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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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 andBinswanger, 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) has 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 does 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 and 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), Elaber 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 Bamby on Fig. 1) and Niouro du Rip (13°44’N, 15°46’W), respectively in the center north (locally known as the Sîne region) and in the south of the groundnut basin (Saloum), corresponding to contrasting drought risk, expected to lead to contrasting constraints on crop intensification (Alfholder, 1997). The average annual cumulative rainfall recorded during the period considered in this study (1991–2010) is 520 mm and 775 mm in Sîne and Saloum respectively.

Throughout the basin the cropping systems are mainly cereal-le-guminous rotations. In the Sîne 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 Sîne. 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).

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 m² 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 Bambeý (14°41′N, 16°24′W) and Niíro 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).

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

Type 1 are the most numerous and the poorest: in Sine1 the average yearly income including self-consumption is only 660,000 CFA (1003 €) for approximately 12 people of which 4.5 workers, while in Saloum1 it amounts to 835,000 CFA (1269 €) for approximately 17 and 20 people in Sine2 and Saloum1 respectively. It includes the farms with the highest land constraint and 3.5 ha in Sine1 and Saloum1 respectively. This type is mainly or extensively oriented toward self-consumption and heavily constrained by its lack of liquidity. Access to credit is very limited. Consequently, the use of external inputs is very low and the proportion of land dedicated to millet and biomass potential yields, the sowing density, and the fertilization practice mobilizing organic and inorganic fertilizers (Table 2). Currently practiced cropping systems may be ’extensive’ i.e. without any organic or inorganic fertilization, or ’intensive’, i.e. with at least fertilization as a way to obtain higher yields than in the latter case. In the case of cereal crops whose yield is currently far below the potential use in the study, re-using existing robust model components changing Sahelian environment) and a multi-periodic, 1-year-planning horizon farm household model, named ANDERS (Agricultural and Development Economics model for the Groundnut basin in Senegal). CELSIUS simulates crop development, growth and biomass and grain yields of a set of typical cropping systems under a 20-year series of historical climate data in order to account for yield variability induced by inter-annual climate variations. As ANDERS is a 1-year model, it takes the 20 yields provided by CELSIUS (proxy for the yield distribution) as equiprobable states of nature that could occur during the simulated year with an equal probability.

2.4.1. Crop yield simulations with CELSIUS

CELSIUS was used to provide inter-annual distributions of grain yields and of above-ground biomass yields, for a set of typical cropping systems. The cropping systems differ by the cultivar used and its grain and biomass potential yields, the sowing density, and the fertilization practice mobilizing organic and inorganic fertilizers (Table 2). Currently practiced cropping systems may be ’extensive’ i.e. without any organic or inorganic fertilization, or ’intensive’, i.e. with at least fertilization as a way to obtain higher yields than in the latter case. In the case of cereal crops whose yield is currently far below the potential permitted by rainfall (Affholder et al., 2013), the typical cropping systems we considered also include hypothetical more intensive alternatives. For each study subzone, cropping system and field type, the average yield and its coefficient of variation are presented in Appendix B.

CELSIUS is a simple dynamic crop model working on a daily time step, based on the concept of a potential yield limited by water and nitrogen stresses (Fig. 3). It was built in Visual Basic and integrated into a database in order to facilitate virtual experimentation and coupling with the farm model (Affholder et al., 2012). We tailored the model to its specific use in the study, re-using existing robust model components and keeping the complexity of the model and its resulting data requirements for parameterization as low as possible (Sinclair and Seligman, 1996; Sinclair and Seligman, 2000; Affholder et al., 2012). CELSIUS was adapted from a previously published model (Potential

Table 1: Characteristics of the farm-types.

<table>
<thead>
<tr>
<th>Variable category</th>
<th>Variable</th>
<th>Definition</th>
<th>Type 1 Sine1</th>
<th>Saloum1</th>
<th>Type 2 Sine2</th>
<th>Saloum2</th>
<th>Type 3 Sine3</th>
<th>Saloum3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household structure and migration</td>
<td>Region</td>
<td>Share of the farm-type on the subzone</td>
<td>62% 83%</td>
<td>13%</td>
<td>13%</td>
<td>25%</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pers</td>
<td>Total number of persons in the households</td>
<td>11.7** 15.1**</td>
<td>17**</td>
<td>19.91***</td>
<td>20.3**</td>
<td>25.3***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Labor</td>
<td>Number of workers</td>
<td>4.5** 5**</td>
<td>7**</td>
<td>8**</td>
<td>9**</td>
<td>10**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OffFarm</td>
<td>Number of persons working off farm</td>
<td>0.29*** 0.56</td>
<td>0.9**</td>
<td>0.75</td>
<td>1.32***</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Migr</td>
<td>Number of migrants</td>
<td>1.4** 1.27</td>
<td>2**</td>
<td>1.66</td>
<td>0.73**</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Land endowment</td>
<td>Area</td>
<td>Total farm land area (ha)</td>
<td>3.5** 6.5**</td>
<td>10.5**</td>
<td>15.2**</td>
<td>7.75**</td>
<td>11.1**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HomeField</td>
<td>% household</td>
<td>0.27 0.06</td>
<td>0.3</td>
<td>0.03</td>
<td>0.16</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BushField</td>
<td>% bushfield</td>
<td>0.73 0.94</td>
<td>0.7</td>
<td>0.97</td>
<td>0.82**</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>Capital endowment</td>
<td>RatioWeedSurf</td>
<td>Number of weeding tools per ha</td>
<td>1.65*** 0.79</td>
<td>0.66***</td>
<td>0.61</td>
<td>1.38***</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RatioHoeSurf</td>
<td>Number of seeders, hoe per ha</td>
<td>0.67*** 0.47</td>
<td>0.37</td>
<td>0.35</td>
<td>0.34</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>Cash and credit access</td>
<td>Cash</td>
<td>Cash level in the farm household per worker (FCFA)</td>
<td>17,000</td>
<td>18,500</td>
<td>40,000</td>
<td>18,000</td>
<td>65,000</td>
<td>70,000</td>
</tr>
<tr>
<td></td>
<td>Credit</td>
<td>Dummy variable: 1 if the farmer gets a credit</td>
<td>0.34 0.4**</td>
<td>0.54</td>
<td>0.5</td>
<td>0.55</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Livestock systems</td>
<td>Cattle</td>
<td>Head of cattle</td>
<td>1 0.56</td>
<td>0.75</td>
<td>17.1**</td>
<td>25**</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DraftAni</td>
<td>Head of draft animal</td>
<td>2.1 0.57***</td>
<td>2.9</td>
<td>5.08***</td>
<td>3.54**</td>
<td>8.66**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CowFat</td>
<td>Head of cow fattening</td>
<td>0.56*** 0</td>
<td>1.9**</td>
<td>0</td>
<td>6**</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sheep</td>
<td>Head of sheep</td>
<td>11.7** 6.65**</td>
<td>22.3**</td>
<td>9.3**</td>
<td>25**</td>
<td>35**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SheepFat</td>
<td>Head of sheep fattening</td>
<td>3.27 0.12</td>
<td>5</td>
<td>0.63</td>
<td>6.3</td>
<td>2**</td>
<td></td>
</tr>
<tr>
<td>Cropping systems</td>
<td>Manure</td>
<td>Dummy variable: 1 if manure is used on farm</td>
<td>0.95 0.68**</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fertilizer</td>
<td>Dummy variable: 1 if fertilizer is used on farm</td>
<td>0.42 0.8</td>
<td>0.45</td>
<td>0.9</td>
<td>0.67</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Millet</td>
<td>Share of the land dedicated to pearl millet</td>
<td>0.55 0.57</td>
<td>0.53</td>
<td>0.49</td>
<td>0.5</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maize</td>
<td>Share of the land dedicated to maize</td>
<td>0.02 0.09</td>
<td>0</td>
<td>0.14</td>
<td>0</td>
<td>0.23**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Groundnut</td>
<td>Share of the land dedicated to groundnut</td>
<td>0.43 0.33</td>
<td>0.47</td>
<td>0.36</td>
<td>0.5</td>
<td>0.41</td>
<td></td>
</tr>
</tbody>
</table>

* 90 observations under each area. Results from ANOVA with unequal sample size conducted on each area are shown.

** Indicate statistically significant differences between groups at 10% level.

*** Indicate statistically significant differences between groups at 5% level.

**** Indicate statistically significant differences between groups at 1% level.
Table 2
Description of the simulated cropping systems.a

<table>
<thead>
<tr>
<th>Name of cropping system</th>
<th>Crop</th>
<th>Seed density (nb of plants/m²)</th>
<th>Organic nitrogen</th>
<th>Inorganic nitrogen</th>
<th>Total N from fertilization</th>
<th>Type of cropping system</th>
</tr>
</thead>
<tbody>
<tr>
<td>MilExt</td>
<td>Pearl millet</td>
<td>1.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Extensive</td>
</tr>
<tr>
<td>MilManu</td>
<td>Pearl millet</td>
<td>1.25</td>
<td>32</td>
<td>0</td>
<td>32</td>
<td>Manure</td>
</tr>
<tr>
<td>MilFert</td>
<td>Pearl millet</td>
<td>1.55</td>
<td>0</td>
<td>80</td>
<td>80</td>
<td>Fertilizer</td>
</tr>
<tr>
<td>MilManuFert</td>
<td>Pearl millet</td>
<td>1.65</td>
<td>40</td>
<td>80</td>
<td>120</td>
<td>ManuFert</td>
</tr>
<tr>
<td>MaizeFert</td>
<td>Maize</td>
<td>6</td>
<td>0</td>
<td>90</td>
<td>90</td>
<td>Fertilizer</td>
</tr>
<tr>
<td>MaizeManuFert</td>
<td>Maize</td>
<td>6</td>
<td>40</td>
<td>90</td>
<td>130</td>
<td>ManuFert</td>
</tr>
<tr>
<td>GroundnutExt</td>
<td>Groundnut</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Extensive</td>
</tr>
<tr>
<td>GroundnutManu</td>
<td>Groundnut</td>
<td>10</td>
<td>14</td>
<td>0</td>
<td>14</td>
<td>Manure</td>
</tr>
<tr>
<td>GroundnutFert</td>
<td>Groundnut</td>
<td>12.5</td>
<td>0</td>
<td>7</td>
<td>7</td>
<td>Fertilizer</td>
</tr>
</tbody>
</table>

*a Currently practiced cropping systems are shown on a gray background, whereas more intensive alternatives are shown on a white background.

Yield Estimator, PYE) in Afholder et al. (2013) which uses formalisms that had proven to be valid across a wide range of environments and crops to simulate the water-limited yield of annual crops, Yw, i.e. the yield that would be obtained in a given locality under idealized conditions where the crop would be maintained free of any growth limitation other than solar radiation, temperature, and rainfall. In this study, CELSIUS is the result of empirical additions made to PYE in order to account for the following additional limiting factors: (i) reduction of rainfall infiltrating into the soil due to runoff using the model from Albergel et al. (1991), (ii) delayed crop emergence due to insufficient moisture in soils after sowing and crop destruction by extreme drought during the juvenile stage following the approach of Afholder (1997), and (iii) low nitrogen availability in soils. The latter factor is accounted for through a nitrogen-limiting coefficient (NLC) applied to leaf and biomass growth defined as:

\[
NLC = \min\left[1; \frac{a(N_{\text{soil}} + N_{\text{org}} + N_{\text{symb}} + N_{\text{org}})}{H_{\text{fert}max}}\right]
\]

where \(N_{\text{soil}}, N_{\text{org}}, N_{\text{symb}}, \) and \(N_{\text{org}}\) are the mineral nitrogen amounts available to crops from, respectively, soil organic matter mineralization, inorganic fertilization, mineralized N from organic fertilization, and symbiotic fixation of atmospheric N by leguminous crops, \(H_{\text{fert}max}\) is the level of nitrogen supply above which growth is not limited, and \(a\) a calibration coefficient (< 1) accounting for losses of mineral N through volatilization and leaching.

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

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

Appendix C provides a fully detailed mathematical description of CELSIUS as well as references to published models from which components were taken, when applicable, and details about model calibration and test against observed yields. The un-compiled software code is available on request to afholder@cirad.fr.

2.4.2. The economic model ANDERS

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

To account for risks, the objective function maximized in the model is the expected utility of income. Risk depends on yields and prices fluctuations represented using the concept of equiprobable ‘states of nature’ i.e. combinations of yield and price sets. The utility function is the exponential one, implying a constant absolute risk aversion (CARA).

\[ EU = \frac{1}{n} \sum_{e=1}^{n} 1 - \exp[-r_e(\pi_e + w)] \]  

where \(EU\) is the expected income, \(e\) the state of nature, \(n\) the number of states of nature, \(r_e\) the absolute risk aversion, \(\pi_e\) the income, \(w\) the initial wealth and \(\exp[.\] is the exponential function.

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

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

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

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

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

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

The supply-utilization account splits the harvest in several utilizations: selling, storage, human or animal consumption. It is combined with a nutritional constraint which ensures that the household consumed enough kcal in each period to represent the food security objective.
Energy and protein balances are also included for animals (digested nitrogen and dry matter). They can be fed through pasture, grain, straw and purchased feedstuffs. Besides their nutritional needs, they are characterized by technical coefficients indicating labor required for tending and herding, vaccines and other veterinary costs. A stochastic return by head is assumed to take risk into account. By contrast the model includes the decision of buying animals for fattening in the sixth period.

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

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

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

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

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

### 2.5. Implementation of insurance in the model

#### 2.5.1. Weather index-based insurance (WII)

As rainfall distribution is the main climatic factor affecting yields in the study area, we developed and used a composite rainfall-based index, for millet, maize and groundnut. This index is very similar to the three-phase index retained.

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

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.

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

$$\text{I}_{WII}^{e,ac,z} = \min\{ \rho M, \max\{ 0, \sum_{s} \text{indemnity}(stage) \} \}$$

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

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

#### 2.5.2. Crop yield insurance (CYI)

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

$$\text{I}_{CYI}^{e,ac,z} = \min\{ M, \max\{ 0, (\rho \gamma - \gamma_{0})P \} \}$$

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

### 3. Scenarios and results

#### 3.1. Simulated scenarios

We first introduce three scenarios without subsidies:

- **Baseline**, in which no insurance is available.
- **WII**, in which a weather index-based insurance, as described in Section 2.5.1, is available.
- **CYI**, hypothetical crop-yield insurance with no basis risk, as described in Section 2.5.2. The comparison between CYI and WII quantifies the impact of the basis risk.

We then introduce four scenarios in which the same amount of public funds is spent. We considered policies typically debated among stakeholders of Sudano-Sahelian West Africa, using scenarios into which, as compared to the WII scenario, the following changes are introduced:
• Premium subsidy scenario (PremiumSub): the WII premium cost is reduced.
• Loan program scenario (CreditSub): a combination of decreasing the interest rate and increasing the maximum access to credit.
• A fertilizer subsidy scenario (FertSub): the cost of fertilizers is reduced.
• A cash transfer program (CashTrsf): simulated farmers unconditionally receive a sum of money.

In these scenarios, unsubsidized WII is not available, and the constant amount of public funds used is set with reference to the first scenario, where the subsidy covers 60% of the cost of the insurance premium paid by simulated farmers, consistent with the fact that most agricultural insurance around the world is heavily subsidized (Mahul, 2012). We first ran the premium subsidy scenario (PremiumSub). This allowed determining the government expenditure level under this scenario on the basis of the level of adoption of subsidized WII by simulated farmers. The amount so calculated was then used as the public expenditure level when running the other three scenarios (i.e. the total amount of government expenditure in each scenario is equal to the expenditure corresponding to the PremiumSub scenario). In the case of the CreditSub scenario the interest rate is decreased by 75% compared to the baseline scenario (from 14% to 3.5%), and if this is not sufficient to make the cost of the program match the public budget, the upper limit of credit accessibility is increased. Furthermore, in every case we assumed that the subsidy does not provoke an increase in the suppliers’ prices (i.e. the insurance premium, the interest rate and the price of fertilizers respectively). Similarly, the possible output price decrease due to an increase in supply is not considered. Estimating how these prices might change is beyond the scope of the present paper and would require the increase in suppliers’ profits to be quantified in order to provide a consistent cost-benefit analysis. Yet the reader should keep in mind that by neglecting these changes, we possibly overestimate the gains from these scenarios, compared to the scenarios without subsidies.

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

### 3.2. Insurance gains and basis risk

When (unsubsidized) WII or CYI is introduced into the model as a possible option, only the Sine1 and Sine2 farms adopt it, with a notable

---

**Table 4**

<table>
<thead>
<tr>
<th>Crop</th>
<th>Millet</th>
<th>Maize</th>
<th>Groundnut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection level&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Lowest</td>
<td>Highest</td>
<td>Lowest</td>
</tr>
<tr>
<td>Premium</td>
<td>4387</td>
<td>21,807</td>
<td>5200</td>
</tr>
<tr>
<td>Indemnity frequency&lt;sup&gt;b&lt;/sup&gt;</td>
<td>10%</td>
<td>30%</td>
<td>15%</td>
</tr>
<tr>
<td>Average indemnity</td>
<td>3375</td>
<td>16,775</td>
<td>4000</td>
</tr>
<tr>
<td>Minimum indemnity</td>
<td>31,500</td>
<td>19,000</td>
<td>14,750</td>
</tr>
<tr>
<td>Maximum indemnity</td>
<td>36,000</td>
<td>34,750</td>
<td>100,000</td>
</tr>
</tbody>
</table>

<sup>a</sup> The level of protection depends on the coverage level, the trigger and the exit values.

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

---

**Table 5**

<table>
<thead>
<tr>
<th>Crop</th>
<th>Millet</th>
<th>Maize</th>
<th>Groundnut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection level</td>
<td>Lowest</td>
<td>Highest</td>
<td>Lowest</td>
</tr>
<tr>
<td>Premium</td>
<td>3303</td>
<td>27,536</td>
<td>5046</td>
</tr>
<tr>
<td>Indemnity frequency</td>
<td>10%</td>
<td>35%</td>
<td>20%</td>
</tr>
<tr>
<td>Average indemnity</td>
<td>2541</td>
<td>21,181</td>
<td>3882</td>
</tr>
<tr>
<td>Minimum indemnity</td>
<td>1490</td>
<td>300</td>
<td>1252</td>
</tr>
<tr>
<td>Maximum indemnity</td>
<td>49,329</td>
<td>100,000</td>
<td>60,752</td>
</tr>
</tbody>
</table>

---

**Table 6**

<table>
<thead>
<tr>
<th>Scenario →</th>
<th>Baseline</th>
<th>WII</th>
<th>CYI</th>
<th>PremiumSub</th>
<th>CreditSub</th>
<th>CreditSub-I</th>
<th>FertSub</th>
<th>FertSub-I</th>
<th>CashTrsf</th>
<th>CashTrsf-I</th>
</tr>
</thead>
<tbody>
<tr>
<td>WII available?</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CYI available?</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insurance subsidy?</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>60% of premium</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Credit subsidized?</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Interest rate at 3.5% instead of 14% plus enhanced credit access</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilizers subsidized?</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Reduced fertilizer price</td>
<td>No</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cash transfer?</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Cash transfer program</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Changes are displayed in the following units: % represents the percentage change relative to the baseline scenario; pp indicates changes in percentage points relative to the baseline scenario. CEI increases by only 18% under WII (from 115,020 FCFA i.e. €157 to 135,561 FCFA i.e. €226 per worker in the baseline scenario to 148,264 FCFA i.e. €226 per worker) and a 1% increase in expected income (from 146,604 FCFA i.e. €203 to 148,264 FCFA i.e. €226 per worker). Sine1, the most constrained farm-type in the Sine subzone, benefits the most from WII with an 18% increase in CEI (from 115,020 FCFA i.e. €157 to 135,561 FCFA i.e. €226 per worker) and a 1% increase in expected income (from 146,604 FCFA i.e. €203 to 148,264 FCFA i.e. €226 per worker). This large increase in the CEI is consistent with the high level of risk aversion and vulnerability to damaging events of this farm-type. Given its small size and its strong cash and credit constraints, yield risk has a large impact on its income that can be reduced by insurance. A total of 54,467 FCFA (84€) is paid in insurance premiums for the whole farm. 42,968 FCFA (65€) are paid for millet for which 67% of total output is insured. The average indemnity paid is 110,174 FCFA (168€) in 30% of the states of nature. 100% of the groundnut is also insured for a total premium of 11,499 FCFA (17€). The average payment is 29,484 FCFA (45€) in 30% of the states of nature. As only 70% in average are given back to simulated states of nature, expected income (from 146,604 FCFA i.e. €203 to 148,264 FCFA i.e. €226 per worker). As observed for Sine1, although to a lower extent, there is an increase in the area allocated to millet at the expense of groundnut. Under WII, technical changes are very limited, while they are significant under CYI under which fertilizer-based cropping systems replace extensive ones. Finally, while cow fattening increases under both types of insurances, sheep fattening increases under CYI only. In the Sine subzone, there is no take-up of insurance which can be explained by the lower climate variability so that cropping systems are characterized by lower exposure to yield risk. These results highlight the fact that the attractiveness of unsubsidized insurance depends on the biophysical and socioeconomic environments (as shown by the different responses to the introduction of insurance between the two subzones) but also on the farm characteristics (as shown by the different responses to the introduction of insurance between the two farm-types of Sine).

Table 8 gives the impact of the subsidy programs on the farmer’s CEI and expected income. Table 8 gives the impact of the subsidy programs on the farmer’s CEI and expected income. As explained above, subsidy program scenarios have been simulated at a constant level of public spending which is determined, for each farm-type, from the insurance premium subsidy scenario (60% of the insurance premium). Since the amount of spending in the premium subsidy scenario depends on the farm-type (Table 8), this hampers comparisons between farm-types.

3.3. Subsidy program scenarios

3.3.1. Impact of subsidy programs on simulated farmers’ CEI and expected income

Table 8 gives the impact of the subsidy programs on the farmer’s CEI and expected income. As explained above, subsidy program scenarios have been simulated at a constant level of public spending which is determined, for each farm-type, from the insurance premium subsidy scenario (60% of the insurance premium). Since the amount of spending in the premium subsidy scenario depends on the farm-type (Table 8), this hampers comparisons between farm-types.

### Table 7

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

### Table 8

<table>
<thead>
<tr>
<th>Table 8</th>
<th>Impacts of the introduction of unsubsidized weather (WII) and crop-yield (CYI) insurances relative to the baseline (BL) scenario on the main model’s outputs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop</td>
<td>BL</td>
</tr>
<tr>
<td>CEI/worker</td>
<td>115,020</td>
</tr>
<tr>
<td>Mean income/worker</td>
<td>146,604</td>
</tr>
<tr>
<td>CV income</td>
<td>23%</td>
</tr>
<tr>
<td>Total Premium</td>
<td>n/a</td>
</tr>
<tr>
<td>Millet prod./worker</td>
<td>362 kg</td>
</tr>
<tr>
<td>Maize prod./worker</td>
<td>26 kg</td>
</tr>
<tr>
<td>Groundnut prod./worker</td>
<td>185 kg</td>
</tr>
<tr>
<td>Extensive</td>
<td>2.33 ha</td>
</tr>
<tr>
<td>Manure</td>
<td>1.11 ha</td>
</tr>
<tr>
<td>Fertilizer</td>
<td>0 ha</td>
</tr>
<tr>
<td>Manufert</td>
<td>0.06 kg</td>
</tr>
<tr>
<td>Cow fattening</td>
<td>0.4 head</td>
</tr>
<tr>
<td>Sheep fattening</td>
<td>0 head</td>
</tr>
<tr>
<td>CV income</td>
<td>23%</td>
</tr>
</tbody>
</table>

Impact on CEI and farm plans. Saloum1 and Saloum2 adopt neither WII nor CYI in the simulations (Table 7).
which PremiumSub does not bring the lowest CEI is Sine1, but even there it is only ranked 4th out of 7 scenarios and is dominated by all the scenarios in which unsubsidized insurance is available: CreditSub-I, FertSub-I and CashTrsf-I. Hence subsidizing insurance is always the worst use of public funds, compared to scenarios in which insurance is available but not subsidized. CreditSub-I is always the best use of public funds in term of CEI, even though in Sine1 CashTrsf-I and FertSub-I bring the same outcome. These results indicate that for a given level of public spending, the simulated farmers’ situation can improve more by alleviating the cash constraint (which prevents farmers from buying productive inputs) than by mitigating the impact of a bad weather.

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

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

### 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 (Fig. E1) 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 Saloum 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.

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

<table>
<thead>
<tr>
<th>Subzone</th>
<th>Cereal</th>
<th>Groundnut</th>
<th>Grain production value</th>
<th>Cow fat</th>
<th>Sheep fat</th>
</tr>
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<tbody>
<tr>
<td>Sine1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Premium</td>
<td>101.9</td>
<td>45.9</td>
<td>126.3</td>
<td>19.2</td>
<td>100</td>
</tr>
<tr>
<td>Credit</td>
<td>126.3</td>
<td>19.2</td>
<td>100</td>
<td>11.1</td>
<td>100</td>
</tr>
<tr>
<td>Credit-1</td>
<td>-56.2</td>
<td>-16.7</td>
<td>-42.5</td>
<td>-9.9</td>
<td>-9.4</td>
</tr>
<tr>
<td>Fert</td>
<td>-9.6</td>
<td>-15.8</td>
<td>-31.2</td>
<td>-6.7</td>
<td>-6.3</td>
</tr>
<tr>
<td>Fert-1</td>
<td>-31.2</td>
<td>-6.7</td>
<td>-9.6</td>
<td>-6.3</td>
<td>-9.4</td>
</tr>
<tr>
<td>Cash</td>
<td>15.5</td>
<td>20.6</td>
<td>15.5</td>
<td>19.4</td>
<td>20.6</td>
</tr>
<tr>
<td>Cash-1</td>
<td>19.4</td>
<td>20.6</td>
<td>15.5</td>
<td>20.6</td>
<td>15.5</td>
</tr>
<tr>
<td>Sine2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Premium</td>
<td>-77.8</td>
<td>-7.3</td>
<td>-64</td>
<td>14.9</td>
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<td>-53.3</td>
<td>14.9</td>
</tr>
<tr>
<td>Credit-1</td>
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<td>-13.4</td>
<td>-27.2</td>
<td>-22.6</td>
<td>-22.6</td>
</tr>
<tr>
<td>Fert</td>
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<td>-22.6</td>
<td>-40.4</td>
<td>-13.4</td>
<td>-13.4</td>
</tr>
<tr>
<td>Fert-1</td>
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<td>-27.2</td>
<td>-22.6</td>
<td>-22.6</td>
</tr>
<tr>
<td>Cash</td>
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<td>14.9</td>
<td>-53.3</td>
<td>-53.3</td>
<td>14.9</td>
</tr>
<tr>
<td>Cash-1</td>
<td>14.9</td>
<td>-53.3</td>
<td>-53.3</td>
<td>14.9</td>
<td>-53.3</td>
</tr>
<tr>
<td>Saloum1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Premium</td>
<td>-1.9</td>
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<td>-1.9</td>
<td>-1.9</td>
<td>-0.9</td>
</tr>
<tr>
<td>Credit</td>
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<td>-1.9</td>
<td>-1.9</td>
<td>-1.9</td>
<td>-0.9</td>
</tr>
<tr>
<td>Credit-1</td>
<td>-0.9</td>
<td>-1.9</td>
<td>-1.9</td>
<td>-1.9</td>
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</tr>
<tr>
<td>Fert</td>
<td>-1.9</td>
<td>-1.9</td>
<td>-1.9</td>
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<tr>
<td>Fert-1</td>
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<td>-1.9</td>
</tr>
<tr>
<td>Cash</td>
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<td>-1.9</td>
<td>-1.9</td>
<td>-1.9</td>
</tr>
<tr>
<td>Cash-1</td>
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<td>-1.9</td>
<td>-1.9</td>
<td>-1.9</td>
<td>-1.9</td>
</tr>
</tbody>
</table>

Fig. 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 (Greatorex 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. re-planting 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.

Acknowledgements

This study was carried out with support from the French agency for research funding (ANR), within the framework of its ‘ESCAPE’ project (Environmental and Societal Changes in Africa – Past, Present and Future) and from the GIS Climat Environnement Société, within the framework of its AGECCAO project (Adaptation de l’agriculture et de la gestion de l’eau au changement climatique en Afrique de l’Ouest). The research leading to these results has received partial funding from the NERC/DFID Future Climate For Africa programme under the AMMA-2050 project, grant number NE/M019926/1.

We are grateful to the farmers of the Senegalese groundnut basin who took part in the study by receiving us in their fields and houses and agreeing to devote some of their time to answering our numerous questions.

Finally, we would like to thank two anonymous referees whose comments have allowed us to greatly improve this article, Dr. Séraphin G. Dorégó (ISRA) for drawing Fig. 1, ISRA-CERAAS and in particular Moustapha Fall for collecting and managing agrometeorological data.

Appendix A. Farm typologies, dendrogram and Calinski-Harabasz index

The number of farm-types was chosen based on dendrogram observation (Figs. A1 and A2) and the Calinski-Harabasz criterion (Table A1). The Calinski-Harabasz criterion is defined as $\frac{SS_B}{SS_W}$, 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 modelling, 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.](image1)

![Fig. A2. Dendrogram truncated after tenth level – Saloum.](image2)

<table>
<thead>
<tr>
<th>Sine subzone</th>
<th>Calinski-Harabasz criterion</th>
<th>Saloum subzone</th>
<th>Calinski-Harabasz criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of farm-types</td>
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<td>69.42</td>
<td>62.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>64.64</td>
<td>54.36</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>63.95</td>
<td>53.68</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>61.5</td>
<td>52.57</td>
</tr>
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<td></td>
<td>10</td>
<td>53.51</td>
<td>49.6</td>
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</table>
Appendix B. Average yield and coefficient of variation, by cropping system

<table>
<thead>
<tr>
<th></th>
<th>Mean yield (kg ha⁻¹) (1991–2010)</th>
<th>Coefficient of variation</th>
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<tbody>
<tr>
<td></td>
<td>Sine</td>
<td>Saloum</td>
</tr>
<tr>
<td>MilExt</td>
<td>Homefield</td>
<td>1175</td>
</tr>
<tr>
<td>MilManu</td>
<td>Bushfield</td>
<td>524</td>
</tr>
<tr>
<td>MilFert</td>
<td>Homefield</td>
<td>1756</td>
</tr>
<tr>
<td></td>
<td>Bushfield</td>
<td>1251</td>
</tr>
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<td>MilManuFert</td>
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<td>2006</td>
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<td></td>
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<td>1589</td>
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<td>MaizeFert</td>
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<td>2167</td>
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<td>Bushfield</td>
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<td>990</td>
</tr>
<tr>
<td></td>
<td></td>
<td>708</td>
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</tbody>
</table>

Appendix C. The crop dynamic simulation model CELSIUS (CEreal and Legume crops Simulator Under Sahelian Environment): conceptual and mathematical description

Part I. General description and credits to other models

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

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

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

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

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

A nitrogen stress coefficient is computed using a simple seasonal estimate of N available in soil from mineralization of soil organic matter, mineralization of a decaying biomass added to the soil, N inorganic fertilizers inputs, and symbiotic fixation of atmospheric N2, with a coefficient of
N losses through N-leaching and volatilization. The nitrogen stress coefficient is a bilinear function of N available in soil, with a threshold parameter corresponding to the level of N available in soil above which N is not limiting crop growth. This approach of the relationship between N availability and yield reduction relatively to a potential yield is a simplification of the relationships used in the model Field (Tittonell et al., 2010) or Quefts (Janssen et al., 1990), especially by assuming that P and K limitations as well as interactions of soil pH with N availability are all constant across the set of situations to be simulated.

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

Daily global solar radiation is intercepted by the resulting leaf area index following a beer law with an extinction coefficient, and converted into biomass following a net conversion efficiency approach, the potential efficiency being reduced by temperature below or above an optimum, and by water or nitrogen stress. CO₂ concentration of the atmosphere increases conversion efficiency by a coefficient depending on the C3 or C4 type of the crop. A part of the accumulated dry matter is allocated to grain following a harvest index approach coupled with a sink limitation accounting for thermal or water stress during a fruit-forming sensitive stage (Brisson et al., 1998).

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

Part II. Detailed mathematical description

1. Modelling options
   See OptionModelClass in the software code.

   A number of Boolean variables (having ‘True’ or ‘False’ as the only possible values) are used to set modelling options.

   These are Simlevee, CyberST, ActiveStressH, ActiveStressN, and CorAlti.

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

   If CyberST is True then sowing, germination and emergence are simulated otherwise sowing is set to input value and germination plus emergence are accounted for according to the value of Simlevee.

   If ActiveStressH is True then water stress is used to reduce growth (Yw or Ywn calculated according to setting of ActiveStressH), else water stress is still calculated but has no impact on growth calculation (Y0 or Yn calculated according to setting of ActiveStressN). Whatever its setting ActiveStressH has no impact on germination plus emergence or on crop survival due to extreme water stress.

   If ActiveStressN is True then nitrogen stress is used to reduce growth (Yn or Ywn calculated according to setting of ActiveStressH), else nitrogen stress is still calculated but has no impact on growth calculation (Y0 or Yw calculated according to setting of ActiveStressH).

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

2. Plant development and growth


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

   Equation CELSIUS.1

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

   with:

   \( n \): current day of simulation,

   \( jsow \): day of sowing,

   \( Tm(j) \): mean temperature of day j,

   \( Tger \): cultivar dependent, min temperature for accumulation of thermal time during germination + emergence phase,

   \( Jlev \): day of emergence,

   \( WConstGer(j) \): water constraint applied to germination plus emergence, for day j. Integer, value 1 (soil water not constraining germination or emergence) or 0 (soil water constraining germination or emergence), calculated in equation CELSIUS.21.2.2. Crop development. See PlanteClass.

   \( \text{phenoCTphot} \) in the software code.

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

   Equation CELSIUS.2

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

   with:

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

   \( \text{If } Tm(j) \leq \text{tdmin} \text{ then } f(Tm(j)) = 0 \)

   \( \text{If } \text{tdmin} < Tm(j) \leq \text{tdmax} \text{ then } f(Tm(j)) = Tm(j) - \text{tdmin} \)

   \( \text{If } Tm(j) > \text{tdmax} \text{ then } f(Tm(j)) = \text{tdmax} - \text{tdmin} \)

   and
If \((i \neq 2 \text{ OR } DL(j) < \text{MOPP})\) then
\[\text{PhotFact}(j) = 1\]
If \(i = 2 \text{ AND } DL(j) \geq \text{MOPP}\) then
\[\text{PhotFact}(j) = 1 - (DL(j) - \text{MOPP}) \times \text{SensPhot}\]

where:
- \(\text{Dstge}(i)\): day of completion of stage \(i\); Positive integer, \(\text{Dstge}(0) = \text{Jlev}\)
- \(\text{CT}(i)\): thermal time accumulated for completing stage \(i\)
- \(\text{tdmin}\): base temperature for thermal time accumulation.
- \(\text{tdmax}\): maximal temperature for thermal time accumulation.
- \(\text{DL}(j)\): photoperiod (astronomic diurnal duration) of day \(j\)
- \(\text{MOPP}\): threshold of photoperiod above which cultivar has its development rate reduced by photoperiod.
- \(\text{SensPhot}\): Coefficient of sensitivity of cultivar to photoperiod
- \(\text{PhotFact}\): reduction coefficient applied to development rate when affected by photoperiod

2.3. Leaf Area Index (LAI).

See \textit{PlanteClass}. \textit{Calcule_LAI_SemiArid} in the software code.

LAI on day \(n\) \((\text{LAI}(n))\) is computed by adding \(dlai(n)\), a daily increase (or decrease if negative), of LAI to the LAI of the previous day \((n - 1)\).

a) During development stages 1 and 2, daily increase of LAI \((d\text{LAI}(n))\) for a day \(n\) is calculated using equations taken from STICS as follows:

Equation CELSIUS.3
\[d\text{LAI}(n) = \frac{d\text{LAI}_\text{max}}{1 + \exp(5.5(\text{Vlai}_\text{max} - \text{Ulai}(n)))} \times f(Tm(n)) \times \text{LAIstress}(n) \times \Delta\text{idens}(\text{denspl})\]

with
- during stage 1: \(\text{Ulai}(n) = 1 + (\text{Vlai}_\text{max} - 1) \times \text{NTT}(n)\);
- During stage 2: \(\text{Ulai}(n) = \text{Vlai}_\text{max} + (3 - \text{Vlai}_\text{max}) \times \text{NTT}(n)\);

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

and

If \(\text{LAI}(n) > \text{LAIcomp And Denspl} > \text{bdens}\) then
\[\Delta\text{idens}(\text{denspl}) = \text{denspl} \times \left(\frac{\text{denspl}}{\text{bdens}}\right)^{\text{adens}} \text{ else } \Delta\text{idens}(\text{denspl}) = \text{denspl}\]

where
- \(f(Tm(n))\) is the same function as in equation CELSIUS.2
- \(d\text{LAI}_\text{max}\): maximum daily increase of LAI
- \(\text{Vlai}_\text{max}\): a general parameter defining the slope at inflexion point of dLAI as a function of thermal time
- \(\text{denspl}\): stand density
- \(\text{Ulai}(n)\): leaf development unit (equal to \(\text{Vlai}_\text{max}\) at inflexion point of \(d\text{lai}(n)\), equal to 3 at end of stage 2)
- \(\text{NTT}(n)\): normalized thermal time
- \(\text{LAIcomp}\): LAI threshold above which competition between plants for light occurs
- \(\Delta\text{idens}\): effect of stand density on LAI
- \(\text{bdens}\): cultivar-dependent stand density threshold above which leaf area per plant is influenced by stand density
- \(\text{adens}\): cultivar-dependent parameter defining the sensitivity to stand density of leaf area per plant when stand density is above \(\text{bdens}\)
- \(\text{LAIstress}(n)\): stress coefficient applied to leaf area index (0 when stress is maximal, 1 when no stress occurs), calculated in equation CELSIUS.31

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

Equation CELSIUS.4
\[d\text{LAI}(n) = (\Delta\text{LAIpot} - (\text{SensSen} \times (1 - \text{LAIstress}(n) \times \text{LAI}(n - 1))) \times f(Tm(n))\]

with
- During stages 3 and 4 no senescence occurs in the absence of stress: \(\Delta\text{LAIpot} = 0\)
- During stage 5: \(\Delta\text{LAIpot} = (\text{LaiRec} - \text{Lai}(\text{Dstge}(4))) / \text{CT}(5)\)

and
- \(\text{SensSen}\): cultivar-dependent sensitivity coefficient for leaf senescence accelerated by stress
- \(\text{LaiRec}\): cultivar-dependent potential value (in the absence of any stress) of LAI at maturity
- \(\Delta\text{LAIpot}\): potential average decrease of LAI after stage 2, in the absence of stress2.4. Above ground biomass. See \textit{PlanteClass}.\textit{biomassein} the software code.

Intercepted solar radiation \(r\text{aint}(n)\) for a day \(n\) is given by:
Equation CELSIUS.5 (taken from STICS)
where:
\( \text{ParSurRg} \) is the ratio of photosynthetically active over total global solar radiation
\( Rg(n) \) is global solar radiation of day \( n \)
\( k_{ext} \): a cultivar-dependent extinction coefficient
Total aboveground biomass of day \( n \) (\( \text{Biom}(n) \)) is computed by adding \( dBiom(n) \), the daily increase of biomass, to \( \text{Biom}(n-1) \).
\( dBiom(n) \) is calculated using the following equation taken from STICS:
Equation CELSIUS.6
\[
\text{dBiom}(n) = \text{CO} \cdot \text{fact} \cdot \text{BiomStress}(n) \cdot \text{Ebmax} \cdot \text{rain}(n) - 0.0815 \times \text{rain}(n)^2
\]
with:
\( \text{CO} \cdot \text{fact} = 2 - \exp(\ln(2 - \text{alphaCO2})) \times (\text{CO2c} - 350)/(600 - 350) \)
where:
\( \text{CO2c} \) is the atmospheric concentration of CO2 at the time of the simulation.
\( \text{alphaCO2} \) is a cultivar-dependent coefficient, mostly accounting for the C3 (\( \text{alphaCO2} = 1.2 \)) or C4 (\( \text{alphaCO2} = 1.1 \)) type of photosynthesis cycle of the species.
\( \text{Ebmax} \) is the cultivar dependent maximum efficiency of net conversion of intercepted photosynthetically radiation into biomass.
\( \text{BiomStress}(n) \) is the stress coefficient applied to Biomass (0 when stress is maximal, 1 when no stress occurs), calculated using equation CELSIUS.31.2.5. Grain yield. See PlanteClass.Rendement in the software code.
Grain yield is calculated using equations taken from STICS.
A non-sink limited harvest index \( HI(n) \) on day \( n \) linearly increases with time at a cultivar dependent rate \( \text{Vitircarb} \), starting at the first day of stage 4 and ending at maturity (\( \text{DayStge}(5) \)), and with a cultivar dependent ceiling value \( HI_{max} \), following the two equations below:
Equation CELSIUS.7:
\[
\text{HI}(n) = \text{Min}(\text{Vitircarb} \times (n - \text{DayStge}(3) + 1); HI_{max})
\]
When calculating final grain yield \( Y \), sink limitation may occur due to a cultivar dependent ceiling value of the weight of 1 grain, \( P_{1g_{max}} \), and a grain number \( Ngrains \), limited by possible stress impacting average growth rate \( \text{Vitmoy} \) during a \( \text{Nbjgrain} \) number of days preceding grain filling stage (starting a \( \text{DayStge}(3) \)), as follows:
Equation CELSIUS.8:
\[
Y = \text{Min}(\text{HI}(\text{DayStge}(5)); P_{1g_{max}} \times Ngrains)
\]
with
\( Ngrains = C_{\text{Grain}} \times \text{Vitmoy} + C_{\text{Grain0}} \)
and
\( \text{Vitmoy} = (\text{Biom}(\text{DayStge}(3)) - \text{Biom}(\text{DayStge}(3) - \text{Nbjgrain}))/\text{Nbjgrain} \)
where:
\( C_{\text{Grain}} \) and \( C_{\text{Grain0}} \): cultivar dependent parameters
2.6. Root growth. See PlantClass.Croirac in the model code.
Root biomass is not explicitly simulated, but the depth of the rooting zone, \( Z_{\text{rac}}(n) \) is dynamically simulated from germination to \( \text{DayStge}(3) \) with a daily rate of root descent governed by thermal time, limited by the thickness of wet soil below root zone and by a maximal root depth \( Z_{\text{rac_{max}}} \), as follows for a day \( n \):
Equation CELSIUS.9
\[
Z_{\text{rac}}(n) = \text{Min}(Z_{\text{rac}}(n - 1) + \text{Min}(W_{\text{ZuR}}(n - 1); \text{DeltaRMax} \times f(Tm(n))); Z_{\text{rac_{max}}})
\]
where:
\( W_{\text{ZuR}} \): Thickness of soil below the current root zone having moisture above wilting point (calculated using water balance equations \( \text{DeltaRMax} \): cultivar dependent maximal rate of root descent per unit thermal time
Equations taken from Scopel et al., 2004.
The biomass of a straw mulch possibly present over the soil’s surface, \( Q_{\text{paillis}}(n) \), is assumed to decrease with time except in case an amount \( Q_{\text{paillisApport}}(n) \) is added that day:
Equation CELSIUS.10
\[
Q_{\text{paillis}}(n) = Q_{\text{paillis}}(n - 1) \times \exp(-\text{Alpha}_{\text{pail}}) + Q_{\text{paillisApport}}(n)
\]
where:
\( \text{Alpha}_{\text{pail}} \): calibration parameter depending on the composition of mulch
An empirical relationship is used to convert \( Q_{\text{paillis}}(n) \) into the fraction of soil covered by the straw, \( \text{FracSoilCover}(n) \):
\[
\text{FracSoilCover}(n) = 1 - \exp(-\text{Betapail} \times Q_{\text{paillis}}(n))
\]
Beta_pail: calibration parameter depending on the composition of mulch.

3.2. Runoff. See MulchClass.Ruisellement in the software code.

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

Water supply precip(n) (consisting of Rainfall plus Irrigation of the day) is split into runoff Ruis(n) and water infiltrated into the soil and a straw mulch possibly present on the soil's surface, accounting for LAI reducing runoff, a typology of crusting of soil's surface, the biomass of straw mulch, and an indicator IKJ(n) characterizing the rainfall sequence of the previous days, increasing with the amounts of rainfall and decreasing when the number of days between rainfall events increases:

Equation CELSIUS.11:

\[
Ruis(n) = \max(0; \exp(-0.5 \cdot \text{LAI}(n)) \times (A_1 + A_3 \times \text{IKJ}(n) + b_{\text{ruis}} \times \text{Qpaillis}(n)) \times (\text{precip}(n) - \text{SeuilRuis}))
\]

with:

\[
\text{IKJ}(n) = (\text{IKJ}(n - 1) + \text{precip}(n - 1)^2 \times \exp(-0.5))
\]

and

\[
\text{If } A_1 + A_3 \times \text{IKJ}(n) = 0 \text{ then } \text{SeuilRuis} = 0
\]

\[
\text{Else } \text{SeuilRuis} = (A_4 - A_2 \times \text{IKJ}(n))/(A_1 + A_3 \times \text{IKJ}(n))
\]

where:

- \( b_{\text{ruis}} \): a parameter controlling the increase of runoff due to the presence of a straw mulch (generally a negative value, since straw mulch generally decreases runoff)
- \( A_1...A_4 \): empirical coefficients controlling runoff on the part of the soil directly exposed to the impact of rain drops. When \( A_2...A_4 \) are set to zero, \( Ruis(n) \) is a constant proportion \( b_{\text{ruis}} \) of the share of daily rainfall exceeding a threshold \( \text{SeuilRuis} \), equal to \( A_1 \) in this particular case. When \( \text{SeuilRuis} \) is set to zero and \( A_1...A_4 \) are non-zero, these coefficients correspond to a typology of soil surface status as in Casenave and Valentin (1989, 1992) as follows:

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1: no crust or predominant structural crust with remnant aggregates &lt; 5%</td>
<td>0.2</td>
<td>0.03</td>
<td>0.004</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>2: runoff crust covering less area than structural crust 5–30%</td>
<td>0.35</td>
<td>0.04</td>
<td>0.004</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3: runoff crust predominating &gt; 30%</td>
<td>0.900</td>
<td>0.05</td>
<td>0.002</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

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

Equation CELSIUS.12

\[
W_{\text{SM}}(n) = \text{Precip}(n) - Ruis(n)
\]

3.3. Water stored into a porous straw mulch and evaporated (not used in the study). See MulchClass.BilanMulch in the software code.

Equations taken from Scopel et al. (2004).

Straw mulch is assumed to have a certain capacity \( \text{CapacityMulch} \), per unit of mulch biomass, for storing water, the corresponding reservoir \( St_{\text{mulch}} \) being updated on a day \( n \) as follows:

Equation CELSIUS.13

\[
St_{\text{mulch}}(n) = \min(Q\text{paillis}(n) \times \text{CapacityMulch}; \text{Stmulch}(n - 1) - E_{\text{mulch}}(n) + \text{FracSoilCover}(n) \times W_{\text{SM}}(n))
\]

where:

- \( E_{\text{mulch}}(n) \) is the amount of water lost by mulch on day \( n \) by evaporation
- The water available for soil infiltration \( \text{Win}(n) \) is the part of \( W_{\text{SM}}(n) \) not stored in \( \text{Stmulch}(n) \)
- Potential evaporation \( E_{\text{oS}M}(n) \) at the top of the straw mulch is calculated on a day \( n \) assuming that reference Penman-Monteith potential evaporation \( E_{TP}(n) \) is reduced by LAI using an extinction law analogy as follows:

Equation CELSIUS.14

\[
E_{\text{oSM}}(n) = E_{TP}(n) \times \exp(1 - 0.2 \times \text{Lain}(n))
\]

Potential evaporation applied to mulch, \( E_{\text{OMulch}}(n) \) is calculated as follows:

Equation CELSIUS.15

\[
E_{\text{OMulch}}(n) = E_{\text{oSM}}(n) \times (1 - \exp(-\text{gamma}_{\text{mulch}} \times \text{Qpaillis}(n)))
\]

where:

- \( \text{Gamma}_{\text{mulch}} \) is a calibration coefficient depending on the species constituting the straw mulch.
- Actual evaporation of mulch \( E_{\text{Mulch}}(n) \) is calculated as:

Equation CELSIUS.16

\[
E_{\text{Mulch}}(n) = \max(\text{Stmulch}(n - 1); \max(E_{\text{OMulch}}(n); E_{\text{decomp}}(n)))
\]

\( E_{\text{decomp}} \) is the amount of water contained in the quantity of mulch that decayed since the previous day:

\[
E_{\text{decomp}}(n) = \text{Stmulch}(n - 1) \times (\text{Qpaillis}(n - 1) - \text{Qpaillis}(n))/\text{Qpaillis}(n)
\]
4. **Soil water balance**

4.1. **Soil moisture.** See `SolClass.EauSol in the software code`.

The soil moisture model is taken from SarraMillet (Afholder, 1997).

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

Equation CELSIUS.17

\[ TAW = (h_{min} - hcc) / da \]

where:

- \( h_{min} \) and \( hcc \): soil water content respectively at wilting point and at field capacity (in mass of water per mass of soil)
- \( da \): soil bulk density

The four main water reservoirs are the following:

- \( Stger \), with a constant thickness \( Zger \) and starting at topsoil: contains the water impacting germination and seedlings growth until crop emergence.
- \( Stsurf \) with a constant thickness \( Zsurf \) and starting at topsoil: contains the water impacting soil evaporation.
- \( Strac \) with a dynamic thickness \( Zrac \) and starting at topsoil, calculated by Equation CELSIUS.9, contains the water impacting crop transpiration, i.e. the transpirable soil water.
- \( Stdeep \) with a dynamic thickness \( Zsol-Zrac \), starting immediately below \( Zrac \) and ending at soil maximum depth \( Zsol \).

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

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

Equation CELSIUS.18

\[
Stres(n) = Max(\min(Stres(n-1) + WIn(n) - Eos(n) \times CEres - Transpi(n) \times CEres - TAW \times TEres);0)
\]

where:

- \( CEres \) and \( TEres \) are coefficients distributing Evaporation and transpiration among the reservoirs as follows:
  - \( CEres = 1 \) in \( Stsurf, Zger/Zsurf \) in \( Stger, Zrac/Zsurf \) until \( Zrac \) is greater than \( Zsurf \) in \( Strac \), and 0 in \( Stdeep \).
  - \( TEres = Zrac/Zsurf \), in \( Stsurf \) until \( Zrac \) overcomes \( Zsurf \), \( Zsurf/Zrac \) afterwards, \( Zrac/Zger \) in \( Stger \) until \( Zrac \) overcomes \( Zger \), \( Zrac/Zger \) afterwards,
- 1 in \( Strac \), and 0 in \( Stdeep \).

and:

- \( WIn(n) \) is water input into the reservoir, corresponding to the drainage from the reservoir immediately above if applying or corresponding to water from irrigation or rainfall infiltrated into the soil.
- \( Water Dres(n) \) drained out of a reservoir is calculated as the amount of water exceeding the storage capacity of the reservoir when calculating the balance, as follows:

Equation CELSIUS.19

\[
Dres(n) = Max(0; TAW \times Zres - (Stres(n-1) + WIn(n) - Eos(n) \times CEres - Transpi(n) \times TEres))
\]

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

Equation CELSIUS.20

\[
WCrac(n) = Stres(n)/(TAW \times Zres)
\]

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

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

Equation CELSIUS.21

\[
WConstGer(n) = WCger(n) \times WConstGer(n) = 1 \ \text{Else} \ WConstGer(n) = 0
\]

4.2. **Soil evaporation.** See `SolClass.Evolution in the software code`.

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

Equation CELSIUS.22

\[
Eos(n) = EoSM(n) - EoSM(n)
\]

Soil evaporation \( Eos(n) \) on a day \( n \) is calculated as follows:

Equation CELSIUS.23:

\[
\text{if } WCSurf(n) \geq SeuilEvap \ \text{Then } Eos(n) = Eos(n)
\]

\[
\text{if } WCSurf(n) < SeuilEvap \ \text{Then}
\]

\[
Eos(n) = (Eos(n))^* WCSurf(n)/SeuilEvap
\]

where:

- \( SeuilEvap \): soil dependent calibration parameter.

4.3. **Crop transpiration.** See `CultureClass.CalcTranspiMC in the software code`.
Potential evapotranspiration is calculated using a crop coefficient $KC(n)$ approach taken from STICS, in which $KC(n)$ is calculated with an empirical relationship between $Kc(n)$ and $LAI(n)$, and taken as follows:

Equation CELSIUS.24
\[ Kc(n) = (1 + (Kmax - 1)/(1 + \exp(-1.5 \times (Lai(n) - 3)))) \]

where:

- $Kmax$: cultivar-dependent parameter
- Potential crop transpiration $eo(n)$ is calculated using the classical crop coefficient approach applied to Penman-Monteith reference potential evapotranspiration $Etp(n)$:

Equation CELSIUS.25
\[ eo(n) = Etp(n) \times Kc(n) \]

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

Equation CELSIUS.26
\[ eop(n) = eo(n) - Eo(n) - EoSM(n) - Esol(n) - Emulch(n) \]

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

Equation CELSIUS.27
\[ Transpi(n) = \begin{cases} 
0.7 & \text{if } WCrac(n) \geq 0.7 \\
Transpi(n) \times WCrac(n) & \text{if } WCrac(n) < 0.7
\end{cases} \]

5. Stress calculations

5.1. Nitrogen constraint. See PlantClass. stressAzoteOld in the software code.

A nitrogen limiting coefficient is calculated as follows:

Equation CELSIUS.28
\[ N_{soil}, N_{org}, N_{orgn}, N_{ symb} \text{ are the mineral nitrogen amounts available to crops from, respectively, soil organic matter mineralization, inorganic fertilization, mineralized N from organic fertilization, and symbiotic fixation of atmospheric N by leguminous crops.} \]

If $WCrac(n) \geq 0.7$ then $Transpi(n) = eo(n)$

if $WCrac(n) < 0.7$ then $Transpi(n) = eo(n) \times WCrac(n)/0.7$

5.2. Temperature stress applied to biomass growth. See PlanteClass.Biomasse in the software code.

Equation taken from STICS.

Equation CELSIUS.29
\[ Tm(n) < Tcopt \text{ then } Ftemp(n) = 1 - \frac{Tm(n) - Tcopt}{Tcmin - Tcopt}^2 \]

\[ Tm(n) \geq Tcopt \text{ then } Ftemp(n) = 1 - \frac{Tm(n) - Tcopt}{Tcmax - Tcopt}^2 \]

$Tcmin$, $Tcopt$, $Tcmax$: cultivar-dependent parameters, respectively the minimal, optimal and maximal air temperatures for light to biomass conversion efficiency.


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

Equation CELSIUS.30:
\[ WSBioT(n) \geq 1 - WSBioT \text{ then } WSfactBio(n) = 1 \]
\[ WSBioT(n) < 1 - WSBioT \text{ then } WSfactBio(n) = WCrac(n)/(1 - WSBioT) \]
\[ WSBioT(n) \geq 1 - WSBioT \text{ then } WSfactLai(n) = 1 \]
\[ WSBioT(n) < 1 - WSBioT \text{ then } WSfactLai(n) = WCrac(n)/(1 - WSBioT) \]

5.4. Interactions between water and nitrogen stresses. See PlanteClass. Calcule_LAI_SemiAride and PlanteClass.Biomasse in the software code.

The stress factors $LAIStress(n)$ and $BiomStress(n)$ reducing growth in LAI and aboveground biomass (Eqs. (3) and (6)) respectively are calculated as follows:

Equation CELSIUS.31
\[ LAIStress(n) = \Min(WSfactLai(n); NLC) \]
\[ BiomStress(n) = \Min(WSfactBio(n); NLC) \]

Part III. Details about model calibration and test

CELSIUS involves a number of empirical parameters, a majority of which are cultivar-dependent, that had to be estimated by calibrating the
The data set used for calibration and test was the data set of millet plots detailed in Affholder (1997), plus data of groundnut plots from the ESPACE-PRODCLIM database (Forest and Cortier, 1989) and data of maize plots under the savannah environment of the Cerrado region of Brazil, as presented in Affholder et al. (2003) and Affholder et al. (2013). The soil water balance model as well as the sowing and emergence model, and their calibration parameters, were taken almost unchanged from Sarra-millet that provided reliable predictions of soil moisture and date chosen by farmers for sowing as depending on the rainfall sequence (Affholder, 1997). Readers may therefore refer to this publication for details about calibration and test of these components.

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

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

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

The parameters relative to nitrogen limitations (Nymb, Ifertmax/α) were set so that the maximum and median values of simulated AGBwn and Ywn, over the set of historical weather data of each of the two Sine and Saloum subzones, was equal to the maximum and median observed value in the database for each of the following crop management types: MilExt on bushfield, MilManu on bushfield, MilManu on homefield, GroundExt on bushfield, GroundManu on bushfield (see Table C1 on main text for characteristics of the cropping systems).

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

![Fig. C1. Model test after calibration.](image-url)
Appendix D. ANDERS-CELSIUS 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 was assigned to all farm-types. The relationship between the absolute risk aversion ($r_a$) and the relative risk aversion ($r$) is given as follows (Hardaker et al., 2004):

$$r_a = \frac{r}{W}$$

(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 Viscusi (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.

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

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

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 in 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.

<table>
<thead>
<tr>
<th>Table D1</th>
<th>Values of the initial wealth and the levels of risk aversion.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sine1</td>
</tr>
<tr>
<td>Initial wealth (FCFA)</td>
<td>700,000</td>
</tr>
<tr>
<td>Relative risk aversion ($r$)</td>
<td>2</td>
</tr>
<tr>
<td>Absolute risk aversion ($r_a$)</td>
<td>0.0000028</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table D2</th>
<th>Comparison between observed and simulated farm operational plan (crop mix) for each farm-type.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sine1</td>
</tr>
<tr>
<td>Obs</td>
<td>Sim</td>
</tr>
<tr>
<td>Millet (ha)</td>
<td>1.91</td>
</tr>
<tr>
<td>Maize (ha)</td>
<td>0.06</td>
</tr>
<tr>
<td>Groundnut (ha)</td>
<td>1.53</td>
</tr>
<tr>
<td>Manure application (ha)</td>
<td>1.14</td>
</tr>
<tr>
<td>Head of cows for fattening</td>
<td>0.5</td>
</tr>
<tr>
<td>Head of sheep for fattening</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Appendix E. Distribution of gross margins for each cropping system

Fig. E1 shows the whole distribution of gross margins (GM) for each cropping system. GMs are defined here as the difference between the stochastic total value of production (yield times unit price) and the production costs. Production costs include only the costs of seeds and chemical inputs. Neither the labor costs nor the value of the manure nutrients has been included in these cumulative distribution functions since the

Fig. E1. Cumulative distribution functions of gross margins for cereals (millet and maize) and groundnut cropping systems.
opportunity cost of family labor and the cost of manure produced on the farm vary between seasons. We observe that extensive cropping systems (i.e., without any use of inorganic fertilizer or manure) give less risky distributions than more intensive cropping systems (i.e., requiring inorganic fertilizer and/or manure). As an example in about 15% of the states of nature, the extra yield of millet obtained from inorganic fertilizer application cannot compensate for the cost of purchasing the fertilizer. This result is in accordance with well-known results from previous research reporting the risk-increasing property of crop intensification (Affholder, 1997; Rötter and van Keulen, 1997). The distribution of manure-based cropping system yields is also flatter. Note that the dominance of manure-based cropping systems over the extensive cropping system could result from not taking into account direct and indirect costs of farm manure in GM calculations. However, in the ANDERS model (and in the real world), the management of manure does involve labor input so that the risk at the field scale of a low yield obtained with manure application in the driest years may translate into economic risk at the farm scale. Moreover, the yield risk related to intensification is much higher in the Sine subzone, where the climate is drier than in Saloum. This risk is also higher for maize than for millet. The groundnut GM distributions indicate that fertilizer-based cropping systems are not much economically profitable since in about 60% and 80% of the states of nature (in the Sine and the Saloum subzones, respectively), extensive cropping systems give higher GM.

Appendix F. The bioeconomic ANDERS model

1. Sets

- \(ac\): agricultural activities
- \(ag\): age of family members
- \(an\): animal types
- \(e\): state of nature
- \(ge\): gender of family members
- \(inp\): inputs
- \(ins\): insurance type
- \(ne\): nutrient type (digestible nitrogen matter/energy in kcal)
- \(p\): period
- \(pdt\): agricultural products
- \(s\): soil types
- \(sps\): subsidy program scenario
- \(str\): straw type (from millet or maize; subset of \(pdt\) for straw)
- \(t\): type of off-farm labor (including agricultural and non-agricultural labor, remittances)
- \(tan\): animals used for traction (subset of \(an\))
- \(z\): field types

2. Variables

Endogenous variables are in \textit{UPPER CASE} and exogenous parameters in \textit{lower case}

- \(\pi_e\): income by state of nature
- \(\text{active}_e, ag\): active family members by gender and age
- \(\text{anim}_{an, p}\): stock of animals by type of animal and period
- \(\text{animneed}_{ne, p}\): animals nutritional needs (\(ne\)) by period
- \(\text{atneed}_{s, an, p}\): animal traction requirements by field type, soil type, agricultural activity and period
- \(\text{BA}_{an, p}\): animals bought by type of animal and period
- \(\text{BC}_{pdt, p, e}\): agricultural products bought for consumption
- \(\text{BRW}_p\): borrowing by period
- \(\text{CASH}_p\): Cash available by period \(p\) and state of nature
- \(\text{cash}_{sps}\): Cash transfer by subsidy program scenario
- \(\text{caniman}\): return from animal selling by animal type
- \(\text{co}_{s, ac, inp, p}\): input coefficient for agricultural activities by animal type by field type, soil type, agricultural activity, input and period
- \(\text{coanim}_{an}\): costs associated with raising animals by animal type
- \(\text{CONSA}_{pdt, p, e}\): animal consumption of farm products by period, product and state of nature.
- \(\text{CONSAT}_{pdt, e}\): Total animal consumption by period, product and state of nature.
- \(\text{CONSH}_{pdt, e}\): human consumption of agricultural products by period, product and state of nature
- \(\text{CONSO}_{pdt, e}\): Other consumption of farm products by period, product and state of nature (straw)
- \(\text{cont}_{ne}\): Nutritional content of purchased feedstock by nutrient type
- \(\text{cont}_{sps, ne}\): Nutritional content of pasturing by nutrient type and period
- \(\text{cont}_{an}\): Nutritional content of straw by nutrient type
- \(\text{FEED}_{an}\): feedstock bought for animals by animal type
- \(\text{FIN}_{pdt, e}\): Cash available at the end of the year, by state of nature
- \(\text{FINSTOCK}_{pdt, e}\): agricultural product stocks at the end of the year by period and state of nature
- \(\text{human}_{ag, ge}\): family members by age and gender
- \(i\): interest rate
- \(\text{incash}\): initial cash
- \(\text{inistock}_{pdt}\): initial stock by agricultural product
- \(\text{isub}_{sps}\): subsidy on interest rate by subsidy program scenario

3. Equations

Objective function

\[ EU = \frac{1}{n} \sum_{i=1}^{n} \left( 1 - \exp \left( -r_a (\pi_i + w) \right) \right) \]  

Certainty equivalent income

\[ CEI = \frac{\ln[1 - EU]}{-r_a} - w \]  

Income

\[ \pi_i = \sum_{p, t, z} \left( X_{i, t, z, ac} \cdot \text{yield}_{i, t, z, ac, pdt, z} \right) \cdot \text{CONSA}_{p, t, z} \cdot \text{CONSO}_{p, t, z} \cdot \sum_{i, p, t, z} \left( \text{CONSA}_{i, t, z} \cdot \text{CO}_i \cdot \text{CONSO}_{i, t, z} \cdot \text{PCO}_{i, t, z} \cdot (1 - \text{insubs}_{i, t, z}) \right) \]

\[- \sum_{p} \text{WX}_p \cdot \text{PX}_p \cdot \sum_{i, p, t, z} \left( \text{INSX}_{i, t, z, ac, ins} \cdot \text{PAYOFF}_{i, t, z, ac, ins, e} \right) \cdot \text{INSX}_{i, t, z, ac, ins, e} \]

\[ + \sum_{i, p} \left( \text{SA}_{i, p} \cdot \text{SA}_{i, p} \right) \cdot \text{BA}_{i, p} \cdot \text{WX}_{i, p} \cdot \text{WX}_{i, p} \]

\[ + \sum_{i, p} \text{OFF}_{i, p} \cdot \sum_{i, p} \text{cash}_{i, p} \cdot \text{BRW}_{i, p} \]

Land constraint

\[ \sum_{i, z, ac} X_{i, t, z, ac} \leq \text{land}_{i, z} \]  

Labor needs

\[ \sum_{i, t, z, ac} \text{lab}_{i, t, z, ac} + \sum_{i, p, t, z} \left( \text{BA}_{i, p} \cdot \text{SA}_{i, p} \right) \cdot \text{lab}_{i, p} + \sum_{i, p} \text{OFF}_{i, p} \leq \text{WFAM}_p + \text{WX}_p \]  

Labor constraint
WFAM_b, + \sum_i OFF_i, p \leq \sum_{a, g} activ_i, a, g * wd_{i, g, ag, p} \quad (F5)

Animal traction constraint
\[ \sum_{s, z, ac} \text{atneed}_{s, z, ac, p} - RENTA_{p} \leq \sum_{i, n} \text{anim}_{i, n} * \text{trac}_{i, n, p} \quad (F6) \]

Cash equations
\[ CASH_{p, e} \geq 0 \quad (F7) \]

For \( p \geq 1 \):
\[ CASH_{p, e} = CASH_{p-1, e} + \sum_{pdt} SC_{pdt, p-1, e} * pvac_{pdt, p-1, e} - \sum_{a, n} \sum_{s, z, ac} X_{s, z, ac} * \text{co}_{a, n, s, z, ac, p-1, e} * \text{pco}_{a, n, p-1} * (1 - \text{insubs}_{a, n, p-1, e}) - WX_{p-1, e} * px_{p-1} \]
\[ \quad - RENTA'Pra + \sum_{a, n} (\text{canim}_{a, n} - \text{coanim}_{a, n} - \text{FEED}_{a, n} * \text{pfeed}_{a, n}) * (\text{anim}_{a, n, p-1} - \text{SA}_{a, n, p-1} + \text{BA}_{a, n, p-1}) + (\text{SA}_{a, n, p-1} - \text{BA}_{a, n, p-1}) * \text{panim}_{a, n, p-1} \]
\[ \quad - \sum_{pdt} \text{BC}_{p-1, pdt, e} * \text{pac}_{pdt, p-1, pdt, e} + \sum_{i, t} OFF_{i, p-1, e} + BRW_{p-1} - \text{minc}_{p-1} - \sum_{a, i, int} \text{insus}_{a, i, int} * (1 - \text{insubs}_{a, i, int}) * \text{INSX}_{a, i, int} \]
\[ + \text{cashtr}_{p} + \text{PAYOFF}_{a, i, int} * \text{INSX}_{a, i, int} \quad (F7B) \]

Final cash
\[ \text{FINCASH}_{e} = CASH_{P-1, e} + \sum_{pdt} SC_{pdt, P-1, e} * pvac_{pdt, P-1, e} + \sum_{a, n} \text{SA}_{a, n, P-1, e} + \text{manuprod}_{a, n, p, P} - \sum_{a, n} \sum_{s, z, ac} X_{s, z, ac} * \text{yield}_{s, z, ac, pdt, e} \]
\[ + \sum_{a, n} \sum_{s, z, ac} \text{yield}_{s, z, ac, pdt, e} \quad (F8) \]

Supply-utilization account for \( p \geq 1 \):
\[ \text{STOCKAC}_{pdt, p, e} = \text{STOCKAC}_{pdt, p-1, e} + \text{BC}_{pdt, p-1, e} - \text{SC}_{pdt, p-1, e} - \text{CONSAT}_{p-1, pdt, e} - \text{CONSH}_{p-1, pdt, e} - \text{CONSO}_{p-1, pdt, e} \]
\[ + \text{if}(P = P6): \sum_{a, s, z, ac} \text{yield}_{a, s, z, ac, pdt, e} \quad (F9) \]

Final stocks
\[ \text{FINSTOCKAC}_{pd, e} = \text{STOCKAC}_{pd, P7, e} + \text{BC}_{pd, P7, e} - \text{SC}_{pd, P7, e} \quad (F10) \]

Family nutritional constraint
\[ \sum_{a, g} \text{kalneed}_{a, g, p} \text{human}_{a, g, p} \leq \sum_{pd} \text{kcal}_{pd} * \text{CONSH}_{pd, p, e} \quad (F11) \]

Animals nutritional constraint
\[ \sum_{a, n, p} \text{anim}_{a, n, p} \text{anim}_{a, n, p, e} * (\text{anim}_{a, n, p} + \text{BA}_{a, n, p} - \text{SA}_{a, n, p}) \leq \text{contpa}_{a, p, p, e} \text{past}_{p, p} + \sum_{a, n} \text{contpd}_{a, n} * \text{CONSAT}_{a, n, pdt, e} + \sum_{a, n} \text{conf}_{a, n} * \text{FEED}_{a, n} \quad (F12) \]

Pasture capacity constraint
\[ \text{past}_{p, p} \leq \text{Pastarea}_{p} * \text{YPast}_{p, p} \quad (F13) \]

Manure production
\[ \sum_{a, n, p} (\text{anim}_{a, n, p} + \text{BA}_{a, n, p} - \text{SA}_{a, n, p}) * \text{manuprod}_{a, n, p} \text{straw}_{a, n, p, e} = \text{CONSO}_{p, e} \quad (F14) \]

Manure balance
\[ \sum_{p} \sum_{s, z, ac} X_{s, z, ac} * \text{co}_{a, n, s, z, ac, p, e} \leq \sum_{a, n} \text{anim}_{a, n, p} * \text{manuprod}_{a, n} \quad (F15) \]

Viability constraint on expected cash
\[ \text{inicash} \leq \frac{1}{n} \sum_{e=1}^{n} \text{FINCASH}_{e} \quad (F16) \]

Viability constraint on expected energy (in kcal) for stocks
\[ \sum_{pd} \text{instock}_{pd} * \text{kcal}_{pd} \leq \frac{1}{n} \sum_{e=1}^{n} \sum_{pd} \text{FINSTOCKAC}_{pd, e} * \text{kcal}_{pd} \quad (F17) \]

Viability constraint on cash (softened by informal insurance)
\[ 0.5* \text{inicash} \leq \text{FINCASH}_{e} \quad (F18) \]

Viability constraint on stocks (softened by informal insurance)
under tropical dryland condition. Field Crop Res. 41, 109–121.