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## **Are subsidies to weather-index insurance the best use of public funds?**

### **A bio-economic farm model applied to the Senegalese groundnut basin**

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# **Are subsidies to weather-index insurance the best use of public funds?**

## **A bio-economic farm model applied to the Senegalese groundnut basin**

### **Keywords**

index insurance; drought insurance; Senegal; crop intensification

### **Highlights**

- We developed a coupled crop-farm simulation model for semi-arid West Africa.
- We assessed the soundness at farm scale of policies supporting cereal intensification.
- Weather-index insurance reduces risks and increases expected income only for certain farms.
- Subsidies to credit or unconditional cash-transfers increase expected income and production more than subsidies to insurance.
- Unsubsidized insurance combined with subsidized credit best favor cereal intensification.

### **Abstract**

While crop yields in Sub-Saharan Africa are low compared to most other parts of the world, weather-index insurance is often presented as a promising tool, which could help resource-poor farmers in developing countries to invest and adopt yield-enhancing technologies. Here, we test this hypothesis on two contrasting areas (in terms of rainfall scarcity) of the Senegalese groundnut basin through the use of a bio-economic farm model, coupling the crop growth model CELSIUS with the economic model ANDERS, both specifically designed for this purpose. We introduce a weather-index insurance whose index is currently being used for pilot projects in Senegal and West Africa. Results show that insurance leads to a welfare gain only for those farmers located in the driest area. These farmers respond to insurance mostly by increasing the amount of cow fattening, which leads to higher crop yields thanks to the larger production of manure. We also find that subsidizing insurance is not the best possible use of public funds: for a given level of public funding, reducing credit rates, subsidizing fertilizers, or just transferring cash as a lump-sum generally brings a higher expected utility to farmers and leads to a higher increase in grain production levels.

## 1 Introduction

In west African countries, agricultural production per capita has decreased over the past half century due to a slow increase in agricultural production compared to the rate of population growth (Pretty *et al.*, 2011). With continued population growth and the diminishing availability of marginal arable land, there is now a common view that crop yield must increase in this region, especially as there is a wide gap between actual and potential yields (World Bank, 2008; HLPE, 2013; Teklewold *et al.*, 2013; The Montpellier Panel, 2013). At field scale, low nutrient availability in soils and high weed pressure predominantly explain this yield gap (Affholder *et al.*, 2013). At farm level, the fact that households are strongly resource-constrained and exposed to risk is widely recognized as a key explanation (Rosenzweig, 1993; Carter and Barrett, 2006). Indeed, risk discourages the adoption of high-risk, high-return agricultural technologies, especially when farmers are poor, which in turn impedes the improvement of yields (Affholder, 1997).

This is the reason why, for over a decade, weather-index insurance (WII) have been seen as a promising tool to mitigate agro-climatic risks at farm level and thus in the improvement of yields (Hazell and Hess, 2010). Here we define WII as insurance whose indemnities are triggered by the value of a weather index chosen for its high correlation with yields or economic losses. As WII do not require loss assessment as in conventional insurance, transaction costs are lower. Additionally, the use of an objective indicator prevents information asymmetries among contractors, while with conventional insurance based on yield loss, the insurer cannot always determine to what extent the loss is due to a bad weather or to farmer's lack of work.

Despite the allocation of many resources by international development organizations, results from pilot WII programs showed up to a recent period very limited success. Binswanger-Mkhize (2012) explained it by the lack of demand. While better-off farmers prefer to use cheaper self-insurance strategies rather than WII, poor farmers would be interested but could not afford it because of lack of liquidity.

Ex-post analysis confirmed this argument by highlighting several factors explaining the low take-up of WII: steep negative price elasticity (Karlan *et al.*, 2014; Cole *et al.*, 2013; Mobarak and Rosenzweig, 2013), liquidity constraints (Cole *et al.*, 2013), lack of trust and misunderstanding of the products (Hill *et al.*, 2013), lack of relevant social networks (Giné *et al.*, 2013) and existence of informal insurance which acts as a substitute (Mobarak and Rosenzweig, 2013). Another key limitation of WII is the basis risk i.e. the imperfect correlation between the index and losses at farm level (Tadesse *et al.*, 2015).

Ex-ante assessments do not provide more optimistic conclusions. McIntosh et al. (2013) compared an ex-ante WTP for WII with ex-post demand based on an actual WII in Ethiopia. They found that the lack of cash (and access to credit) to pay for the WII product reduced the interest of farmers and that subsidizing premium improved the take-up of insurance but not as much as expected.

Other ex-ante assessments are based on agro-economic simulation models. Berg et al. (2009) and Leblois et al. (2014) found that the benefits of insurance were very limited for, respectively, maize growers in Burkina Faso and cotton growers in Cameroon. These results were explained by the large basis risk and, in the case of cotton, the higher exposure of farmers to price risk than to climatic risk.

Aware of these drawbacks, new programs were developed and seem scaling up and providing demonstrable benefits for a larger number of farmers, even if in a lower extent to poorest ones (Greatrex et al., 2015; Bertram-Huemmer & Kraehnert, 2015). The experiences in India, Kenya, Ethiopia and Mongolia innovated by linking insurance to credit or improved inputs, involved the farmers into the product design and were encompassed into a strong institutional setting favoring trust between farmers and insurers as well as improving the understanding of the products. It appears from those programs that when the WII is included in a larger basket of risk management options, the benefits of the programs are larger.

Although these studies and experiences are helpful to know the factors influencing the adoption of WII by farmers, knowledge of the impacts of WII on farmers' production decisions is still very limited: while De Nicola (2015), Elabed and Carter (2014), Karlan et al. (2014) and Mobarak and Rosenzweig (2013) provide evidence that WII can boost adoption of new technologies, Giné and Yang (2009) come to the opposite conclusion. Carter et al. (2016) have shown in a theoretical model that whether WII may or not boost the adoption of improved agricultural technologies depends in particular on the agro-ecological and economic environments, which calls for more applied work on this issue.

The objective of this paper is thus to evaluate the potential benefit from WII in terms of farmers' income and its impact on adoption of more intensive cropping and livestock systems. We write "potential" because our model represents simulated farmers who would be perfectly aware of the way WII works. We also assess whether insurance subsidies are the best use of public funds by comparing this policy option with others such as credit subsidies, fertilizer subsidies or lump-sum cash transfers, considered separately or in conjunction with WII. We develop a coupled whole-farm bio-economic model (Janssen and van Ittersum, 2007; Le Gal et al, 2011), reproducing the complexity

of farmers' decisions in a risky environment, applied to typical farms in the Senegalese groundnut basin. The model explicitly represents the cropping and livestock systems, with a biophysical component simulating the impact on crop yields of changes in crop management techniques and of inter-annual variations of climate, as well as the various nutritional, financial and labor management constraints of the household. The coupled model simulates farm households' decisions in response to a series of historical weather data, which are assumed to represent the perception of the inter-annual variability of weather. Furthermore, we characterize the diversity of the farming systems in the study areas in order to account for possible differences between farm-types regarding the relevance and impacts of WII.

## 2 Material and methods

The analysis took place in the "groundnut basin" of Senegal. It is a region typical in many aspects of the Sudano-Sahelian region of Africa, with high levels of poverty, where family farming based on rainfed crops is overwhelmingly predominant, with a semi-arid climate, and with a steep South-North gradient of risks of drought limiting crop production (Boulier and Jouve, 1990). A consistent background was available about the farming systems of that region and their dependencies to both the biophysical and the socio economic environment of farms, thanks to many studies at field, farm and village scales that were carried out at regular time intervals in the past (Lericollais, 1972; Benoit-Cattin, 1986; Lhoste, 1986; Pieri, 1989; Boulier and Jouve, 1990; Garin *et al.*, 1990; Badiane *et al.*, 2000a; ISRA, 2008). However, a new survey was carried out within the framework of the present study at field and farm levels in order to get adequately updated data for the specific purpose of developing and calibrating our whole-farm model.

### 2.1 General presentation of the study area

We considered two subzones in the study area, the districts of Niakhar (14°28'N, 16°24'W, 25 km South of Bambey on Figure 1) and Nioro du Rip (13°44'N, 15°46'W), respectively in the center north (locally known as the *Sine* region) and in the south of the groundnut basin (*Saloum*), corresponding to contrasting drought risk, expected to lead to contrasting constraints on crop intensification (Affholder, 1997). The average annual cumulative rainfall recorded during the period considered in this study (1991-2010) is 520 mm and 775 mm in *Sine* and *Saloum* respectively.

Throughout the basin the cropping systems are mainly cereal-leguminous rotations. In the *Sine* subzone the cereal used in the rotation is almost exclusively millet (the staple food) and the use of mineral fertilizers is extremely rare. Horses and donkeys provide traction power for carts as well as for sowing and weeding machines. In *Saloum* maize, grown as a cash crop or staple food, is common

although millet remains the main cereal. Manure is more widely employed than in *Sine*. Traction power is provided by horses (carts) and oxen (cultivation tools). In both zones farmers also carry out very extensive cattle production and slightly more intensive breeding of a few small ruminants (sheep and goats), and in many cases a short-term fattening activity involving a few cattle or small ruminants. All this livestock activities provide manure that is used in several ways for organic fertilization of fields. Very few mineral fertilizers or pesticides are used. No improved seeds are available for millet. Groundnut seeds are all improved seeds produced and distributed under the control of public services. An important feature of the farming system is the ring cultivation system which involves dividing the landscape into two concentric circular areas around the household's compounds. The area closer to the compounds, the "home-fields", is under continuous cereal cropping and receives all of the household's organic waste, as opposed to the bush-fields, which are far from the compounds and where cereals alternate with groundnut. Crop yields obtained on home-fields are thus generally higher thanks to the higher levels of soil organic matter (Prudencio, 1993).

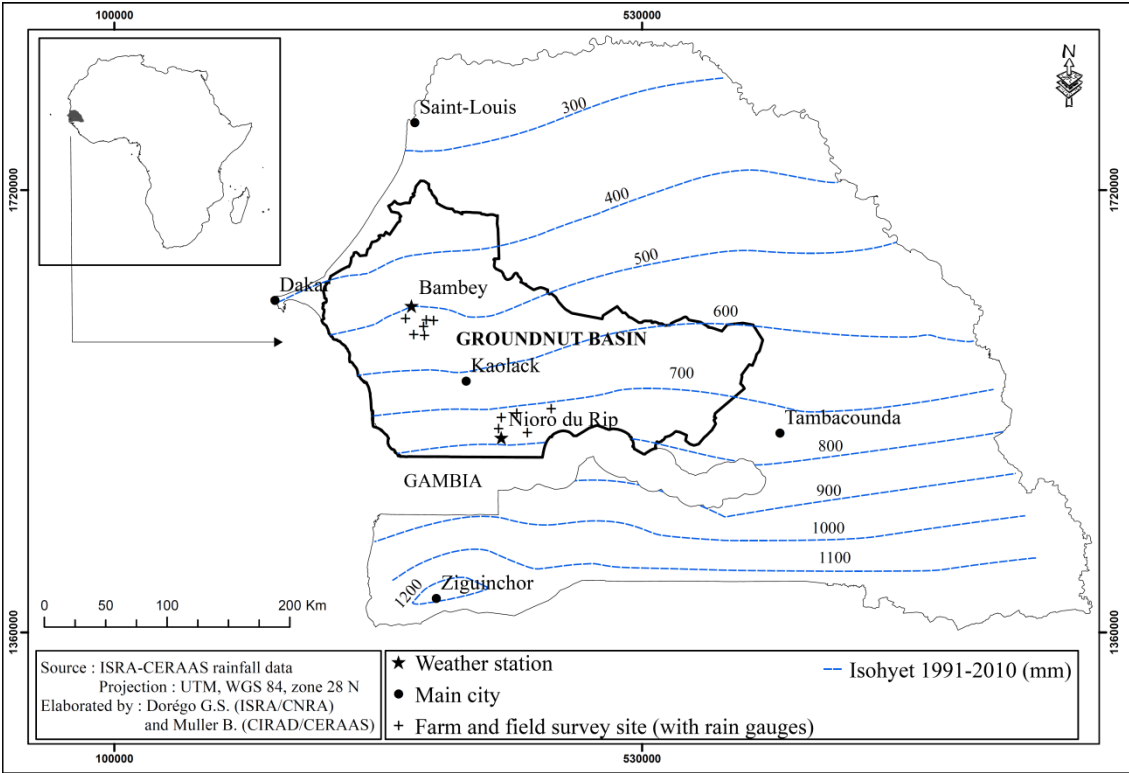


Figure 1: Study area and rainfall levels in Senegal over the period 1991-2010

## 2.2 Data

The dataset comprises socio demographic and economic data from a farm household survey conducted in 2012. Local experts identified five representative villages for each study subzone, in which 18 households were randomly selected. 180 households were surveyed overall. The structured questionnaire included questions on household structure (composition, ages, gender, etc.), detailed land, capital (seeder, plow, etc.), and livestock (cattle, horses, sheep, etc.) holdings, socio-demographic characteristics of the family, numbers of migrants, financial and credit constraints, crop and livestock systems management and performance (labor requirements, input prices, etc.).

Data on local monthly output prices over 1996-2011 were obtained from the Senegalese Economics and Statistics Administration (DAPS).

Biophysical and technical data describing the field management practices were collected in 2013 from 206 fields (134 in Sine and 72 in Saloum) belonging to 40 households selected from the previous sample (20 households per subzone) using a proportionate random sampling based on farm typologies built up from the farm household survey and presented below. The structured plot level questionnaire aimed to gather data on soil characteristics, details of crop management (cultivar chosen, sowing date, plant density, amounts of inorganic and organic fertilizers used, weeding sequence, etc.), and decision rules related to the sowing date.

The data used for calibration of the biophysical component of the model were extracted from the ESPACE-PRODCLIM (Forest and Cortier, 1989; Baron, 1991) and AMMA databases (Kouakou, 2013), built from surveys among farmers' fields and trials in the study area carried out in 1990-1992 and 2006-2008, respectively. Overall, the merged database consisted of 959 plot-year observations of c. 25 m<sup>2</sup> delineated within fields, allowing comparisons between observed and simulated values of grain and biomass yields under a large range soils, rainfall intra-annual distributions, and management techniques. Organic N in soils was taken as constant for each soil type in each cultivation ring, using estimates from Badiane et al. (2000b). N contents in manure from the various sources used in the region were taken from Fall et al. (2000). Historical series of climate data for yield simulations were those available from the two main stations of this network, namely the weather stations of Bambey (14°41'N, 16°24'W) and Nioro du Rip (13°44'N, 15°46'W), respectively assumed to represent the current climate of the Sine and Saloum subzones. Both climatic datasets cover 1950-2010 and include daily values of rainfall, temperatures, relative humidity, wind speed and sunshine duration (used to estimate solar radiation).



### **2.3 Farm-types**

Farm diversity had to be characterized since insurance may be appropriate for some farmers but inadequate for others due to variations among farms in the nature and importance of the risks faced. For each subzone we built a farm typology reflecting the resource access and the needs of the family, following the livelihoods approach (Bebbington, 1999). Individual farms were grouped into farm-types by using an Agglomerative Hierarchical Clustering (AHC) method consisting of progressively grouping farm households according to their degree of resemblance. In accordance with common practice (e.g. Blazy *et al.*, 2009) we used Euclidean distance as the measure of distance between pairs of observations, and the Ward Criterion as the linkage algorithm. It appeared that the 6 variables capturing the best the farm heterogeneity were related to farm resources and needs: total farm land area, number of persons making up the household, area per worker, herd size, number of draught animals and number of migrants (see Appendix A for details on the method and characteristic of farm-types).

1 Table 1 Characteristics of the farm-types<sup>1</sup>

Variable category	Variable	Definition	Type 1		Type 2		Type 3	
			Sine1	Saloum1	Sine2	Saloum2	Sine3	Saloum3
	Region	Share of the farm-type on the subzone	62%	83%	13%	13%	25%	4%
<u>Household structure and migration:</u>	Pers	Total number of persons in the households	11.7***	15.1***	17***	19.91***	20.3***	25.3***
	Labor	Number of workers	4.5***	5***	7***	8***	9***	10***
	OffFarm	Number of persons working off farm	0.29***	0.56	0.9***	0.75	1.32***	0.66
	Migr	Number of migrants	1.4**	1.27	2**	1.66	0.73**	1
<u>Land endowment:</u>	Area	Total farm land area (ha)	3.5***	6.5***	10.5***	15.2***	7.75***	11.1***
	HomeField	% homefield	0.27	0.06	0.3	0.03	0.18**	0.16
	BushField	% bushfield	0.73	0.94	0.7	0.97	0.82**	0.84
<u>Capital endowment :</u>	RatioWeedSurf	Number of weeding tools per ha	1.65***	0.79	0.66***	0.61	1.38***	0.85
	RatioHoeSurf	Number of seeders, hoe per ha	0.67**	0.47	0.37	0.35	0.34	0.57
	Cart	Number of handcart per ha	0.35***	0.11	0.13***	0.08	0.2***	0.18
<u>Cash and credit access:</u>	Cash	Cash level in the farm household per worker (FCFA)	17000	18500	40000	18000	65000	70000
	Credit	Dummy variable: 1 if the farmer gets a credit	0.34	0.4**	0.54	0.5**	0.55	1**
<u>Livestock systems:</u>	Cattle	Head of cattle	1	0.56	1	0.75*	17.1***	25***
	DraftAni	Head of draught animal	2.1	0.57***	2.9	5.08***	3.54**	8.66***
	CowFat	Head of cow fattening	0.56***	0	1.9***	0	6***	0
	Sheep	Head of sheep	11.7***	6.65***	22.3***	9.3***	25***	35***
	SheepFat	Head of sheep fattening	3.27	0.12	5	0.16	6.3	2***
<u>Cropping systems:</u>	Manure	Dummy variable : 1 if manure is used on farm	0.95	0.68**	1	1	1	1
	Fertilizer	Dummy variable : 1 if fertilizer is used on farm	0.42	0.8	0.45	0.9	0.67	1
	Millet	Share of the land dedicated to pearl millet	0.55	0.57*	0.53	0.49*	0.5	0.36*
	Maize	Share of the land dedicated to maize	0.02	0.09*	0	0.14*	0	0.23**
	Groundnut	Share of the land dedicated to groundnut	0.43	0.33	0.47	0.36	0.5	0.41

2 <sup>1</sup> 90 observations under each area. Variables used to build the classification are in bold. Results from ANOVA with unequal sample size conducted on each area are showed. \*, \*\* and  
3 \*\*\* indicate statistically significant differences between groups at 10%, 5% and 1% level respectively.

1 A similar picture appears in the two subzones: two farm-types are characterized by a mixed  
2 crop-livestock farming system and represent 75% and 96% of the farms in the Sine and Saloum  
3 subzone, respectively. The remaining households constitute a third type, oriented almost exclusively  
4 toward livestock systems (see Table 1). It was excluded from the analysis for three reasons: (i) its low  
5 representativeness, (ii) the absence of insurance contract for livestock in the region; (iii) the inability  
6 of the model designed (yearly planning horizon) to properly predict significant changes in the size of  
7 extensive livestock in such farms, whereas short-term animal fattening activities of other farm types  
8 were accounted for in the model.

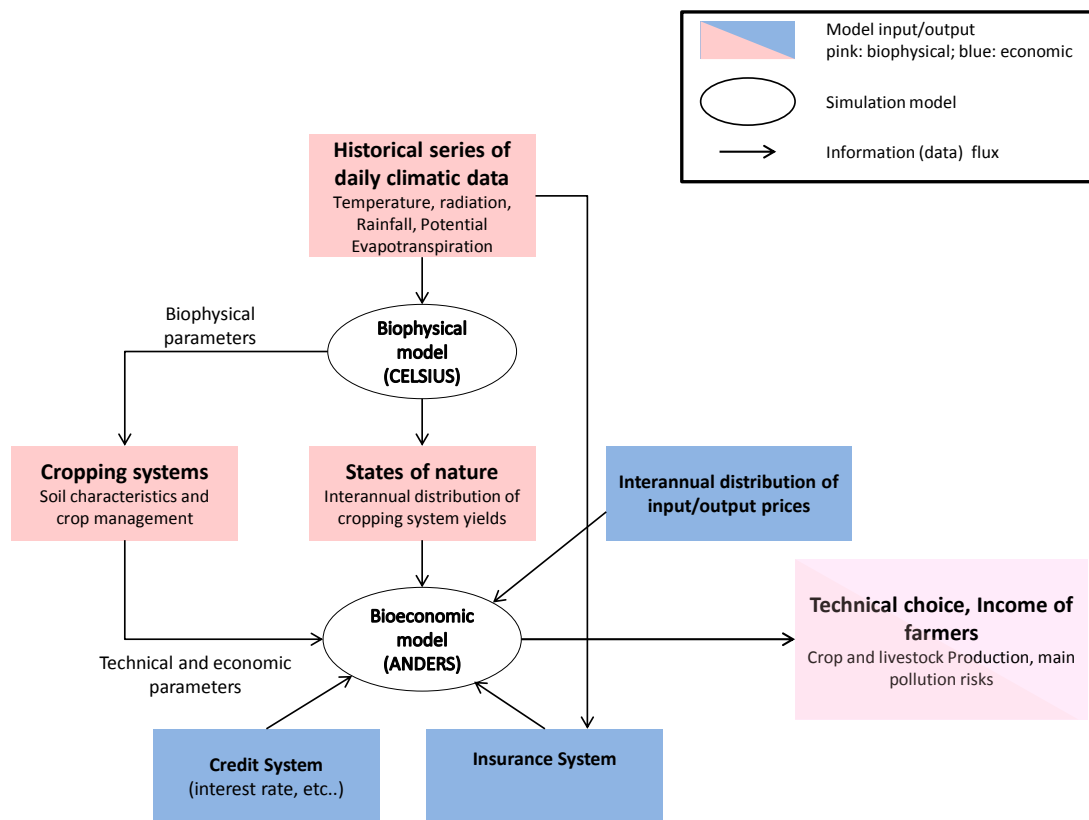
9 Type 1 are the most numerous and the poorest: in Sine1 the average yearly income including  
10 self-consumption is only 660 000CFA (1 003€) for approximately 12 people of which 4.5 workers,  
11 while in Saloum1 it amounts to 835 000 CFA (1 269€) for approximately 15 people of which 5  
12 workers. Thus the income per worker is far below the poverty line of 225 000 CFA (343 €; BCEAO,  
13 2012), and the income per capita is even further away. The land constraint is heavy with farm area of  
14 only 3.5 and 6.5 ha in Sine1 and Saloum1 respectively. This type is mainly oriented toward self-  
15 consumption and heavily constrained by its lack of liquidity. Access to credit is very limited.  
16 Consequently, the use of external inputs is very low and the proportion of land dedicated to millet is  
17 higher than for the other types. They also have very few head of livestock.

18 Type 2 are better off but still far below the poverty line when the dependents are considered,  
19 with an income of 1 910 000 CFA (2 903€) and 1 800 000 (2 736€) for approximately 17 and 20  
20 people in Sine2 and Saloum2 respectively. It includes the farms with the highest land holding (10.5  
21 and 15.2 ha) and labor is the main constraint. As for type 1, they own very few head of livestock but  
22 animal fattening, a risky but profitable activity, is slightly larger. The access to credit is higher and  
23 they use more fertilizer than type 1.

#### 24 **2.4 The bio-economic model**

25 The bio-economic ANDERS-CELSIUS model was designed to simulate the choices of farmers  
26 characterized by a mixed crop-livestock farming system, especially their crop choice, crop  
27 management strategy (manure, fertilizer), animal production strategy (uniquely short-term animal  
28 fattening), consumption, credit and insurance decisions. The model accounts for price and yield risks  
29 and includes policies targeted at favouring crop intensification, defined in this paper as the increase  
30 in yield through a change in the crop's technical management. It was designed by developing and  
31 coupling two models (Figure 2): a dynamic crop model named CELSIUS (CEreal and Legume crops  
32 Simulator Under changing Sahelian environment) and a multi-periodic, 1-year-planning horizon farm  
33 household model, named ANDERS (Agricultural aNd Development Economics model for the

1 gRoundnut basin in Senegal). CELSIUS simulates crop development, growth and biomass and grain  
 2 yields of a set of typical cropping systems under a 20-year series of historical climate data in order to  
 3 account for yield variability induced by inter-annual climate variations. As ANDERS is a 1-year model,  
 4 it takes the 20 yields provided by CELSIUS (proxy for the yield distribution) as equiprobable states of  
 5 nature that could occur during the simulated year with an equal probability.

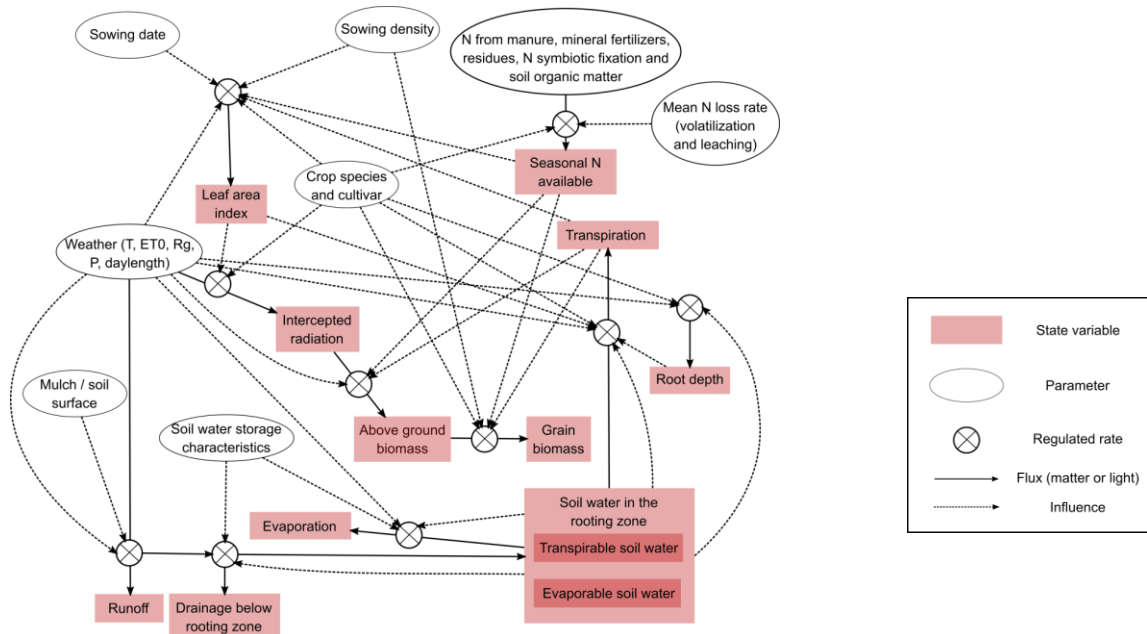


6  
 7 Figure 2. General flow chart of the coupled model ANDERS (“bioeconomic model”) – CELSIUS  
 8 (“biophysical model”)

9 **2.4.1 Crop yield simulations with CELSIUS**

10 CELSIUS was used to provide inter-annual distributions of grain yields and of above-ground  
 11 biomass yields, for a set of typical cropping systems. The cropping systems differ by the cultivar used  
 12 and its grain and biomass potential yields, the sowing density, and the fertilization practice mobilizing  
 13 organic and inorganic fertilizers (Table 2). Currently practiced cropping systems may be ‘extensive’  
 14 i.e. without any organic or inorganic fertilization, or ‘intensive’, i.e. with at least fertilization as a way  
 15 to obtain higher yields than in the latter case. In the case of cereal crops whose yield are currently far  
 16 below the potential permitted by rainfall (Affholder et al., 2013), the typical cropping systems we

1 considered also include hypothetical more intensive alternatives. For each study subzone, cropping  
 2 system and field type, the average yield and its coefficient of variation is presented in Appendix B.



3  
 4 Figure 3. Flow chart of CELSIUS

5 CELSIUS is a simple dynamic crop model working on a daily time step, based on the concept of  
 6 a potential yield limited by water and nitrogen stresses (Fig. 3). It was built in Visual Basic and  
 7 integrated into a database in order to facilitate virtual experimentation and coupling with the farm  
 8 model (Affholder *et al.*, 2012). We tailored the model to its specific use in the study, re-using existing  
 9 robust model components and keeping the complexity of the model and its resulting data  
 10 requirements for parameterization as low as possible (Sinclair and Seligman, 1996; Sinclair and  
 11 Seligman, 2000; Affholder *et al.*, 2012). CELSIUS was adapted from a previously published model  
 12 (Potential Yield Estimator, PYE) in Affholder *et al.* (2013) which uses formalisms that had proven to  
 13 be valid across a wide range of environments and crops to simulate the water-limited yield of annual  
 14 crops,  $Y_w$ , i.e. the yield that would be obtained in a given locality under idealized conditions where  
 15 the crop would be maintained free of any growth limitation other than solar radiation, temperature,  
 16 and rainfall. In this study, CELSIUS is the result of empirical additions made to PYE in order to account  
 17 for the following additional limiting factors: (i) reduction of rainfall infiltrating into the soil due to

1 runoff using the model from Albergel et al. (1991), (ii) delayed crop emergence due to insufficient  
2 moisture in soils after sowing and crop destruction by extreme drought during the juvenile stage  
3 following the approach of Affholder (1997), and (iii) low nitrogen availability in soils. The latter factor  
4 is accounted for through a nitrogen-limiting coefficient (NLC) applied to leaf and biomass growth  
5 defined as:

$$6 \quad NLC = \text{Min}[1; \alpha * (N_{soil} + N_{inorg} + N_{org} + N_{symb}) / I_{fertmax}] \quad (1)$$

7 where  $N_{soil}$ ,  $N_{inorg}$ ,  $N_{org}$ , and  $N_{symb}$  are the mineral nitrogen amounts available to crops  
8 from, respectively, soil organic matter mineralization, inorganic fertilization, mineralized N from  
9 organic fertilization, and symbiotic fixation of atmospheric N by leguminous crops,  $I_{fertmax}$  is the  
10 level of nitrogen supply above which growth is not limited, and  $\alpha$  a calibration coefficient (less than  
11 1) accounting for losses of mineral N through volatilization and leaching.

12 CELSIUS also includes a management system component simulating the decision to sow the  
13 crop at the beginning of the season or after a drought-induced failure of the crop, following rules  
14 based on the sequence of rainfall within a pre-defined sowing period. This component was taken  
15 from Affholder (1997), in which it had been tested against actual sequences of sowing, emergence,  
16 failure and re-sowing observed in farmers' fields of the same region.

17 Parameters relative to the simulation of Yw were set at values available in the literature when  
18 applicable and otherwise calibrated using the ESPACE-PRODCLIM and AMMA plot-level databases)  
19 following the method detailed in Affholder et al. (2013). The value of  $\alpha / I_{fertmax}$ , and in the case of  
20 groundnut, of  $N_{symb}$ , were calibrated by minimizing the cumulated quadratic error of simulated  
21 yields against observed yields of a sample of plots extracted from the database for which all N  
22 amounts brought by fertilization were available.

23 Appendix [x] provides a fully detailed mathematical description of CELSIUS as well as  
24 references to published models from which components were taken, when applicable, and details  
25 about model calibration and test against observed yields. The un-compiled software code is available  
26 on request to [affholder@cirad.fr](mailto:affholder@cirad.fr).

27

1 Table 2 Description of the simulated cropping systems<sup>1</sup>

Name of cropping system	Crop	Seed density (nb of plants/m <sup>2</sup> )	Organic nitrogen	Inorganic nitrogen	Total N from fertilization	Type of cropping system
MilExt	Pearl millet	1.2	0	0	0	Extensive
MilManu	Pearl millet	1.25	32	0	32	Manure
MilFert	Pearl millet	1.55	0	80	80	Fertilizer
MilManuFert	Pearl millet	1.65	40	80	120	ManuFert
MaizeFert	Maize	6	0	90	90	Fertilizer
MaizeManuFert	Maize	6	40	90	130	ManuFert
GroundnutExt	Groundnut	10	0	0	0	Extensive
GroundnutManu	Groundnut	10	14	0	14	Manure
GroundnutFert	Groundnut	12.5	0	7	7	Fertilizer

2 <sup>1</sup> Currently practiced cropping systems are shown on a grey background, whereas more intensive alternatives are shown on  
 3 a white background.

#### 4 2.4.2 The economic model ANDERS

5 Insurance demand takes place in the complex decision process of farmers, mobilizing diverse  
 6 resources (natural, human, economic) to satisfy present and future family needs. Mathematical  
 7 (linear or non-linear) programming models provide a convenient way to represent farmers' labor and  
 8 cash allocation among a large range of agricultural, livestock and off-farm activities under several  
 9 constraints. They allow considering simultaneously a wide range of technical parameters and  
 10 economic nutritional or social constraints (e.g. Jacquet et al. 2011, Louichi et al., 2010; Paas et al.,  
 11 2016, Sanfo and Gérard, 2012). Their multi-periodic modality is particularly suited to a highly risky  
 12 environment with several strong constraints (Boussard and Daudin, 1988). Here we represent only  
 13 one year because we focus on yearly crop insurance, with a premium paid at the beginning of the  
 14 cropping season in exchange of an indemnity at harvest time if the rainfall-based index is below a  
 15 predetermined threshold. This is consistent with the very short planning horizon generally observed  
 16 when risks are high and people poor. In these conditions investment decisions, regarding equipment  
 17 or livestock for example, based on expected returns on several years, cannot be represented  
 18 dynamically and are set as exogenous parameters. By contrast it is possible to represent in details the  
 19 intra-annual dynamics in which insurance takes place and the importance of strongly seasonal  
 20 constraints. We divide the year into seven periods to reflect that labor, cash and stocks constraints  
 21 are strongly seasonal. Inputs costs have to be paid at the beginning of the cropping season, while  
 22 cash corresponding to harvest will be only available at the end of the period, consumption needs  
 23 being smoothed all over the year (Table 3).

24 To account for risks, the objective function maximized in the model is the expected utility of  
 25 income. Risk depends on yields and prices fluctuations represented using the concept of

1 equiprobable 'states of nature' *i.e.* combinations of yield and price sets. The utility function is the  
 2 exponential one, implying a constant absolute risk aversion (CARA).

$$3 \quad EU = \frac{1}{n} \sum_{e=1}^n 1 - Exp[-r_a(\pi_e + w)] \quad (2)$$

4 Where  $EU$  is the expected income,  $e$  the state of nature,  $n$  the number of states of nature,  $r_a$   
 5 the absolute risk aversion,  $\pi_e$  the income,  $w$  the initial wealth and  $Exp[.]$  is the exponential function.

6 Expected utility increases with expected income and decreases with associated risk. A level of  
 7 income is associated to each state of nature. (See Appendix F for equations list)

8 Income is calculated as the sum of the income generated by cropping, livestock and off-farm  
 9 activities summed up with the assets variation at the end of the period, plus the insurance payoffs (if  
 10 any) minus the insurance premium (if any) plus the various subsidies (if any).

11 Cropping activities are defined by a cropping system as presented in section 2.4.1, *i.e.* the  
 12 combination of a given crop, cultivar and crop management, applied on a given field type. In ANDERS  
 13 they are characterized by yield distributions of crop grain and above-ground biomass, as well as  
 14 technical coefficients, specific to the field type, indicating the quantity of labor required, the draught  
 15 animal requirements and the quantities of seed, manure and inorganic fertilizer.

16 A set of constraints is related to farm endowment in natural (land), human (labor) and  
 17 economic resources (equipment, cash, access to credit). They state that utilizations of a resource  
 18 cannot be greater than its availability for a given period of the year. They limit the access to land,  
 19 credit, pasture and traction (with the possibility to rent animals).

20

21 Table 3 Periods considered within a year

	P1	P2	P3	P4	P5	P6	P7
<b>Period</b>	15 <sup>th</sup> May- 20 <sup>th</sup> June	21 <sup>st</sup> June- 15 <sup>th</sup> July	16 <sup>th</sup> July- 30 <sup>th</sup> August	31 <sup>th</sup> August- 25 <sup>th</sup> Sept.	26 <sup>th</sup> Sept.- 30 <sup>th</sup> Nov.	1 <sup>st</sup> Dec.- 14 <sup>th</sup> May (dry season)	Next year provisions
<b>Main agricultural activities</b>	Soil preparation. Millet sowing	Soil preparation. Groundnut and maize sowing	Manual weeding		Millet, maize and groundnut harvest	Fattening activities	Sales of fattened animals

22



1 In each period, the labor need for agricultural activity or livestock can be filled through family  
2 labor or hired worker. Family members can work on the farm or outside.

3 The cash equations (F7-F8 in Appendix F) focus on the money flows for each period and  
4 ensures that it remains positive. Money comes in at the harvest time or when selling animals, while  
5 expenditures are related either to cropping or animals activities or to household's consumption. A  
6 limited credit is available.

7 The supply-utilization account splits the harvest in several utilizations: selling, storage, human  
8 or animal consumption. It is combined with a nutritional constraint which ensures that the household  
9 consumed enough kcal in each period to represent the food security objective.

10 Energy and protein balances are also included for animals (digested nitrogen and dry matter).  
11 They can be fed through pasture, grain, straw and purchased feedstuff. Beside their nutritional  
12 needs, they are characterized by technical coefficients indicating labor required for tending and  
13 herding, vaccines and other veterinary costs. A stochastic return by head is assumed to take risk into  
14 account. By contrast the model includes the decision of buying animals for fattening in the sixth  
15 period.

16 The interactions between the cropping and livestock systems are considered through draught  
17 animal power, feeding of animals with suitable crop products and production of farm manure.

18 Final constraints oblige to keep at the end of simulation the same amount of cash and kcal in  
19 stocks in average over the states of nature as at the beginning, so that a new year could start in  
20 adequate conditions. However, to account for the social links between farmers at the village level  
21 providing informal insurance, the amount of cash and kcal in stocks in each state of nature has only  
22 to reach half of its initial value.

23 Finally exogenous parameters include technical input-output coefficients and the farm  
24 endowment in resources (natural, human, economic) while endogenous variables represents the  
25 decisions on (i) land allocation among cropping systems, (ii) insurance demand, (iii) labor and cash  
26 allocation among activities (crop production, livestock, off-farm).

27 The key output variables to be analyzed are the level of production, the cropping systems  
28 chosen, the level of animal fattening activity, the average income, the coefficient of variation of  
29 income, and the certain equivalent income (CEI) *i.e.* the certain income which provides the same  
30 utility as a given probability distribution of uncertain incomes (equation F1B in Appendix F).

1 Appendix D presents the model calibration and its evaluation against observations and  
2 appendix E the gross margin distribution for each cropping system. Figure D1 shows the good  
3 consistency between the observed production choices and the simulations in the baseline scenario,  
4 i.e. a simulation under the current environment of farms (without considering any hypothetical  
5 policy).

## 6 **2.5 Implementation of insurance in the model**

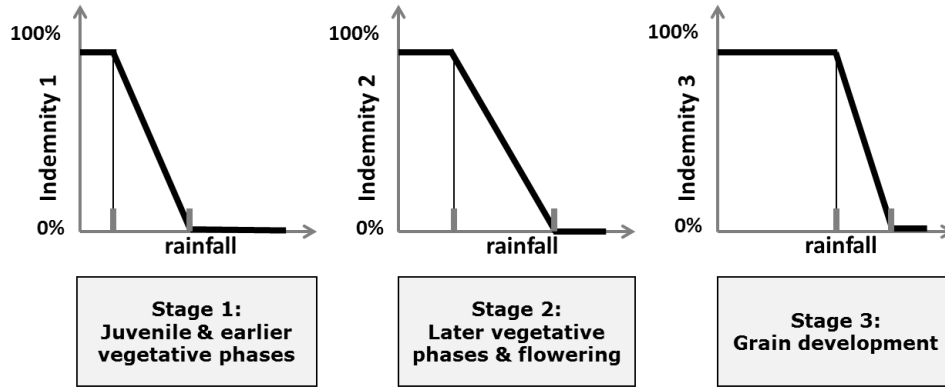
### 7 *2.5.1 Weather index-based insurance (WII)*

8 As rainfall distribution is the main climatic factor affecting yields in the study area, we  
9 developed and used a composite rainfall-based index, for millet, maize and groundnut. This index is  
10 very similar to the ones used in the insurance projects which are currently implemented in West  
11 Africa<sup>1</sup> and other regions of the world, as it splits the crop growing cycle into three stages to account  
12 for variations in drought sensitivity throughout the crop cycle<sup>2</sup>: (i) juvenile and earlier vegetative  
13 phases, (ii) later vegetative phases and flowering and (iii) grain development (fructification). For each  
14 stage, a rainfall-based index is used to determine an indemnity to be paid (if any) according to (i) the  
15 rainfall amount recorded during the given phase, (ii) the insured value, (iii) the phase-specific trigger  
16 value (amount of rainfall below which indemnity starts) and (iv) the phase-specific exit value (amount  
17 of rainfall below which the total indemnity is paid). Between the trigger and the exit values, the  
18 indemnity is proportional to rainfall. Rainfall amounts are capped at 80 mm per dekad (10-day  
19 period) to account for runoff and drainage. The global indemnity to be paid is the sum of the three  
20 indemnities identified above and its value is capped at the maximal insured value, 100 000 FCFA (152  
21 €) which is the highest possible expenditure on external inputs (Fig. 4). Under each phase, the  
22 insured value is also 100 000 FCFA.

---

<sup>1</sup> Insurance pilot projects initiated by World Bank and PlaNet Guarantee in West African countries (Senegal, Burkina Faso, Mali and Benin).

<sup>2</sup> We also tested pure rainfall indices but the results showed a much lower CEI gain compared to the three-phase index retained.



$$Total\ Indemnity = \sum_{stage} Indemnity(stage)$$

Figure 4: Mechanism of the composite rainfall index-based insurance

For each year of simulation the start of the index was forced to the sowing date of the crop as simulated by CELSIUS. For a given crop variety we developed and used several indices having the same structure (crop phases, rainfall capping value) but different trigger, exit, and level of coverage in order to introduce a menu of insurance options, with different levels of protection and associated premium cost available to the simulated farmers.

Table 4. Description of the weather index-based insurances (WII) in the Sine zone

Crop	Millet		Maize		Groundnut	
	Lowest	Highest	Lowest	Highest	Lowest	Highest
Protection level <sup>1</sup>	Lowest	Highest	Lowest	Highest	Lowest	Highest
Premium	4387	21807	5200	22928	2827	23448
Indemnity frequency <sup>2</sup>	10%	30%	15%	30%	5%	30%
Average indemnity	3375	16775	4000	17637	2175	18037
Minimum Indemnity	31500	30000	19000	14750	43500	3500
Maximum Indemnity	36000	100000	34750	100000	43500	63000

<sup>1</sup> the level of protection depends on the coverage level, the trigger and the exit values. According to the crop, 9 to 12 contracts are available per crop. In the table, we only show the least and the most two protecting contracts for each crop.

<sup>2</sup> Indemnity frequency is a ratio: the number of times the farmer receives an indemnity over the number of states of nature.

Global indemnities for this weather index-based insurance (WII) are calculated for each crop and field type as follows:

$$I_{e,ac,z}^{WII} = \text{Min}\{\rho M, \text{Max}[0, \sum_{stage} indemnity(stage)]\} \quad (3)$$

1           Where  $I_{e,ac,z}^{WII}$  is the indemnity at state e for the cropping activity ac and the field type z. M is  
2 the maximal insured value (in FCFA/ha),  $\rho$  is the coverage level, and indemnity(stage) is the  
3 indemnity under a given phase.

4           Depending on the chosen option, the frequency of indemnity payments to simulated farmers  
5 varies between 5% and 40% of the years being considered in the weather data series used in the  
6 study. The premium is equal to the expected indemnity payment plus a loading factor accounting for  
7 administrative costs and insurer's profit. This parameter is fixed at 30% in accordance with previous  
8 literature (Berg et al., 2009). Details on the WII are given in table 4.

### 9   2.5.2   Crop yield insurance (CYI)

10           Furthermore, in order to assess the effect of the basis risk (the imperfect correlation between  
11 the index and the actual farmer's crop yield) on the farmer's decision to insure or not, we also  
12 computed an index perfectly correlated with yields, the farmer's yield itself. Indemnities for this crop  
13 yield insurance (CYI) are calculated for each crop and field type using the following indemnity  
14 function:

$$15 \quad I_{e,ac,z}^{CYI} = \text{Min}\{M, \text{Max}[0, (\rho\bar{y} - y_e)P]\} \quad (4)$$

16           Where  $I_{e,ac,z}^{CYI}$  is the indemnity at state e for the cropping activity ac and the field type z. M is  
17 the maximal insured value (in FCFA/ha), P is the value of damages estimated at the average crop  
18 price (in FCFA/kg) and  $\rho$  is the yield coverage specified as a percentage of the farmer's average yield  
19  $\bar{y}$  over the 20 states of nature (in kg/ha). We fixed M at 100 000 FCFA/ha which is the highest  
20 possible expenditure on external inputs and corresponds to the same insured value as the weather  
21 index. Several values of  $\rho$  were chosen (80%, 90% and 100%) in order to obtain a menu of insurance  
22 options available to the farmer in this case too. The loading factor was also fixed at 30%. This CYI is  
23 purely hypothetical but provides a useful benchmark, the limit towards which index-based insurance  
24 would tend, should the index become perfect, i.e. the nil basis risk situation. Details on the CYI are  
25 given in table 5.

26

1 Table 5. Description of the crop yield insurances (CYI) in the Sine zone

Crop	Millet		Maize		Groundnut	
Protection level	Lowest	Highest	Lowest	Highest	Lowest	Highest
Premium	3303	27536	5046	16727	2274	12902
Indemnity frequency	10%	35%	20%	40%	5%	35%
Average indemnity	2541	21181	3882	12867	1749	9924
Minimum Indemnity	1490	85	300	1252	34985	6877
Maximum Indemnity	49329	100000	31290	60752	34985	77845

2

### 3 3 Scenarios and results

#### 4 3.1 Simulated scenarios

5 We first introduce three scenarios without subsidies:

- 6 • *Baseline*, in which no insurance is available.
- 7 • *WII*, in which a weather index-based insurance, as described in section 2.5, is available.
- 8 • *CYI*, hypothetical crop-yield insurance with no basis risk, as described in section 2.5. The
- 9 comparison between CYI and WII quantifies the impact of the basis risk.

10 We then introduce four scenarios in which the same amount of public funds is spent. We  
 11 considered policies typically debated among stakeholders of Sudano-Sahelian West Africa, using  
 12 scenarios into which, as compared to the *WII* scenario, the following changes are introduced:

- 13 • Premium subsidy scenario (*PremiumSub*): the WII premium cost is reduced
- 14 • Loan program scenario (*CreditSub*): a combination of decreasing the interest rate and increasing  
 15 the maximum access to credit.
- 16 • A fertilizer subsidy scenario (*FertSub*): the cost of fertilizers is reduced.
- 17 • A cash transfer program (*CashTrsf*): simulated farmers unconditionally receive a sum of money.

18 In these scenarios, unsubsidized WII is not available, and the constant amount of public funds  
 19 used is set with reference to the first scenario, where the subsidy covers 60% of the cost of the  
 20 insurance premium paid by simulated farmers, consistent with the fact that most agricultural  
 21 insurance around the world is heavily subsidized (Mahul 2012). We first ran the premium subsidy  
 22 scenario (*PremiumSub*). This allowed determining the government expenditure level under this  
 23 scenario on the basis of the level of adoption of subsidized WII by simulated farmers. The amount so  
 24 calculated was then used as the public expenditure level when running the other three scenarios (i.e.

1 the total amount of government expenditure in each scenario is equal to the expenditure  
 2 corresponding to the *PremiumSub* scenario). In the case of the *CreditSub* scenario the interest rate is  
 3 decreased by 75% compared to the baseline scenario (from 14% to 3.5%), and if this is not sufficient  
 4 to make the cost of the program match the public budget, the upper limit of credit accessibility is  
 5 increased. Furthermore, in every case we assumed that the subsidy does not provoke an increase in  
 6 the suppliers' prices (i.e. the insurance premium, the interest rate and the price of fertilizers  
 7 respectively). Similarly, the possible output price decrease due to an increase in supply is not  
 8 considered. Estimating how these prices might change is beyond the scope of the present paper and  
 9 would require the increase in suppliers' profits to be quantified in order to provide a consistent cost-  
 10 benefit analysis. Yet the reader should keep in mind that by neglecting these changes, we possibly  
 11 overestimate the gains from these scenarios, compared to the scenarios without subsidies.

12 Finally, in order to study the effect of combining access to WII with subsidized credit, fertilizer  
 13 or cash transfers, we considered 3 additional scenarios, *CreditSub-I*, *FertSub-I* and *CashTrsf-I*, as  
 14 variants of the scenarios *CreditSub*, *FertSub* and *CashTrsf* respectively, in which the unsubsidized WII  
 15 insurance is available in combination with the subsidy program. Table 6 summarizes the simulations  
 16 performed:

17

18 Table 6 Description of the programs simulated

Scenario →	Baseline	WII	CYI	PremiumSub	CreditSub	CreditSub-I	FertSub	FertSub-I	CashTrsf	CashTrsf-I
WII available?	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
CYI available?	No	No	Yes	No	No	No	No	No	No	No
Insurance subsidy?	No	No	No	60% of premium	No	No	No	No	No	No
Credit subsidized?	No	No	No	No	interest rate at 3.5% instead of 14% plus enhanced credit access		No	No	No	No
Fertilizers subsidized?	No	No	No	No	No	No	reduced fertilizer price		No	No
Cash transfer?	No	No	No	No	No	No	No	No	Cash transfer program	

19

### 20 3.2 Insurance gains and basis risk

21 When (unsubsidized) WII or CYI is introduced into the model as a possible option, only the  
 22 Sine1 and Sine2 farms adopt it, with a notable impact on CEI and farm plans. Saloum1 and Saloum2  
 23 adopt neither WII nor CYI in the simulations (Table 7).

1 Sine1, the most constrained farm-type in the Sine subzone, benefits the most from WII with a  
2 18% increase in CEI (from 115 020 FCFA i.e. 175€/worker in the baseline scenario to 135 561 FCFA i.e.  
3 142€/worker) and a 1% increase in expected income (from 146 604 FCFA i.e. 223€/worker to 148 264  
4 FCFA i.e. 226€ /worker. This large increase in the CEI is consistent with the high level of risk aversion  
5 and vulnerability to damaging events of this farm-type. Given its small size and its strong cash and  
6 credit constraints, yield risk has a large impact on its income that can be reduced by insurance. A  
7 total of 54 467 FCFA (84 €) is paid in insurance premiums for the whole farm. 42 968 FCFA (65 €) are  
8 paid for millet for which 67% of total output is insured. The average indemnity paid is 110 174 FCFA  
9 (168 €) in 30% of the states of nature. 100% of the groundnut is also insured for a total premium of  
10 11 499 FCFA (17 €). The average payment is 29 484 FCFA (45€) in 30% of the states of nature. As only  
11 70% in average are given back to simulated farmers in the form of indemnities and the rest is the  
12 loading factor, the welfare gain for the farmer arises through the drop of the income variability (the  
13 coefficient of income variation drops by -9 percentage points) rather than through the improvement  
14 in expected income. As expected, CYI leads to higher welfare and income gains (+22% in CEI and + 4%  
15 in expected income), relatively to WII. These higher benefits of CYI are due to the absence of basis  
16 risk which makes the insurance more efficient for a given amount of premium. Hence, for the same  
17 drop of income variability (-9 percentage points), the amount of insurance premium to pay is only  
18 34 518 FCFA (52 €), only for millet production (100% of the production is covered). Changes in the  
19 farming system induced by the supply of insurance are significant. A large portion of the land  
20 dedicated to groundnut is converted to millet (+34 percentage points and +45 percentage points  
21 under WII and CYI, respectively). The observed switch from groundnut to millet is explained by the  
22 price volatility that becomes the main source of risk when crop insurance is provided. Given that  
23 price volatility is higher for groundnut than for cereals, the simulated farmer allocates more land to  
24 millet. Moreover, insurance reduces the yield risk which entails intensification of millet. Given the  
25 level of land and liquidity constraints, the intensification of millet is necessarily at the expense of  
26 another crop, here groundnut which requires cash, even under the extensive cropping system.

27 WII has less impact on Sine2 than on Sine1. CEI increases by only 2% and 4% under WII and CYI,  
28 respectively, while expected income decreases by -5% and -4.5% respectively, showing that the  
29 loading factor is not totally compensated by production changes. Insurance premium amounts to  
30 73 195 FCFA (111€) and 47 079 FCFA (71€) under WII and CYI, respectively. Insurance is only used for  
31 millet, and cover 43% and 53% of total production of this crop, respectively. Here also, given that the  
32 drops in the coefficient of income variation are equal between both insurances (-6 percentage  
33 points), the lower premium for the CYI is attributable to the absence of basis risk that makes the  
34 insurance more efficient for a given amount of premium. As observed for Sine1, although to a lower

1 extent, there is an increase in the area allocated to millet at the expense of groundnut. Under WII,  
 2 technical changes are very limited, while they are significant under CYI under which fertilizer-based  
 3 cropping systems replace extensive ones. Finally, while cow fattening increases under both types of  
 4 insurances, sheep fattening increases under CYI only.

5 In the Saloum subzone, there is no take-up of insurance which can be explained by the lower  
 6 climate variability so that cropping systems are characterized by lower exposure to yield risk. These  
 7 results highlight the fact that the attractiveness of unsubsidized insurance depends on the  
 8 biophysical and socioeconomic environments (as shown by the different responses to the  
 9 introduction of insurance between the two subzones) but also on the farm characteristics (as shown  
 10 by the different responses to the introduction of insurance between the two farm-types of Sine).

11

12 Table 7 Impacts of the introduction of unsubsidized weather (WII) and crop-yield (CYI) insurances relative to  
 13 the baseline (BL) scenario on the main model's outputs

	Sine1			Sine2			Saloum1		Saloum2	
	BL	WII	CYI	BL	WII	CYI	BL	WII/CYI	BL	WII/CYI
CEI/worker	115 020	18 <sup>(%)</sup>	22	232 152	2	4	150 183	0	205 577	0
Mean income/worker	146 604	1 <sup>(%)</sup>	4	272 920	-5	-4.5	167 067	0	225 407	0
CV income	23%	-9 <sup>(pp)</sup>	-9	22.3%	-6	-6	15.8%	0	19.1%	0
Total Premium	n/a	54 467	34 518	n/a	73 195	47 079	n/a	0	n/a	0
Millet prod./worker	362 kg	+34 <sup>(pp)</sup>	0.45	777 kg	+23	0.32	467 kg	0	678 kg	0
Maize prod./worker	26 kg	-2 <sup>(pp)</sup>	-0.02	0 kg	0	0	136 kg	0	363 kg	0
Groundnut prod./worker	185 kg	-32 <sup>(pp)</sup>	-0.43	349 kg	-23	-0.32	244 kg	0	356 kg	0
Extensive	2.33 ha	-27 <sup>(pp)</sup>	-0.49	6.24 ha	-2	-0.11	4.28 ha	0	9.36	0
Manure	1.11 ha	+2 <sup>(pp)</sup>	0.11	3.68 ha	-2	-0.02	1.83 ha	0	3.01	0
Fertilizer	0 ha	+27 <sup>(pp)</sup>	0.4	0.59 ha	+5	0.13	0.04 ha	0	2.27	0
ManuFert	0.06 ha	-2 <sup>(pp)</sup>	-0.02	0 ha	0	0	0.34 ha	0	0.55	0
Cow fattening	0.4 head	0.22 <sup>(a)</sup>	0.22	1.6 head	0.61	0.49	n/a	n/a	n/a	n/a
Sheep fattening	0 head	0 <sup>(a)</sup>	2.28	4.8 head	-4.81	0.25	0 head	0	0.8 head	0

14 Note: Under each farm-type, BL column shows the output's values corresponding to the baseline scenario (CEI and income  
 15 are given in FCFA). WII and CYI columns show the changes relative to the baseline with weather-index- and crop yield  
 16 insurances, respectively. Extensive, Manure, Fertilizer and ManuFert refer to the type of cropping systems given in Table 2.  
 17 Changes are displayed in the following units: % represents the percentage change relative to the baseline scenario; pp  
 18 indicates changes in percentage points relative to the baseline scenario (e.g. Extensive gives the difference in percentage  
 19 points of the proportion of the total area dedicated to this given cropping system, and (a) means changes in absolute value  
 20 (head of livestock). Total premiums are given in FCFA spent (no percentage change can be calculated since there is no  
 21 insurance in the baseline scenario).

22

### 23 3.3 Subsidy program scenarios

24 As explained above, subsidy program scenarios have been simulated at a constant level of  
 25 public spending which is determined, for each farm-type, from the insurance premium subsidy



1 scenario (60% of the insurance premium). Since the amount of spending in the premium subsidy  
2 scenario depends on the farm-type (Table 8), this hampers comparisons between farm-types.

### 3 *3.3.1 Impact of subsidy programs on simulated farmers' CEI and expected income*

4 Table 8 gives the impact of the subsidy programs on the farmer's CEI and expected income and  
5 also ranks these programs in term of CEI. PremiumSub is never the best use of public funds; it is even  
6 the worst one for every farm-type in term of expected income, and the worst for three farm-types  
7 out of four in term of CEI. The only farm-type in which PremiumSub does not bring the lowest CEI is  
8 Sine1, but even there it is only ranked 4<sup>th</sup> out of 7 scenarios and is dominated by all the scenarios in  
9 which unsubsidized insurance is available: CreditSub-I, FertSub-I and CashTrsf-I. Hence subsidizing  
10 insurance is always the worst use of public funds, compared to scenarios in which insurance is  
11 available but not subsidized. CreditSub-I is always the best use of public funds in term of CEI, even  
12 though in Sine1 CashTrsf-I and FertSub-I bring the same outcome. These results indicate that for a  
13 given level of public spending, the simulated farmers' situation can improve more by alleviating the  
14 cash constraint (which prevents farmers from buying productive inputs) than by mitigating the  
15 impact of a bad weather.

16 Another insight from Tables 8 and 9 is that in Sine2, while introducing unsubsidized WII  
17 increases CEI by only 2% in a scenario without any subsidy (Table 7), it raises CEI by almost 8  
18 percentage points if credit is subsidized (from 9.7 to 17.6%, cf. Table 8). This indicates that the value  
19 of mitigating the impact of a bad weather is higher when the cash constraint is alleviated. This  
20 complementarity between insurance and credit is consistent with the results of the contingent  
21 valuation study lead in Ethiopia by McIntosh et al. (2013) which indicates a higher willingness to  
22 purchase insurance when interlinked with a credit on inputs.

23 Comparing our two subzones, we see that in Sine insurance is taken under every scenario in  
24 which it is available, while in Saloum it is taken only under PremiumSub and, for Saloum2, under  
25 CreditSub-I. As explained above, this is due to the lower risk of drought in Saloum.

1

2 Table 8. Impact of the subsidy programs on farmer's CEI and expected income (% increase relative to the baseline scenario) and their ranking

	Public spending (FCFA)	PremiumSub			CreditSub			CreditSub-I			FertSub			FertSub-I			CashTrsf			CashTrsf-I		
		CEI	Exp. Income (CV)	Rank	CEI	Exp. Income (CV)	Rank	CEI	Exp. Income (CV)	Rank	CEI	Exp. Income (CV)	Rank	CEI	Exp. Income (CV)	Rank	CEI	Exp. Income (CV)	Rank	CEI	Exp. Income (CV)	Rank
Sine1	44 257	29.3	11.3 (-10.2)	4	20	18.7 (-1)	5	30.5	19.1 (-6.4)	1	19.7	16.3 (-1.1)	7	30.5	13.5 (-9.1)	1	19.9	16.5 (-1.1)	6	30.5	13.5 (-9.1)	1
Sine2	110 308	9.1	-1.8 (-10.6)	7	9.7	14.2 (1)	4	17.6	14 (-4.3)	1	9.5	12.3 (0.8)	5	12.6	4.9 (-6.9)	2	9.5	12.3 (0.8)	5	12.6	4.9 (-6.9)	2
Saloum1	668	0.1	-0.1 (-0.1)	7	1.3	1.8 (0.3)	1	1.3	1.8 (0.3)	1	0.2	0.2 (0)	3	0.2	0.2 (0)	3	0.2	0.2 (0)	3	0.2	0.2 (0)	3
Saloum2	34 162	0.6	-0.7 (-1.8)	7	8.3	11.5 (1.8)	2	8.4	11.1 (1.6)	1	3.3	3.5 (-0.1)	3	3.3	3.5 (-0.1)	3	3.3	3.5 (-0.1)	3	3.3	3.5 (-0.1)	3

3 Note: The first column gives the amount of government spending under each scenario. For each scenario, CEI and expected income changes relative to the baseline scenario are given in percentage changes while CV  
4 of income change is given in percentage point. The Rank column gives the ranking of the policy based on the percentage change in CEI.

5

1 Table 9. Impact of the subsidy programs on crop production and animal fattening (% increase relative to the baseline scenario)

	PremiumSub	CreditSub	CreditSub-I	FertSub	FertSub-I	CashTrsf	CashTrsf-I	
Sine1	Cereal <sup>1</sup>	101.9	45.9	126.3	19.2	100	11.1	100
	Groundnut	-74.7	-6.9	-62.2	14.7	-65	19.4	-65
	Grain production value	16.8	20.8	35.6	17.7	20.6	15.5	20.6
	Cow fat. <sup>2</sup>	0.4	1	0.9	0.1	0.3	0.1	0.3
	Sheep fat.	0.2	4.8	9.5	0	1.2	0	1.2
Sine2	Cereal	55.2	40.4	117.4	10.2	50.7	10.2	50.7
	Groundnut	-77.8	-7.3	-64	14.9	-53.2	14.9	-53.3
	Grain production value	-7.3	18	32	12.4	1.9	12.4	1.9
	Cow fat.	0.8	2	2.1	0.1	1.1	0.1	1.1
	Sheep fat.	-4.2	13.4	20.3	2.3	-4.8	2.3	-4.8
Saloum1	Cereal	1.2	4.1	4.1	0.2	0.2	0.2	0.2
	Groundnut	-1.9	3.9	3.9	0.2	0.2	0.2	0.2
	Grain production value	-0.1	3.9	3.9	0.2	0.2	0.2	0.2
	Sheep fat.	0	0	0	0	0	0	0
Saloum2	Cereal	27.7	16.4	18.8	2.3	2.3	2.3	2.3
	Groundnut	-45.7	20	16.5	4	4	4	4
	Grain production value	0.2	20	19.8	2.8	2.8	2.8	2.8
	Sheep fat.	5	-0.9	-0.9	-0.2	-0.2	-0.2	-0.2

2 <sup>1</sup> Grain production and value changes are given as percentages relative to the baseline scenario; <sup>2</sup> Cow fattening and sheep fattening changes are given in absolute value relative to the baseline scenario.

### 3.3.2 *Impact of the subsidy programs on the development of intensive cereal crops or of fattening activity*

As a simple way to assess the impact of our scenarios in terms of crop intensification, we compared the total value of grain production (cereal and groundnut), thus aggregating crops with different prices.

The only farm-type in which PremiumSub entails intensification is Sine1 where the total value of grain production increases by 16.8% (Table 9), due to a surge in the use of fertilizers (Fig. 5). The explanation goes as follows: in case a very bad weather, fertilizers reduce income (Figure E.1) because they do not increase yield significantly while the farmer must purchase them. Because of risk aversion, intensification reduces farmers' CEI, so they are not adopted even though they would raise average income. Under PremiumSub, fertilizers increase average income without worsening the situation under very bad weather since in this case farmers receive an indemnity. Nevertheless, even for Sine1, the increase in grain value is lower than under other policies. For the other farm-types, while subsidizing WII increases simulated farmers' CEI, it neither directly provides the cash required for increasing the herds producing manure nor for purchasing inorganic fertilizer. On the contrary, since the insurance premium must be paid upfront it reduces the cash available to invest in external inputs.

In Sine, animal fattening activity increases a lot under CreditSub and CreditSub-I, which provide the relatively large investments required for such activities. Hence, these scenarios foster the greatest amount of cereal intensification since the use of both manure (through the fattening activity) and inorganic fertilizer (through purchase) greatly increases (Fig. 5). Furthermore, the availability of (unsubsidized) insurance reinforces the positive effect of credit or fertilizer subsidies as well as of cash transfer on cereal intensification, the latter development being highest under CreditSub-I. Two factors explain this intensification of millet: (i) insurance is more efficient at stabilizing the gross margin of millet than that of groundnut, due to the strong component of price instability in gross margin variation for groundnut, which cannot be reduced with the use of a WII; (ii) the labor requirement for millet is far lower (around 40%) than for groundnut. WII allows simulated farmers to mitigate crop risk and thus to accept more risk in fattening activities, which are the most profitable but require labor (and cash obtained thanks to the policy tools). This is why the availability of WII in addition to a subsidy program encourages the intensive production of millet and decreases the groundnut area which releases labor used for fattening activities. When WII is unavailable, the tested scenarios lead to a limited increase in both cereal and groundnut productions and to a slightly enhanced animal fattening activity (Table 9).

In the Saloum subzone, the simulated programs increase the production of both cereals and groundnut, through an increased use of inorganic fertilizer (in Saloum1 yet, the increase is barely perceptible because of the very low amount of subsidy). The subsidy programs lead to a reduction in the area allocated to extensively managed millet and an increase in fertilized millet and fertilized maize, the latter two being more profitable but also more risky. Furthermore, as in the Sine subzone, the loan program produces the largest development of intensive cereals.

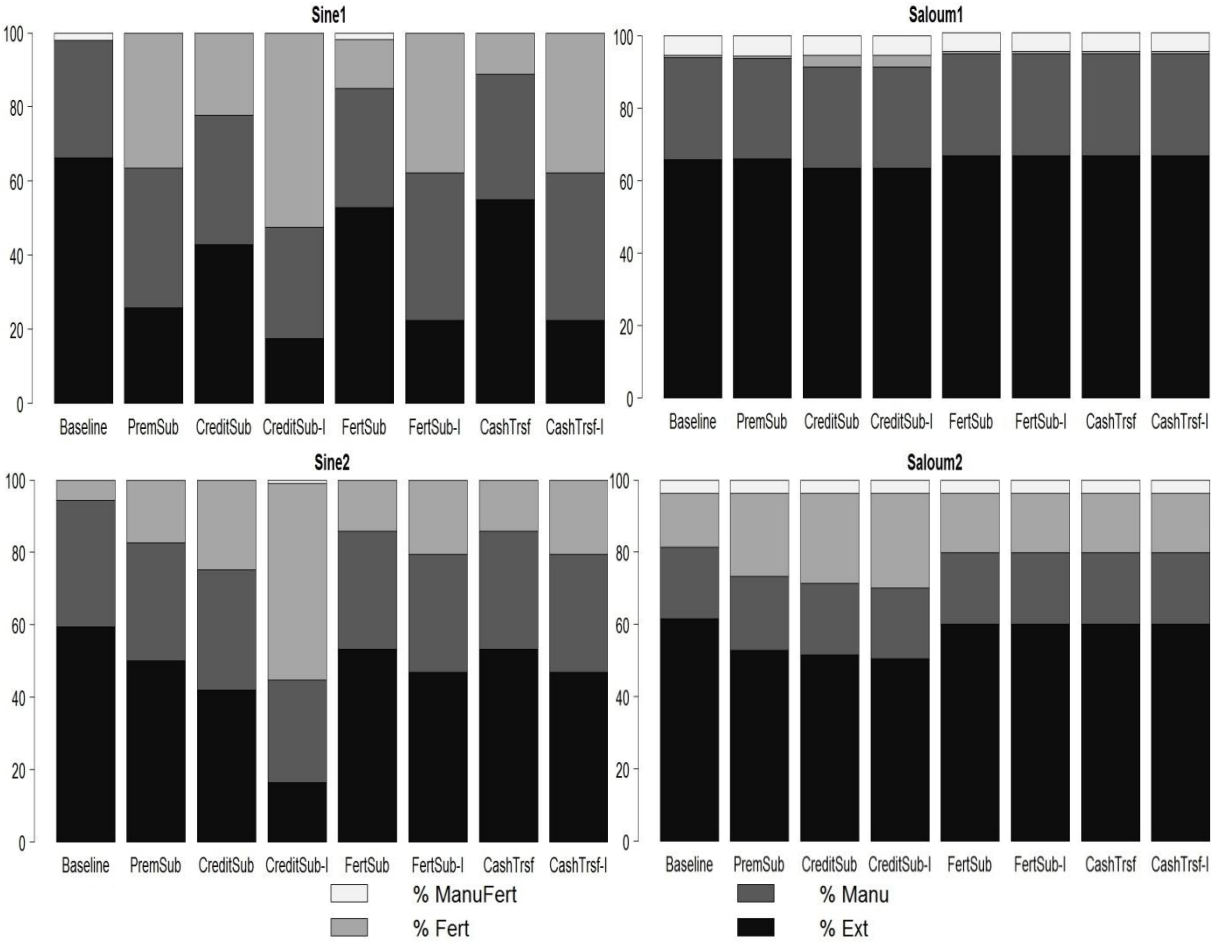


Figure 5: Share of land across cropping systems under each scenario for Sine (left) and Saloum (right).

**4 Discussion and conclusion**

Although in the mind of numerous stakeholders the groundnut basin of Senegal may be a region of the typical minimum size for agricultural policy design, the relative impacts at farm level of the policies tested strongly differ between the two subzones that we considered. These subzones show differences in rainfall distributions that influence only slightly the current production systems, remarkably similar in the two subzones. In contrast, our study suggests that these differences in

rainfall have strong consequences in terms of the potential benefit of weather index insurance. In the wetter subzone (Saloum), the benefit from insurance is very low because the risk of water stress on crops is not the major constraint faced by simulated farmers even using more intensive cropping systems. Subsidizing the insurance premium by 60% (PremiumSub) induces simulated farmers to take up insurance but is much less efficient at increasing their expected utility or production than other uses of public funds, i.e. subsidizing credit (CreditSub) and fertilizers (FertSub), or just transferring cash as a lump sum (CashTrsf).

In the drier subzone (Sine), insurance, even unsubsidized (Insu), increases simulated farmers' utility, especially for the poorest ones. Simulated farmers respond to insurance by increasing their cow fattening activity, which allows them to increase millet yield by spreading more manure on the fields. For the less cash-constrained farms, crop intensification is further developed by using inorganic fertilizers on millet. However, here again, subsidizing insurance is not the best possible use of public funds, because the cash availability constraint clearly prevails over other constraints in the way simulated farmers can develop short-term fattening activities or intensive cereal production, which are the two main pathways for increasing farm income considered in this study.

The direct policy implication of these results is that while a public intervention to develop weather index insurance in the driest part of the Sudano-Sahelian zone may be justified, permanently subsidizing insurance, a current practice worldwide, is not. In areas prone to yield risk, the most benefit was seen from bundling government subsidies on other climate risk variables (e.g. subsidized loans, fertilizers or cash transfers) with unsubsidised insurance. This echoes the experience of operational programmes that have scaled up such as the R4 Resilience programme implemented recently in Senegal (Greatrex et al., 2015) or ACRE, where (unsubsidized) insurance is integrated with government interventions.

Four limits to our work, all of which reinforce the latter conclusion, are worth pointing out. First, when analyzing subsidies, we have deliberately excluded their possible inflationary impact on the subsidized goods and services (loans, fertilizers and insurance contracts). Hence, we may overestimate the benefits of these subsidies to farmers.

Second, as we ignored yield variations due to factors other than rainfall and fertility, the insurance index retained is necessarily better correlated to simulated yields than to the actual ones, which include idiosyncratic shocks (Leblois et al., 2013). Among these shocks are insect attacks or health problems which can reduce the workforce available at critical times. As a result, we underestimate the basis risk and overestimate the benefits of weather-index insurance.

Third, it would be worth analyzing more policy and technical options. For example, we did not assess dry-resistant seeds bundled with credit and insurance that may be relevant to this area. We also did not test different business models of index insurance programmes (e.g. replanting guarantee, meso-insurance) that are promising ways to implement index insurances. There are also more crop management options, especially (i) those based on the principles of ecological intensification such as the retention of crop residues on the soil, expected to reduce water runoff and soil evaporation and to increase soil fertility (at the expense, however, of the loss of the corresponding amount of residues as feed contributing to livestock and manure production), and (ii) those pertaining to “climate-smart” agriculture such as the decision whether or not to use fertilizers, depending on accumulated rainfall and seasonal or short-term weather predictions (Roudier et al., 2016). It would also be worth assessing the efficiency of subsidies to other inputs than fertilizers (e.g. seeds of improved cultivars with drought resistance characteristics). Such enhanced analyses would require further investigations at field scale. Since these options typically mitigate the weather risk, they would most likely reduce the demand for weather-index insurance.

Fourth, in reality, WII face many obstacles which were not represented in the model, in particular widespread lack of trust in insurance products in general, and of knowledge of this kind of insurance products.

Since all these limits lead to overestimate the benefit from insurance, overcoming them could only reinforce our conclusion that while there may be a room for WII, there is little rationale for subsidizing them permanently, at least at the farm level in the kind of environment of our study. Our result on the superiority of subsidizing credit rather than insurance matches the view expressed by farmers themselves in surveys in similar regions (Zorom et al., 2013)

Finally, global warming will have an uncertain impact on rainfall in the Sudano-Sahelian region in the next decades (Sultan et al., 2013). This increases the need for risk management options but at the same time makes WII more risky for insurers, thus may raise the insurance premium (Mills 2007). Since our model was also designed to simulate, in a future study, different climate change scenarios, this issue could be addressed in a future work. Weather distributions could be derived from climate change scenarios and different adaptations strategies by farmers could be simulated, distinguishing for instance myopic expectations, in which farmers take decisions on the basis of the past climate, and more forward-looking but not necessarily perfect expectations of the changing climate.

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**Appendix A. Farm typologies, Dendrogram and Calinski-Harabasz index**

The number of farm-types was chosen based on dendrogram observation (Fig A1 and A2) and the Calinski-Harabasz criterion (Table A1). The Calinski-Harabasz criterion is defined as  $\frac{SS_B}{SS_W} \frac{N-k}{k-1}$  where  $SS_B$  is the between-cluster variance,  $SS_W$  the within-cluster variance,  $N$  the number of observations and  $k$  the number of clusters. The higher the index, the best the clustering quality. We kept 3 farm-types in each subzone because i) with more farm-types the observed farming system heterogeneities represented would have been too similar to one another to be reproduced through modeling, and ii) the classes across the two subzones share common characteristics, thus facilitating their description and the interpretation of the model outputs.

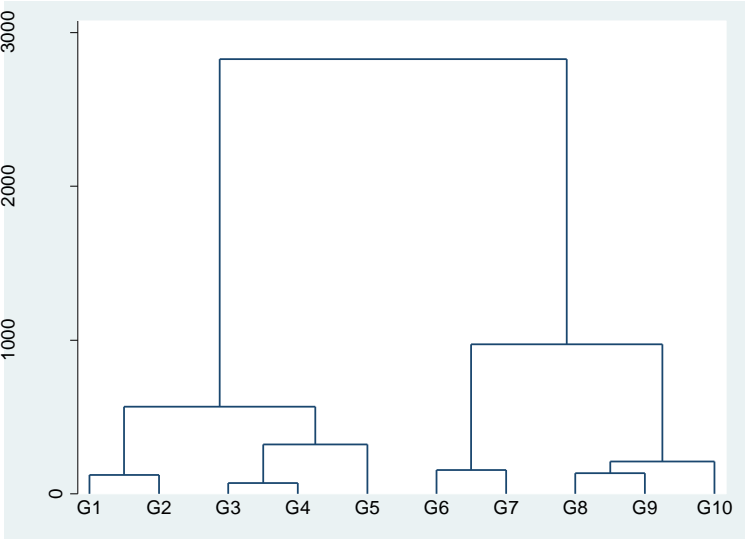


Fig. A1: Dendrogram truncated after tenth level - Sine

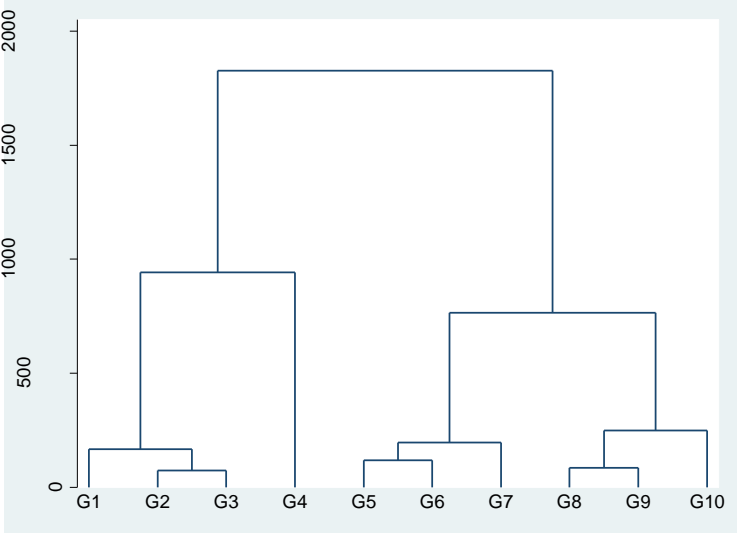


Fig. A2: Dendrogram truncated after tenth level – Saloum

Table A1 Calinski-Harabasz criterion depending on the number of cluster (left: Sine; right: Saloum)

Number of farm-types	Calinski-Harabasz criterion
2	69.42
3	64.64
4	63.95
5	61.5
6	58.78
7	56.52
8	55.62
9	55.59
10	53.51

(Sine subzone)

Number of farm-types	Calinski-Harabasz criterion
2	47.44
3	49.26
4	60.32
5	56.22
6	54.17
7	53.68
8	52.57
9	50.86
10	49.6

(Saloum subzone)

1

1 **Appendix B. Average yield and coefficient of variation, by cropping system**

		Mean yield (kg.ha <sup>-1</sup> ) (1991-2010)		Coefficient of variation	
		Sine	Saloum	Sine	Saloum
MilExt	Homefield	1175	1131	14	12
	Bushfield	524	422	10	5
MilManu	Homefield	1756	1709	19	20
	Bushfield	1251	1130	14	13
MilFert	Homefield	2006	1983	22	24
	Bushfield	1589	1450	17	18
MilManuFert	Homefield	2167	2216	25	18
	Bushfield	2167	2216	25	18
MaizeFert	Homefield	2050	2217	13	20
	Bushfield	1865	1934	14	17
MaizeManuFert	Homefield	2127	2335	14	21
	Bushfield	2127	2335	14	21
GroundnutExt	Homefield	828	817	11	7
	Bushfield	592	558	9	6
GroundnutManu	Homefield	965	950	13	8
	Bushfield	726	686	10	6
GroundnutFert	Homefield	990	971	15	9
	Bushfield	708	670	11	7

2

3

## 1 **Appendix C: The crop dynamic simulation model CELSIUS (CEreal and Legume crops** 2 **Simulator Under Sahelian Environment): Conceptual and mathematical description**

### 3 **Part I. General description and credits to other models.**

4 CELSIUS (CEreal and Legume crops Simulator Under changing Sahelian environment) is a  
5 simulation model and as such it has a conceptual form (i.e. a schematic representation of the system  
6 simulated with the main variables and relationships between variables, a mathematical form i.e. the  
7 list of mathematical equations of the model, and a software form, the latter with the code expressed  
8 in a programming language as well as in a compiled, executable file. In the present document, we  
9 provide a simplified conceptual description and a commented, mathematical form of the model. The  
10 only exact description of the simulation model, however, is its un-compiled software form, which is  
11 available on request at [francois.affholder@cirad.fr](mailto:francois.affholder@cirad.fr), and was written using Microsoft Visual Basic for  
12 Application under Microsoft Access, using the principles of interfacing between models and  
13 databases in order to facilitate virtual experiments (Affholder et al., 2012).

14 CELSIUS consists on the previously published model PYE (Potential Yield Estimator - (Affholder  
15 et al., 2013)) plus a number of additions, with a system of simulation options allowing, among other  
16 possible combinations, to choose to simulate a crop exactly as PYE would do, or to use all the  
17 components forming CELSIUS.

18 Thus CELSIUS allows simulating crop development and growth, total above ground biomass at  
19 harvest (AGB) and grain yield (Y) under, depending on the simulation option chosen, the typical  
20 potential and limiting conditions corresponding to the concept of yield gap (Van Ittersum and  
21 Rabbinge, 1997; van Ittersum *et al.*, 2013). More precisely, CELSIUS simulates AGB0 and Y0 which are  
22 respectively total above ground biomass and yield under potential conditions (no limitation other  
23 than temperature and radiation), AGBw and Yw corresponding to the same variables under water  
24 limiting conditions (rainfall limitation added to the potential conditions), AGBn and Yn under nitrogen  
25 limiting conditions (nitrogen limitation added to the potential conditions) and also AGBwn and Ywn  
26 under nitrogen and water limiting conditions (nitrogen and rainfall limitations added to the potential  
27 conditions).

28 CELSIUS runs on a daily time step and takes its whole crop development and growth module  
29 from STICS (Brisson *et al.*, 1998; Brisson *et al.*, 2003). Seed germination and crop emergence are  
30 calculated as a single phase controlled by thermal time and water content of the topsoil. Crop  
31 phenology and potential leaf area index (LAI0) are simulated as determined by photo-thermal time.



1 Except the calculation of runoff, taken from Albergel *et al.* (1991) and the effect on soil  
2 evaporation and runoff of a mulch of straw residues, taken from Scopel *et al.* (2004), its whole water  
3 balance module comes from Sarra (Forest and Clopes, 1994; Affholder, 1997), also used in the more  
4 recent version of the model, Sarrah (Dingkuhn *et al.*, 2003). The water balance module of Sarra is  
5 based on the classical 'tipping bucket' approach (van Keulen, 1975) and is very similar to the one  
6 used in STICS, hence the possibility to consistently couple the Sarra water balance module with the  
7 crop module of STICS while reusing many standard parameters of the latter. The water balance  
8 accounts for the interaction between root growth and the seasonal descent of the wetting front of  
9 the soil, a feature that proved to significantly affect crop growth in tropical environments with a  
10 relatively long dry season and where the soil profile is generally at or below wilting point at the onset  
11 of the cropping season (Affholder, 1995). Runoff is computed following the approach of Sissoko  
12 (2009). The latter combines the runoff model from Albergel *et al.* (1991) based on the interaction  
13 between the time sequence of daily rainfall and soil crusting, according to a typology of soil crusting  
14 sensitivity, and a model of the impact on runoff of a straw mulch decaying over time as in Scopel *et*  
15 *al.* (2004). Soil evaporation is reduced in case of the presence of a straw mulch following Scopel *et al.*  
16 (2004) or of a plastic film following Luu Ngoc Quyen (2012). A water stress coefficient is computed as  
17 a bilinear function of the fraction of transpirable soil water (FTSW) with a threshold parameter as in  
18 Allen *et al.* (1998).

19 A nitrogen stress coefficient is computed using a simple seasonal estimate of N available in soil  
20 from mineralization of soil organic matter, mineralization of a decaying biomass added to the soil, N  
21 inorganic fertilizers inputs, and symbiotic fixation of atmospheric N<sub>2</sub>, with a coefficient of N losses  
22 through N-leaching and volatilization. The nitrogen stress coefficient is a bilinear function of N  
23 available in soil, with a threshold parameter corresponding to the level of N available in soil above  
24 which N is not limiting crop growth. This approach of the relationship between N availability and  
25 yield reduction relatively to a potential yield is a simplification of the relationships used in the model  
26 Field (Tittonell *et al.*, 2010) or Quefts (Janssen *et al.*, 1990), especially by assuming that P and K  
27 limitations as well as interactions of soil pH with N availability are all constant across the set of  
28 situations to be simulated.

29 Under stress resulting from water-limiting or nitrogen limiting conditions, potential daily increase  
30 in leaf area index during vegetative growth is multiplied by a stress coefficient which is the lowest  
31 value of the water and nitrogen stress coefficients. During post flowering development phases, LAI  
32 decrease is accelerated by stresses.

1 Daily global solar radiation is intercepted by the resulting leaf area index following a beer law  
2 with an extinction coefficient, and converted into biomass following a net conversion efficiency  
3 approach, the potential efficiency being reduced by temperature below or above an optimum, and  
4 by water or nitrogen stress. CO<sub>2</sub> concentration of the atmosphere increases conversion efficiency by  
5 a coefficient depending on the C<sub>3</sub> or C<sub>4</sub> type of the crop. A part of the accumulated dry matter is  
6 allocated to grain following an harvest index approach coupled with a sink limitation accounting for  
7 thermal or water stress during a fruit-forming sensitive stage (Brisson et al., 1998).

8 Sowing date can be simulated as the first date at which the amount of daily rainfall exceeds a  
9 certain threshold, within a certain interval of dates. The crop can be killed by extreme stress and a  
10 new sowing can automatically be computed using the same decision rule.

11

## 1 **Part II. Detailed mathematical description**

### 2 *1. Modelling Options*

3 *See OptionModelClass in the software code.*

4 A number of Boolean Variables (having 'True' or 'False' as the only possible values) are used to  
5 set modelling options.

6 These are *Simlevee*, *CyberST*, *ActiveStressH*, *ActivestressN*, and *CorAlti*

7 If *Simlevee* is True then germination plus emergence are simulated, else they are forced to  
8 input values.

9 If *CyberST* is True then sowing, germination and emergence are simulated otherwise sowing is  
10 set to input value and germination plus emergence are accounted for according to the value of  
11 *SimLevee*

12 If *ActiveStressH* is True then water stress is used to reduce growth ( $Y_w$  or  $Y_{wn}$  calculated  
13 according to setting of *ActiveStressN*), else water stress is still calculated but has no impact on  
14 growth calculation ( $Y_0$  or  $Y_n$  calculated according to setting of *ActiveStressN*). Whatever its setting  
15 *ActiveStressH* has no impact on germination plus emergence or on crop survival due to extreme  
16 water stress.

17 If *ActiveStressN* is True then nitrogen stress is used to reduce growth ( $Y_n$  or  $Y_{wn}$  calculated  
18 according to setting of *ActiveStressH*), else nitrogen stress is still calculated but has no impact on  
19 growth calculation ( $Y_0$  or  $Y_w$  calculated according to setting of *ActiveStressH*)

20 If *CorAlti* is True then Temperature is corrected according to difference of elevation between  
21 weather station and simulated plot else temperature from weather station is applied.

### 22 *2. Plant development and growth*

#### 23 *2.1.- Crop emergence*

24 *See PlanteClass. GerminLevee in the software code.*

25 A day  $n$  after the starting day of the simulation is the day of crop emergence if the thermal  
26 time accumulated since the day of sowing  $jsow$ , discounting days with soil moisture below a certain  
27 threshold, exceeds a cultivar- dependent thermal time constant  $CT_{ger}$  as follows:

28 Equation CELSIUS.1

$$\text{If } \sum_{j=jsow}^n \min((Tm(j) - Tger) \times WConstGer(j); 0) \geq CTger \text{ then } Jlev = n$$

1 With:

2  $n$ : current day of simulation,

3  $jsow$ : day of sowing,

4  $Tm(j)$  = mean temperature of day  $j$ ,

5  $Tger$ = cultivar dependent, min temperature for accumulation of thermal time during  
6 germination + emergence phase,

7  $Jlev$ = day of emergence,

8  $WConstGer(j)$ : water constraint applied to germination plus emergence, for day  $j$ . Integer,  
9 value 1 (soil water not constraining germination or emergence) or 0 (soil water constraining  
10 germination or emergence), calculated in equation CELSIUS.21.

11

## 12 2.2 Crop development

13 See *PlanteClass.phenoCTphot* in the software code

14 Five development stages are considered. A day  $n$  after starting day of the simulation is the day  
15 of completion of a certain stage  $i$  if the accumulated photo-thermal time since the preceding stage  
16 corresponds to the thermal constant of stage  $i$ , as in the following equation:

17 Equation CELSIUS.2

$$\text{If } \sum_{j=Dstge(i-1)+1}^n PhotFact(j) \times (f(Tm(j))) \geq CT(i) \text{ then } Dstge(i) = n$$

18 With:

$i \in [1; 6] \cap \mathbb{N}; n \in \mathbb{N}; j \in \mathbb{N}; f$ : function defined as:

$\text{If } Tm(j) \leq t_{dmin} \text{ then } f(Tm(j)) = 0$

$\text{If } t_{dmin} < Tm(j) \leq t_{dmax} \text{ then } f(Tm(j)) = Tm(j) - t_{dmin}$

If  $T_m(j) > t_{dmax}$  then  $f(T_m(j)) = t_{dmax} - t_{dmin}$

1 And

If  $(i \neq 2 \text{ OR } DL(j) < MOPP)$  then  $PhotFact(j) = 1$

If  $i = 2 \text{ AND } DL(j) \geq MOPP$  then

$PhotFact(j) = 1 - (DL(j) - MOPP) \times SensPhot$

2 Where:

3  $Dstge(i)$ : day of completion of stage i; Positive integer,  $Dstge(0) = Jlev$

4  $CT(i)$ : thermal time accumulated for completing stage i

5  $t_{dmin}$ : base temperature for thermal time accumulation

6  $t_{dmax}$ : maximal temperature for thermal time accumulation

7  $DL(j)$ : photoperiod (astronomic diurnal duration) of day j

8  $MOPP$ : threshold of photoperiod above which cultivar has its development rate reduced by  
9 photoperiod.

10  $SensPhot$ : Coefficient of sensitivity of cultivar to photoperiod

11  $PhotFact$ : reduction coefficient applied to development rate when when affected by  
12 photoperiod

13

### 14 2.3 Leaf Area Index (LAI)

15 See *PlanteClass. Calcule\_LAI\_SemiAride* in the software code

16 LAI on day  $n$  ( $LAI(n)$ ) is computed by adding  $dlai(n)$ , a daily increase (or decrease if negative),  
17 of LAI to the LAI of the previous day ( $n-1$ ).

18 a) During development stages 1 and 2, daily increase of LAI ( $dLAI(n)$ ) for a day  $n$  is calculated  
19 using equations taken from STICS as follows:

20

21 Equation CELSIUS.3

22

23 
$$dLAI(n) = \frac{dlaimax}{1 + \exp(5.5 * (Vlaimax - Ulai(n)))} \times f(T_m(n)) \times LAIStress(n) \times \Delta idens(denspl)$$

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With

$$\text{during stage 1: } U_{lai}(n) = 1 + (V_{laimax} - 1) \times NTT(n);$$

$$\text{During stage 2: } U_{lai}(n) = V_{laimax} + (3 - V_{laimax}) \times NTT(n);$$

$$\text{For a stage } i, \quad NTT(n) = \sum_{j=Dstge(i-1)+1}^n PhotFact(j) \times (f(Tm(j))) / CT(i)$$

And

If  $LAI(n) > LAI_{comp}$  And  $Densplt > bdens$  then  $\Delta idens(densplt)$

$$= densplt \times \left( \frac{densplt}{bdens} \right)^{adens} \quad \text{else } \Delta idens(densplt) = densplt$$

Where

$f(Tm(n))$  is the same function as in equation CELSIUS.2

$dLAI_{max}$ : maximum daily increase of LAI

$V_{laimax}$  is a general parameter defining the slope at inflexion point of  $dLAI$  as a function of thermal time.

$densplt$ , stand density

$U_{lai}(n)$  leaf development unit (equal to  $V_{laimax}$  at inflexion point of  $d_{lai}(n)$ , equal to 3 at end of stage 2)

$NTT(n)$ : normalized thermal time

$LAI_{comp}$ : LAI threshold above which competition between plants for light occurs

$\Delta idens$ : effect of stand density on LAI

$bdens$ : cultivar dependant stand density threshold above which leaf area per plant is influenced by stand density

$adens$ : cultivar dependant parameter defining the sensitivity to stand density of leaf area per plant when stand density is above  $bdens$

1             $LAIStress(n)$ : stress coefficient applied to leaf area index (0 when stress is maximal, 1 when no  
2 stress occurs), calculated in equation CELSIUS.31

3            b) During development stage  $i$  among stages 3 to 5 (senescence of leaves accelerated by  
4 stress) LAI dynamics is simulated as follows:

5            Equation CELSIUS.4

$$dLAI(n) = \{\Delta LAI_{pot} - (SensSen \times (1 - LAIstress(n) \times LAI(n - 1)))\} \times f(Tm(n))$$

6            With

*During stages 3 and 4 no senescence occurs in the absence of stress:  $\Delta LAI_{pot} = 0$*

$$\text{During stage 5: } \Delta LAI_{pot} = (LaiRec - Lai(Dstge(4)))/CT(5)$$

7            And:

8             $SensSen$ : cultivar dependent sensitivity coefficient for leaf senescence accelerated by stress

9             $LaiRec$ : cultivar dependent potential value (in the absence of any stress) of LAI at maturity

10            $\Delta LAI_{pot}$ : potential average decrease of LAI after stage 2, in the absence of stress

11

## 12            2.4 Above Ground Biomass

13            See *PlanteClass.biomasse* in the software code

14            Intercepted solar radiation  $raint(n)$  for a day  $n$  is given by:

15            Equation CELSIUS.5 (taken from STICS)

$$raint(n) = 0.95 * ParSurRg * Rg(n) * (1 - Exp(-kext \times Lai(n)))$$

16            Where:

17             $ParSurRg$  is the ratio of photosynthetically active over total global solar radiation

18             $Rg(n)$  is global solar radiation of day  $n$

19             $kext$ : a cultivar-dependent extinction coefficient.

20

1 Total aboveground biomass of day  $n$  ( $Biom(n)$ ) is computed by adding  $dBiom(n)$ , the daily  
2 increase of biomass, to  $Biom(n-1)$ .

3  $dBiom(n)$  is calculated using the following equation taken from STICS:

4 Equation CELSIUS.6

$$dBiom(n) = CO2fact \times BiomStress(n) \times (Ebmax \times raint(n) - 0.0815 \times raint(n)^2)$$

5 With:

$$CO2fact = 2 - Exp(Ln(2 - alphaCO2)) \times (CO2c - 350) / (600 - 350)$$

6 Where:

7  $CO2c$  is the atmospheric concentration of  $CO_2$  at the time of the simulation

8  $alphaCO2$  is a cultivar dependant coefficient, mostly accounting for the C3 ( $alphaCO2=1.2$ ) or  
9 C4 ( $alphaCO2=1.1$ ) type of photosynthesis cycle of the species.

10  $Ebmax$  is the cultivar dependent maximum efficiency of net conversion of intercepted  
11 photosynthetically radiation into biomass

12  $BiomStress(n)$  is the stress coefficient applied to Biomass (0 when stress is maximal, 1 when  
13 no stress occurs), calculated using equation CELSIUS.31

#### 14 2.5 Grain yield

15 See *PlanteClass.Rendement* in the software code

16 Grain yield is calculated using equations taken from STICS

17 A non sink limited harvest index  $HI(n)$  on day  $n$  linearly increases with time at a cultivar  
18 dependent rate  $Vitircarb$ , starting at the first day of stage 4 and ending at maturity ( $DayStge(5)$ ), and  
19 with a cultivar dependent ceiling value  $HI_{max}$ , following the two equations below:

20 Equation CELSIUS.7:

*if  $n > DayStge(3)$  And  $n \leq DayStge(5)$  then*

$$HI(n) = Min(Vitircarb \times (n - DayStge(3) + 1); HI_{max})$$

21



1 When calculating final grain yield  $Y$ , sink limitation may occur due to a cultivar dependent  
2 ceiling value of the weight of 1 grain,  $P1gmax$ , and a grain number  $Ngrains$ , limited by possible stress  
3 impacting average growth rate  $Vitmoy$  during a  $Nbjgrain$  number of days preceding grain filling stage  
4 (starting a  $DayStge(3)$ ), as follows:

5 Equation CELSIUS.8:

$$Y = \text{Min}(HI(\text{DayStge}(5)); P1gmax \times Ngrains)$$

6 With

$$Ngrains = Cgrain \times Vitmoy + Cgrainv0$$

7 And

$$Vitmoy = (\text{Biom}(\text{DayStge}(3)) - \text{Biom}(\text{DayStge}(3) - Nbjgrain)) / Nbjgrain$$

8 Where:

9  $Cgrain$  and  $Cgrainv0$ : cultivar dependant parameters.

10

## 11 2.6 Root growth

12 See *PlantClass.Croirac* in the model code

13 Root biomass is not explicitly simulated, but the depth of the rooting zone,  $Zrac(n)$  is  
14 dynamically simulated from germination to  $DayStge(3)$  with a daily rate of root descent governed by  
15 thermal time, limited by the thickness of wet soil below root zone and by a maximal root depth  
16  $Zracmax$ , as follows for a day  $n$ :

17 Equation CELSIUS.9

$$Zrac(n) = \text{Min}(Zrac(n - 1) + \text{Min}(WZuR(n - 1); \text{DeltaRMax} \times f(Tm(n))); Zracmax)$$

18 Where:

19  $WZuR$ : Thickness of soil below the current root zone having moisture above wilting point  
20 (calculated using water balance equations).

21  $\text{DeltaRMax}$ : cultivar dependent maximal rate of root descent per unit thermal time.

1 3. *Mulch or soil - climate interface*

2 3.1 *Mulch biomass (Not used in the study)*

3 See *MulchClass.BiomasseMulch* in the software code

4 Equations taken from Scopel *et al.*, 2004.

5 The biomass of a straw mulch possibly present over the soil's surface,  $Q_{paillis}(n)$ , is assumed  
6 to decrease with time except in case an amount  $Q_{paillisApport}(n)$  is added that day:

7 Equation CELSIUS.10

$$Q_{paillis}(n) = Q_{paillis}(n - 1) \times \text{Exp}(-\text{Alpha}_{pail}) + Q_{paillisApport}(n)$$

8 Where:

9  $\text{Alpha}_{pail}$  : calibration parameter depending on the composition of mulch

10

11 An empirical relationship is used to convert  $Q_{paillis}(n)$  into the fraction of soil covered by the  
12 straw,  $\text{FracSoilCover}(n)$ :

$$\text{FracSoilCover}(n) = 1 - \text{Exp}(-\text{Beta}_{pail} \times Q_{paillis}(n))$$

13 Where

14  $\text{Beta}_{pail}$  : calibration parameter depending on the composition of mulch

15

16 3.2. *Runoff*

17 See *MulchClass.Ruissellement* in the software code

18 The model combines a model from Albergel *et al.* (1991) for bare soils, with the model of  
19 mulch reducing runoff from Scopel *et al.* (2004), according to the following equation:

20 Equation CELSIUS.11:

21 Water supply  $\text{precip}(n)$  (consisting on Rainfall plus Irrigation of the day) is split into runoff  
22  $\text{Ruis}(n)$  and water infiltrated into the soil and a straw mulch possibly present on the soil's surface,  
23 accounting for LAI reducing runoff, a typology of crusting of soil's surface, the biomass of straw

1 mulch, and an indicator  $IKJ(n)$  characterizing the rainfall sequence of the previous days, increasing  
 2 with the amounts of rainfall and decreasing when the number of days between rainfall events  
 3 increases:

$$Ruis(n) = \text{Max}(0; \text{Exp}(-0.5 * Lai(n)) \times (Ap1 + Ap3 \times IKJ(n) + b_{ruis} \times Qpaillis(n)) \\ \times (\text{precip}(n) - \text{Seuil\_Ruis}))$$

4 With:

$$IKJ(n) = (IKJ(n - 1) + \text{precip}(n - 1)) * \text{Exp}(-0.5)$$

5 And

$$\text{If } Ap1 + Ap3 * IKJ(n) = 0 \text{ Then } \text{Seuil\_Ruis} = 0$$

*Else*

$$\text{seuil} = (Ap4 - Ap2 \times IKJ(n)) / (Ap1 + Ap3 \times IKJ(n))$$

6 Where:

7  $b_{ruis}$ : a parameter controlling the increase of runoff due to the presence of a straw mulch  
 8 (generally a negative value, since straw mulch generally decreases runoff)

9  $Ap1...Ap4$ : empirical coefficients controlling runoff on the part of the soil directly exposed to  
 10 the impact of rain drops. When  $Ap2...Ap4$  are set to zero,  $Ruis(n)$  is a constant proportion  $b_{ruis}$  of  
 11 the share of daily rainfall exceeding a threshold  $\text{Seuil\_Ruis}$ , equal to  $Ap1$  in this particular case. When  
 12  $\text{Seuil\_Ruis}$  is set to zero and  $Ap1...Ap4$  are non zero, these coefficients correspond to a typology of  
 13 soil surface status as in Casenave and Valentin (1989; 1992) as follows:

Soil surface type	Vesicular porosity	Ap1	Ap2	Ap3	Ap4
1: no crust or predominant structural crust with remnant aggregates	<5%	0.2	0.03	0.004	3
2: runoff crust covering less area than structural crust	5 -30%	0.35	0.04	0.004	3
3: runoff crust predominating	>30%	0.900	0.05	0.002	10

14

15 Water available for infiltration into soil and the porosity of the straw mulch is  $W_{SM}(n)$ :

16 Equation CELSIUS.12

$$W_{SM}(n) = Precip(n) - Ruis(n)$$

1

2 3.3. Water stored into a porous straw mulch and evaporated (not used in the study)

3 See *MulchClass.BilanMulch* in the software code

4 Equations taken from Scopel *et al.*, 2004.

5 Straw mulch is assumed to have a certain capacity *CapacityMulch*, per unit o mulch biomass,  
6 for storing water, the corresponding reservoir *Stmulch* being updated on a day *n* as follows:

7 Equation CELSIUS.13

$$Stmulch(n) = Min(Qpaillis(n) \times CapacityMulch; Stmulch(n - 1) - Emulch(n) + FracSoilCover(n) \times W_{SM}(n))$$

8 Where:

9 *Emulch(n)* is the amount of water lost by mulch on day *n* by evaporation

10 The water available for soil infiltration *Win(n)* is the part of *W<sub>SM</sub>(n)* not stored in *Stmulch(n)*

11

12 Potential evaporation *EoSM(n)* at the top of the straw mulch is calculated on a day *n* assuming  
13 that reference Penman-Monteith potential evaporation *ETP(n)* is reduced by LAI using an extinction  
14 law analogy as follows:

15 Equation CELSIUS.14

$$EoSM(n) = Etp(n) \times Exp(-(kext - 0.2) \times Lai(n))$$

16 Potential evaporation applied to mulch, *EoMulch(n)* is calculated as follows:

17 Equation CELSIUS.15

$$EoMulch(n) = EoSM(n) \times (1 - Exp(-gamma_{mulch} * Qpaillis(n)))$$

18 Where:

19 *Gamma\_mulch* is a calibration coefficient depending on the species constituting the straw  
20 mulch.

1 Actual evaporation of mulch  $Emulch(n)$  is calculated as :

2 Equation CELSIUS.16

$$Emulch(n) = \text{Max}(Stmulch(n - 1); \text{Max}(EoMulch(n); Edecomp(n)))$$

3  $Edecomp$  is the amount of water contained in the quantity of mulch that decayed since the  
4 previous day:

$$Edecomp(n) = Stmulch(n - 1) \times (Qpaillis(n - 1) - Qpaillis(n)) / Qpaillis(n)$$

5

6 *4 Soil water balance*

7 *4.1 Soil moisture*

8 *See SolClass.EauSol in the software code*

9 The soil moisture model is taken from SarraMillet (Affholder, 1997)

10 Four main water reservoirs are accounted for dynamically, all having a water storage capacity  
11 calculated as the product of the thickness of the reservoir and a total available water per unit  
12 thickness TAW, the latter being constant throughout the soil, and calculated as follows:

13 Equation CELSIUS.17

$$TAW = (hmin - hcc) * da$$

14 Where:

15  $hmin$  and  $hcc$ : soil water content respectively at wilting point and at field capacity (in mass of  
16 water per mass of soil)

17  $da$ : soil bulk density

18

19 The four mains water reservoirs are the following:

20  $Stger$ , with a constant thickness  $Zger$  and starting at topsoil: contains the water impacting  
21 germination and seedlings growth until crop emergence.

1            *Stsurf* with a constant thickness *Zsurf* and starting at topsoil: contains the water impacting soil  
2 evaporation.

3            *Strac* with a dynamic thickness *Zrac* and starting at topsoil, calculated by equation CELSIUS.9,  
4 contains the water impacting crop transpiration, i.e. the transpirable soil water.

5            *Stdeep* with a dynamic thickness *Zsol-Zrac*, starting immediately below *Zrac* and ending at soil  
6 maximum depth *Zsol*.

7            More specifically three accessory reservoirs *Stnonrac* (thickness=*Zracmax-Zrac*), *Stmes*  
8 (*Zmes*), and *StTot* (*Zsol*) are calculated using the same principle, allowing calculation of drainage  
9 below the part of soil actually explored by roots at the end of root growth period, comparisons of  
10 simulated soil water with measurements performed down to a depth *Zmes* possibly differing from  
11 *Zsol*, and the calculation of the overall soil balance (*StTot* being the sum of *Strac* and *Stnonrac*).

12            For any of these reservoirs, noted generically *Stres(n)* or a reservoir of thickness *Zres*, the  
13 water balance accounting for soil evaporation *Esol(n)* and crop transpiration *Transpi(n)* is calculated  
14 as follows for a day *n*:

15            Equation CELSIUS.18

$$Stres(n) = Max(Min(Stres(n - 1) + Win(n) - Esol(n) \times CEres - Transpi(n) \times TEres; TAW \\ \times Zres); 0)$$

16            Where:

17            *CEres* and *TEres* are coefficients distributing Evaporation and transpiration among the  
18 reservoirs as follows:

19            *CEres*=1 in *Stsurf*, *Zger/Zsurf* in *Stger*, *Zrac/zsurf* until *zrac* is greater than *Zsurf* in *Strac*, and  
20 0 in *Stdeep*

21            *TEres*= *Zrac/Zsurf*, in *Stsurf* until *Zrac* overcomes *Zsurf*, *Zsurf/Zrac* afterwards, *Zrac/Zger* in  
22 *Stger* until *Zrac* overcomes *Zger*, *Zrac/Zger* afterwards, 1 in *Strac*, and 0 in *Stdeep*

23            And:

24            *Win(n)* is water input into the reservoir, corresponding to the drainage from the reservoir  
25 immediately above if applying or corresponding to water from irrigation or rainfall infiltrated into the  
26 soil.

1 Water  $Dres(n)$  drained out of a reservoir is calculated as the amount of water exceeding the  
2 storage capacity of the reservoir when calculating the balance, as follows:

3 Equation CELSIUS.19

$$Dres(n) = \text{Max}(0; TAW \times Zres \\ - (Stres(n - 1) + Win(n) - Esol(n) \times CEres - Transpi(n) \times TEres))$$

4

5 Water constraint  $WCSres(n)$  is calculated for a reservoir  $Stres(n)$  as the ratio of actual water  
6 content of the reservoir over its storage capacity as follows:

7 Equation CELSIUS.20

$$WCres(n) = Stres(n) / (TAW \times Zres)$$

8 This applies to  $WCsurf(n)$ ,  $WCger(n)$  and  $WCrac(n)$ , the water constraint respectively in the  
9 surface reservoir (water constraint reducing evaporation relatively to potential evaporation), in the  
10 germination plus emergence reservoir and the root zone reservoir (limiting transpiration relatively to  
11 potential).

12 The factor  $WConstGer(n)$  in equation CELSIUS.1, delaying germination and emergence in the  
13 reservoir  $Stger(n)$  is calculated from  $WCger(n)$  as follows:

14 Equation CELSIUS.21

$$\text{If } WCger(n) > 0 \text{ then } WConstGer(n) = 1 \text{ Else } WConstGer(n) = 0$$

15 *4.2 Soil evaporation*

16 *See SolClass.Evaporation in software code*

17 Potential soil evaporation  $Eos(n)$  is calculated accounting from the reduction of energy  
18 reaching soil surface due to the presence of leaves and a straw mulch as follows:

19 Equation CELSIUS.22:

$$Eos(n) = EoSM(n) - EoMulch(n)$$

20 Soil evaporation  $Esol(n)$  on a day  $n$  is calculated as follows:

21 Equation CELSIUS.23:

1

*if WCSurf(n) ≥ SeuilEvap Then Esol(n) = Eos(n)*

*if WCsurf(n) < SeuilEvap Then*

*Esol(n) = Eos(n) \* WCSurf(n) / SeuilEvap*

2       Where:

3       *SeuilEvap*: soil dependent calibration parameter

4

5       4.3 Crop transpiration

6       See *CultureClass.CalcTranspiMC* in the software code

7       Potential evapotranspiration is calculated using a crop coefficient *KC(n)* approach taken from  
8       STICS, in which *Kc(n)* is calculated with an empirical relationship between *Kc(n)* and *LAI(n)*, and  
9       taken as follows:

10       Equation CELSIUS.24

$$Kc(n) = (1 + (Kmax - 1) / (1 + Exp(-1.5 \times (Lai(n) - 3))))$$

11       Where:

12       *Kmax* : cultivar-dependent parameter

13       Potential crop transpiration *eo(n)* is calculated using the classical crop coefficient approach  
14       applied to Penman-Monteith reference potential evapotranspiration *Etp(n)*:

15       Equation CELSIUS.25

$$eo(n) = Etp(n) * Kc(n)$$

16       Potential crop transpiration *eop(n)* is calculated by subtracting potential evaporation to *eo(n)*,  
17       and accounting for an increase of up to 40% in the atmosphere's water demand at the vicinity of the  
18       crop when soil (and mulch) evaporation is low:

19       Equation CELSIUS.26

$$eop(n) = (eo(n) - EoSM(n)) \times (1.4 - (0.4 \times (Esol(n) + Emulch(n)) / EoSM))$$

20



1 Actual transpiration is reduced by the fraction of transpirable soil water following the  
2 approach of Allen *et al.* (1998) as follows:

3 Equation CELSIUS.27

$$\text{If } WCrac(n) \geq 0.7 \text{ then } Transpi(n) = eop(n)$$

$$\text{if } WCrac(n) < 0.7 \text{ then } Transpi(n) = eop(n) \times WCrac(n)/0.7$$

4

## 5 *5 Stress calculations*

### 6 *5.1 Nitrogen constraint*

7 *See PlantClass.stressAzoteOld in the software code*

8 A nitrogen limiting coefficient is calculated as follows:

9 Equation CELSIUS.28

$$NLC = \text{Min}[1; \alpha * (N_{soil} + N_{inorg} + N_{org} + N_{symb})/I_{fertmax}]$$

10

11 Where:

12  $N_{soil}$ ,  $N_{inorg}$ ,  $N_{org}$ , and  $N_{symb}$  are the mineral nitrogen amounts available to crops from,  
13 respectively, soil organic matter mineralization, inorganic fertilization, mineralized N from organic  
14 fertilization, and symbiotic fixation of atmospheric N by leguminous crops

15  $I_{fertmax}$  is the level of nitrogen supply above which growth is not limited,

16  $\alpha$  a calibration coefficient (less than 1) accounting for losses of mineral N through volatilization  
17 and leaching.

18

### 19 *5.2 Temperature stress applied to biomass growth*

20 *See PlanteClass.Biomasse in the software code*

21 Equation taken from STICS

22 Equation CELSIUS.29

$$\text{If } Tm(n) < Tcopt \text{ then } Ftemp(n) = 1 - \left( \frac{Tm(n) - tcopt}{tcmin - tcopt} \right)^2$$

$$\text{If } Tm(n) \geq Tcopt \text{ then } Ftemp(n) = 1 - \left( \frac{Tm(n) - tcopt}{tcmax - tcopt} \right)^2$$

1

2 *Tcmin, tcopt, tcmax*: cultivar-dependent parameters, respectively the minimal, optimal and  
3 maximal air temperatures for light to biomass conversion efficiency

4 *5.3 Water stress*

5 *See PlanteClass. Calcule\_LAI\_SemiAride and PlanteClass.Biomass in the software code*

6 Water stress reducing biomass growth (*WSfactBio(n)*) and LAI growth (*WSFactLAI(n)*) a day *n*  
7 are calculated using the respective thresholds *WSBioT* and *WSLaiT* of the reduction of the fraction  
8 of available soil water above which growth is reduced relatively to potential, as follows:

9 Equation CELSIUS.30:

$$\text{if } WCrac(n) \geq (1 - WSBioT) \text{ then } WSfactBio(n) = 1$$

$$\text{if } WCrac(n) < (1 - WSBioT) \text{ then } WSfactBio(n) = WCrac(n)/(1 - WSBioT)$$

$$\text{if } WCrac(n) \geq (1 - WSLaiT) \text{ then } WSfactLai(n) = 1$$

$$\text{if } WCrac(n) < (1 - WSLaiT) \text{ then } WSfactLai(n) = WCrac(n)/(1 - WSLaiT)$$

10 *5.4 Interactions between water and nitrogen stresses.*

11 *See PlanteClass. Calcule\_LAI\_SemiAride and PlanteClass.Biomass in the software code*

12 The stress factors *LAIStress(n)* and *BiomStress(n)* reducing growth in LAI and aboveground  
13 biomass (equations 3 and 6) respectively are calculated as follows:

14 Equation CELSIUS.31

$$LAIStress(n) = \text{Min}(WSfactLai(n); NLC)$$

$$BiomStress(n) = \text{Min}(WSfactBio(n); NLC)$$

15

### 1 **Part III. Details about model calibration and test**

2 CELSIUS involves a number of empirical parameters, a majority of which are cultivar-dependent,  
3 that had to be estimated by calibrating the model against measurements of key variables controlled  
4 by these parameters.

5 The data set used for calibration and test was the data set of millet plots detailed in Affholder  
6 (1997), plus data of groundnut plots from the ESPACE-PRODCLIM database (Forest and Cortier, 1989)  
7 and data of maize plots under the savannah environment of the Cerrado region of Brazil, as  
8 presented in Affholder *et al* (2003) and Affholder *et al* (2013). The soil water balance model as well as  
9 the sowing and emergence model, and their calibration parameters, were taken almost unchanged  
10 from Sarra-millet that provided reliable predictions of soil moisture and date chosen by farmers for  
11 sowing as depending on the rainfall sequence (Affholder, 1997). Readers may therefore refer to this  
12 publication for details about calibration and test of these components.

13 Cultivar and species dependent parameters relative to growth and development under non  
14 nitrogen limited environment of millet cultivar 'Souna3', the cultivar most commonly grown in  
15 Senegal, were taken unchanged from Affholder *et al* (2013). This also applied to species dependent  
16 parameters relative to maize. Readers interested to specific values and the literature sources in  
17 which they were found may refer to that article.

18 Two groundnut cultivars had to be considered, each for one of the two subzones of the study,  
19 namely the cultivars 55-437 and 73-33, used respectively in the Sine and Saloum zones. Species  
20 dependent parameters were taken from the literature (table C1). Thermal time development  
21 constants of these cultivars were obtained by summing thermal time over the corresponding  
22 observed dates of beginning and end of the key phenological stages as recorded in plots of the  
23 ESPACE database. Cultivar-dependent parameters of groundnut were calibrated using the same  
24 principle as in Affholder *et al*, (2013), and notably parameters Cgrain and CgrainV0 were estimated  
25 for each cultivar by fitting the simulated number of grains to the boundary line of observed Ngrain  
26 plotted against simulated Vitmoy, for the whole set of groundnut plots in the database and setting  
27 the model for PYE calculation (*i.e.* with nitrogen stress not accounted for).

28 Except for thermal time constants, too few data were available in our database for calibrating  
29 with the same method as above the cultivar dependent parameters of maize for cultivar Noor96. We  
30 instead adapted the parameters of a cultivar used in family farms of Brazil, for which PYE had been  
31 previously calibrated (Affholder *et al.*, 2003), to obtain a potential yield Y0 of 3Mg.ha<sup>-1</sup>, matching  
32 with the potential yield claimed in the technical leaflet provided with seeds of that cultivar.

1 The parameters relative to nitrogen limitations ( $N_{symb}$ ,  $I_{fertmax}/\alpha$ ) were set so that the  
 2 maximum and median values of simulated AGB<sub>w</sub> and Y<sub>w</sub>, over the set of historical weather data of  
 3 each of the two Sine and Saloum subzones, was equal to the maximum and median observed value  
 4 in the database for the species and crop management considered, for each of the following crop  
 5 management types: MilExt on bushfield, MilManu on bushfield, MilManu on homefield, GroundExt  
 6 on bushfield, GroundManu on bushfield (see table C1 on main text for characteristics of the cropping  
 7 systems).

8 Figure C1 shows a final comparison, after calibration of CELSIUS, between simulated and  
 9 observed yield for Millet, using the same data set as in the validation of SarraMillet (Affholder, 1997)  
 10 with the exception of 12 plots (over 89) from a village in the north of the millet production area, for  
 11 which rainfall data have been lost. With this plot sample for which Nitrogen amounts brought by  
 12 organic and inorganic fertilization as well as organic N stocks in soils had been estimated in each plot,  
 13 the model shows a relatively good capacity to predict the impact of nitrogen inputs and varying  
 14 water stress on millet yield, as also denoted by the relatively satisfactory values of the Relative Root  
 15 Mean Square of Error (RRMSE) and of model efficiency (ME), of respectively 27% and 0.68.

16

17 Table C1: Species dependent parameters taken from the literature for simulation of groundnut.  
 18 See Affholder *et al.*, 2013 for parameters relative to Millet and Maize.

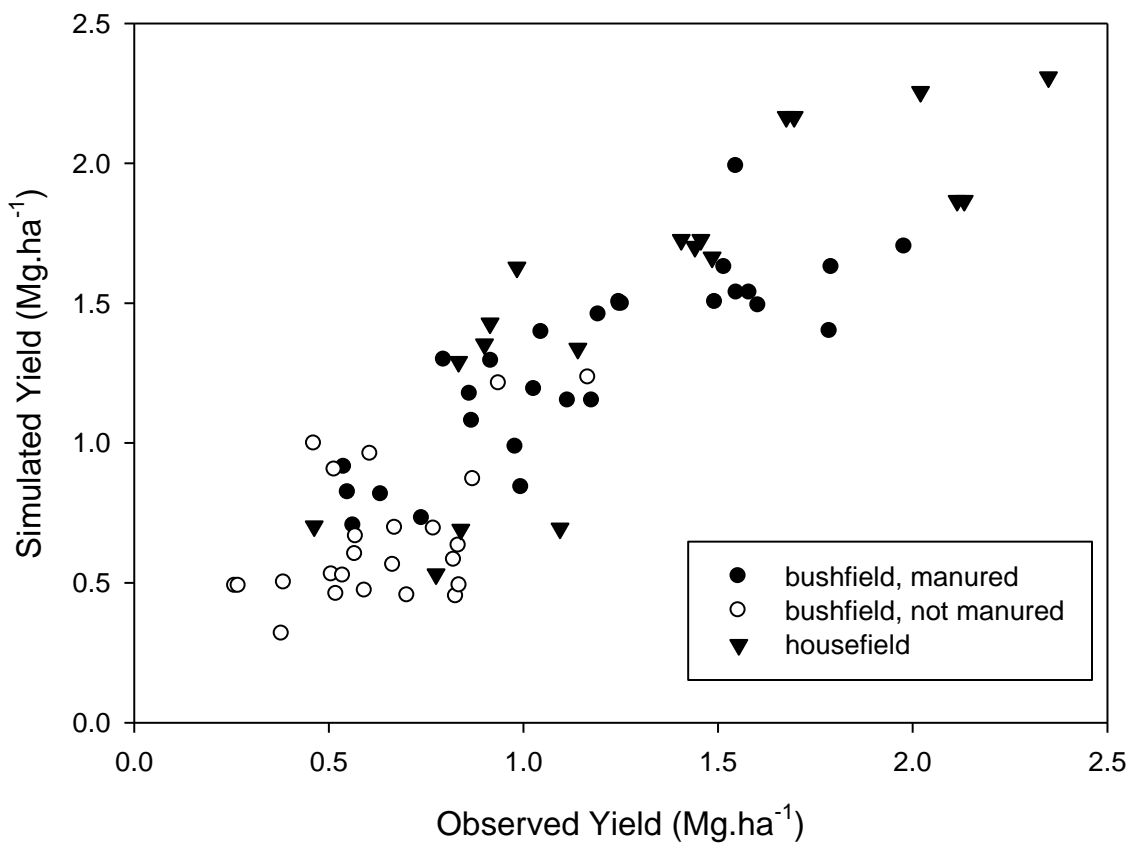
	Value	Unit	References
tdmin	10	°C	(Leong and Ong, 1983; Mohamed <i>et al.</i> , 1988; Bell and Wright, 1998; Caliskan <i>et al.</i> , 2008)
tdmax	45	°C	
tcmn	10	°C	
tcmax	45	°C	
tcopt	32	°C	
Ebmax	2.6		(Sarr <i>et al.</i> , 2004; Clavel <i>et al.</i> , 2005; Kiniry <i>et al.</i> , 2005)
kext	0.62		
Hlmax	0.47		
LAlmax	6		
Zracmax	170	cm	(Allen <i>et al.</i> , 1998; Collino <i>et al.</i> , 2000; Collino <i>et al.</i> , 2001; Dardanelli <i>et al.</i> , 2004; Sarr <i>et al.</i> , 2004)
Kmax	1.2		

19

20

1

Figure C1. Model test after calibration



2

3

## Appendix D. ANDERS-CELCIUS model calibration and evaluation

We used time-series observations of local monthly product prices to simulate price distributions. We first calculated the average price at harvest over the period 2008-2012. We also estimated the standard deviation and correlation matrix of the crop prices over the period 1996-2012. We then performed Latin-Hypercube sampling using the method described in Richardson et al. (2000) to generate 20 equi-probable states of nature relative to prices and taking into account the correlations between the prices of products.

The parameters used to calibrate the model were the absolute risk aversion ( $r_a$ ) and transaction cost coefficients, the latter defined as the gap between the selling and the purchase output prices at the farm gate. The values of risk aversion and transaction costs were assigned so as to minimize the deviation between the observed and the simulated farm operational plan (cropping system and animal fattening). While the values of transaction costs were assigned per subzone, the values of the absolute risk aversion were calibrated for each farm, according to their own initial wealth, but the same relative risk aversion were assigned to all farm-types. The relationship between the absolute risk aversion ( $r_a$ ) and the relative risk aversion ( $r_r$ ) is given as follows (Hardaker *et al.*, 2004):

$$r_a = \frac{r_r}{W} \quad (D1)$$

To calculate  $r_a$  we thus first assessed the initial wealth for each simulated farm using as proxies the number of seeders, hoes, plows and carts, and the herd size (cattle, draught animal). The values and the corresponding levels of risk aversion are given in Table D1. The calibration led to a value of the relative risk aversion equal to 2 for all the types which is a reasonable level according to the literature. For example, Hardaker et al. (2004) proposed a classification where the coefficients range from 0 (risk neutral) to 4 (extremely risk averse) with values of 2 referring to *rather* risk averse farmers. Recently, De Nicola (2015a) estimated a risk aversion coefficient of 2.67 for Malawian farmers while the estimates by Charness and Viceisza (2012) for Senegalese farmers correspond to a coefficient of 1.39, according to calculations by De Nicola (2015b). Transactions costs depend on the crop and their highest level reach 1.17 in the Sine subzone and 1.13 in the Saloum subzone.

1 Table D1. Values of the initial wealth and the levels of risk aversion

	Sine1	Sine2	Saloum1	Saloum2
Initial wealth (FCFA)	700 000	1 800 000	800 000	2 000 000
Relative risk aversion ( $r_r$ )	2	2	2	2
Absolute risk aversion ( $r_a$ )	0.0000028	0.0000011	0.0000025	0.000001

2

3 The model shows a good level of consistency between observed production choices and those  
 4 simulated in the baseline scenario (i.e. without any insurance or subsidy program). At the aggregated  
 5 level of crops, it reproduces the quasi-absence of maize in the Sine farm-types (present in a marginal  
 6 proportion in Sine1) and its presence in the Saloum farm-types (Table D2). Furthermore, the  
 7 simulated hierarchy among the three crops (crop mix) corresponds to the observations in every farm-  
 8 type. We also observe that the total amount of manure produced through animal husbandry is close  
 9 to the observed figure (as indicated by the total area dedicated to manure-based cropping systems).  
 10 Also, if the number of animal for fattening is slightly under-estimated for Sine, values obtained are  
 11 acceptable.

12

13 Table D2: comparison between observed and simulated farm operational plan (crop mix) for each farm-type

	Sine1		Sine2		Saloum1		Saloum2	
	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim
Millet (ha)	1.91	1.81	5.66	5.75	3.73	3.8	7.47	8.01
Maize (ha)	0.06	0.07	0	0	0.59	0.34	2.16	1.7
Groundnut (ha)	1.53	1.62	4.84	4.75	2.18	2.35	5.57	5.49
Manure application (ha)	1.14	1.17	4.01	3.67	2.48	2.18	4.86	3.57
Head of cows for fattening	0.5	0.4	1.9	1.6			n/a	
Head of sheep for fattening	3.3	0	5	4.8	0.2	0	0.5	0.8

14

15 At the cropping system level, the same cropping systems (extensive and manure-based millet,  
 16 extensive groundnut and, in Saloum, fertilized maize) dominate in both observations and simulations  
 17 (Fig. D1).

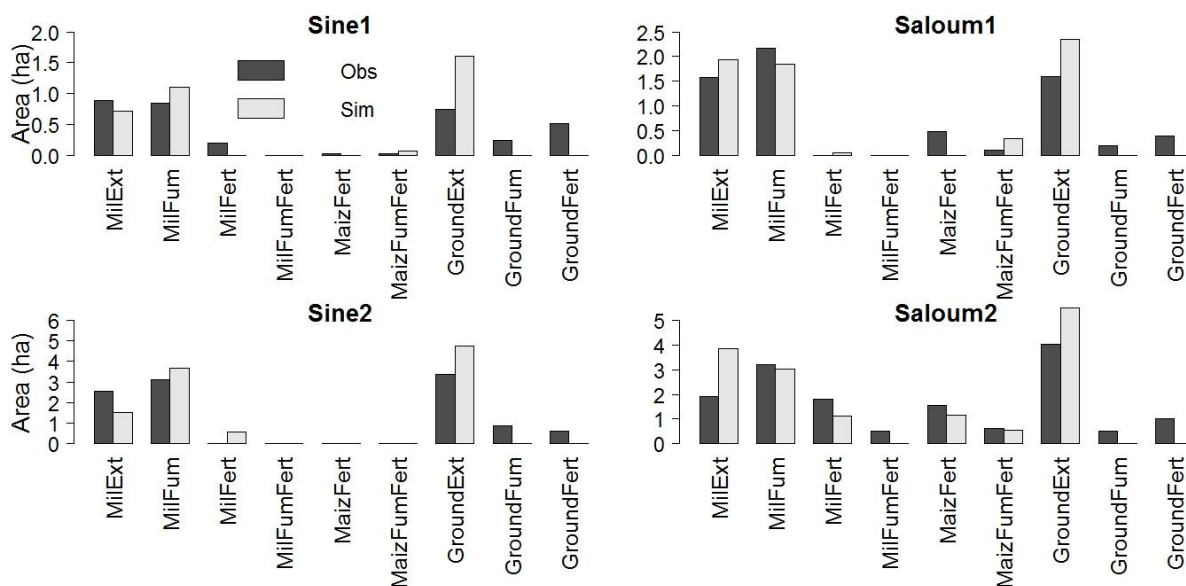


Fig. D1: comparison between observed (Obs) and simulated (Sim) land allocation across crops and cropping systems.

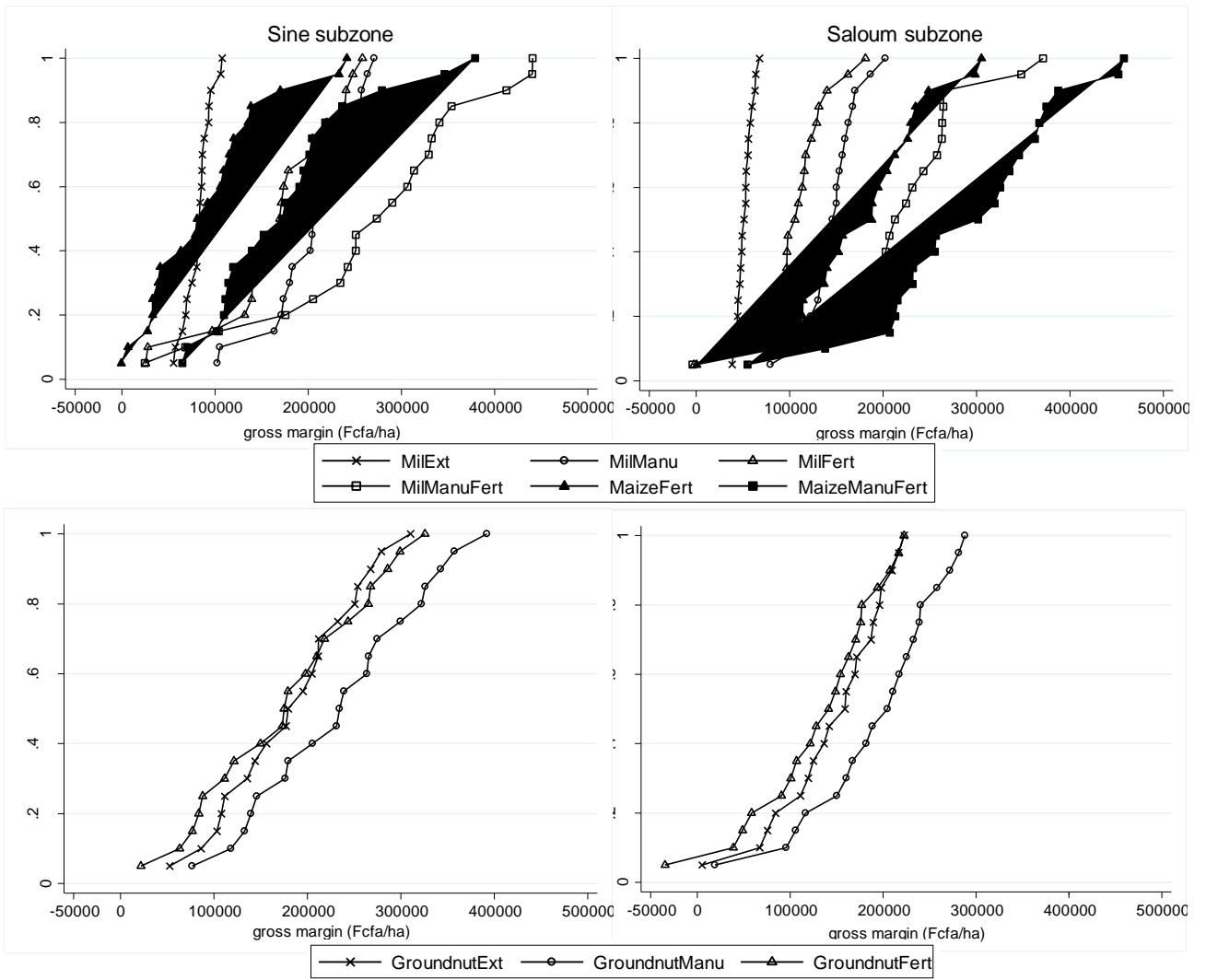
The main discrepancies between the observed results and the simulations bear on the slight but systematic overestimation of extensive groundnut and a concomitant underestimation of intensive groundnut compared to observations. Interviews with farmers and local experts regarding this point suggest that the typical practice is closer to the predictions of the model than to what was observed during our farm survey of 2012. The expectancies of farmers, at sowing time, regarding the selling price of groundnut at harvest, may some years be strongly influenced by the government's communication encouraging farmers to invest more in groundnut, leading to cultivation choices that may slightly differ from what would be expected from prices expectancies based on series of past observed prices as in our model. Nevertheless, in the observed farms, whatever the subzone and farm-type, areas cropped with extensive groundnut clearly overcome the areas with more intensive groundnut, and this is well captured by the baseline simulation.



1 **Appendix E. Distribution of gross margins for each cropping system**

2 Fig. E1 shows the whole distribution of gross margins (GM) for each cropping system. GMs are  
3 defined here as the difference between the stochastic total value of production (yield times unit  
4 price) and the production costs. Production costs include only the costs of seeds and chemical inputs.  
5 Neither the labor costs nor the value of the manure nutrients have been included in these cumulative  
6 distribution functions since the opportunity cost of family labor and the cost of manure produced on  
7 the farm vary between seasons. We observe that extensive cropping systems (i.e. without any use of  
8 inorganic fertilizer or manure) give less risky distributions than more intensive cropping systems (i.e.  
9 requiring inorganic fertilizer and/or manure). As an example in about 15% of the states of nature, the  
10 extra yield of millet obtained from inorganic fertilizer application cannot compensate for the cost of  
11 purchasing the fertilizer. This result is in accordance with well-known results from previous research  
12 reporting the risk-increasing property of crop intensification (Affholder, 1997; Rötter and van Keulen,  
13 1997). The distribution of manure-based cropping system yields is also flatter. Note that the  
14 *dominance* of manure-based cropping systems over the extensive cropping system could result from  
15 not taking into account direct and indirect costs of farm manure in GM calculations. However, in the  
16 ANDERS model (and in the real world), the management of manure does involve labor input so that  
17 the risk at the field scale of a low yield obtained with manure application in the driest years may  
18 translate into economic risk at the farm scale. Moreover, the yield risk related to intensification is  
19 much higher in the Sine subzone, where the climate is drier than in Saloum. This risk is also higher for  
20 maize than for millet. The groundnut GM distributions indicate that fertilizer-based cropping systems  
21 are not much economically profitable since in about 60% and 80% of the states of nature (in the Sine  
22 and the Saloum subzones, respectively), extensive cropping systems give higher GM.

23



1

2

Fig. E1: Cumulative distribution functions of gross margins for cereals (millet and maize) and groundnut cropping systems

3

4

# 1 Appendix F: The bioeconomic ANDERS model

2

## 3 1. Sets:

4

5 *ac*: agricultural activities

6 *ag*: age of family members

7 *an*: animal types ,

8 *e*: state of nature

9 *ge*: gender of family members

10 *inp*: inputs

11 *ins*: insurance type

12 *ne*: nutrient type (digestible nitrogen matter / energy in kcal)

13 *p*: period

14 *pdt*: agricultural products

15 *s*: soil types,

16 *sps*: subsidy program scenario

17 *str*: straw type (from millet or maize; subset of *pdt* for straw)

18 *t*: type of off-farm labor (including agricultural and non-agricultural labor, remittances)

19 *tan*: animals used for traction (subset of *an*)

20 *z*: field types

21

## 22 2. Variables

23

24 Endogenous variables are in *UPPER CASE* and exogenous parameters in *lower case*

25

26  $\pi_e$  income by state of nature

27  $activ_{ge,ag}$  active family members by gender and age

28  $anim_{an,p}$  stock of animals by type of animal and period

29  $animneed_{ne,p}$  animals nutritional needs (*ne*) by period

30  $atneed_{z,s,ac,p}$  animal traction requirements by field type, soil type, agricultural activity and period

31  $BA_{an,p}$  animals bought by type of animal and period

32  $BC_{pdt,p,e}$  agricultural products bought for consumption

33  $BRW_p$  borrowing by period

34  $CASH_{p,e}$  Cash available by period *p* and state of nature

35  $cashtr_{sps}$  Cash transfer by subsidy program scenario

36  $canim_{an}$  return from animal selling by animal type

37  $co_{s,z,ac,inp,p}$  input coefficient for agricultural activities by animal type by field type, soil type,

38 agricultural activity, input and period

39  $coanim_{an}$  costs associated with raising animals by animal type

40  $CONSA_{p,pdt,e}$  animal consumption of farm products by period, product and state of nature

41  $CONSAT_{p,pdt,e}$  Total animal consumption by period, product and state of nature

42  $CONSH_{p,pdt,e}$  human consumption of agricultural products by period, product and state of nature

43  $CONSO_{p,pdt,e}$  Other consumption of farm products by period, product and state of nature (straw)

44  $contf_{ne}$  Nutritional content of purchased feedstock by nutrient type

45  $contpa_{ne,p}$  Nutritional content of pasturing by nutrient type and period

46  $contpdt_{ne}$  Nutritional content of straw by nutrient type

47  $FEED_{an}$  feedstock bought for animals by animal type

48  $FINCASH_e$  Cash available at the end of the year, by state of nature

49  $FINSTOCKAC_{pdt,e}$  agricultural product stocks at the end of the year by product and state of nature

50  $human_{ag,ge}$  family members by age and gender

- 1  $i$  interest rate
- 2  $inicalsh$  initial cash
- 3  $inistock_{pdt}$  initial stock by agricultural product
- 4  $isubv_{sps}$  subsidy on interest rate by subsidy program scenario
- 5  $inpsubs_{sps}$  subsidy on inputs price by subsidy program scenario
- 6  $inssubs_{sps}$  subsidy on insurance premium by subsidy program scenario
- 7  $INSX_{ac,ins}$  insured area cultivated by activity and insurance type
- 8  $kcal_{pdt}$  Energy (in kcal) contained in each product, by product
- 9  $kcalneed_{ge,ag,p}$  Energy (in kcal) necessary to feed households members by gender, age and period
- 10  $Lab_{ac,p}$  labor need by agricultural activity and period
- 11  $land_{s,z}$  farm endowment in land by type and zone
- 12  $manuprod_{an}$  manure production by animal type
- 13  $minc_p$  minimum expenditure in cash for the household by period
- 14  $OFF_{t,p}$  off farm activities by type of off-farm labor and period
- 15  $pac_{pdt,p,e}$  crop buying prices by product, period and state of nature
- 16  $panim_{an,p}$  animal prices by type of animals and period
- 17  $past_{p,e}$  feed from pasture by period and state of nature
- 18  $Pastarea_p$  pasture Area by period
- 19  $PAYOFF_{ac,ins,e}$  Payoff associated with insurance by agricultural activity, insurance type and state of
- 20 nature
- 21  $pco_{inp,p}$  inputs prices by input and period
- 22  $pfeed_{an}$  feed price by animal type
- 23  $pinsu_{ac,ins}$  Insurance premium by agricultural activity and insurance type
- 24  $pvac_{pdt,p,e}$  crop selling prices by product, period and state of nature
- 25  $pwx_p$  agricultural labor price by period
- 26  $ra$  absolute risk aversion
- 27  $RENTA_p$  rented animals for traction by period
- 28  $SA_{an}$  animals sold by animal type
- 29  $SC_{pdt,p,e}$  crops sold by product, period and state of nature
- 30  $STOCKAC_{pdt,p,e}$  agricultural product stocks by product, period and state of nature
- 31  $straw_{str,e}$  coefficient for straw used for manure by straw type and state of nature
- 32  $tracd_{tan,p}$  days of traction by animal type and period
- 33  $w$  initial wealth
- 34  $wd_{ge,ag,p}$  working days by gender, age and period
- 35  $WFAM_p$  family labor used on farm by period
- 36  $WX_p$  agricultural labor bought by period
- 37  $X_{s,z,ac}$  area cultivated by soil type, field type and agricultural activity
- 38  $Y_{s,z,ac,pdt,e}$  yield by animal type by soil type, field type, agricultural activity, product and state of nature
- 39  $YPast_{p,e}$  pasture capacity by period and state of nature
- 40

### 3. Equations

Objective function

$$EU = \frac{1}{n} \sum_{e=1}^n 1 - \text{Exp}[-r_a(\pi_e + w)] \quad (\text{F1})$$

Certainty equivalent income

$$CEI = \frac{\ln[1-EU]}{-r_a} - w \quad (\text{F1B})$$

Income

$$\begin{aligned} \pi_e = & \sum_{p,pdt} (\sum_{ac,s,z} (X_{s,z,ac} * \text{yield}_{s,z,ac,pdt,e}) - \text{CONSA}_{p,pdt,e} - \text{CONSO}_{p,pdt,e}) * \text{pvac}_{pdt,p,e} - \sum_{inp,p} \sum_{s,z,ac} X_{s,z,ac} * \\ & \text{co}_{s,z,ac,inp,p} * \text{pco}_{inp,p} * (1 - \text{inpsubs}_{inp,sps}) - \sum_p \text{WX}_p * \text{pwx}_p - \sum_{ac,ins} \text{pinsu}_{ac,ins} * (1 - \text{inssubs}_{sps}) * \\ & \text{INSX}_{ac,ins} + \text{PAYOFF}_{ac,ins,e} * \text{INSX}_{ac,ins} \\ & + \sum_{p,an} (\text{canim}_{an} - \text{coanim}_{an} - \text{FEED}_{an} * \text{pfeed}_{an}) * (\text{anim}_{an,p} + \text{BA}_{an,p} - \text{SA}_{an,p}) + (\text{BA}_{an,p} - \text{SA}_{an,p}) * \\ & \text{panim}_{an,p} + (\text{anim}_{an,"p7"} - \text{SA}_{an,"p7"}) * \text{panim}_{an,p} + \sum_{t,p} \text{OFF}_{t,p} + \sum_{sps} \text{cashtr}_{sps} - \sum_p i * (1 - \text{isubs}_{sps}) * \text{BRW}_p \end{aligned} \quad (\text{F2})$$

Land constraint

$$\sum_{ac} X_{s,z,ac} \leq \text{land}_{s,z} \quad (\text{F3})$$

Labor needs

$$\sum_{s,z,ac} X_{s,z,ac} * \text{lab}_{s,ac,p} + \sum_{an} (\text{anim}_{an,p} + \text{BA}_{an,p} - \text{SA}_{an,p}) * \text{lab}_{an,p} + \sum_t \text{OFF}_{t,p} \leq \text{WFAM}_p + \text{WX}_p \quad (\text{F4})$$

Labor constraint

$$\text{WFAM}_p + \sum_t \text{OFF}_{t,p} \leq \sum_{ge,ag} \text{activ}_{ge,ag} * \text{wd}_{ge,ag,p} \quad (\text{F5})$$

Animal traction constraint

$$\sum_{s,z,ac} X_{s,z,ac} * \text{atneed}_{s,z,ac,p} - \text{RENTA}_p \leq \sum_{tan} \text{anim}_{tan} * \text{tracd}_{tan,p} \quad (\text{F6})$$

Cash equations

$$\text{CASH}_{p,e} \geq 0 \quad (\text{F7})$$

For  $p \geq 1$ :

$$\begin{aligned} \text{CASH}_{p,e} = & \text{CASH}_{p-1,e} + \sum_{pdt} \text{SC}_{pdt,p-1} * \text{pvac}_{pdt,p-1,e} \\ & - \sum_{inp} \sum_{s,z,ac} X_{s,z,ac} * \text{co}_{s,z,ac,inp,p-1} * \text{pco}_{inp,p-1} * (1 - \text{inpsubs}_{inp,sps}) \\ & - \text{WX}_{p-1} * \text{pwx}_{p-1} - \text{RENTA} * \text{Pra} \\ & + \sum_{an} (\text{Canim}_{an} - \text{coanim}_{an} - \text{FEED}_{an} * \text{pfeed}_{an}) * (\text{anim}_{an,p-1} - \text{SA}_{an,p-1} + \text{BA}_{an,p-1}) \\ & + (\text{SA}_{an,p-1} - \text{BA}_{an,p-1}) * \text{panim}_{an,p-1} - \sum_{pdt} \text{BC}_{p-1,pdt,e} * \text{pac}_{p-1,pdt,e} \\ & + \sum_t \text{OFF}_{t,p-1} + \text{BRW}_{p-1} - \text{minc}_{p-1} \\ & - \text{if}(P=3) \sum_{ac,ins} \text{pinsu}_{ac,ins} * (1 - \text{inssubs}_{sps}) * \text{INSX}_{ac,ins} + \text{cashtr}_{sps} \\ & + \text{if}(P=6) \text{PAYOFF}_{ac,ins} * \text{INSX}_{ac,ins} \end{aligned} \quad (\text{F7B})$$

Final cash

$$\begin{aligned} \text{FINCASH}_e = & \text{CASH}_{p7,e} \\ & + \sum_{pdt} \text{SC}_{pdt,"p7"} * \text{pvac}_{pdt,"p7"} + \sum_{an} \text{SA}_{an,"p7"} * \text{panim}_{an,"p7"} - \sum_{pdt} \text{BC}_{p7",pdt,e} * \text{pac}_{p7",pdt,e} \\ & - \sum_p \text{BRW}_p * (1 + i(1 - \text{isubs}_{sps})) \end{aligned} \quad (\text{F8})$$

Supply-utilization account for  $p \geq 1$ :

$$\begin{aligned}
& 1 \\
& 2 \quad STOCKAC_{pdt,p,e} = STOCKAC_{pdt,p-1,e} \\
& 3 \quad + BC_{pdt,p-1,e} - SC_{pdt,p-1,e} - CONSAT_{p-1,pdt,e} - CONSH_{p-1,pdt,e} - CONSO_{p-1,pdt,e} \\
& 4 \quad + \text{if}(P = P6) \sum_{ac,s,z} X_{s,z,ac} * yield_{s,z,ac,pdt,e} \quad (F9)
\end{aligned}$$

$$\begin{aligned}
& 5 \\
& 6 \quad \text{Final stocks} \\
& 7 \quad FINSTOCKAC_{pdt,e} = STOCKAC_{pdt,"P7",e} + BC_{pdt,"P7",e} - SC_{pdt,"P7",e} \quad (F10)
\end{aligned}$$

$$\begin{aligned}
& 8 \\
& 9 \quad \text{Family nutritional constraint} \\
& 10 \quad \sum_{ge,ag} kcalneed_{ge,ag,p} * human_{ge,ag} \leq \sum_{pdt} kcal_{pdt} * CONSH_{p,pdt,e} \quad (F11)
\end{aligned}$$

$$\begin{aligned}
& 11 \\
& 12 \quad \text{Animals nutritional constraint} \\
& 13 \quad \sum_{an} animneed_{an,ne,p} * (anim_{an,p} + BA_{an,p} - SA_{an,p}) \leq contpa_{ne,p} * past_{p,e} + \sum_{pdt} contpdt_{ne} * \\
& 14 \quad CONSAT_{p,pdt,e} + \sum_{an} conf_{ne} * FEED_{an} \quad (F12)
\end{aligned}$$

$$\begin{aligned}
& 15 \\
& 16 \quad \text{Pasture capacity constraint} \\
& 17 \quad past_{p,e} \leq Pastarea_p * YPast_{p,e} \quad (F13)
\end{aligned}$$

$$\begin{aligned}
& 18 \quad \text{Manure production} \\
& 19 \quad \sum_{an} (anim_{an,p} + BA_{an,p} - SA_{an,p}) * a_{an} * manuprod_{an} * straw_{str,e} = CONSO_{p,str,e} \quad (F14)
\end{aligned}$$

$$\begin{aligned}
& 20 \quad \text{Manure balance} \\
& 21 \quad \sum_p \sum_{s,z,ac} X_{s,z,ac} * CO_{s,z,ac,"man",p} \leq \sum_{an} (anim_{an,p} + BA_{an,p} - SA_{an,p}) * manuprod_{an} \quad (F15)
\end{aligned}$$

$$\begin{aligned}
& 22 \\
& 23 \quad \text{Viability constraint on expected cash} \\
& 24 \quad inicash \leq \frac{1}{n} \sum_{e=1}^n FINCASH_e \quad (F16)
\end{aligned}$$

$$\begin{aligned}
& 25 \\
& 26 \quad \text{Viability constraint on expected energy (in kcal) for stocks} \\
& 27 \quad \sum_{pdt} inistock_{pdt} * kcal_{pdt} \leq \frac{1}{n} \sum_{e=1}^n \sum_{pdt} FINSTOCKAC_{pdt,e} * kcal_{pdt} \quad (F17)
\end{aligned}$$

$$\begin{aligned}
& 28 \\
& 29 \quad \text{Viability constraint on cash (softened by informal insurance)} \\
& 30 \quad 0.5 * inicash_e \leq FINCASH_e \quad (F18)
\end{aligned}$$

$$\begin{aligned}
& 31 \\
& 32 \quad \text{Viability constraint on stocks (softened by informal insurance)} \\
& 33 \quad 0.5 * \sum_{pdt} inistock_{pdt,e} * kcal_{pdt} \leq \sum_{pdt} FINSTOCKAC_{pdt,e} * kcal_{pdt} \quad (F19)
\end{aligned}$$

34

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