; Odru, 2013; Saunier-Zoltobroda, 2015) (Josserand and da Silva, 2002) | 0.03 | (Audouin, 2014; Dugy, 2015; Odru, 2013; Saunier-Zoltobroda, 2015) |
| Fish | 0.04 (0.200kgFW x 0.20 kgFW/kgDM) | Survey; (Audouin, 2014; Dugy, 2015; Odru, 2013; Saunier-Zoltobroda, 2015) | 0.1 | (Audouin, 2014; Dugy, 2015; Odru, 2013; Saunier-Zoltobroda, 2015) |

$$Household\ waste\ (kgDM/day) = kitchen\ wastes + yard\ wastes \quad (8)$$

Where **kitchen waste** are the waste produced by the inhabitants while eating, function of the food ingested (see Table 33) (kgDM/day)

**yard waste** is the daily waste production produced while living within the household (dust, tree leaves, etc.) (kgDM/day)

## 5.3. Surplus estimations

Stock surplus, especially for food, feed and wood, is the difference between the estimated annual need for the given biomass and the actual stock level (at the end of the cropping season).

Annual need is based on the daily need of the household (see 5.2 for home consumption and 5.4.2 for livestock feed need) multiplied by the number of days per year (i.e. 360). Thus it is assumed that the daily need is constant over the year.

## 5.4. Livestock management

### 5.4.1. Livestock trade

Only herds on fattening management are traded. Other herds remain with the household for the whole simulation. Fattening herds have a fixed fattening cycle, i.e. the duration the herd will stay within the house before being sold on the market (`fatteningDuration_day`). Each sold herd is replaced by a new one, purchased on the market. New herds always have the same management and are of the same species than the sold herd. The new herd size in TLU is determined according to the same range as that used for herd initialization.

### 5.4.2. Livestock feeding

In the model, the households decide the targeted quantity they want their animals to ingest daily (herd needs). As described in Figure 12, there are different targeted levels in terms of forage quantity. First quantity level (Q1) is dedicated to outdoor forage (Graminae) and forages with low digestibility such as straw. It is considered as the only need for free-grazing livestock herds and a constant value for all managements. Quantity levels 2 (Q2a and Q2b) are used for gathered or stored forage with greater digestibility such as cut grass (weeds) and hay. These values are specific to fattening herds and draft animals. For the fattening management, it depends on the fattening cycle. For fattening herds, households aim to give more forage with high digestibility to its cattle a few weeks before selling it. Draft animals require more forage during cropping activities (manure spreading, sowing, crop harvesting). Table 34 and Table 35 show the forage quantities targeted for livestock herds, for each parameter from the Figure 12 (Q1, Q2, Q3 and Nw).

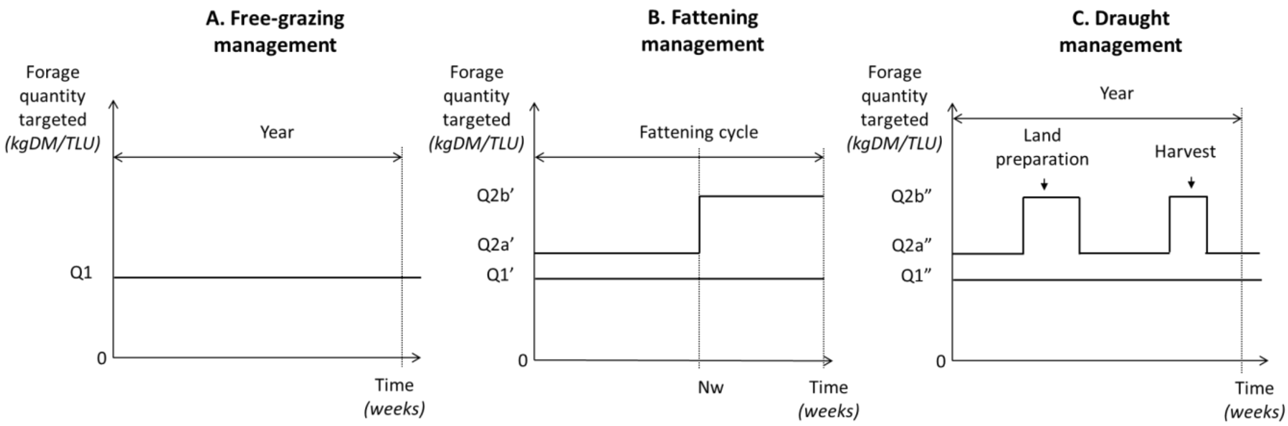


**Figure 12. Forage targeted quantities according to livestock herd management**
A. Free-grazing herd; B. Fattening herd; C. Draft animals
Q1= in-field grass or straw; Q2 and Q3 = hay or cut grass; Nw = number of weeks after the beginning of the fattening cycle before switching to increased feed quantities

Livestock herd feed needs can be fulfilled in four ways. The management type determines the preference for the forage origin. First of all, if the livestock is on free-grazing management, it grazes on an agricultural plot (see below). Then households can provide their herds with forage by destocking it from their own stock, buying it from another household or picking it up on agricultural plots. When forage is available in stocks, it will be used first. Then, depending on the herd management and period, it will be either gathered or bought. Gathered forages are cut fresh grass (weeds) and leaves from pruning trees.

Fresh grass is much used in West African crop-livestock systems as it is a good energy provider for fattening livestock (Powell et al., 2004). Thus in the model, only fattening herds and draft animals receive fresh grass. It is cut during the rainy season on agricultural plots. First, the priority is given to plots that belong to the herd owner and are closer from its home. Second, if no fresh grass is available in the households' plots, they collect it on the plots holding the highest quantity of it, even if they don't own it.

Leaves are directly pruned from trees and left in the agricultural plots for the livestock to graze. Leaves are dedicated to free-grazing livestock herds. The maximum quantity of leaves that can be pruned per year and per tree is fixed (`maxLeavesPrunedQuantity_kgDM_ptree`), as well as the ratio of pruned wood over pruned leaves quantity (`ratioWoodPruned_overLeaves_kgDM_ptree`). Households start pruning while crop residues become scarce due to herd consumption and trampling. It is done until there is no more tree vegetation or until agricultural plots are sown (thus becoming unavailable for livestock). Households first look for their own trees and those closer to their home, then, if they cannot prune them, they search for any tree with vegetation (without considering the plot ownership). Households will always target a tree that was already pruned the current year; if not possible, they target trees pruned the least recently (in terms of years), allowing other trees to rest as much as possible.

**Table 34. Daily forage quantities targeted for Bovine and Small Ruminants**

| | Parameter | Unit | Bovine | | Small ruminant | |
|---|---|---|---|---|---|---|
| | | | Value | Source | Value | Source |
| Free-grazing | Q1 | kgDM/TLU/day | 3.0 | (unpublished results, Assouma et al., submitted to Animal) | 2.0 | (unpublished results, Assouma et al., submitted to Animal) |
| Fattening | Q1 | kgDM/TLU/day | 3.0 | | 2.0 | |
| | Q2a | kgDM/TLU/day | 2.0 | | 1.0 | |
| | Q2b | kgDM/TLU/day | 3.0 | | 2.0 | |
| | Nw* | Weeks | 12 | | | |

* number of weeks after the beginning of the fattening cycle before switching to increased feed quantities

**Table 35. Daily forage quantities targeted for Equine**

| | Parameter | Unit | Equine | |
|---|---|---|---|---|
| | | | Value | Source |
| Draft animals | Q1 | kgDM/TLU/day | 3.0 | (unpublished results, Assouma et al., submitted to Animal) |
| | Q2a | kgDM/TLU/day | 3.0 | |
| | Q2b | kgDM/TLU/day | 2.0 | |

Fattening herds and draft animals also need concentrate feeds. As described in Figure 13, needs are updated in a similar way as for forage. Herd needs vary upon the fattening cycle for fattening management, and upon the cropping activities for draft animals. Concentrate feeds are purchased on the market and directly fed to herds. All types of biomasses and quantities ingested by the herd are recorded in a variable updated daily used to determine the daily quantity of excreta produced by the herd (see below).

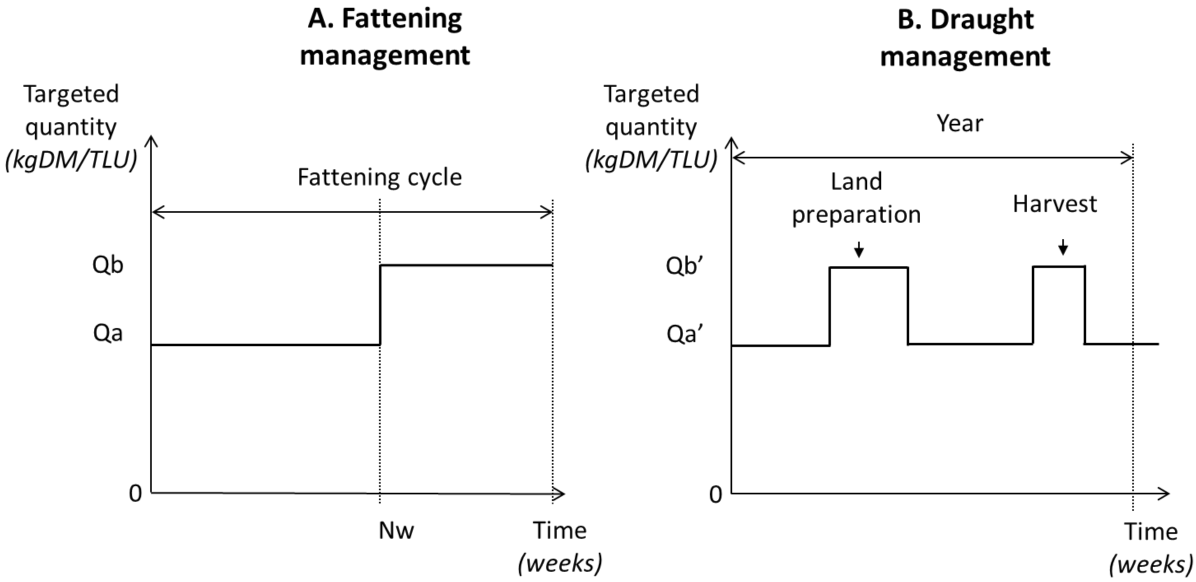


**Figure 13. Concentrate feeds need for fattening herds and draft animals**
A. Fattening herd; B. Draft animals; Nw: number of weeks after the beginning of the fattening cycle before switching to increased feed quantities

## 6. Livestock system

### 6.1. Free-grazing

Free-grazing herds also have the ability to choose their corral: they always target one agricultural plot which requires fertilization. Theoretically, a livestock herd's corral can change weekly but this depends, in fact, on specific rules. As shown in Figure 14, main determinants are related to:

- 1) plot availability (`isGrazable`),
- 2) the plot need for fertilization (`organicfertilizationNeed_kgDM` > 0),
- 3) the land unit,
- 4) the land use,
- 5) the plot fertilization intensity (`fertilizationStatus`) and level of productivity (`yieldHaPerCrop`).

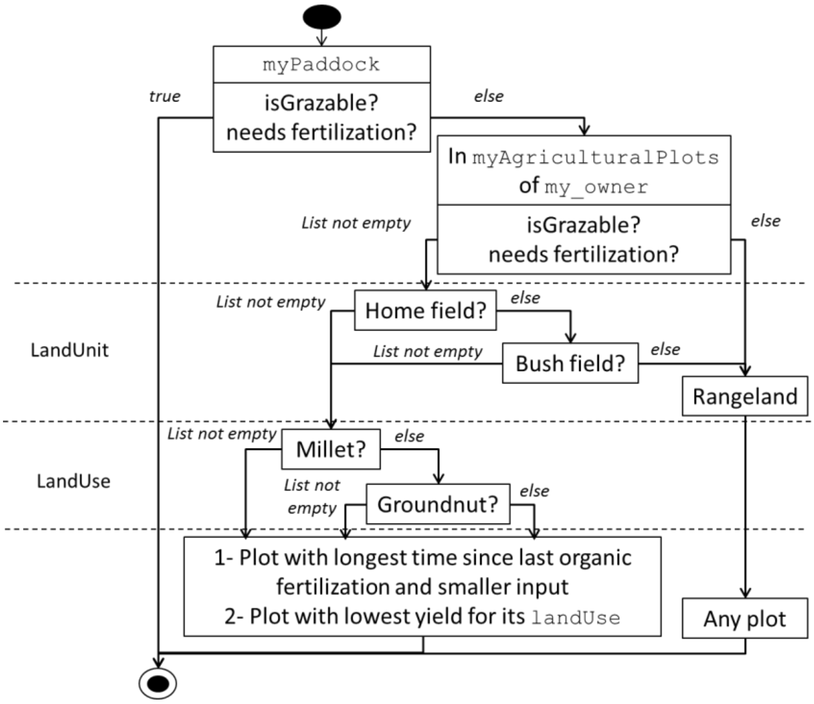


Figure 14. Livestock decision tree for corral choice (process updateCorral)

Free-grazing livestock herds fulfill their needs by grazing on agricultural plots; they (more precisely their herder component) sequentially choose agricultural plots where they will graze on the remaining biomass. The plot choice is determined first by its availability (e.g. not cultivated), then by the type and the quantity of biomass it holds. For instance, crop residues remaining in the field are preferred to grass. If possible, herds graze as a priority on the agricultural plots belonging to their owners. After grazing on a plot, herds move to another plot if they still have feeding needs. If required, households can destock straw or start pruning trees to feed them.

Table 36 shows the biomass preferences for grazing livestock (`biomass preferences`)

Table 36. Grazing livestock biomass preferences

| Priority ranking | Biomass |
|---|---|
| 1st | Grass (rainy season) |
| 2st | Straw, hay |
| 3nd | Grass, leaves |
| 4th | Fresh grass |

## 6.2. Excreta

Every day, the livestock herds excrete dung and urine. As described in Table 37, excreted quantities of dung (in kgN) depend on the quantity of nitrogen ingested the previous day (see Equation (9)); the quantity of nitrogen excreted by urine depends on the dung excretion. Excreta deposits are proportional to the time spent on the plot. For instance, free-grazing herds spend a given time on their corral at night (by default, 10hours, then the herd will deposit 10/24 of its daily excreta on the corral). As for daytime (12/24 of their daily time and excretion), it is assumed that herds excrete proportionally to the quantity they ingest on a plot. For instance if a herd grazes only on one plot, it will excrete only on this plot but, in a case where the herd grazes on more than one plot in a day, the daily excretion is deposited accordingly to the quantity ingested on each plot over the total daily ingestion.

$$previousDayIngestedQuantity = \Sigma\ ingested\ quantity_i\ x\ nitrogen\ quantity_i \quad (9)$$

Where **ingested quantity$_i$** is the ingested quantity for a given type of biomass during the previous day (in kgDM)

**nitrogen quantity$_i$** is the nitrogen content in kg per kgDM of the ingested biomass

Table 37. Livestock excretion rates

| Livestock system | Rate of dung excreted w.r.t. ingested biomass (kgN excreted/kgN ingested) | Rate of urine excreted w.r.t. dung excreted (kgN excreted in urine/kgN excreted in dung) | Total rate of N excreted w.r.t. ingested (kgN/kgN) | Source |
|---|---|---|---|---|
| Grazing animal | 0.59 | 0.53 | 0.90 | (Grange, 2015; Wade, 2016) |
| Fattening animal | 0.33 | 1.24 | 0.74 | |
| Draft animals | 0.33 | 1.24 | 0.74 | |

w.r.t. = with respect to

## 7. References


Achard, F., Banoin, M., 2003. Fallows, forage production and nutrient transfers by livestock in Niger. Nutr. Cycl. Agroecosystems 65, 183–189.

Affholder, F., 1997. Empirically modelling the interaction between intensification and climatic risk in semiarid regions. Field Crops Res. 79–93.

Affholder, F., Poeydebat, C., Corbeels, M., Scopel, E., Tittonell, P., 2013. The yield gap of major food crops in family agriculture in the tropics: Assessment and analysis through field surveys and modelling. Field Crops Res. 143, 106–118. doi:10.1016/j.fcr.2012.10.021

Affholder, F., Tittonell, P., Corbeels, M., Roux, S., Motisi, N., Tixier, P., Wery, J., 2012. Ad Hoc Modeling in Agronomy: What Have We Learned in the Last 15 Years? Agron. J. 104, 735. doi:10.2134/agronj2011.0376

Akponikpè, P.B.I., Minet, J., Gérard, B., Defourny, P., Bielders, C.L., 2011. Spatial fields' dispersion as a farmer strategy to reduce agro-climatic risk at the household level in pearl millet-based systems in the Sahel: A modeling perspective. Agric. For. Meteorol. 151, 215–227. doi:10.1016/j.agrformet.2010.10.007

Andrieu, N., Vayssières, J., Corbeels, M., Blanchard, M., Vall, E., Tittonell, P., 2015. From farm scale synergies to village scale trade-offs: Cereal crop residues use in an agro-pastoral system of the Sudanian zone of Burkina Faso. Agric. Syst. 134, 84–96. doi:10.1016/j.agsy.2014.08.012

Assouma, M.H., 2016. Approche écosystémique du bilan des gaz à effet de serre d'un territoire sylvo-pastoral sahélien : contribution de l'élevage (Doctorat). AgroParisTech, Montpellier, France.

Audouin, E., 2014. Terroirs comparison in terms of biomass flows and nitrogen balances : study case of Diohine and Barry Sine in the former groundnut bassin (Mémoire de master 2). Isara Lyon, Ecole d'ingénieurs de purpan, Norwegian University of Life Sciences.

Audouin, E., Vayssières, J., Odru, M., Masse, D., Dorégo, G.S., Delaunay, V., Lecomte, P., 2015. Réintroduire l'élevage pour accroître la durabilité des terroirs villageois d'Afrique de l'Ouest: le cas du bassin arachidier au Sénégal, in: Sultan, B., Lalou, R., Oumarou, A., Sanni, M.A., Soumaré, A. (Eds.), Les Sociétés Rurales Face Aux Changements Environnementaux En Afrique de l'Ouest. Marseille, pp. 403–427.

CTFT, 1988. Faidherbia albida (Del.) A. Chev. Monographie., Centre Technique Forestier Tropical. ed. Nogent-sur-Marne, Cedex, France.

Cushing, J.M., Yicang, Z., 1994. The net reproductive value and stability in matrix population models. Nat. Resour. Model. 8, 297–333.

Defoer, T., De Groote, H., Hilhorst, T., Kante, S., Budelman, A., 1998. Participatory action research and quantitative analysis for nutrient management in southern Mali: A fruitful marriage? Agric. Ecosyst. Environ. 71, 215–228.

Delon, C., Galy-Lacaux, C., Boone, A., Liousse, C., Serça, D., Adon, M., Diop, B., Akpo, A., Lavenu, F., Mougin, E., others, 2010. Atmospheric nitrogen budget in Sahelian dry savannas. Atmospheric Chem. Phys. 10, 2691–2708.

Depommier, D., Guérin, H., 1996. Emondage traditionnel de Faidherbia albida. Production fourragère, valeur nutritive et récolte de bois à Dossi et Watinoma (Burkina Faso). Cah. Sci. Cirad-For., Les parcs à Faidherbia (Acacia albida Parklands) 55–84.

Dugué, P., 1998. Gestion de la fertilité et stratégies paysannes : le cas des zones de savanes d'Afrique de l'Ouest et du Centre. Agric. Dév. 18, 13–20.

Dugy, T., 2015. Diagnostic des flux de biomasse à l'échelle de terroirs agro-sylvopastoraux et représentation de leur état & fonctionnement : Etude comparative des terroirs de Sob, Diohine et Barry Sine dans l'Ancien Bassin Arachidier au Sénégal (Mémoire d'ingénieur (master 2)). ISTOM, Cergy Pontoise.

Freschet, G., Masse, D., Hien, E., Sall, S., Chotte, J., 2008. Long-term changes in organic matter and microbial properties resulting from manuring practices in an arid cultivated soil in Burkina Faso. Agric. Ecosyst. Environ. 123, 175–184. doi:10.1016/j.agee.2007.05.012

Garcia, L., 2015. Impact du changment climatique sur les rendements du mil et de l'arachide au Sénégal : Approche par expérimentation virtuelle (Mémoire d'ingénieur (master 2)). Montpellier SupAgro, Montpellier.

Gaudou, B., Sibertin-Blanc, C., Therond, O., Amblard, F., Auda, Y., Arcangeli, J.-P., Balestrat, M., Charron-Moirez, M.-H., Gondet, E., Hong, Y., others, 2014. The MAELIA multi-agent platform for integrated

assessment of low-water management issues, in: International Workshop on Multi-Agent-Based Simulation-MABS 2013. p. pp–85.
Grange, G., 2015. Suivi du cycle de l'azote en fermes réelles : Cas des systèmes agropastoraux du bassin arachidier du Sénégal (Ingénieur agronome). Montpellier SupAgro, Montpellier.
Grignard, A., Taillandier, P., Gaudou, B., Vo, D.A., Huynh, N.Q., 2013. GAMA 1.6 : Advancing the Art of Complex Agent-Based Modeling and Simulation, in: Boella, G., Elkind, E., Savarimuthu, B.T.R., Dignum, F., Purvis, M.K. (Eds.), PRIMA 2013: Principles and Practice of Multi-Agent Systems. Presented at the 16th International Conference, Dunedin, New Zealand.
Hiernaux, P., Fernandez-Rivera, S., Schlecht, E., Turner, M.D., Williams, T.O., 1997. Livestock-mediated nutrient transfers in Sahelian agro-ecosystems, in: Soil Fertility Management in West Africa Land Use Systems. Niamey, Niger, pp. 339–347.
Huss, H.H., 1999. Composition chimique, in: La Qualité et Son Évolution Dans Le Poisson Frais, Document Technique Sur Les Pêches. FAO, Département des pêches, Rome.
Josserand, H., da Silva, A., 2002. Rapport spécial - Mission FAO/PAM D'ÉVALUATION DES RÉCOLTES ET DES APPROVISIONNEMENTS ALIMENTAIRES AU SÉNÉGAL.
Jung, G., 1969. Cycles biogéochimiques dans un écosystème de région tropicale sèche Acacia albida (Del.) sol ferrugineux tropical peu lessivé (dior) (Note préliminaire).
Le Thiec, G., 1996. Agriculture africaine et traction animale. Cirad, Montpellier, France.
Lemmens, R., Louppe, D., Oteng-Amoako, A., 2012. Prota : Ressources végétales de l'Afrique tropicale - Bois d'oeuvre 2, CTA Prota. ed. Wageningen.
Manlay, R.J., Ickowicz, A., Masse, D., Floret, C., Richard, D., Feller, C., 2004. Spatial carbon, nitrogen and phosphorus budget of a village in the West African savanna — I. Element pools and structure of a mixed-farming system. Agric. Syst. 79, 55–81. doi:10.1016/S0308-521X(03)00053-2
Murray, J., Burt, J.R., 2001. The composition of fish, Torry advisory note. FAO, Ministry of technology.
Odru, M., 2013. Flux de biomasse et renouvellement de la fertilité des sols à l'échelle du terroir (Diohine) (Mémoire d'ingénieur (master 2)). ISTOM, Cergy Pontoise.
Perret, C., 2008. Le climat et les changements climatiques (Atlas de l'intégration régionale en Afrique de l'Ouest), Série Environnement. CEDEAO-CSAO/OCDE.
Pieri, C., 1989. Fertilité des terres de savanes : bilan de trente ans de recherche et de développement agricole au sud du Sahara. CIRAD-IRAT, Montpellier, France.
Powell, J.M., Pearson, R.A., Hiernaux, P.H., 2004. Crop–Livestock Interactions in the West African Drylands. Agron. J. 96, 469. doi:10.2134/agronj2004.0469
Ramisch, J.J., 2005. Inequality, agro-pastoral exchanges, and soil fertility gradients in southern Mali. Agric. Ecosyst. Environ. 105, 353–372. doi:10.1016/j.agee.2004.02.001
Rufino, M.C., Hengsdijk, H., Verhagen, A., 2009. Analysing integration and diversity in agro-ecosystems by using indicators of network analysis. Nutr. Cycl. Agroecosystems 84, 229–247. doi:10.1007/s10705-008-9239-2
Saunier-Zoltobroda, T., 2015. Flux de biomasse à l'échelle du paysage et hétérogénéité spatiale des bilans d'azote : Cas de trois terroirs du bassin Arachidier au Sénégal (Mémoire d'ingénieur (master 2)). ISTOM, Cergy Pontoise.
Schilling, R., Gibbons, R., 2002. Groundnut, Macmillan Education Ltd. ed, The tropical agriculturist. CTA.
Taillandier, P., Grignard, A., Gaudou, B., Drogoul, A., 2014. Des données géographiques à la simulation à base d'agents : application de la plate-forme GAMA. Cybergeo. doi:10.4000/cybergeo.26263
Therond, O., Sibertin-Blanc, C., Lardy, R., Gaudou, B., Balestat, M., Hong, Y., Louail, T., Nguyen, V.B., Panzoli, D., Sanchez-Perez, J.-M., Sauvage, S., Taillandier, P., Vavaseur, M., Mazzega, P., 2014. Integrated modelling of social-ecological systems: The MAELIA high-resolution multi-agent platform to deal with water scarcity problems, in: Ames, D.P., Quinn, N.W., Rizzoli, A.E. (Eds.), iEMSs 7th: International Congress on Environmental Modelling and Software. San Diego, California, USA.
Vall, E., Koutou, M., Blanchard, M., Coulibaly, K., Diallo, M.A., Andrieu, N., 2011. Intégration agriculture-élevage et intensification écologique dans les systèmes agrosylvopastoraux de l'Ouest du Burkina Faso, province du Tuy, in: Partenariat, Modélisation, Expérimentations: Quelles Leçons Pour La Conception de L'innovation et L'intensification Écologique? Cirad, Bobo-Dioulasso, p. 13–p.
Wade, C., 2016. Analyse des flux d'azote en milieu paysan : Cas des systèmes agropastoraux du bassin arachidier du Sénégal (Mémoire d'ingénieur (master 2)). Ecole Nationale Supérieure d'Agriculture de Thies, Thies, Sénégal.